Cardinal temperatures and required biological days from sowing to emergence of three millet species (common, foxtail, pearl millet)

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Abstract: The modeling of germination and seedling emergence is required for the construction of a simulation model of three species of millet (*panicum miliaceum, pennisetum galucum* and *setaria italica*). This study provides the necessary temperature parameters to model these processes. For this purpose, different non-linear regression models including flat, logistic, quadratic, sigmoidal, dent-like, segmented, beta and curvilinear were used. Root Mean Square of Errors, coefficient of determination and regression coefficients of predicted values versus observed were used to find the appropriate model. Investigating regression coefficients indicated that dent-like model has the least RMSE and *a* coefficient (RMSE=0.000009, a=0.0006) and the biggest R^2 and *b* coefficient (R^2=0.96, b=0.98) in common millet. These coefficients were (RMSE=0.01, a=0.005) and (R^2=0.94, b=0.97), and (RMSE=0.004, a=0.05) and (R^2=0.99, b=0.99), for beta in foxtail and pearl millet, respectively. According to these coefficients, dent-like, was chosen as the best model to describe the response of common millet germination to temperature (T_b=7℃ and T_c=49.50℃). Also beta, was chosen for foxtail millet (T_b=7℃, T_c=49.50℃). Beta, was chosen as the best model for pearl millet (T_b=6.5 ℃ and T_c=4 ℃). These parameters can be used in millet simulation models to predict sowing to emergence duration based on a thermal time concept. Also, required biological days from sowing to emergence using these models varied from 3.57, 4.29 and 5.54, for common millet, foxtail millet and pearl millet, respectively.

Key words: cardinal temperature; germination rate; nonlinear fitting; millet

1. Introduction

Emergence is probably the single most important event that affects the success of an annual crop[1] and also success or failure of crop production[2]. Rapid, uniform and complete emergence of vigorous seedlings leads to high grain yield potential by shortening the time from sowing to complete ground cover, allows the establishment of optimum canopy structure to minimize interplant competition, maximizing crop yield and providing plants with time and spatial advantages to compete with weeds[1] and also reduces water and wind erosion[3]. Seed germination is a complex biological process that is influenced by various environmental and genetic factors[4]. Seedling emergence is controlled by species-specific requirements and the availability of favorable seedbed conditions[5]. Environmental conditions directly surrounding a seed determine germination success and subsequent seedling emergence and establishment[5].

Temperature and water mainly drive the rate of seed germination when aeration is not restrictive[6]. Temperature is the most important driving force influencing crop development rate[7]. The effects of temperature on plant development are the basis for models used to predict the time of germination. Three cardinal temperatures (maximum, minimum and optimum) describe the range of temperature over which seeds of a particular species can germinate[8]. Estimation of the cardinal temperatures, including base, optimum, and maximum, is essential because rate of development increases between base and optimum, decreases between optimum and maximum, and ceases above the maximum and below the base temperatures[4-9]. A portion of a crop model is to predict the time of crop development processes (phenology)[10]. Many mathematical models have been developed to

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describe germination patterns in response to temperature (e.g.[11-13]). Non-linear growth curves can be specified to model the time of germination at various temperatures[4]. Non-linear regression models have been used to quantitatively describe development rate in many crops. Angus et al.[14] revealed that development rate changes at different temperatures from sowing to radicle emergence follow a non-linear function. Blackshow[15] used a logistic model to study the emergence rate of wheat in terms of soil temperature and water potential. Kamkar et al.[14-16] also used segmented and logistic models to determine cardinal temperatures of three millet varieties and wheat cv. "Tajan", respectively. Many kinds of functions such as beta[18], power[19], logistic[20], exponential[14], sigmoid[21], and intersected functions have been used to describe crop responses to temperature. Carberry and Campbell[22] revealed that the cubic polynomials described the rates of development for germination and coleoptile elongation over a temperature range of 15℃ to 40℃ in pearl millet. Population-based modeling approaches to predict germination as a function of temperature and/or water potential have been well developed in the last two decades as thermal time[11] and hydrothermal time concepts[6, 23-26]. Several studies have illustrated the effectiveness of using thermal time models to predict germination in a variety of species including common lambsquarters (*Chenopodium album* L.), winterfat (*Eurotia lanata* (Pursh) Moq.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), lentil (*Lens culinaris* Medik.), and many grasses[12-13, 27-31]. Thermal time model has been implemented successfully in predicting agronomically important phenology for crops and weedy species as well as seed germination under non water limiting conditions[11, 32].

Thermal time (Degree-day or hour), the heat unit for plant development, is a firmly established developmental principle for plants (Angus et al., 1981; including seed germination[11-12, 14].

The simple concept of constant thermal time is most commonly used for predicting the time required from sowing to crop emergence (Thermal time has the unit of degree-days (°C days) and is defined as:

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

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:

$$T = \left(T_{\max} + T_{\min}\right)\Big/2$$

Where T_{max} and T_{min} are maximum and minimum temperature of each day (i), respectively.

Common millet (*panicum miliaceum*), pearl millet (*pennisetum galucum*) and foxtail millet (*setaria italica*) are common millet species that are cultivated in arid and semi arid regions of Iran. There is not any comprehensive information about cardinal temperatures of emergence for these species[16].

Predicting crop developmental events is fundamental to simulation models and crop management decisions[33]. Determining germination and emergence responses to temperature and their cardinal temperatures (including base, optimum and ceiling temperature) are useful to predict germination and emergence time by simulation models, determination of the best sowing dates and tolerant genotypes to critical temperatures[34]. These prediction models can also be useful to determine crop final size, the time of companion weed emergence, the amount of yield reduction by crop-weed interactions and weed control time[2]. Non-linear regression models have been used to quantitatively describe seed emergence in many crops.

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 sowing to emergence of three species of millet that include common millet (*panicum miliaceum*), pearl millet (*pennisetum galucum*) and foxtail millet (*setaria italica*).

2. Materials and methods

Field experiment with a series of sowing dates (30 April, 1 Jun, 31 May, 4 July, 5 August, 1 September, 2 October and 3 November) was conducted at the Gorgan University of Agricultural Sciences Research Farm, Gorgan (36°51′N, 54°16′E and 100 m asl), Iran. The field soil was clay loam with pH=7.6 and electrical conductivity (EC) of 1.3 dSm^{-1}. The experiment started in April 2008 and continued until November 2008. Three millet species (*panicum miliaceum, pennisetum galucum* and *setaria italica*) were sown at eight different sowing dates. The species were selected from Southern regions of Iran. These sowing dates do not necessarily reflect common practices, but were selected to create different temperature regimes and to trigger seedling emergence responses in a wide range of temperatures. The irrigation optimized so that there was no flooding or water deficit. The experimental design was a randomized complete block design, with four replications. Plot size was 1.5 m by 4 m. Seeds were hand-sown at a rate of 50 plants m^{-2} and at the depth of 5 cm with row spacing of 25 cm. The number of emerged seedlings was recorded daily. Counting was done once or twice each day from two rows with 1 m lengths located in the center of each plot.

Table 1 Flat, logistic, dent-like, segmented, curvilinear, quadratic, sigmoidal and beta functions formula

Function	Formula	
Flat (Abr. F)	$f(T)=\frac{(T-Tb)}{(To-Tb)}$	if $T_b<T<T_o$
	$f(T)=1$	if $T \geq T_o$
Logistic (Abr. L)	$f(T)=\left[1/(1+\exp(-a\times(T-To)))\right]$	
Dent-like (Abr. D)	$f(T)=\frac{(T-Tb)}{(To1-Tb)}$	if $T_b<T\leq T_{o1}$
	$f(T)=\frac{(Tc-T)}{(Tc-To2)}$	if $T_{o2}<T\leq T_c$
	$f(T)=1$	if $T_{o1}<T\leq T_{o2}$
	$f(T)=0$ r $T\geq Tc$	
Segmented (Abr. SE)	$f(T)=\frac{(T-Tb)}{(To-Tb)}$	if $T_b\leq T\leq T_o$
	$f(T)=\left[1-\left(\frac{T-To}{Tc-To}\right)\right]$	if $T_o\leq T<T_c$
	$f(T)=0$	if $T\leq T_b$ or $T\geq T_c$
Curvilinear (Abr. C)	$f(T)=\left[\left(1\Big/\left((To-Tb)\times(Tc-To)^{\left(\frac{Tc-To}{To-Tb}\right)}\right)\right)\times(T-Tb)\times(Tc-T)^{\left(\frac{Tc-To}{To-Tb}\right)}\right]$	
Quadratic (Abr. Q)	$f(T)=\left[(T-Tb)\times(Tc-T)\times\left(\frac{Tc-Tb}{2}\right)^{-2}\right]$	
Sigmoidal (Abr. SI)	$f(T)=C+(1-C)/(1+\exp(-b\times(T-a)))$	
Beta (Abr. B)	$f(T)=\left[\left(\left(\frac{(T-T_b)}{(T_p-T_b)}\right)\times\left(\frac{(T_c-T)}{(T_c-T_p)}\right)^{\left(\frac{(T_c-T_p)}{(T_p-T_b)}\right)}\right)^{a}\right]$	

In order to formulate and validate mathematical functions that can be used to quantify the effect of temperature on required biological days from sowing to emergence of these species of millet, eight non-linear regression models were fitted to emergence rate as inverse of time from sowing to emergence versus mean temperature (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), segmented (SE), and beta (B) models are mean air temperature, base temperature, optimum temperature, lower optimum temperature, and upper optimum temperature, respectively. a and T_0 are specific temperature related to 1/2 emergence rate. In Sigmoidal (SI) model, T indicates mean daily temperature and *a*, *b*, and *c* are constant coefficients.

To determine the best parameters of models for each species, iterative optimization method was applied. To select the best model, also, statistical indices such as Less Standard Deviation (LSD) and Root Mean Square of Errors (Eq. 1) and *a* and *b* coefficients analyzed for significant difference by SAS program[35] were used (Eq. 1).

$$RMSE = \sum_{i=1}^{n} (P_i - O_i)^2 / n)^{0.5} \quad (1)$$

Where P_i and O_i 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, was selected as the best model to estimate emergence rate. *a* and *b* (as intercept and slop 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 sowing to emergence the following equation was used (Eq. 2):

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

Where 1/e, f(T) and eo indicate emergence rate, temperature function and minimum days to germination at optimum temperature, respectively.

3. Results and discussion

Fitted models to relative emergence rate versus mean experienced temperatures by individuals has illustrated in Fig. 1. Also estimated parameters for different models have presented in Table 2. The result indicated that logistic model for common millet; segmented, flat, logistic and dent-like models for foxtail millet; and segmented, flat and dent-like models for pearl millet 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 (Table 2). Among other models, dent-like, model for common; and beta for foxtail and pearl millet are introduced as the best models, because of lower RMSE and higher R^2 (Table 2). Therefore these models considered as appropriate predictive non-linear models to estimate the emergence rate of three species of millet when mean temperature varies at a range of 8.9℃ to 32.3℃.

Estimated values for cardinal temperatures of three species of millet emergence are presented in Table 3. These values are basic and primary data needed to simulate time to emergence. These parameters are used directly in thermal time calculation and determine extreme temperatures which will suppress seed germination. This temperature range is defined as cardinal temperature, i.e., a minimum or base temperature (T_b), maximum temperature (T_c) that development rate above that will be zero and optimum temperature (T_o) at which the development rate is the highest[9]. Estimated base temperature based on flat, logistic, quadratic, cubic, dent-like, segmented, beta and curvilinear models for three species varied from 6.50℃ to 8.15℃, while estimated values by the best models varied between 6.50℃ to 7℃.

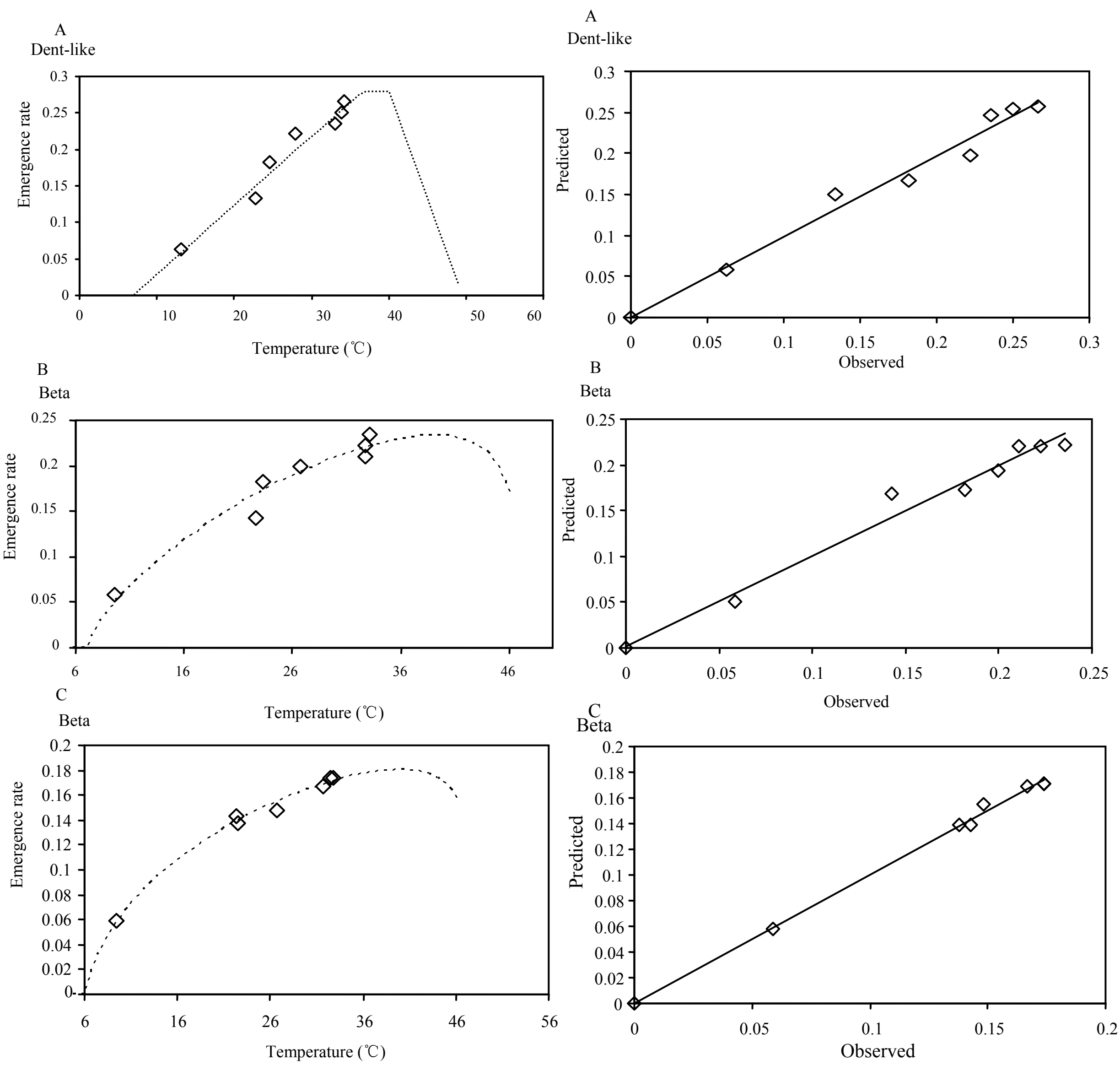

Fig. 1 (Left) Observed versus predicted values of relative emergence rate by dent-like and beta models. (Right) Distribution of observed against predicted values of emergence rate around 1:1 line by dent-like and beta models for (A) common millet, (B) foxtail millet and (C) pearl millet

Related values of estimated optimum temperature based on these models varied from 35.50℃ to 41℃, while estimated values by the best models varied from 36.51℃ to 40℃. Estimated ceiling temperature by eight used models for three species of millet varied between 41.50℃ to 49.50℃, while estimated values by the best models varied from 46.50℃ to 49.50℃ (Table 3). Kamkar et al.[16] reported that these germination values of same species varied from 7.30℃ to 10.6℃, 37℃ to 42.20℃ and 45℃ to 48℃ for T_b, T_o and T_c, respectively.

In spite of using a wide range of sowing dates, the points obtained and used to fit models did not include higher temperatures than ceiling temperature. Therefore these selected models as the best models just can be used only in a temperature range of around 8.9℃ to 32.3℃. If we face 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 these three species of millet emergence rate to temperature.

Also results showed that ceiling temperature changes between 46.50℃ to 49.50℃. Although these values just were extrapolated by models, but can be considered as a range of ceiling temperature for some unimportant calculations.

Our results indicated that non-linear regression models and their coefficient concepts can be used 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 tolerance range (ecological magnitude) of these three species of millet varies between about 6.50 ℃ to 49.50℃. Also, the number of required biological days from sowing to emergence for three species using the best models varied between 3.57 and 5.54 (Table 3). These parameters can be used in phenology sub-models, which is the most important component of crop simulation models.

Table 2 Root mean square of errors (RMSE) and determination coefficients (R^2) of flat (F), dent-like (D), curvilinear (V), quadratic (Q), logistic (L), segmented (SE), sigmoidal (SI) and beta(B) models used to describe relationship between emergence rate versus temperature in millet. *a* and *b* are regression coefficients related to regressed line between observed versus predicted values of days from sowing to emergence for (A) common millet, (B) foxtail millet, (C) pearl millet

A	Segmented	Beta	Flat	Curvilinear	Logistic	Quadratic	Sigmoidal	Dent-like
RMSE	0.02	0.02	0.02	0.02	0.02	0.04	0.02	0.000009
R^2	0.94	0.92	0.94	0.93	0.92	0.62	0.87	0.96
a	-0.02^{ns}	0.01^{ns}	0.03^{ns}	0.02^{ns}	0.05**	0.03^{ns}	3E-06^{ns}	0.006^{ns}
b	1.11^{ns}	0.92^{ns}	0.84^{ns}	0.87^{ns}	0.76**	0.82^{ns}	1^{ns}	0.98^{ns}
B	**Segmented**	**Beta**	**Flat**	**Curvilinear**	**Logistic**	**Quadratic**	**Sigmoidal**	**Dent-like**
RMSE	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01
R^2	0.94	0.94	0.94	0.94	0.91	0.78	0.92	0.94
a	0.04**	0.005^{ns}	0.04**	0.02^{ns}	-0.00^{ns}	0.02^{ns}	-2E-06^{ns}	0.04**
b	0.76**	0.97^{ns}	0.78**	0.87^{ns}	1.03**	0.88^{ns}	1.0001^{ns}	0.76**
C	**Segmented**	**Beta**	**Flat**	**Curvilinear**	**Logistic**	**Quadratic**	**Sigmoidal**	**Dent-like**
RMSE	0.01	0.004	0.01	0.006	0.01	0.01	0.004	0.01
R^2	0.95	0.99	0.95	0.98	0.92	0.88	0.99	0.95
a	0.05**	0.05^{ns}	0.05**	0.04^{ns}	-0.00^{ns}	0.02^{ns}	-0.0001^{ns}	-0.07**
b	0.64**	0.99^{ns}	0.65**	0.73^{ns}	1.03^{ns}	0.81^{ns}	1.0005^{ns}	1.49**

Notes: ns means non significant and ** means significant at $P<0.05$.

Table 3 Estimated values of base temperature (Tb), optimum temperature (To), ceiling temperature (Tc) and minimum days from sowing to emergence under optimum temperature (fo) by flat (F), dent-like (D), curvilinear (V), quadratic (Q), logistic (L), segmented (SE), sigmoidal (SI) and beta(B) models for (A) common millet, (B) foxtail millet, (C) pearl millet.

A	Segmented	Beta	Flat	Curvilinear	Logistic	Quadratic	Sigmoidal	Dent-like
T_b	7.00	7.00	7.00	7.00	-	8.15	-	7.00
T_p	38.08	41.00	37.70	39.34	35.50	-	-	-
T_c	48.00	46.00	-	41.50	-	49.50	-	49.50
F_o	3.35	3.65	3.39	3.56	1.67	4.41	4.32	3.57

(to be continued)

Cardinal temperatures and required biological days from sowing to emergence of three millet species (common, foxtail, pearl millet)

T_{o1}	-	-	-	-	-	-	-	36.55
T_{o2}	-	-	-	-	-	-	-	40.00
a	-	0.91	-	-	-	-	23.31	-
b	-	-	-	-	-	-	11.08	-
c	-	-	-	-	-	-	0.27	-
B	Segmented	Beta	Flat	Curvilinear	Logistic	Quadratic	Sigmoidal	Dent-like
T_b	7.00	7.00	6.50	7.00	-	7.59	-	7.00
T_p	38.99	39.00	39.99	36.62	37.00	-	-	-
T_c	49.00	46.50	-	49.50	-	49.50	-	48.00
F_o	1.85	4.29	1.82	4.38	1.89	4.77	4.76	3.71
T_{o1}	-	-	-	-	-	-	-	36.51
T_{o2}	-	-	-	-	-	-	-	40.00
a	-	0.72	-	-	0.06	-	22.67	-
b	-	-	-	-	-	-	21.90	-
c	-	-	-	-	-	-	0.28	-
C	Segmented	Beta	Flat	Curvilinear	Logistic	Quadratic	Sigmoidal	Dent-like
T_b	7.00	6.50	6.50	7.00	-	7.00	-	7.00
T_p	37.67	40.00	38.17	37.00	37.00	-	-	-
T_c	49.00	47.00	-	49.5	-	49.50	-	48.00
F_o	2.11	5.54	2.10	5.46	2.49	6.04	4.68	4.61
T_{o1}	-	-	-	-	-	-	-	36.65
T_{o2}	-	-	-	-	-	-	-	40.00
a	-	0.54	-	-	0.05	-	-21.41	-
b	-	-	-	-	-	-	0.06	-
c	-	-	-	-	-	-	-4.43	-

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