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Evaluating Non-Linear Regression Models to Describe Response of Wheat Emergence Rate to Temperature

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ABSTRACT

We aimed to formulate and validate mathematical functions that can be used to determine cardinal temperatures and the effect of temperature on biological days required from seeding to emergence of wheat cv. 'Tajan'. For this purpose, different non-linear regression models including flat, logistic, quadratic, cubic, dent-like, segmented and Curvilinear were used. Root mean square of errors, coefficient of determination and regression coefficients of predicted versus observed values were used to find the appropriate model. Investigating regression coefficients indicated that only in flat and logistic models, related coefficients were not significant. Other models (quadratic, cubic, dent-like, segmented and curvilinear) were not used to select the best model. Because the root mean square of errors was less in the logistic model than in the flat one, the former was chosen as the best model to describe the response of emergence rate to temperature. Using this function, base and optimum temperatures were 5.2 and 24.8°C. This function and its parameters can be used in wheat simulation models to predict seedling to emergence duration based on a thermal time concept. Also, required biological days from seeding to emergence using these models varied from 2.78 to 3.98.

Keywords: cardinal temperatures, germination rate, nonlinear fitting, wheat

INTRODUCTION

A portion of a crop model is devoted to predict the timing of crop developmental processes (phenology) (Hodges 1991). In a crop model, the simulation of crop phenology is generally divided into several growth stages to mark sequential turning points in crop development and biomass partitioning. Without accurate prediction of phenology, the model will simulate growth processes as occur at different times and under different conditions than they actually do, and conditions during each growth stage affect the ability of the crop to respond to conditions during later stages (Jame and Cutforth 2004). The simple concept of constant thermal time is most commonly used for predicting the time required from seeding to crop emergence (Thermal time has the unit of degree-days (°C days) and is defined as:

$$TT = \sum_{i=1}^{n} (T - T_b)$$

where T, T_b and n are mean daily temperature, base temperature and days number till a given stage, respectively. Mean daily temperature also is equal to:

$$T = \frac{(T\max + T\min)}{2}$$

where Tmax and Tmin are maximum and minimum temperature of each day (i), respectively.

Temperature is the most important driving force influencing crop development rate. It seems that the relationship between development rate and temperature is linear at a wide range of temperatures. Developmental phenomena, including days to emergence, are affected by temperature. Emergence is probably the most important phenological stage that determines the success or failure of crop production (Forcella 1993). Uniform and rapid emergence and favorable establishment of seedlings can resulted in rapid covering of land and consequently will improve crop production. On the other hand, such rapid and extensive growth not only increases the competitive ability of crop with weeds (Soltani *et al*. 2001), but also reduces water and wind erosion (Papendick and McCool 1994). Determining germination and emergence responses to temperature and their cardinal temperatures (including base, optimum and ceiling temperatures) are useful to predict germination and emergence time by simulation models, determination of the best sowing dates and tolerant genotypes to critical temperatures (Ramin 1997). These prediction models can be useful to determine crop final size, the time of crop and companion weed emergence, the amount of yield reduction by crop-weed interactions and weed control time (Forcella 1993).

Non-linear regression models have been used to quantitatively describe seed emergence in many crops. Angus *et al*. (1981) revealed that development rate changes at different temperatures from sowing to radicle emergence follow a non-linear function. Blackshow (1991) used a logistic model to study the emergence rate of wheat in terms of soil temperature and water potential. Kamkar *et al*. (2005) also used segmented models to determine cardinal temperatures of three millet varieties. Many kinds of functions such as beta (Yin *et al*. 1997), Power (Stapper *et al*. 2001), logistic (Grimm *et al*. 1997), exponential (Angus *et al*. 1981), sigmoidal (Olsen *et al*. 1993), and intersected functions have been used to describe crop responses to temperature.

This study was conducted to formulate and validate non-linear regression models that can be used to determine cardinal temperatures and the effect of temperature on biological days required from seeding to emergence of wheat cv. 'Tajan'.

MATERIALS AND METHODS

A completely randomized block design with four replications was conducted during the 2005-2006 growing season at the Research Field of Gorgan University of Agricultural Science and Natural

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Table 1 Non-linear regression models were fitted to emergence rate versus temperature data.

Function	Formula	
Flat	$f(T)=\frac{(T-T_b)}{(T_o-T_b)}$	If $T_b<T<T_o$
	$f(T)=1$	If $T\geq T_o$
Logistic (Abbrev. L)	$f(T)=\left[1/(1+\exp(-a\times(T-T_o)))\right]$	
Dent-like (Abbrev. D)	$f(T)=\frac{(T-T_b)}{(T_{o1}-T_b)}$	If $T_b<T\leq T_{o1}$
	$f(T)=\frac{(T_c-T)}{(T_c-T_{o2})}$	If $T_{o2}<T\leq T_c$
	$f(T)=1$	If $T_{o1}<T\leq T_{o2}$
	$f(T)=0$	If $T\leq T_b$ or $T\geq T$
Segmented (Abbrev. S)	$f(T)=\frac{(T-T_b)}{(T_o-T_b)}$	If $T_b\leq T\leq T_o$
	$f(T)=\left[1-\frac{(T-T_o)}{(T_c-T_o)}\right]$	If $T_o\leq T<T_c$
	$f(T)=0$	If $T\leq T_b$ or $T\geq T_c$
Curvilinear (Abbrev. S)	$f(T)=\left[\left(1\Big/\left((T_o-T_b)\times(T_c-T_o)^{\left(\frac{Tc-To}{To-Tb}\right)}\right)\right)\times(T-Tb)\times(Tc-T)^{\left(\frac{Tc-To}{To-Tb}\right)}\right]$	---
Quadratic (Abbrev. Q)	$f(T)=\left[(T-T_b)\times(T_c-T)\times\left(\frac{T_c-T_b}{2}\right)^{-2}\right]$	---
Cubic (Abbrev. C)	$f(T)=a+bT+cT^2+dT^3$	---

Resources located at 37° 45′ N, 54° 30′ E, 13 m asl. Wheat grains (cv. 'Tajan', as a dwarf and high yield variety for irrigated systems, released by CYMMIT with the most yield in Golestan province, North of Iran) were seeded in 8 sowing dates (14 December, 20 January, 18 February, 20 March, 16 April, 21 May, 30 July and 6 August) to expose seeds to different temperature regimes. In all sowing dates, soil water content was maintained constant up to field capacity to eliminate the effects of soil moisture on results.

The field soil was a silty clay loam with pH = 7.9 and electrical conductivity (EC) of 0.6 dSm^{-1}. Each plot (5 m × 1 m) included five rows, 15 cm apart. Seed rate was controlled to achieve 330 plants/m^2 as target density. Weeding was done as needed.

After sowing, cumulative emerged seeds were counted every day and days to 50% emergence (D_{50}) was calculated by fitting a Gompertz function and interpolation method. Emergence rate was considered as $1/D_{50}$ to quantify emergence responses to different temperatures and to estimate cardinal temperatures.

In order to formulate and validate mathematical functions that can be used to quantify the effect of temperature on the biological days required from seeding to emergence of this wheat cultivar, seven non-linear regression models were fitted to emergence rate versus temperature data, as shown in **Table 1**, where, T, T_b, T_o, T_{o1}, T_{o2} and T_c for flat (F), dent-like (D), curvilinear (V), quadratic (Q), logistic (L) and segmented (S) models are mean air temperature, base temperature, lower optimum temperature, upper optimum temperature, and ceiling temperature, respectively. *a* and T_0 are constant coefficients in logistic function, as *a* shows increasing slope of emergence rate versus temperature and T_0 is specific temperature related to 1/2 emergence rate. In cubic model (Q), T indicates mean daily temperature and *a*, *b*, and *c* are constant coefficients.

To obtain the best estimates for models parameters, we applied an iterative optimization procedure and non-linear fitting was done based on PROC NLIN procedure in SAS program (SAS Institute 1992). Less Standard Deviation (SD) and Root Mean Square of Errors (Eq. 1) were used as criteria to detect best estimates of parameters by non-linear models.

$$\mathrm{RMSE} = \left(\sum_{I=1}^{n} (P_i - O_i)^2 / n\right)^{0.5} \quad (1)$$

where Pi and Oi indicate predicted and observed values of emergence rate and n is observation numbers.

The model with lower RMSE, higher determination coefficient (R^2), lower bias of linear regressed line between observed versus predicted values from the 1:1 line, and lower coefficient of variance (CV) was selected as the best model to estimate emergence rate. *a* and *b* (as intercept and slope values of linear regression between observed versus predicted values of emergence rate) were compared with zero and 1. A closer *a* to 0 and closer *b* to 1 indicate better estimates of models.

In order to evaluate required biological days from seeding to emergence the following equation was used (Eq. 2):

$$1/e = f(T)/eo \quad (2)$$

where 1/e, f(T) and e0 indicate emergence rate, temperature function and minimum days to germination in optimum temperature, respectively.

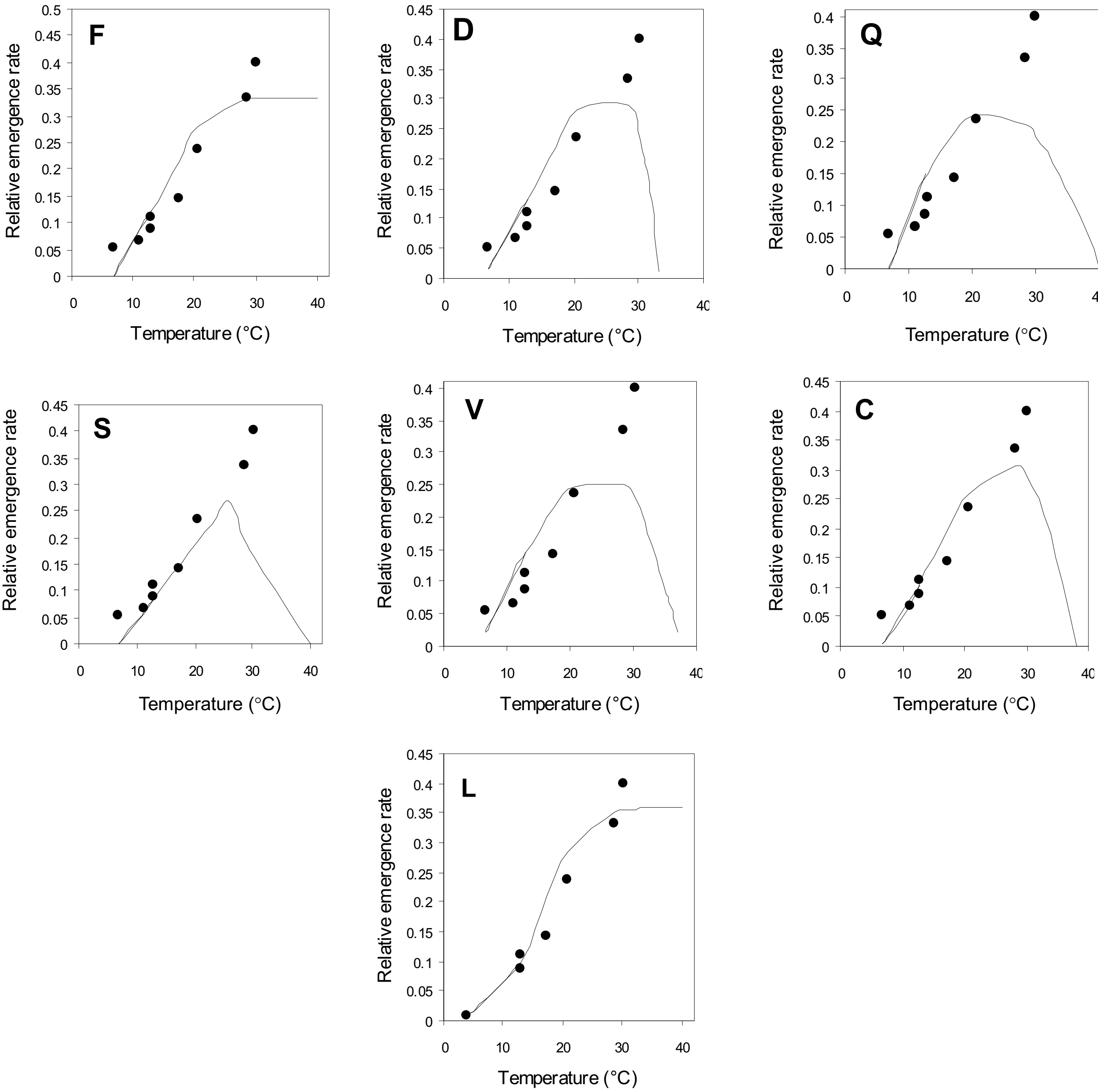

Fig. 1 Predicted (solid line) and observed (solid circles) values of relative emergence rate versus temperature by flat (**F**), dent-like (**D**), cubic (**C**), curvilinear (**V**), quadratic (**Q**), logistic (**L**) and segmented (**S**) models.

RESULTS AND DISCUSSION

Fitted models to relative emergence rate versus mean experienced temperatures by individuals have illustrated in **Fig. 1**. Also estimated parameters for different models have presented in **Table** 2. The results indicated that dent-like, curvilinear, quadratic, and cubic models were not appropriate models to predict emergence rate, because at least *a* or *b* coefficient of linear regressed line between observed versus predicted values was significantly different from 0 or 1 (**Fig. 2**). A significant coefficient indicates significant bias of intercept of regressed line against the 1:1 line. But neither *a* nor *b* were not significant in logistic and flat models. Among these two models, logistic model was introduced as the best model, because of lower RMSE and higher R^2 (**Table 2**). Therefore a logistic model can considered as an appropriate predictive non-linear model to estimate the emergence rate of wheat at a temperature range of 0 to 31°C.

Estimated values for cardinal temperatures of wheat emergence are presented in **Table 3**. These values are basic and primary data needed to simulate time to emergence. These data are used directly in thermal time calculation and determine extreme temperatures which will suppress seed germination. This temperature range has been defined as cardinal temperatures, i.e., a minimum or base temperature (T_b), maximum temperature (T_c) that germination rate at above of that would be zero, and optimum temperature (T_o) at which the germination rate is the highest (Mwale et al. 1994). Estimated base temperature based on flat, dent-like, quadratic, segmented and curvilinear models were 6.8, 6.07, 6.8, 6.9 and 5.9°C, respectively, while estimated value by the superior model (L) was 5.2°C. Other reported base temperatures for emergence of wheat cultivars are 0-2°C (Ali *et al*. 1994), 4°C (Slafer and Savin 1991), 2.6°C (for spring wheat, Angus *et al*. 1981), 1-2°C (Petr 1991). Related values of estimated optimum temperature by flat, quadratic, segmented and curvilinear models were 23.3, 23, 25 and 25°C, respectively, while the superior model estimated it as 24.8°C (**Table 3**). These values were consistent with other reports, such as 24-38°C (Petr 1991) and 22.1-29.8°C (Ali *et al*. 1994).

Estimated ceiling temperature based on flat, dent-like, quadratic, segmented and curvilinear models were 36, 37, 40, 39.9 and 35°C, respectively.

In spite of that we used a wide range of sowing dates, but obtained and used points to fit models did not include

Table 2 Root Mean Square of Errors (RMSE) and determination coefficients (R^2) of flat, logistic, segmented, dent-like, curvilinear, quadratic and cubic models used to describe relationship between emergence rate versus temperature in wheat (cv. 'Tajan'). *a* and *b* are regression coefficients and CV is coefficient of variance related to regressed line between observed versus predicted values of days from seeding to emergence.

Model	RMSE	R^2	a ± SE	b ± SE	CV
Flat	2.15	0.76	0.93 ± 0.54	0.67 ± 0.06	12.21
Logistic	1.11	0.79	-0.44 ± 0.94	1.03 ± 0.10	17.58
Segmented	2.04	0.74	3.19 ± 0.50	0.33 ± 0.05	11.87
Dent-like	2.72	0.73	1.99 ± 0.63	0.51 ± 0.07	14.43
Curvilinear	3.29	0.62	2.87 ± 0.42	0.37 ± 0.04	9.99
Quadratic	3.40	0.55	3.19 ± 0.50	0.33 ± 0.05	11.87
Cubic	1.20	0.92	0.56 ± 0.79	0.85 ± 0.09	15.21

Table 3 Estimated values of base temperature (T_b), optimum temperatures (T_o), ceiling temperature (T_c) and minimum days from seeding to emergence under optimum temperature (e_o) by flat, quadratic, segmented, curvilinear and logistic models.

Model	a	T_b	T_o	T_c	e_o
Flat	-	6.8 ± 1.24	23.3 ± 4.7	36	3.00 ± 0.91
Logistic	0.3	5.2 ± 0.03	24.8 ± 2.2	-	2.78 ± 0.35
Segmented	-	6.9 ± 0.0	25.0 ± 3.1	39.9	3.80 ± 0.4
Quadratic	-	6.8 ± 1.3	23.0 ± 1.4	40	3.98 ± 0.78
Curvilinear	-	5.9 ± 0.04	25.0 ± 2.8	35	3.80 ± 0.4

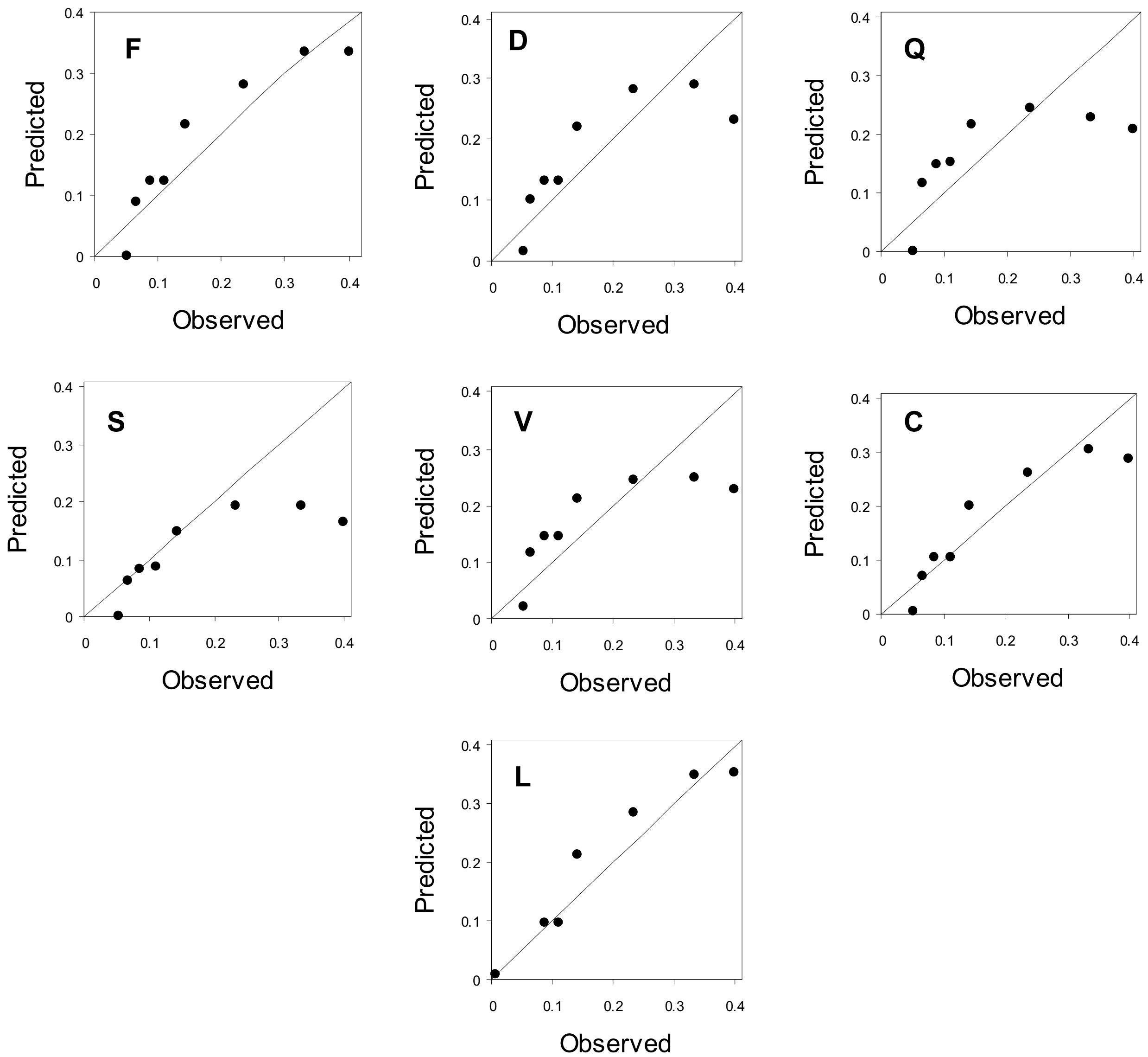

Fig. 2 Observed versus predicted values of relative emergence rate by flat (F), dent-like (D), cubic (C), curvilinear (V), quadratic (Q), logistic (L) and segmented (S) models. Solid line indicates 1:1 line.

higher temperatures than ceiling temperature. Therefore the model introduced as the best model (Logistic model) just can be used in a temperature range of around 5 to 40°C. If we face by higher temperatures than ceiling one, it is likely that other models, especially those that can extrapolate the diminishing trend of development rate after extra-ceiling temperatures, are used as superior model(s). Therefore it is advisable to repeat this experiment with more sowing dates to clarify the response of wheat emergence rate to temperature.

Also, all models estimates showed that ceiling temperature changes between 35 to 40°C. Although these values just were extrapolated by models, but can consider as a range of ceiling temperature for some unimportant calculations.

Our results indicated that non-linear regression models and their coefficient concepts can use successfully to predict sowing to emergence time, as one of the most important and determinant phenological stages, especially in competition and interference studies. Also, these results revealed that the tolerance range of wheat cv. 'Tajan' as one of the major varieties in north of Iran, varies between about 5.2 to 40°C. Also, the number of required biological days from seeding to emergence using these models varied between 2.78 to 3.98 (**Table 3**).

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