Estimation of Viable Root-length Density of Heat-tolerant 'Crenshaw' and 'L93' Creeping Bentgrass by an Accumulative Degree-day Model

Maxim J. Schlossberg[1] and Keith J. Karnok[2]
Department of Crop and Soil Sciences, University of Georgia, Athens, GA 30602-7272

Gil Landry, Jr.[2]
Department of Crop and Soil Sciences, University of Georgia, Griffin, GA 30223-1797

ADDITIONAL INDEX WORDS. *Agrostis stolonifera* var. *palustris,* rhizotron, turfgrass, high temperature stress, golf course putting greens

ABSTRACT. Subjection of intensively managed creeping bentgrass *[Agrostis stolonifera* L. *var. palustris* (Huds.). Farw., (syn. *Agrostis palustris* Huds.)] to supraoptimal soil temperatures is deleterious to root viability and longevity. The ability to estimate viable root length would enable creeping bentgrass managers to more accurately schedule certain management practices. The purpose of this rhizotron study was to develop a model, based on an accumulated degree-day (ADD) method, capable of estimating viable root length density of established 'Crenshaw' and 'L93' creeping bentgrass maintained under putting green conditions. Viable root length density observations were made biweekly and soil temperature data collected April through September 1997, and January through August 1998 and 1999. Relative viable root length density (RVRLD) is defined as the measured viable root length density divided by the maximum density attained that spring. In both years, maximum annual viable root length density for all plots was reached, on average, by 138 days from the beginning of the year (18 May). Cultivar and year effects were nonsignificant *(P* = 0.67 and 0.20, respectively). Degree-day heat units were calculated using an array of base temperatures by integral and arithmetical methods. Although the two accumulative methods proved suitable, the model regressing arithmetical degree-day accumulations against the bentgrass RVRLD provided a better fit to the data set. Use of the 10 °C base temperature in the arithmetical ADD calculations provided the following model; RVRLD = 0.98 - [1.30 x 10^{-1} (ADD)], accounting for 83.8% of the experimental variability *(P* < 0.0001). As several abiotic/edaphic factors have been shown to significantly influence root growth and viability, development of a widely usable model would include additional factors.

Cool-season turfgrasses maintain optimum root growth at soil temperatures between 10 and 18 °C , and optimum shoot growth at 15 to 24 °C (Beard, 1973). This temperature range limits regions where cool season grasses such as creeping bentgrass *[Agrostis stolonifera* var. *palustris* (Huds.). Farw., (syn. *Agrostis palustris* Huds.)] proliferate. As creeping bentgrass is maintained in temperate and subtropical climates worldwide, soil temperatures often exceed this optimum range for varying periods of time.

For the aforementioned reason, several studies have been conducted to investigate cessation of bentgrass root growth at supraoptimal soil temperatures. In a growth chamber study, Beard and Daniel (1965) showed root growth to be reduced by temperatures of 32.2 °C compared to lower temperatures. Overall root length of creeping bentgrass maintained at 32.2 °C was 15%, 30%, and 75% of root length in pots maintained at 15.6, 21.1 °C, and 26.7 °C, respectively, over a 45-d period. Discoloration and desiccation of roots at 26.7 °C were noted within 5 weeks of initiation, and similar effects on root tissue were observed immediately at 32.2 °C (Beard and Daniel, 1965).

Schmidt and Blaser (1967) evaluated root and shoot growth of 'Cohansey' bentgrass maintained at 12,24, or 36 °C. Dry weights of roots grown at 36 °C were 70% and 54% of the weight of roots grown at 24 or 12 °C, respectively. Physiological effects of elevated temperatures included increased respiration rates and decreased acid-extractable carbohydrates. A subsequent examination of the effects of temperature, soil texture, and water table height on root length of 'Penncross' creeping bentgrass was performed in controlled climate rooms. Root length following 9 weeks at 30 °C was 33.1 % that of creeping bentgrass maintained at 15 °C (Ralston and Daniel, 1972).

Recent growth chamber experiments (Huang et al., 1998) examined 'Penncross' and 'Crenshaw' creeping bentgrass cultivars under optimal and supraoptimal days/nights of 22/15 °C or 35/25 °C over a 35-d period. Root parameters were significantly reduced under the elevated temperature regimen, as early as 21 [dry weight (DW)] and 7 d (percentage root viability) following temperature initiation (Huang et al., 1998). Temperature interactions with cultivar were generally nonsignificant. More recent growth chamber investigations utilized water baths to compare bentgrass root and shoot growth under factorial combinations of supraoptimal air and/or soil temperatures. Twenty-four days following temperature regime initiation, bentgrass grown at air/soil temperatures of 35/20 °C had significantly greater root DW than bentgrass grown at air/soil temperatures of 20/35 °C. Root mortality for 'L93', specifically, was less at air/soil temperatures of 35/20 °C than at air/soil temperatures of 20/35 °C (Huang and Xu, 2000). These results suggest that creeping bentgrass root growth is highly responsive to soil temperature and that prolonged supraoptimal root temperatures alone have greater detrimental effects on shoot growth than supraoptimal shoot temperatures alone.

In field studies, Beard and Daniel (1966) concluded that soil temperature was the most influential abiotic factor affecting bentgrass root growth variability under irrigated conditions.

Received for publication 18 Apr. 2001. Accepted for publication 26 Nov. 2001. Research conducted at the University of Georgia Rhizotron, Athens, from the MS thesis of Maxim J. Schlossberg. The authors wish to acknowledge the thorough internal reviews by Hugh Earl and Tim Murphy, the constructive advice provided by the anonymous volunteer reviewers, and the financial and material contributions of the Georgia Turfgrass Assn. and RapidTurf, Inc., respectively.
'Doctoral candidate.
"Professor.

Their 15 cm soil depth temperature measurements were highly correlated with creeping bentgrass root growth and was the best predictor of seasonal variation for root growth. Field work in Kansas reported root growth and root initiation ceased by late July and severe root dieback occurred through Aug. (Liu and Huang, 1999). Again, cultivar differences were nonsignificant.

Root length density of creeping bentgrass is directly related to survivability under intense management and use. Reduction in root length density often precedes overall turfgrass quality decline (Aldous and Kaul'mann, 1979). A functional, extensive root system provides buffering capacity during plant adaptation to cdaphic and abiotic stresses. Ultimately, it is the root system alone that provides access to the essential mineral nutrients and water thai enable the turfgrass plant to persist (Duncan and Carrow, 1999).

Degree-days or heat accumulation units are used commonly to measure or predict the effect of temperature on biological processes and/or phenological changes. This concept applies to insects, plants, and most other ectotherms. The intrinsic value of degree-day prediction lies within linearization of temperature accumulation most pertinent to the plant growth response of interest. The accumulated degree-day concept integrates heat units over diurnal periods, minimizing inter-year variability. Some of the first published degree-day accumulation models for prediction include: corn *(Zeumays* L. var. *mays)* maturity (Gilmore and Rogers, 1958), sweet corn *(Zea mays* L. var. *ntgosa* Bonaf.) growth stages (Arnold, 1974), leaf emergence of sour cherry *(Primus cerasus* L.) (Eisensmith et al., 1980), completion of rest of peach | *Primus persica* (L.) Batsch (Peach Group)] (Richardson et al., 1974), germination of alfalfa *(Medicago sativa* L.) (Bahler etal., 1989), and date of full bloom for apple | *Mains sylvestris (L.)* Mill. var. *domestica* (Borkh.) Mansf.]. peach, and pear *(Pyrus communis* L.) (Anstey, 1966).

Several models have been developed and published for use in predicting growth and development of turfgrasses. These models include stress periods of cool season grasses (Danneberger and Turgcon, 1985). seedhead emergence of annual bluegrass *(Poa annua* L.) (Danneberger and Vargas, 1984), kentucky bluegrass *(Poa pratensis* L.) (Branham and Danneberger, 1989), and tall fescue *(Festuca* ***arundinacea*** Schreb.) (DiPaola et al., 1987), kentucky bluegrass root growth (Koski etal., 1988), and optimum growth regulator application timing (Danneberger et al., 1987). Additional models have been developed for turfgrass pest emergence prediction. These include brown patch *(Rhizoctonia solani* Kuhn) (Schumann et al., 1994), anthracnose *(CoHetotrichum graminicola*Ces. Wils.) (Dannebergeretal., 1984), andpythium *(Pythium uliimum* Trow.) disease outbreaks (Nutter et al., 1983), as well as crabgrass *[Digitaria ischaemum* (Schreb. ex Schweig.) Schreb. ex Muhl.| emergence (Fidanza et al., 1996), and sod webworm *[Crambuspraefectellus* (Zinck.)J (Tolley, 1986) and chinch *b\ig(Blissus leucopterus* Say) life cycles (Lin and McEwen, 1979).

Instant estimation of decline in creeping bentgrass viable root length during periods of stress would be helpful to turfgrass managers. For example, golf course superintendents managing creeping bentgrass putting greens often alter cultural practices before or during periods of high temperature stress. These alterations include customary increasing of mowing height and/or irrigation frequency, as well as reduction or discontinuation of N fertilization (Lucas, 1996). A predictive model would eliminate guesswork associated with these important decisions. Additionally, soil temperature degree-day accumulation (ADD) could be implemented to normalize independent temperature effects in similar field experimentation across different geographical regions. This could permit researchers to compare multisite phenological processes more accurately, reducing error associated with temperature interactions.

Thus, the objective of this research was to develop a simple and effective model to estimate the extent of bentgrass viable root length density decline in climates where soil temperatures exceed the established optimum range for extended time periods.

Materials and Methods

This study was conducted in the University of Georgia (UGA) Rhizotron, Athens. A rhizotron is an underground root observation laboratory with several individual soil-filled observation chambers with transparent viewing walls (Taylor, 1969). The facility allows vegetative plant growth to occur outdoors under field conditions while the root systems of those plants may be monitored continually in situ. The major advantage of studying plant roots in a rhizotron is root morphology and function can be observed extensively while the root system remains intact (Huck and Taylor, 1982). The UGA rhizotron is comprised of 24 observation chambers 1.9 m deep. The observation window of each chamber consists of a single pane of 2-cm-thick tempered plate glass set at 12.5° from vertical. The other three sides of each chamber are comprised of cinder block.

Chamber preparation began with placement of a wire screen over a 15-cm-diameter drainage hole at the bottom of each chamber. The chamber bottoms were then covered with 5 cm of coarse gravel and rinsed with a 1.1 % sodium hypochlorite solution and allowed to drain. Coarse sand was then packed into each chamber to a height of 139 cm in 15-cm increments. The bulk density of each installed increment was measured with a moisture density gauge (model 341 IB; Troxler Laboratories, Research Triangle Park, N.C.) and maintained between 1.3 and 1.4 gcm^{-1}. Layering between increments was prevented by lightly scratching the top 2 cm of each increment with a rake before the next addition of sand. Each observation chamber was divided with I-cm-thick plexiglass into four chambers 25 cm wide and 1 m long. The root zone was comprised of a 17 quartz sand : 3 sphagnum peat mixture (by volume), and was prepared off-site.

All chambers were constructed to U.S. Golf Association putting green specifications which included a 3-cm intermediate layer (USGA, 1993). Layering of the root-zone medium was prevented by the method mentioned above and bulk density maintained between 1.4 and 1.5 $genr^{1}$. Type-T copper-constantan thermocouples (Omega Eng., Inc., Stamford, Conn.) were installed in the root zones at depths of 10 and 20 cm, with the coupled junctions 14 and 12 cm from the viewing window, respectively.

On 23 Feb. 1997, sod of 'L93' and 'Crenshaw' creeping bentgrass were obtained from a local sod producer (RapidTurf, Inc., Rincon, Ga.) and transported to Athens. One week later the sod was cut into 25 x 100-cm strips and power-washed to remove all sand. Roots were clipped back to the mat/crown region and the sod was installed on the chambers. During the establishment phase, the plots were mowed daily and lightly topdressed weekly with the root medium material. Mowing height was reduced gradually during this period. On 10 Apr. 1997, mowing height was lowered to 0.4 cm and plots mowed 6 d a week for the remainder of the experiment.

Labeled fungicides and insecticides were applied equally to all plots on a curative basis. Weed encroachment was monitored weekly and weeds removed by hand. The turfgrass plots were topdressed with 8 m^3-ha^{-1} of the root zone medium approximately monthly and all plots irrigated equally to prevent wilt. Beginning 6 Mar. 1997, all plots were fertilized with 10-10-10 water soluble fertilizer providing N at 12.2 kg-ha ', P at 5.4 kg-ha^{-1}, and K at 10.1 kg-ha ' every 7 d through 10 Apr. Following experiment initiation, N at 15 kg-ha^{-1} was applied every 14 d in a nutrient solution (Hoagland and Arnon, 1938) beginning 18 Apr. 1997, and provided an annual N rate of 390.6 kg-ha^{-1}. One application of slow-release fertilizer (12-8-8) was applied in lieu of biweekly water soluble applications in Nov. 1998, providing N at 98 kg-ha^{-1} (42 kg N as methylene urea), P at 28.7 kg-ha^{-1}, and K at 54.2 kg-ha^{-1}. Biweekly fertilizer applications resumed mid-February 1999.

Root observations were taken every 14 ± 1 d on a 0.1 x 0.3-m grid centered permanently in the rhizotron viewing window. Long-wave ultraviolet (UV) (320 to 400 nm) light (model B-I00A/R Blak-Ray ultraviolet lamp; UVP, Inc.," San Gabriel, Calif.) was used to facilitate observation of actively growing, viableroots(Cooperetal., 1987; DyerandBrown, 1983;Goodwin and Kavanagh, 1948). Only roots which fluoresced under UV radiation visibly through the viewing window were quantified. Root measurements were initiated 12 Apr. 1997 and continued uninterrupted through August 1998, then resumed 1 Apr. 1999 and terminated 21 Aug. 1999. Styrofoam-insulated shields covered the viewing pane of each rhizotron chamber when measurements were not being taken. Air temperature in the viewing room was not artificially altered during the experimental period.

Viable root length was determined using the line intersect method as described by Newman (1966) and later modified by Tennant (1975). In the present study, 2-cm grid squares were used for quantification. Root length density (RLD) measurements are preferred to root lengths per unit area, as root water and mineral nutrient uptake are best related to RLD and models of uptake use RLD data (Upchurch, 1987). Therefore, we multiplied viable root length per unit area by the estimated depth of field into the soil (Sanders and Brown, 1978; Taylor and Bohm, 1976; Taylor and Klepper, 1971). Commonly used soil depths of field are 1 to 3 mm (Taylor and Bohm, 1976; Taylor and Klepper, 1971); we used a value of 2 mm. Due to structural supports inherent to the rhizotron construction, the top 2 cm of the soil profile was not visible. Therefore, viable root length density (VRLD) measurements consisted of all fluorescing roots at depths >2 cm.

Beginning 10 Apr. 1997, soil temperatures were recorded at the UGA rhizotron via installed thermocouples. To best serve potential users of the model, the authors weighed the ubiquity of 10-cm-depth soil probes in currently installed weather stations as well as 10-cm-depth soil temperature data via state sponsored environmental data sites on the world wide web. For this reason, the 10-cm-depth soil temperature data was the depth for which we accumulated degree-day units for entry into the model. Over the 3-year study, some thermocouples failed. Therefore, all temperature data presented are the averages of the last six functioning thermocouples at the 10 cm depth. A 21x datalogger (Campbell Scientific, Inc., Logan, Utah) recorded maximum and minimum soil temperatures on a 24 h basis. Distribution of temperature values recorded by the thermocouples was normal and without block effect. Maximum and minimum hourly averages for each 24 h period (f) beginning at midnight were used to calculate degree-days (DD) according to the following integral (Baskerville and Emin, 1969) and arithmetical methods:

$$\text{Arithmetical DD} = m - k \quad \text{Eq. [1]}$$

$$\text{Integral DD} = \pi^{-1} [\, w \int_{\theta}^{\pi/2} \sin t \, dt - \int_{\theta}^{\pi/2} (k - m)\, dt \,] \quad \text{Eq. [2]}$$

where m = (maximum "C + minimum "C)/2, w = (maximum °C - minimum "C)/2, k = base temperature ("C), t = 24 h period beginning at midnight, and 0 = arcsin f(k - minimum °C)/w]

Calculations for the integral method were facilitated by MathCad 6.0 (MathSoft, Inc., Cambridge, Mass.).

Accumulated degree days (ADD) are simply the running summation of DD from the start of the calendar year through September. The above equations were chosen for use in the present study because they permit use of a threshold (base) temperature, below which the observed process ceases. Accordingly, if the average (arithmetical) or maximum (integral) hourly temperature for the given 24-h period did not exceed the base temperature, then no degree-days (DD) accumulated during that 24-h period.

Paramount to degree-day accumulation model success is accurate selection of base temperature. Koski et al. (1988) modeled rooting of Kentucky bluegrass using integral ADD and a base temperature of 10 °C. In the present study, accumulated degree-day units were tabulated corresponding to base temperatures of 10. 12, 14. 16. 18, 20, 22, and 24 "C and evaluated iteratively. Turfgrass researchers have inferred temperature-stress degree day units by implementing an upper threshold (32 "C) in an integral ADD model, then subtracting those degree-day units from the same approximation without an upper threshold (Danneberger and Turgeon. 1985). In the present investigation, no upper threshold was used in calculation of ADD, as increasingly supraoptimal soil/solution temperature has been shown to be further deleterious to viable bentgrass root length (Kurtz and Kneebone, 1980).

The experimental design was a randomized complete block with four replications of each cultivar. Degree-day accumulations of each base temperature were correlated with relative viable root length density (RVRLD). Correlation coefficients relating RVRLD to ADD values, regardless of base temperature instituted, were negative and very similar. Diagnostic regression analysis was conducted iteratively for independent variable(s) selection. Multivariate analysis by addition of terms (ADD of other base temperatures and/or transformed ADD values) improved *r* values, but not beyond typical novel second-term contributions, and was not examined further. Univariate least squares prediction and analysis of variance (ANOV A) of RVRLD and ADD data were facilitated by the PROC REG and ANOVA subroutines of SAS (SAS Inst., Inc., 1987).

Results

ANOVA identified years as a significant source of variance *(P* = 0.031). The specific source was 1997, the establishment year. RVRLD in 1997 reached its maximum in July, then diminished slowly, resulting in an inverse quadratic response of RVRLD to ADD for all base temperatures. These data corresponded well with other establishment-season root data reported by Briscoe and Jacobs (1997). In that field study, root length of 'Penncross' and 'SR 1020' creeping bentgrass followed an asymptotic response to time in the year following establishment by seed. Considering bentgrass is a resilient perennial species and that establishment seasons are uncommon in typical management scenarios, the 1997 data were removed. For the 1998 and 1999 data set (n = 168), only integral and arithmetical ADD signifi-

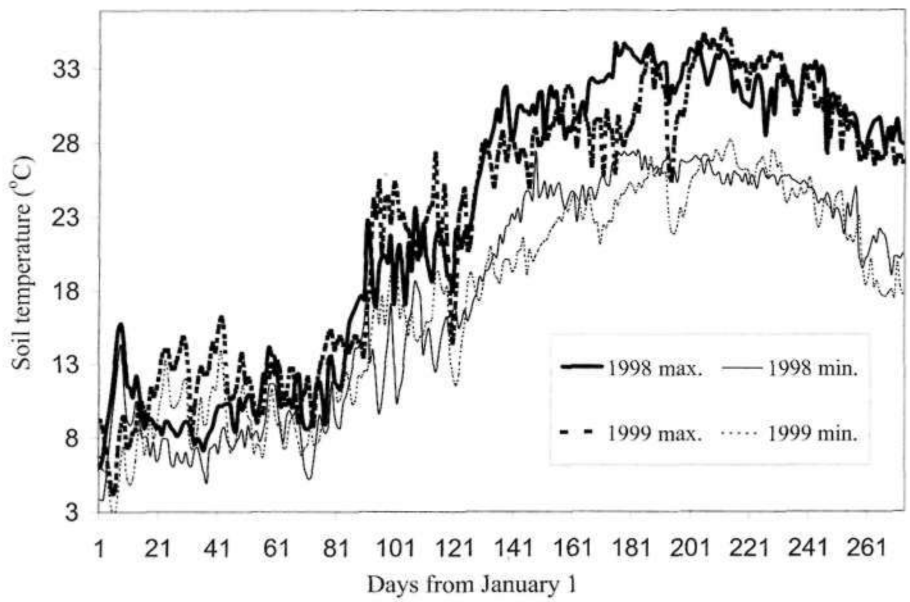

Fig. I. Seasonal maximum and minimum soil temperatures (10 em depth) recorded at UGA rhizotron, 1998 and 1999.

cantly varied RVRLD. Therefore, intercept and slope estimates for both cultivars and years were inferred to be statistically equal and pooled for regression analysis.

Soil temperatures over the two experimental seasons, 1998 and 1999, were similar (Fig. I). Seasonal arithmetic DD accumulation was more linear than the integral DD accumulation over the same period.As the 10 cm soil depth is buffered against extreme temperature fluctuations, a lower base temperature selection could be expected to provide an evenly metered accumulation of heat units. The arithmetical DD method using 10 °C as the base temperature provided an ADD trend with which the observed reduction in relative viable root length data was best associated. Having the highest *r* and regression F value, $ADD_{10°C}$ yielded the following relation of response to independent variables in the linear regression

$$RVRLD = \beta_0 + \beta_1(ADD) + \epsilon \qquad \text{Eq. [3]}$$

where $ADD_{10°C}$ equals 10 cm deep soil temperature degree-day accumulation above 10 °C beginning 1 Jan.; β_0 and β_1 equal the least squares estimates of the partial regression coefficients; and ϵ is a normally distributed random variable with mean zero and variance σ^2. The regression fit to experimental data is (Fig. 2):

$$RVRLD = 0.98 - 1.30 \times 10^{-4}(ADD_{10°C}) \qquad \text{Eq. [4]}$$

All regression assumptions and linear goodness of fit (F_{lf}) were met by this regression equation accounting for 57.6% of the experimental variability (Table 1). Furthermore, the regression F value exceeded the critical F value (*P* = 0.01) by a factor of 33. This validates the accuracy and value of Eq.[4] under stringent regression model adequacy testing (Draper and Smith, 1966; Suich and Derringer, 1977). Ostensibly, this full model (n = 168) carried error associated with eight replications at each of the 21 observations. As ANOVA revealed replications to be a nonsignificant source of variation, we reduced the data set by averaging the eight replications for each observation date (n = 21). Univariate least squares regression of the reduced data set yielded the model shown in equation 4. All regression

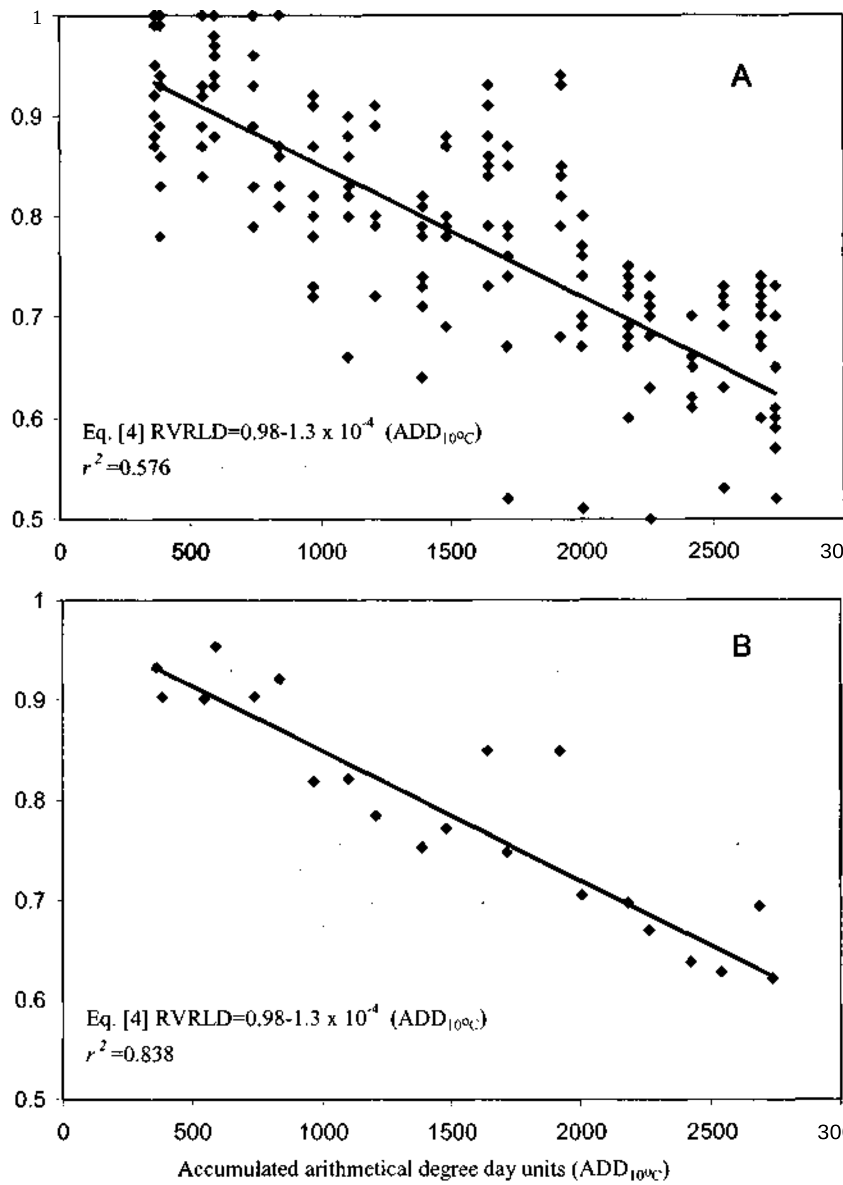

Fig. 2. (A) Full model estimate for RVRLD using the arithmetical degree-day calculation method and (B) reduced model estimate for RVRLD using the arithmetical degree-day calculation method. Each symbol is based on eight observations.

Table 1. Full regression parameters of relative viable root length density (RVRLD) by degree day accumulation model and base temperature selection ($n = 168$).

Base	Integral method					Arithmetical method				
temp (°C)	B_0 ($\times 10^{-1}$)	B_1 ($\times 10^{-4}$)	r^2 (%)	cv	F_0	B_0 ($\times 10^{-1}$)	B_1 ($\times 10^{-4}$)	r^2 (%)	cv	F_0
10	9.3	−1.7	36.1	11.8	6.41***	9.8	−1.3	57.6	10.5	2.35
12	9.3	−2.0	36.2	11.8	6.39***	9.6	−1.4	56.9	10.6	2.50***
14	9.2	−2.3	36.6	11.8	6.31***	9.5	−1.6	56.6	10.7	2.56***
16	9.2	−2.6	37.3	11.7	6.15***	9.4	−1.9	56.6	10.7	2.57***
18	9.1	−3.2	37.8	11.7	6.04***	9.3	−2.2	55.7	10.8	2.76***
20	9.0	−3.8	37.2	11.7	6.19***	9.2	−2.7	53.4	11.1	3.24***
22	8.9	−4.8	35.5	11.9	6.57***	9.0	−3.5	50.4	11.4	3.86***
24	8.8	−6.3	32.2	12.2	7.28***	8.9	−4.8	46.2	11.9	4.75***

***F statistic for linear regression lack of fit testing significant at $P < 0.001$ ($F_{0.001, 19, 147} = 2.49$).

assumptions were met by this regression equation and the r^2 was improved to 0.838 (Fig. 3).

Discussion

Within the confines of the above-described research, heat tolerant bentgrasses lose 1% of viable root length every 77 ADD|,)O$_c$ of soil temperature (10 cm depth). In growth chamber experimentation, the decline of creeping bentgrass viable root length density has been reported to occur near a threshold soil temperature of 30 °C, and has been attributed to an imbalance of respiration and photosynthesis rates (Huang and Gao, 2000). Beard and Daniel (1966) concluded temperature was the most consistent environmental factor accounting for variation in root number and color of irrigated creeping bentgrass. They determined the cv to be decreased substantially when mean soil temperature of the 4 d previous to root length observations were used instead of 1 d. This indicates cumulative effect of temperature is more influential than instantaneous temperature, and adds merit to our degree-day predictive model. Koski (1983) showed that root growth of Kentucky bluegrass was closely related to changes in soil temperature, with 76% of the variability in root production accounted for by regression of the average soil temperature for the 24-h period before collection of rooting growth data. However, when average temperature for the previous 5 d was used, 89% of the variability in root growth was accounted for by regression. Xu and Huang (2000) concluded soil temperature was more critical than air temperature when evaluating root growth of creeping bentgrass.

Differences in geography would be expected to impart some influence on soil temperature; however, turfgrass systems lend themselves to the universal application of soil temperature-based model equations. Densely growing perennial grasses minimize the extremes of the daily sinusoidal soil temperature curve compared to bare soil (Jury et al., 1991). Another inherent property of grasses is reduction of soil type/heat retention interaction effects. Soil temperature heat flux is most significantly influenced by incoming solar radiation, which affects the albedo of variously colored soil differently. This probable source of model error is effectively neutralized by the prostrate growth habit and opaque qualities of a healthy turfgrass canopy. In the case of extreme variation between golf course putting green microenvironments (e.g., shaded/northern slope vs. full sun/ southern slope), a weighted coefficient could be used to increase or reduce acquired soil temperature ADD|$_0$o$_c$ values accordingly.

The above proposed model could help determine timing of management practices that optimize root growth, or when to discontinue practices which deter growth. Examples of cultural management practices implemented commonly by turf managers which may optimize root growth include replacement of N fertilizer applications with foliar Fe feeding for canopy color maintenance, and raising mowing height. Examples of cultural management practices that would be expected to adversely affect plant health under conditions of low RVRLD may include greens rolling, double cutting, topdressing, or infrequent irrigation scheduling.

Although the present study has demonstrated a relationship between RVRLD and ADD|$_0$o$_c$, it is important to note the results are clearly confined by the cultural conditions imposed. This model was developed from two seasons which possessed very similar soil heat accumulation patterns (Fig. 1). An improved model would include other terms: possibly mowing height, degree of imposed traffic, soil moisture, air temperature, solar irradiance/quality, and atmospheric humidity levels.

Literature Cited

Aldous, D.E. and J.E. Kaufmann. 1979. Role of root temperature on shoot growth of two Kentucky bluegrass cultivars. Agron. J. 71:545-547.

Anstey, T.H. 1966. Prediction of full bloom date for apple, pear, peach and apricot from air temperature data. Proc. Amer. Soc. Hort. Sci. 88:57-68.

Arnold. C.Y. 1974. Predicting stages of sweet corn *(Zea mays* L.) development. J. Amer. Soc. Hort. Sci. 99:501-505.

Bahler, C, R.R. Hill, and R.A. Byers. 1989. Comparison of logistic and Weibull functions: The effects of temperature on cumulative germination of alfalfa. Crop Sci. 29:142-146.

Baskerville, G.L. and P. Emin. 1969. Rapid estimation of heat accumulation from maximum and minimum temperatures. Ecology 50:514-517.

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice-Hall, Englewood Cliffs, N.J.

Beard, J.B. andW.H. Daniel. 1965. Effect of temperature and cutting on the growth of creeping bentgrass *(Agrostis palustris* Huds.) roots. Agron. J. 57:249-250.

Beard, J.B. and W.H. Daniel. 1966. Relationship of creeping bentgrass *(Agrostispalustris* Huds.) root growth to environmental factors in the field. Agron. J. 58:337-339.

Branham, B.E. and T.K. Danneberger. 1989. Growth suppression of 'Kenblue' Kentucky bluegrass using plant growth regulators and degree day application timing. Agron. J. 81:749-752.

Briscoe. C. and B.C. Jacobs. 1997. Changes in root growth in the twelve months following establishment of two cultivars of bent, *Agrostis stolonifera.* Intl. Turfgrass Soc. Res. J. 8:621-627.

Cooper. R.J., P.R. Henderlong. J.R. Street, and K.J. Karnok. 1987. Root growth, secdhead production, and quality of annual bluegrass as affected by mefluidide and a wetting agent. Agron. J. 79:929-934.

Danneberger,T.K.,B.E.Branham,andJ.M.Vargas, Jr. 1987. Mefluidide applications for annual bluegrass seedhead supression based on degree day accumulation. Agron. J. 79:69-71.

Danneberger, T.K. and A.J. Turgeon. 1985. Climate adaptability of three cool season grasses in the northeast U.S. based on growing degree days. p. 801-806. In: F. Lemaire (ed.). Proc. Intl. Turfgrass Res. Conf. vol. 5.

Danneberger, T.K. and J.M. Vargas, Jr. 1984. Annual bluegrass seedhead emergence as predicted by degree day accumulation. Agron. J. 76:756-758."

Danneberger. T.K., J.M. Vargas, Jr., and A.L. Jones. 1984. A model for weather forecasting of anthracnose on annual bluegrass. Phytopathology. 74:448-45 L.

DiPaola. J.M.. W.M. Lewis, and W.B. Gilbert. 1987. A growing degree index for tall fescue seedhead suppression. Agron. Abstr. p. 134.

Draper, N.R. and H. Smith. 1966. Applied regression analysis. Wiley. New York.

Duncan, R.R. and R.N. Carrow. 1999. Turfgrass molecular genetic improvementforabiotic/edaphic stress resistance. Adv. Agron. 67:233-305.

Dyer, D. and D.A. Brown. 1983. Relationship of fluorescent intensity to ion uptake and elongation rates of soybean roots. Plant Soil 72:127—134.

Eisensmith, S.P., A.L. Jones, and J.A. Flore. 1980. Predicting leaf emergence of 'Montmorency' sour cherry from degree day accumulations. J. Amer. Soc. Hort. Sci. 105:75-78.

Fidanza, M.A.. P.H. Dcrnoeden, and M. Zhang. 1996. Degree-days for predicting smooth crabgrass emergence in cool season turfgrass. Crop Sci. 36:990-996.

Gilmore. Jr., E.C. and J.S. Rogers. 1958. Heat units as a method of measuring maturity in corn. Agron. J. 50:611-615.

Goodwin. R.H. and F. Kavanagh. 1948. Fluorescing substances in roots. Bui. TorreyBot. Club 75:1-17

Hoagland, D.R. and D.I. Arnon. 1938. The water-culture method for growing plants without soil. Univ. Calif. Agr. Expt. Sta. Circ. 347.

Huang. B. and H. Gao. 2000. Growth and carbohydrate metabolism of creeping bentgrass cultivars in response to increasing temperatures. Crop Sci. 40:1115-1120.

Huang, B.. X. Liu, and J.D. Fry. 1998. Effects of high temperature and poor soil aeration on root growth and viability of creeping bentgrass. Crop Sci. 38:1618-1622.

Huang, B. and Q. Xu. 2000. Root growth and nutrient element status of creeping bentgrass cultivars differing in heat tolerance as influenced by supraoptimal shoot and root temperatures. J. Plant Nutr. 23:979-990.

Huck, M.G. and H.M.Taylor. 1982.Therhizotronasatool for research. Adv. Agron. 35:1-35.

Jury. W.A., W.R. Gardner, and W.H. Gardner. 1991. Soil physics. Wiley, New York.

Koski. A.J. 1983. Seasonal rooting characteristics of five cool season turfgrasses. MS thesis. Ohio State Univ., Columbus.

Koski, A.J.. J.R. Street, and T.K. Danneberger. 1988. Prediction of kentucky bluegrass root growth using degree day accumulation. Crop Sci. 28:848-850.

Kurtz, K.W. and W.R. Kneebone. 1980. Influence of aeration and genotype upon root growth of creeping bentgrass at supra-optimal temperatures. Intl. Turfgrass Res. J. 3:145-148.

Lin, B. and R.A. McEwen. 1979. Chinch bug life cycle forecast and prediction model. Environ. Entomol. 8:512-515.

Liu, X. and B. Huang. 1999. Genetic and seasonal variations in turf and root growth of creeping bentgrass. Agron. Abstr.

Lucas, L.T. 1996. Heat stress and decline of creeping bentgrass. Turfgrass Trends 5(7): 1-8.

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

Nutter. L.J., D. Cole, and A.L. Schein. 1983. A model for prediction of pythium blight in turfgrass. Plant Dis. 67:1 126-1 128.

Ralston, D.S. and W.H. Daniel. 1972. Effect of temperatures and water table depth on the growth of creeping bentgrass roots. Agron. J. 64:709-713.

Richardson, E.A., S.D. Seclcy, and D.R. Walker. 1974. A model for estimating the completion of rest for 'Redhaven' and 'Elberta' peach trees. HortScience 9:331-332.

Sanders. J.L. and D.A. Brown. 1978. A new fiber optic technique for measuring root growth of soybeans under field conditions. Agron. J. 70:1073-1076.

SAS Institute, Inc. 1987. SAS user's guide: Statistics. 6th ed. SAS Inst., Inc., Cary, N.C.

Schmidt, R.E. and R.E. Blazer. 1967. Effect of temperature, light and nitrogen on growth and metabolism of 'Cohansey' bentgrass *(Agrostis palustris* Huds.). Crop Sci. 7:447^151.

Schumann, G.L., B.B. Clarke. L.V. Rowley, and L.L. Burpee. 1994. Use of environmental parameters and immunoassays to predict rhizoctonia blight and schedule fungicide applications on creeping bentgrass. Crop Protection 13:211-218.

Suich, R. and G.C. Derringer. 1977. Is the regression equation adequate?—One criterion. Technometrics 19:213-216.

Taylor, H.M. 1969. The rhizotron at Auburn, Alabama: A plant root observation laboratory. Auburn Univ. Agr. Expt. Sta. Circ. 171.

Taylor, H.M. and W. Bohm. 1976. Use of acrylic plastic as rhizotron windows. Agron. J. 68:693-694.

Taylor, H.M. and B. Klepper. 1971. Water uptake by cotton roots during an irrigation cycle. Austral. J. Biol. Sci. 24:853-859.

Tennant, D. 1975. A test of a model line intersect method of estimating root length. J. Ecol. 63:995-1001.

Tolley, R. 1986. Predictive model for emergence of sod webworm larvae. J. Econ. Entomol. 79:400-404.

Upchurch. D.R. 1987. Conversion of minirhizotron-root intersections to root length density, p. 51-65. In: H. Taylor (ed.). Minirhizotron observation tubes: Methods and applications for measuring rhizosphere dynamics. Amer. Soc. Agron. Spec. Publ. 50.

U.S. Golf Association (USGA). 1993. USGA recommendations for a method of putting green construction. USGA Green Section Record (Mar./Apr.):l-2I.

Xu, Q. and B. Huang. 2000. Growth and physiological responses of creeping bentgrass to changes in air and soil temperatures. Crop Sci. 40:1363-1368.