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Estimation of cardinal temperatures for seedling emergence in corn

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Abstract

To grow corn successfully, it is necessary to obtain information about the effects of planting date on its yield performance. Therefore, the main objective of this study was to develop a model for its seedling emergence. For this purpose, a two-year field experiment (2011 and 2012) with different sowing dates (21th and 28th of May, 4 th, 11th, 18th, 24 th of June, 1th and 8th of July) was conducted to determine minimum, optimum and maximum temperature for seedling emergence (cardinal) temperatures required for seedling emergence. The experimental design was split plot with nine sowing dates in main plot and four genotypes in sub plot in four replications. Three non-linear models including den-like, segmented, and beta functions were used to describe the relationship between emergence rate and temperature. Results showed that the effect of year and cultivars' emergence time were not significant, but the effect of sowing date was significant. By contrast, effects of sowing date, cultivar and their interaction were significant for emergence percentage. The response of corn emergence to temperature was best described by a segmented function with minimum cardinal temperatures ranging from 9.4 to 9.9^{o}C, optimum temperatures of 28.9 to 30.0^{o}C, and maximum temperatures 39.1 to 40^{o}C. Using these data, a seedling emergence model was developed which can be used to optimize corn sowing date.

Keywords: Beta function, Corn, Dent-like function, Emergence time, Segmented function.

Introduction

Corn (*Zea mays* L.) is one of major crops cultivated in Fars province, Iran due to its short growing season, and potentially high yield. Developmental stages of determinate crops such as cereals consist of two separate phases; vegetative and reproductive. The simulation of plant development is an important tool, which may help growers to track crop development, and is part of many crop simulation models (Costa and Barros, 2001). Photoassimilates are partitioned to different organs depending upon the developmental stage. Selection of adapted genotypes and field crop management practices such as fertilization, pests control and irrigation scheduling are better based on developmental stages than on calendar days (Streck et al., 2003). Accurate prediction of crop development is also very important in studies of the performance of agroecosystems under climate change scenarios (Streck and Alberto, 2006). Seedling emergence *per se* is probably the most important phenological event during vegetative phase which influences the success of an annual plant. This phenomenon represents the point in time when a seedling is weaned from dependence upon nonrenewable seed reserves originally produced by its parent, and when photosynthetic autotrophism begins. Timing of emergence often determines plant's successful competition in a stand, it's consumption by herbivores, disease infection, flowering, reproduction, and its maturity at the end of season. With so many important plant processes at stake, a thorough understanding of seedling emergence seems warranted. Surprisingly, emergence has not been studied in sufficient detail to permit reliable predictions for even our most common and important annual species (Forcella et al., 2000).

Maize (*Zea mays* L.) development is primarily driven by temperature (Coelho and Dale, 1980; Warrington and Kanemasu, 1983; Cutforth and Shaykewich, 1990), with air temperature being assumed to drive maize development from emergence to physiological maturity (Daughtry et al., 1984; Cutforth and Shaykewich, 1990). Temperature is arguably the most important environmental factor that affects plant development, growth, and yield. All biological processes respond to temperature, and all responses can be summarized in terms of three cardinal temperatures: a base or minimum (T_{min}), an optimum (T_{opt}), and a maximum (T_{max}). Knowledge of cardinal temperatures is necessary for successful seedling emergence of corn and is useful in decision making with respect to optimal sowing (Hant et al., 2001). The literature describing temperature effects on seedling emergence in corn is scarce, but there are some studies on other developmental stages at laboratory level. Birch et al. (1998a) reported a base temperature of 8^{o}C, optimum temperature of 34^{o}C and a ceiling temperature of 40^{o}C for leaf production in five corn genotypes. The same researchers studied temperature and photoperiod sensitivity of development in five cultivars of maize from emergence to tassel initiation (Birch et al., 1998b). The temperature response was the same in all cultivars, and was best described by a three-stage broken-stick linear function. Photoperiod sensitivity was linear at photoperiods in excess of 12.5 h. The minimum, optimum and maximum temperatures were 8, 34 and 40°C, respectively. Considering the insufficiency of studies about quantitative data on corn emergence, this research was conducted to estimate cardinal temperatures

Table 1. Results of two years combine analysis of variance for days to Table 1. 50% emergence and final emergence percentage for the field experiment.

SOV	Mean Squares	
	Days to emergence	Final emergence percentage
Block	0.59	0.058
Sowing Date	39.69*	0.372*
Error A	0.021	0.122
Cultivar	0.037	13.89*
Cultivar × Sowing date	0.16*	3.95*

* Significant at 5% level of probability.

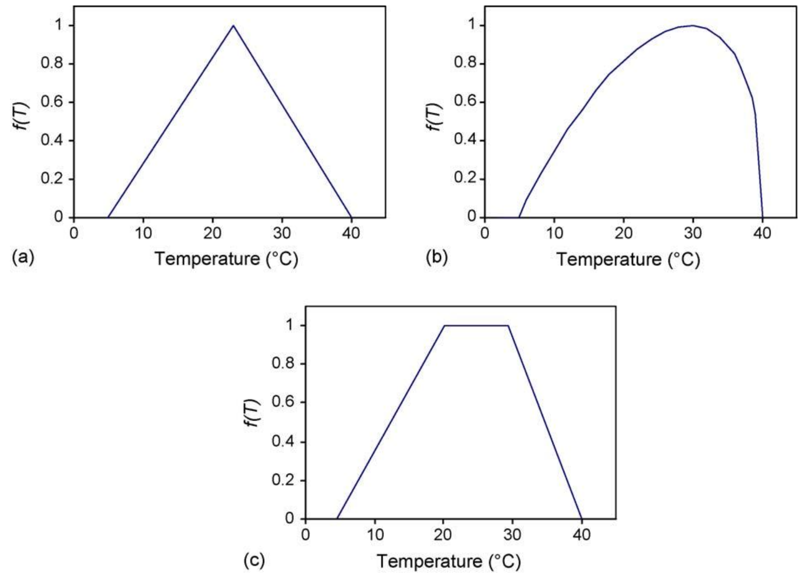

Fig 1. Functions used to describe the response of emergence rate to temperature: (a) segmented, (b) beta, and (c) dent-like (*f(T):* Thermal function).

(base, optimum and ceiling) required for seedling emergence and to construct its model.

Results and Discussion

Analysis of variance and corn emergence response to temperature

Daily maximum and minimum temperatures and 30 years average temperature were showed in Fig. 2. Temperature flactuations in both years of experiment follow the long term data. Maximum temperatures ranged from 25 to 37.5^{o}C and minimum temperature from 8 to 17^{o}C. Analysis of variance showed that the effect of year was not significant. Therefore combined analysis was performed. The results indicated that there was no significant effect of cultivar or cultivar sowing date interaction for time to emergence, but the effect of sowing date was significant (Table 1). However the effects of sowing date, cultivar and their interaction were all significant for emergence percentage (Table 1). Mean of days to 50% emergence and final emergence percentage for different sowing dates was shown in Table 2. There were significant differences between days to emergence and final emergence percentage in different sowing dates. The highest and the lowest amounts for days to emergence were obtained from 21st of May (8.78 days) and 15th of July (3.60 days) sowing dates, respectively (Table 2). On the other hand, maximum and minimum percentage for final emergence were observed from 21st of May (92.03%) and 15th of July (77.87%) sowing dates, respectively which significantly differed with each other (LSD, 5%). Although in late sowing dates, time to emergence was shorter than early sowing dates due to the greater thermal energy, but final emergence percentage has been reduced because of poor growing conditions in such sowing dates. Hayhoe et al (1996) reported that early sowing dates can be conflicted by low spring soil temperatures, which can reduce seed germination and the rate of seedling emergence. Early sowing of corn hybrids increased the time to 50% emergence, a result of lower soil temperatures, which increase the time, required for germination and decrease the rate of shoot elongation (Millner and Toor, 2007). These results showed the importance of sowing date in early growth and stand uniformity of corn canopy. In proper sowing dates all conditions such as climatic factors (temperature, relative humidity…) were suitable to plant growth so the plants germinated and emerged well.

Comparison of models

Root mean square of deviations (RMSD), coefficient of determination (R^2) for the relationship between emergence rate (R_{50}) and temperature in four corn cultivars described by various functions are shown in Table 3. Two or more statistical models may be compared using their RMSDs as a measure of how well they explain a given set of observations:

Table 2. Means of days to 50% emergence and final emergence percentage for different sowing dates in the field experiment.

Date	Days to emergence	Final Emergence Percentage
21-May	8.78 a	92.03 a
28-May	7.69 b	90.12 b
4-Jun	7.79 c	87.40 d
11-Jun	6.58 d	85.05 c
18-Jun	5.32 e	82.60 e
24-Jun	4.52 g	81.15 f
1-Jul	4.55 f	80.25 f
8-Jul	4.32 h	80.05 g
15-Jul	3.60 i	77.87 h

In each column, means followed by the same letter do not differ significantly (LSD, 5%).

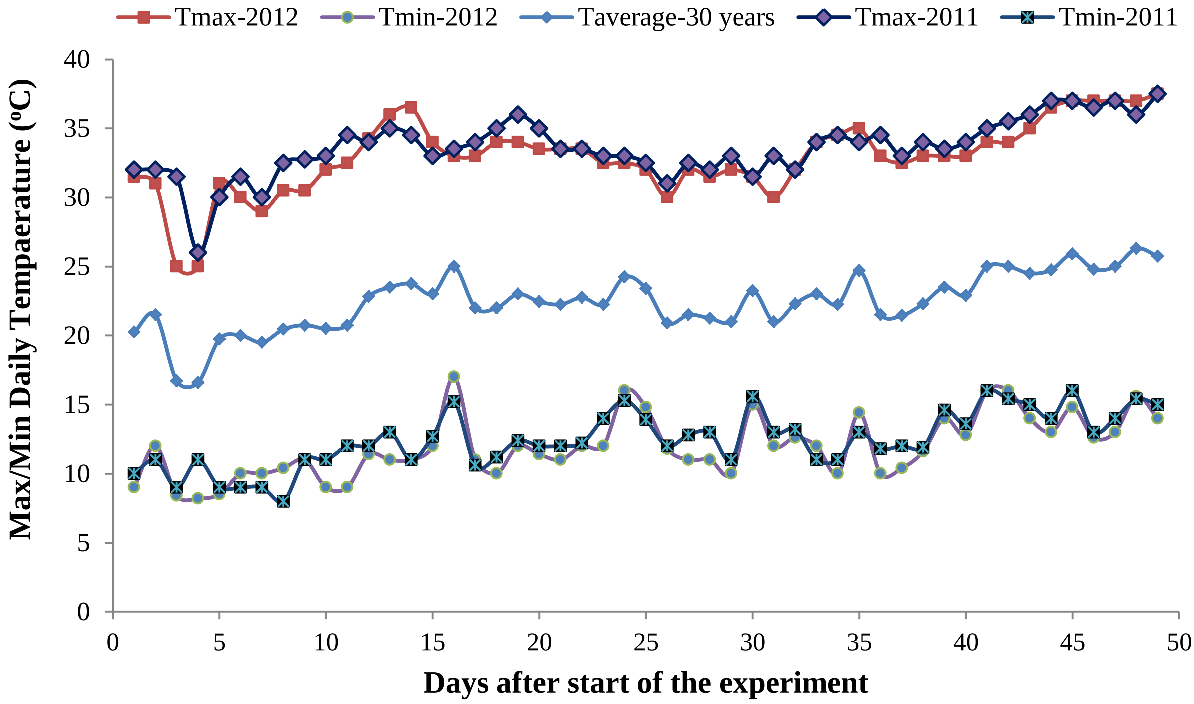

Fig 2. Average 30 years temperature, minimum and maximum temperatures during the field experiment at Shiraz, Iran during the experiment (years 2011 and 2012).

The unbiased model with the smallest RMSD is generally interpreted as best explaining the variability in the observations. In this study RMSD was ranged between 1.43 (segmented function for Hido cultivar) and 2.84 (dent-like function for Hido cultivar) for all the temperature functions (Table 3). RMSD means for all functions were 1.97 for beta function, 2.28 for dent-like and 1.67 for segmented function. Segmented and dent-like functions had significantly higher mean R^2 values compared to the beta function (0.83, 0.73 and 0.54 respectively). Regression coefficients (*a* and *b*) and correlation coefficient (*r*) for the relationship between observed and predicted days to emergence are also shown in Table 3. Regression coefficients (*a* and *b*) were significantly different among functions and cultivars. So that, the greatest amount of *a* coefficient (responsible for regression slope) was recorded for 704 (1.29) and Hido (1.20) in beta function, which were significantly differ from other functions and cultivars. The greater value of *a* coefficient means that the regression line ($y=ax+b$) is more angled than perfect-fit line ($y=x$) and this model is not a good estimator. There was no significant difference between functions with respect to the Pearson correlation coefficient between predicted and observed days to emergence (0.80, 0.88 and 0.92 for beta, dent-like and segmented functions, respectively). Despite this, *r* was greater for segmented function than other functions. It means that in segmented function there was more correlation between predicted and observed days to emergence. Predicted days to emergence versus observed days to emergence in the field experiment are shown in Fig. 3. More distance between distributed points around the perfect-fit line ($y=x$) indicating less compliance between the model with the line. Beta function had more scattered point accordingly. In addition, predictions based on the beta function had significant bias as indicated by significant *a* and *b* coefficients in the linear regression between predicted and observed days to emergence (Table 3). However, there was no bias with segmented and dent-like functions (Table 3). Due to higher RMSD value (1.97 *vs* 1.67), lower R^2 values (0.54 *vs* 0.73 and 0.83), significant bias (*a* and *b* coefficients) and lower *r* value (0.80 *vs* 0.88 and 0.92) for the beta

Table 3. Root mean square of deviations (RMSD) and coefficient of determination (R^2) for the relationship between emergence rate (R_{50}) and temperature in four corn cultivars described by various functions. Regression coefficients (a and b) and correlation coefficient (r) for the relationship between observed and predicted days to emergence are also indicated.

Function	RMSD	R^2	a ± S.E.	b ± S.E.	r
Beta					
704	1.87	0.52	1.20±0.201*	0.77±0.076*	0.79
HIDO	1.91	0.60	1.29±0.385*	0.73±0.081*	0.82
677	2.00	0.52	0.54±1.023	1.01±0.078	0.88
666	2.09	0.53	0.02±1.210	1.13±0.091	0.71
mean	1.97	0.54			0.80
Dent-like					
704	2.18	0.71	0.31±0.761	0.89±0.081	0.82
HIDO	2.84	0.69	0.23±0.792	1.04±0.092	0.87
677	2.31	0.71	0.12±0.631	0.89±0.69	0.91
666	1.80	0.80	0.45±0.450	1.02±0.072	0.90
mean	2.28	0.73			0.88
Segmented					
704	1.75	0.81	0.89±0.671	0.93±0.045	0.92
HIDO	1.43	0.87	0.65±0.213	0.89±0.056	0.96
677	1.61	0.81	0.34±0.186	0.91±0.067	0.90
666	1.87	0.85	0.44±0.441	0.99±0.071	0.89
mean	1.67	0.83			0.92

*Significant difference from 0 for a and significant difference from 1 for b (LSD, 5%).
No sign: no significantly difference (LSD, 5%).

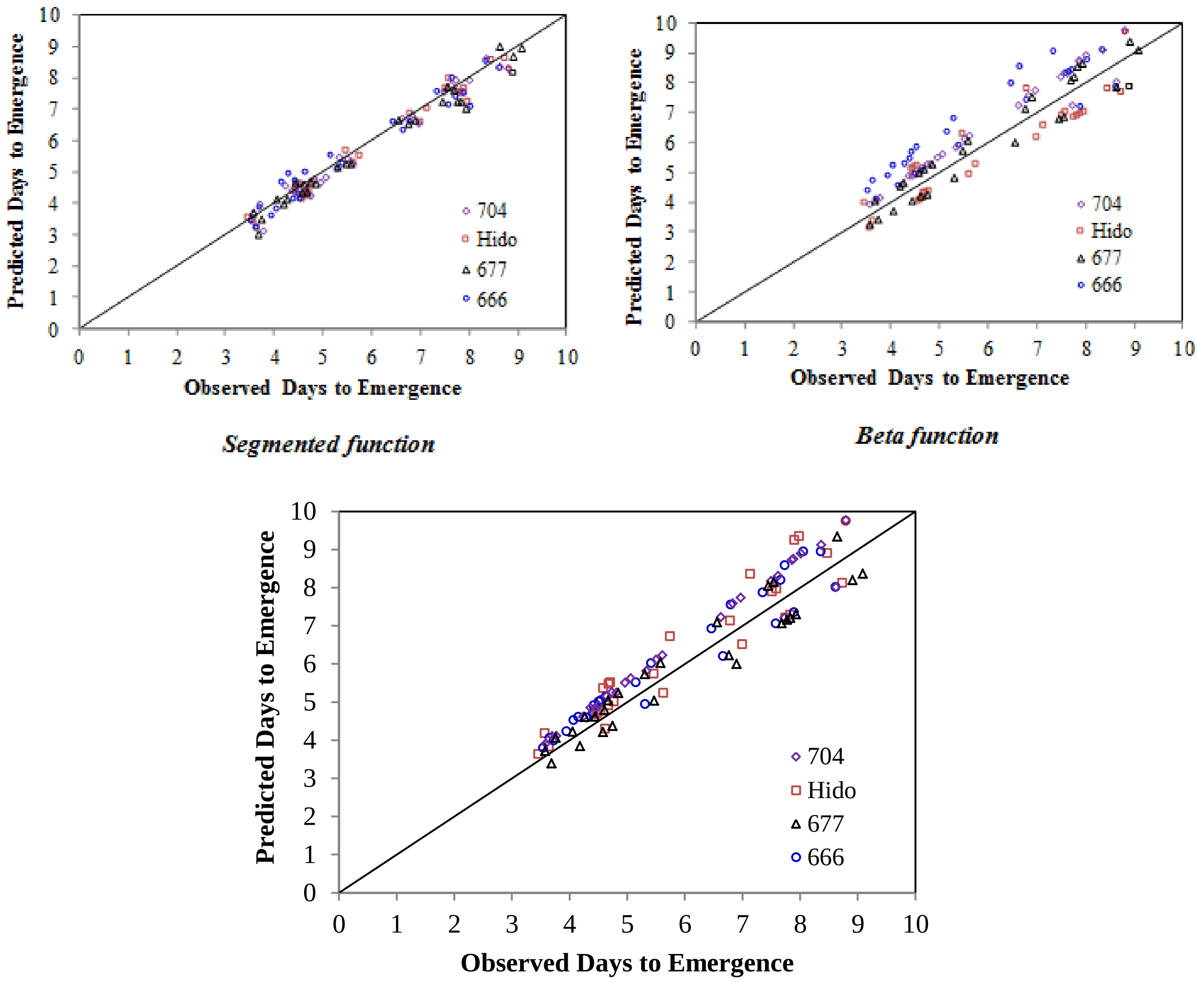

Fig 3. Predicted *vs.* observed days to emergence in four corn cultivars using segmented, beta, and dent-like functions to describe response of emergence rate to temperature. The solid line is a 1:1 line (y=x).

Table 4. Estimates of base temperature (T_b, ^oC), optimum temperature (T_o, ^oC), lower optimum temperature (T_{o1}, ^oC), upper optimum temperature (T_{o2}, ^oC), ceiling temperature (T_c, ^oC) shape parameter (α) and minimum physiological day requirement (e), for emergence of four corn genotypes using segmented, beta and dent-like functions.

Function	α	T_b	T_o	T_c	e_0
Beta					
704	0.92±0.91	9.2±4.81	27.6±0.78	39.8±2.98	5.1±0.45
HIDO	1.02±0.89	6.0±3.93	23.9±0.89	32.7±1.09	4.9±0.29
677	0.93±0.93	5.9±5.50	31.1±1.09	33.8±2.03	5.0±0.98
666	0.98±0.96	4.8±5.67	25.4±1.99	36.7±2.01	4.1±0.56
Dent-like	T_b	T_{o1}	T_{o2}	T_c	e_0
704	9.5±3.98	25.6±1.09	29.2±0.67	39.5±0.99	5.9±0.66
HIDO	9.8±2.54	27.8±1.34	30.1±0.98	38.9±0.85	5.2±0.78
677	9.2±3.33	24.8±0.98	30.0±0.87	39.1±0.82	5.0±0.56
666	9.4±3.98	25.5±1.14	29.9±1.01	39.0±1.02	5.5±0.92
Segmented	T_b		T_o	T_c	e_0
704	9.9±1.25		29.2±0.88	40.0±1.09	5.8±0.26
HIDO	9.4±1.04		28.9±0.69	39.9±0.55	5.7±0.58
677	9.7±0.99		30.0±0.99	39.3±0.77	5.5±0.34
666	9.7±0.82		29.9±0.53	39.1±0.52	5.6±0.42

function, the results of this study indicate that this function is not a suitable for modeling seedling emergence of corn. This is in accordance with findings of other researchers where the segmented and dent-like functions adequately described the response of germination, leaf appearance and development rate to temperature in different crops such as sunflower (Mwale et al., 1994) and legumes (Robertson et al., 2002).

Cardinal temperatures estimation

Estimates of base temperature (*Tb*, ^oC), optimum temperature (*To*, ^oC), lower optimum temperature (*To1*, ^oC), upper optimum temperature (*To2*, ^oC), ceiling temperature (*Tc*, ^oC) shape parameter (α) and minimum physiological day requirement (*e0*), for emergence of four corn genotypes using segmented, beta and dent-like functions are given in Table 4. Using beta function, base temperature varied from 4.8 (for 666 hybrid) to 9.2 ^oC (for 704 hybrid), optimal temperature from 23.9 (for Hido hybrid) to 31.1^oC (for 677 hybrid), ceiling temperature from 32.7 (for Hido hybrid) to 39.8 ^oC (for 704 hybrid) and e_0 from 4.1 (for 666 hybrid) to 5.1 (for 704 hybrid) days. Base temperature varied from 9.2 (for 677 hybrid) to 9.8 ^oC (for Hido hybrid), 24.8 (for 677 hybrid) to 27.8 ^oC (for Hido hybrid) for lower optimum temperature, 29.2 (for 704 hybrid) to 30.1 ^oC (for Hido hybrid) for upper optimum temperature, ceiling temperature from 38.9 (for Hido hybrid) to 39.5 ^oC (for 704 hybrid) and 5.0 (for 677 hybrid) to 5.9 (for 704 hybrid) days for e_0 using dent-like function. For segmented function these parameters were 9.4 (for Hido hybrid) to 9.9 ^oC (for 704 hybrid) for base temperature, 28.9 (for Hido hybrid) to 30 ^oC (for 677 hybrid) for optimum temperature, ceiling temperature from 39.1 (for 666 hybrid) to 40 ^oC (for 704 hybrid) and 5.5 (for 677 hybrid) to 5.8 ^oC (for 704 hybrid) for e_0. Based on this results, beta function estimates the cardinal temperatures with large fluctuations and in some cases (such as base temperature for 666, 677 and Hido hybrids), estimated temperatures is far from reality. On the other hand, dent-like and segmented functions had more realistic estimations for cardinal temperatures. From these two functions, the segmented function was included in the emergence model of corn because it had lower standard errors for cardinal temperatures and gave more precise estimates (Tables 3 and 4). Birch et al. (1998a) reported a base temperature of 8^oC, optimum temperature of 34^oC and a ceiling temperature of 40^oC for leaf production in five corn genotypes. A seedling emergence model for corn was constructed based on findings of this study. The model requires sowing date and maximum and minimum daily temperatures as input to predict corn emergence date. The model calculates the value of e_0, then finds sowing date in the weather data file, and each day after sowing it computes a daily value of $f(T)$ based on the segmented function Eq. (5) and using parameter estimates as presented in Table 4. Emergence occurs when $\sum f(T)=e_0$. Daily maximum and minimum soil temperatures are computed as presented in Ritchie (1991). This work shows that a segmented distribution equation, describes well the temperature response of seedling emergence of corn hybrids. It is attractive for several reasons. First, it has only three parameters, namely the base, optimum and maximum temperature. Second, all three parameters are self-explanatory and have clear biological definitions. Third, it deals with the plant response to the whole range of temperatures, rather than just a fraction of them. Fourth, the thermal time concept summarized the time from sowing to emergence at different temperatures between *Tb* and *To* to be expressed as a single coefficient (Moot et al., 2000; Lonati et al., 2009). As temperatures rose above *To*, emergence rate decreased linearly to zero at *Tc*. The strong linear relationships confirm the appropriateness of using the linear response models when estimating thermal time at sub- and supra-optimal temperatures (Lonati et al., 2009). The observed differences in emergence rate among hybrids of corn were predictable. In most cases emergence rate is genetically determined (Moot et al., 2000) and, in this study differences between hybrids maturity grouping (FAO 700 *vs* FAO 600) could explain some variations in this regard.

Materials and methods

A two-year field experiment was conducted during the 2011-2012 growing season at the research station, college of agriculture Shiraz University, Iran. The research station is located at latitude of 29^{o}44' N, a longitude of 52^o 37'E, and an altitude of 1810 m. The area has hot and dry summers and cold and rainy winters. The soil physical properties in the 0–0.3 m top layer were: clay18%, silt 61%, sand 21%, bulk density1.4 g cm^{-3} and pH 7.8. The experiment commenced in May and continued until July in each year.

Plant materials and treatments

Four corn genotypes (SC704, BC666 and ZP677; a late season cultivar belonging to the maturity groups of 600 and 700 which originated from Croatia, and the cultivar Hido; a long season cultivar originated from Turkey) which are widely cultivated in the experiment region were sown at 9 different sowing dates. Sowing started on 21 May of each year and continued in weekly intervals until 15^{th} of July (Sowing dates were 21^{th} and 28 May, 4 th, 11^{th}, 18^{th}, 24 th of June, first, 8^{th} and 15^{th} of July for both years). These dates were selected to diversify temperature and consequently trigger seedling emergence responses. As a nitrogen source, urea (175 kg N ha^{-1}) and as a phosphorous source, super phosphate (30 kg P_2O_5 ha^{-1}) were applied to plots at the time of sowing. The plants were irrigated optimally so that there was no flooding or water deficit. The experimental design was split plot with sowing dates in main plots and genotypes in sub plots with four replications. Plot size was 3 m by 5 m. Seeds were hand-sown at a rate of 8 plants m^{-2} and a depth of 5 cm with row spacing of 75 cm.

Measurements

The number of emerged seedlings was recorded daily in two three- metered length rows located in the center of each plot. Emergence percentage was obtained by dividing the number of emerged seedlings at any time by total number of seeds sown, multiplied by 100. Estimates of the time taken for cumulative emergence to reach 50% (D50) of maximum in each replication of each treatment were interpolated from the progress of emergence (%) versus time (days) curve. Emergence rate (R_{50}, day^{-1}) was then calculated as follows (Soltani et al., 2001, 2002)

$$R_{50}=\frac{1}{D_{50}} \qquad (1)$$

Daily maximum and minimum temperatures were measured at a standard weather station just located a few meters from the experiments site.

Data analysis

Data was first subjected to analysis of variance and means of treatments were compared using least significant difference (LSD) at 5% level of probability using PROC ANOVA procedure in SAS.

To quantify the response of emergence rate to temperature and to determine cardinal temperatures for emergence, the following model was used

$$R_{50} = \frac{f(T)}{e_0} \qquad (2)$$

where R_{50} is the emergence rate (day^{-1}), $f(T)$ is a temperature function that ranges between 0 and 1, and e_o is the physiological day requirement for emergence. e_o indicates the minimum number of days for emergence at optimal temperature and $1/e_o$ is, thus, the maximum emergence rate. Three temperature functions were used (Fig. 1):

- Segmented function (Ritchie and NeSmith 1991)

$$f(T) = \frac{T-T_b}{T_o-T_b}, \qquad \text{if } T_b < T \le T_o;$$

$$f(T) = \frac{T_o-T}{T_c-T_o}, \qquad \text{if } T_o < T < T_c;$$

$$f(T) = 0, \qquad \text{if } T \le T_b \text{ or } T \ge T_c;$$

- Beta function (Yin et al., 1995)

$$f(T) = \left\{\left[\left(\frac{T-T_b}{T_o-T_b}\,\frac{T_c-T}{T_c-T_o}\right)\right]^{((T_c-T_o)/(T_o-T_b))}\right\}^{\propto}$$

if $T > T_b$ and $T < T_c$;

$f(T)=0$, if $T \le T_b$ or $T \le T_c$

- Dent-like function (Piper et al., 1996)

$$f(T) = \frac{T-T_b}{T_{o1}-T_b}, \qquad \text{if } T_b < T < T_{o1};$$

$$f(T) = \frac{T_c-T}{T_c-T_{o2}}, \qquad \text{if } T_{o2} < T < T_c;$$

$$f(T) = 1, \qquad \text{if } T_{o1} \le T \le T_{o2};$$

$$f(T) = 0, \qquad \text{if } T \le T_b \text{ or } T \ge T_c$$

Where, T is the average temperature from sowing to emergence, T_b is the base temperature, T indicates the optimum temperature, T_{o1} and T_{o2} represent the lower and upper optimum temperature for dent-like function, respectively. T_c shows the ceiling temperature and α is the shape parameter for the beta function which determines the curvature of the function. A ceiling temperature represents a biological upper limit for developmental processes in most plants (Yin et al. 1995; Jame and Cutforth 2004). Parameters were estimated by the least squares' method using the nonlinear (NLIN) regression (R_{50} as y and T as x) procedure in the Statistical Analysis System (SAS Institute 1989). Quadratic, cubic and curvilinear (Hammer et al., 1989) functions were also used in curve fitting, but the results are not shown as the beta function encompasses these curve forms.

Conclusions

This study examined the feasibility of implementing the nonlinear functions (beta, dent-like and segmented) into a corn emergence model. Strength of these functions is following the nonlinear nature of temperature responses of plants appropriately using minimum number of biologically meaningful parameters. Functions stability and predictability were compared using some statistics and the best function was used to construct a model to predict seedling emergence of corn hybrids. Results showed that the segmented function had better prediction for cardinal temperatures of seedling emergence in corn hybrids. There was no significant difference between cultivars for cardinal temperatures. A seedling emergence model was constructed based on this information and was successful in predicting emergence date and optimizing corn's sowing date.

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