International Journal of Plant Developmental Biology ***©2011 Global Science Books***

Quantification of Stem Elongation Rate in Response to Temperature and Photoperiod by 24 Multiplicative Models

Leyla Eshghi[1] • Majid Pouryousef[1] • Behnam Kamkar[2*]

[1] Department of Agronomy, University of Zanjan, Postal code: 45371-38111 Zanjan, Iran
[2] Department of Agronomy, Gorgan University of Agricultural Science and Natural Resources (GUASNR), Pardise 2, Postal code: 49189-43464 Gorgan, Iran
***Corresponding author*: * behnamkamkar@yahoo.com**

ABSTRACT

The first step to quantify crop phenology is to precisely estimate the parameters which affect it. These main parameters are temperature and photoperiod. Therefore we aimed to formulate and validate 24 mathematical functions that can be used to determine cardinal temperatures, critical photoperiod (below which development rate decreases due to short photoperiods) and the effect of temperature and photoperiod on biological days required from emergence to stem elongation for wheat (cv. 'Koohdasht'). For this purpose, 24 multiplicative non-linear regression models (including flat, logistic, quadratic, cubic, dent-like, segmented, curvilinear and beta) for response to temperature, and quadratic, dent-like and negative exponential, to assess the response to photoperiod, were used. Also, the phenological data obtained from an independent experiment were used for independent model evaluation. A multiplicative model that included a quadratic function for response to both temperature and photoperiod was the most adequate to describe the response of stem elongation rate to temperature and photoperiod. Using this function, a base temperature of 7.62°C, a ceiling temperature of 37.60°C, a critical photoperiod of 14.006 h and a photoperiod sensitivity coefficient of 0.11 h^{-1} were obtained. This function and its parameters can be used in wheat simulation models to predict the duration of emergence to stem elongation based on a thermal time concept. Also, the required number of biological days from seedling to stem elongation using this model was 26.90.

Keywords: cardinal temperatures, non-linear fitting, photoperiod, stem elongation rate, wheat
Abbreviations: F, flat; **S**, segmented; Q, quadratic; **C**, cubic; **V**, curvilinear; **D**, dent-like; **B**, beta; **L**, logistic; **Ne**, negative-exponential

INTRODUCTION

A portion of a crop model is devoted to predicting the timing of crop development 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 occurs at different times and under different conditions that 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 emergence to stem elongation (thermal time has the unit of degree-days (°C days) and is defined as (Eq. 1) (Hodges 1991).

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

where T, T_b and n are mean daily temperature, base temperature and number of days until a given stage, respectively.

Temperature is the most important driving force influencing crop development rate and its function is linear at a wide range of temperatures (Forcella 1993). The main environmental variables that affect wheat development (when expressed in thermal time unites) are temperature and photoperiod (Slafer and Rawson 1994). Many studies have demonstrated that photoperiod influences the rate of development well beyond the end of the vegetative phase (Slafer and Rawson 1994).

The stem elongation phase in wheat [*Triticum aestivum* (L.)] is considered to be critical for yield determination. A longer duration of this phase could hypothetically increase grain set and therefore yield (Whitechurch *et al*. 2007). Wheat development from seedling emergence to flowering can be divided into three sub-phases (Slafer and Rawson 1994): (i) vegetative (when all leaf primordia on the main shoot are initiated until floral initiation, i.e. the formation of the first reproductive primordium or collar); (ii) early reproductive (from floral initiation to the formation of the terminal spikelet when all spikelets and few florets within them are differentiated); (iii) late reproductive (from terminal spikelet initiation to flowering, a stem elongation phase when most florets are differentiated to reach a maximum number of floret primordia that then experience a drastic reduction to end up with a number of fertile florets as flowering).

The correct timing of phonological events is generally considered to be the most important factor for adaptation and maximum yield in individual environments (Syme 1968; Fischer 1979; Richards 1991). The time from sowing to anthesis is dependent on the cumulative durations of three phenological phases, vegetative from sowing (S) to double ridge (DR), spikelet initiation from DR to terminal spikelet (TS) and stem elongation from TS to anthesis (A) (Davidson and Christian 1984). The three phases contribute differently to yield; thus, their relative durations must be balanced within the time available from sowing to anthesis. Early sowing increases the number of days or thermal units to anthesis (Stapper and Fischer 1990), but the effects on the duration of the three component phases are not known. Knowledge of the effect of sowing date on development is also necessary to improve wheat crop models (Manupeerapan and Pearson 1993).

Non-linear regression models have been extensively used to quantify stem elongation of many crops. Ritchie

Received: 23 March, 2011. Accepted: 30 August, 2011.

Original Research Paper

Table 1 Non-linear regression models were fitted to stem elongation rate versus combined temperature and photoperiod data.

Function	**Formula**	
Flat	$f(T)=\frac{(T-T_b)}{(T_o-T_b)}$	If $T_b<T<T_o$
	$f(T)=1$	If $T_o\le T$
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 $T_b<T<T_{o1}$
	$f(T)=\frac{(T_c-T)}{(T_c-T_{o2})}$	If $T_{o2}<T<T_c$
	$f(T)=1$	If $T_{o2}<T<T_{o1}$
	$f(T)=0$	If $T\ge T_c$ or $T\le T_b$
Segmented (Abbrev. S)	$f(T)=\frac{(T-T_b)}{(T_o-T_b)}$	If $T_b<T<T_o$
	$f(T)=\left[1-\left(\frac{(T-T_b)}{(T_o-T_b)}\right)\right]$	If $T_o\le T<T_c$
	$f(T)=0$	If $T\ge T_c$ or $T\le T$
Curvilinear (Abbrev. C)	$f(T)=\left[\left[1/\left((T_o-T_b)\times(T_c-T_o)^{\left(\frac{T_c-T_o}{T_o-T_b}\right)}\right)\right]\times(T-T_b)\times(T_c-T)^{\left(\frac{T_c-T_o}{T_o-T_b}\right)}\right]$	
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)	$f(T)=a+bT+cT^2+dT^3$	
Beta (Abbrev. B)	$f(T)=\left[\left(\frac{T-T_o}{T_o-T_b}\times\frac{T_c-T}{T_c-T_b}\right)^{\left(\frac{T_c-T_o}{T_o-T_b}\right)}\right]^a$	

(1991) used a dent-like function for response to temperature and a quadratic function for response to photoperiod. Ahmadi (2008) used a multiplicative model that included a segmented function for response to temperature and photoperiod to describe development rate in wheat over a wide range temperatures and photoperiods. Kamkar *et al.* (2011) used a multiplicative model that included a segmented function for response to temperature and an intersected line function for response to photoperiod to determine cardinal temperatures, photoperiod sensitivity coefficient and critical photoperiod of cumin. Eshraghi-Nejad (2009) also used logistic-quadratic and quadratic-quadratic models to determine cardinal temperature, photoperiod sensitivity coefficient and critical photoperiod of three millet varieties. Kamkar *et al.* (2005, 2008) used segmented and logistic models to determine cardinal temperatures of germination of three millet species and emergence of wheat cv. 'Tajan', respectively.

This study aimed to formulate and validate cardinal temperatures, critical photoperiod and the photoperiod sensitivity coefficient and the effect of temperature and photoperiod on biological days required from emergences to stem elongation of wheat (cv. 'Koohdasht', one of the most common cultivars in Iran).

MATERIALS AND METHODS

Field experiments

A four replicated completely randomized block design was conducted during 2009–2010 growing season at the Research Field of Gorgan University of Agricultural Science and Natural Resources located at 37° 45′ N, 54° 30′ E, 13 m asl. Wheat grains (cv. 'Koohdasht', as a high yield variety for irrigated systems, released by CYMMIT with the most yield in Golestan province, North of Iran) was sown on seven sowing dates (6 Nov, 19 Nov, 7 Dec, 14 Dec, 23 Dec, 17 Feb and 10 May) to expose them to different temperature and photoperiod 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 ds m^{-1}. Each plot (1 m × 1 m) included 7 rows, 15 cm apart. Seed rate was adjusted to 330 plants/m^2 as target density. Weeding was done as needed. After sowing, stem elongation (50% of plants with one node at the main stem that growing point is above ground level 2-3 cm) was recorded every 1-3 days (Zadoks *et al.* 1974). Stem elongation rate was considered as 1/DSD to quantify stem elongation response to different temperatures and photoperiods to estimate cardinal temperatures, critical photoperiod and photoperiod sensitivity coefficient.

Model parameterization

In order to formulate and validate mathematical functions that can be used to quantify the effect of temperature and photoperiod on the biological days required from emergence to stem elongation of this cultivar ('Koohdasht'), for this, 8 non-linear regression models and 24 multiplicative non-linear regression models (including 8 temperature functions (**Table 1**) and 3 photoperiod functions) were fitted to stem elongation rate versus temperature and photoperiod data, where T, T_b, T_o, T_{o1}, T_{o2} and T_c for flat (F), beta (B) (Yin *et al.* 1997), dent-like (D) (Soltani *et al.* 2006), curvilinear (V) and quadratic (Q) (Ahmadi *et al.* 2009), logistic (L) (Grimm *et al.* 1997), and segmented (S) Kamkar *et al.* (2005, 2008) models (**Table 1**) represent mean air temperature, base temperature, lower optimum temperature, upper optimum temperature and ceiling temperature, respectively. *a* and t0 are constant coefficients in logistic function. In the cubic model (C) (Ahmadi *et al.* 2009), T indicates mean daily temperature and a, b and c are constant coefficients. In the beta model, *a* indicates shape bent (Olsen *et al.* 1993; Yin *et al.* 1997; Robertson *et al.* 2002a, 2002b).

Functions used for photoperiod were:

Segmented function (Soltani *et al.* 2006):

$$f(PP)=\begin{cases}1, & if\ \ pp\ge P,\\ 1-(Pc-PP)\times PS & if\ \ pp<P\end{cases}$$

Quadratic function (Soltani *et al.* 2006):

$$f(PP)=\begin{cases}1, & if\ \ pp\ge P,\\ 1-PS(Pc-PP)^2 & if\ \ pp<P\end{cases}$$

Negative exponential (Ahmadi 2008):

$$f(PP)=\{\exp(-PS\times(P_c-PP)\}$$

where PP, P_c and PS are photoperiod, the critical photoperiod below which development rate decreases due to short photoperiod and the photoperiod sensitivity coefficient respectively.

To obtain the best estimates for models parameters, an iterative optimization procedure was used and non-linear fitting was done based on the PORC NLIN procedure in SAS program (SAS Institute 1992). Root mean square of errors (Eq. 2), determination coefficient (R^2), model efficiency (EF) and model bias from a 1: 1 line were used as criteria to detect best estimates of parameters by non-linear models.

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

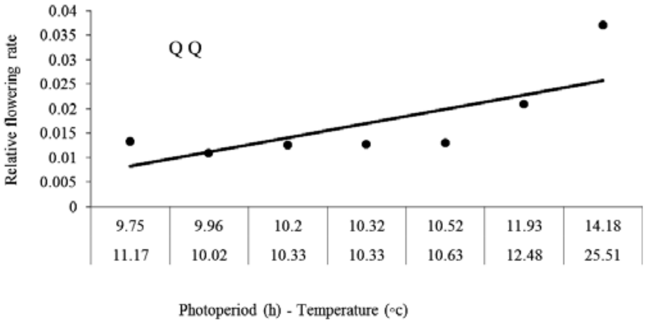

Fig. 1 Predicted (solid line) and observed (solide circles) Values of relative stem elongation rate versus mean experienced temperatures (°C) and .photoperiods (h) by quadratic-quadratic (Q-Q) model.

where P_i and O_i indicate predicted and observed values of stem elongation rate and n is the number of observations. The model with lower RMSE, higher determination coefficient (R^2), higher model efficiency (EF) and correlation coefficient (closer to 1) (Wallach *et al.* 2006), lower bias of linear regressed line between observed versus predicted values from the 1:1 line was selected as the best model to estimate stem elongation rate. *a* and *b* (as intercept and slope values of stem elongation rate) were compared with zero and unit. A closer *a* to zero and closer *b* to unit indicates better estimates of models (Kamkar *et al.* 2012).

Model structure and algorithm

In order to evaluate required biological days from emergence to stem elongation the following equation (Eq. 3) was used to compute development rate as a function of temperature and photoperiod (Hammer *et al.* 1989; Horie 1994):

$$1/e = f(T) \times f(PP)/eo \qquad (3)$$

where 1/e, f(T), f(P) and eo are stem elongation rate, temperature function, photoperiod function and minimum days to stem elongation in optimum temperature and photoperiod, respectively. The mean daily temperature and photoperiod corresponded to sowing dates used to calculate required biological days to stem elongation.

RESULTS AND DISCUSSION

Selection of models

Relative stem elongation rate (stem elongation rate divided by maximum stem elongation rate, R/Rmax) versus mean experienced temperatures and photoperiods is illustrated in **Fig. 1**, which reflects the dual interaction of photoperiod and temperature on stem elongation rate. The response of wheat to photoperiod as a facultative long-day plant (LDP) has been reported by others (Davidson and Christian 1984; Slafer and Rassown 1996; Ahmadi 2008). Also, estimated parameters for different models are presented in **Table 3**. The results indicate that the flat-quadratic model (combination of flat model for temperature and quadratic model for photoperiod) was not an appropriate model to predict stem elongation rate because at least one (*a* or *b*) coefficient of linear regressed line between observed versus predicted values was significantly different from zero or unit (**Table 3**). A significant coefficient indicates significant bias of intercept of the regressed line against the 1: 1 line. The remaining models performed similarly with respect to R^2, RMSE and regression of predicted versus observed days from emergence to stem elongation. However, results of evaluation of the model using independent data (Ahmadi 2008) indicated that a model that included the quadratic function for both temperature and photoperiod was the best model, because neither *a* nor *b* were significant (**Fig. 2; Table 2**) and R^2 was higher. RMSE was almost similar and ranged from 0.001 to 0.1 for all the functions.

Estimates of cardinal temperature based on a superior model (Q-Q) 7.62°C for T_b and 37.6°C for T_c for wheat (cv. ‘Koohdasht’) are presented in **Table 4**.

The base temperature for stem elongation of wheat reported in a segmented-segmented model was 4.14°C (Ah-

Table 2 Root mean square of errors (RMSE), determine coefficients (R^2), correlation coefficient (r), model efficiency (EF) of models used to describe relationship between stem elongation rate versus temperature and photoperiod in wheat (cv. ‘Koohdasht’) using independent data (Ahmadi 2008). *a* and *b* are regression coefficients.

Model	R^2	a	b	RMSE	r	EF
Quadratic-Quadratic	0.99	0.0001	0.99	0.009	0.55	0.3

Table 3 Root mean square of errors (RMSE), determination coefficients (R^2), correlation coefficient (r) and model efficiency (EF) of multiplicative models (8 temperature functions and 3 photoperiod functions) used to describe relationship between stem elongation rate as a function of temperature and photoperiod in wheat (cv. ‘Koohdasht’). *a* and *b* are intercept and slope of regression line between observed versus predicted stem elongation.

Photoperiod functions	Temperature functions	R^2	a	b	RMSE	r	EF
Quadratic	Quadratic	0.98	0.0001	0.99	0.0009	0.99	0.98
	Beta	0.99	-0.0003	1.001	0.0008	0.99	0.99
	Segmented	0.99	0.0001	0.99	0.0008	0.99	0.99
	Cubic	0.98	-0.0002	0.90	0.0129	-0.58	-1.24
	Curvilinear	0.99	0.0010	0.908	0.001	0.997	0.985
	Logistic	0.99	0.00009	0.99	0.0007	0.99	0.99
	Dent-like	0.99	0.0001	0.99	0.0008	0.99	0.44
	Flat	0.32	0.011	0.18	0.13	0.14	0.57
Segmented	Quadratic	0.98	0.001	0.89	0.001	0.97	0.99
	Beta	0.99	0.00003	0.99	0.0008	0.99	0.99
	Segmented	0.99	0.0001	0.99	0.0008	0.99	0.99
	Cubic	0.98	-0.0002	1.01	0.0009	0.98	0.99
	Curvilinear	0.99	0.0010	0.90	0.011	-0.72	-0.09
	Logistic	0.99	0.0001	0.99	0.0007	0.99	0.99
	Dent-like	0.99	-0.0002	1.002	0.0009	0.98	0.99
	Flat	0.98	0.0007	0.94	0.001	0.98	0.99
Negative exponential	Quadratic	0.98	0.0001	0.98	0.0009	0.98	0.99
	Beta	0.99	0.00007	0.99	0.0008	0.99	0.99
	Segmented	0.95	0.001	0.94	0.001	0.95	0.97
	Cubic	0.99	-0.0009	1.03	0.0009	0.98	0.99
	Curvilinear	0.99	0.0020	0.83	0.01	-0.40	-0.11
	Logistic	0.99	0.0001	0.99	0.0007	0.99	0.99
	Dent-like	0.99	-0.00002	1.0002	0.0008	0.99	0.99
	Flat	0.98	0.001	0. 89	0.001	0.97	0.99

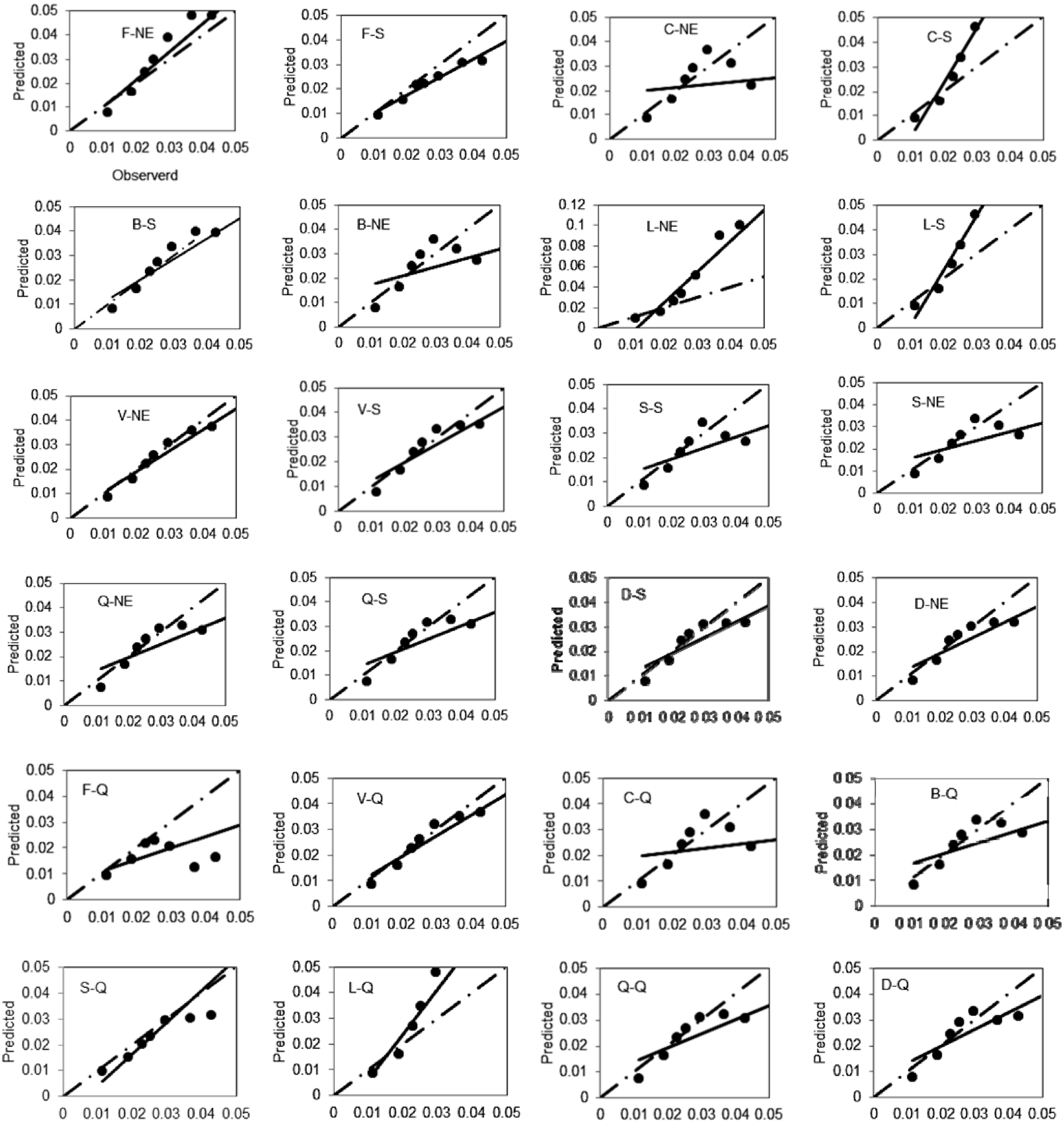

Fig. 2 Observed versus predicted values of stem elongation rate using independent data (Ahmadi 2008) by multiplicative models (8 temperature functions in combination with negative exponential and segmented models for photoperiod). Solid line indicates 1:1 line. **V-Q**, curvilinear-quadratic; **V-S**, curvilinear- segmented; **V-Ne**, curvilinear-negative exponential; **Q-Q**, quadratic-quadratic; **Q-S**, quadratic- segmented; **Q-Ne**, quadratic-negative exponential; **S-Q**, segmented-quadratic; **S-S**, segmented-segmented; **S-Ne**, segmented –negative exponential; **D-Q**, dent like-quadratic; **D-S**, dent like-segmented; **D-Ne**, dent like-negative exponential; **B-Q**, beta-quadratic; **B-S**, beta-segmented; **B-Ne**, beta-negative exponential; **C-Q**, cubic-quadratic; **C-S**, cubic-segmented; **C-Ne**, cubic-negative exponential; **F-Q**, flat-quadratic; **F-S**, flat-segmented; **F-Ne**, flat –negative exponential; **L-Q**, logistic-quadratic; **L-S**, logistic-segmented; **L-Ne**, logistic-negative exponential.

madi 2008). Other reported base temperatures for stem elongation of wheat cultivars are 4°C (Slafer and Savin 1991; Slafer and Rawson 1996), 1°C (Wier *et al.* 1984), and 3.6°C (for spring wheat, Angus *et al.* 1981). Estimated ceiling temperatures were comparable with reported values of 37°C by Ahmadi (2008) and Narciso *et al.* (1992) and 38°C by Peter (1991).

Estimated photoperiod parameters by the superior model (Q-Q) were 14.006 h for P_c, 0.11 for PS and 26.13 for photothermal days from emergence to stem elongation (eo) (**Table 4**). Other reported critical photoperiod and photoperiod sensitivity coefficients for stem elongation of wheat cultivars ('Arapahoo' and 'Karel 92') are 9.5 and 7 h, 0.34 and 0.16 h^{-1} respectively (Xue 2000), while Ahmadi (2008) reported P_c and PS for stem elongation of wheat cultivars 12.96 to 14.002 h and 0.1 to 0.18 h^{-1}, respectively.

These values are basic and primary data needed to simulate emergence to stem elongation duration. These data are used directly in thermal time calculation and determine extreme temperatures and photoperiod which will suppress stem elongation. This temperature range has been defined as cardinal temperatures, i.e., a minimum or base temperature (T_b), maximum temperature (T_c) that stem elongation rate at above of that would be zero, and optimum temperature (T_o) at which the stem elongation rate is highest (Whitechurch *et al.* 2007), PP is photoperiod (h), P_c the crit-

Table 4 Estimated values of base temperature (T_b), optimum temperature (T_o), ceiling temperature (T_c), photoperiod sensitivity coefficient (PS),critical photoperiod (P_c) and minimum days from emergence to stem elongation under optimum temperature and photoperiod (eo) by multiplicative models (3 photoperiod functions and 8 temperature functions).

Photoperiod Functions	**Temperature Functions**	**T_b(˚C)**	***a***	**t0**	**T_{o1}(˚C)**	**T_{o2}(˚C)**	**T_0(˚C)**	**T_c(˚C)**	**eo**	**PS (h^{-1})**	**P_c (h)**
Quadratic	Quadratic	7.62	-	-	-	-	-	37.60	26.90	0.11	14.006
	Beta	3.08	-	-	-	-	21.85	38.19	22.79	0.01	12.04
	Segmented	7.14	-	-	-	-	23.04	36.97	16.70	0.11	12.007
	Cubic	-	-	-	-	-	-	-	20	0.15	15.70
	Curvilinear	7.64	-	-	-	-	18.51	34.60	26.82	0.16	12.04
	Flat	7.24	-	-	-	-	22.07	-	17.25	0.15	12.32
	Logistic	-	0.35	13.8	-	-	-	-	18.97	0.13	12.03
	Dent-like	6.59	-	-	21.53	28	-	37	20.48	0.11	12
Segmented	Quadratic	7.46	-	-	-	-	-	37.93	27.59	0.17	14.18
	Beta	3.79	-	-	-	-	21.95	37.98	23.15	0.17	0.17
	Segmented	7.15	-	-	-	-	24.80	37	15.06	0.34	0.34
	Cubic	-	-	-	-	-	-	-	22	0.11	0.11
	Curvilinear	7.83	-	-	-	-	17.99	36	27.32	0.16	0.16
	Flat	7.24	-	-	-	-	22.14	-	17.16	0.15	0.15
	Logistic	-	0.35	13.8	-	-	-	-	18.97	0.02	12.03
	Dent-like	7.15	-	-	20	29	-	37	20.67	0.27	13.19
Negative exponential	Quadratic	7.69	-	-	-	-	-	38.37	26.29	0.02	14.19
	Beta	6.49	-	-	-	-	22.22	35.77	24.02	0.004	12.03
	Segmented	2.19	-	-	-	-	29.58	38.77	22.5	0.12	16.00
	Cubic	-	-	-	-	-	-	-	20	0.15	15.70
	Curvilinear	7.83	-	-	-	-	18.33	35	28.89	0.16	12
	Flat	7.24	-	-	-	-	20.57	-	19.18	0.15	12.76
	Logistic	-	0.35	13.8	-	-	-	-	18.97	0.06	12.04
	Dent-like	7.15	-	-	20.53	28	-	37	19.85	0.06	12.01

ical photoperiod below which development rate decreases due to short photoperiod and PS the photoperiod sensitivity coefficient (Soltani *et al.* 2006).

Other considerations

Despite us having used a wide range of sowing dates, obtained and used points to fit models did not include a temperature higher than ceiling temperature. Therefore, the model introduced as the best model (quadratic-quadratic model) can only be used in a temperature range of around 3 to 39°C. If temperatures higher than the ceiling temperature are faced, it is likely that other models, especially those that can extrapolate the diminishing trend of development rate after extra-ceiling temperature, can be used as the superior model. Therefore, it is advisable to repeat this experiment with more sowing dates to clarify the response of wheat stem elongation rate to higher temperatures along with photoperiod.

Also, all models' estimates showed that ceiling temperature changes between 35 to 39°C. Although these values were just extrapolated by models, they can be considered warily as a range of ceiling temperatures for related calculations.

In addition, this study on the effect of temperature and photoperiod on stem elongation phase indicated that 'Kohdasht' has a quantitative or facultative LDP response to photoperiod. This means that with increasing photoperiod to 14.002 h, quickly entering the reproductive phase of wheat increased and with a photoperiod exceeding 14.002 h, no effect on development rates and growth rate constant remains. If this plant were exposed to a short photoperiod, there would be a reduction in growth rate, but it would not stop development.

ACKNOWLEDGEMENTS

The authors thank Dr. Jaime A. Teixeira da Silva for improving the grammar.

REFERENCES

Ahmadi M (2008) Predicting of phenological development in wheat (*Triticum aestivum* L.). MSc thesis, Gorgan University of Agricultural Sciences and Natural Resources, 93 pp

Ahmadi M, Kamkar B, Soltani A, Zeinali E (2009) Evaluation of non-linear regression models to predict stem elongation rate of wheat (Tajan cultivar) in response to temperature and photoperiod. *Electronic Journal of Crop Production* **4**, 39-54

Angus JF, Mackanzie DH, Morton R, Slafer CA (1981) Phasic development in field crops. II. Thermal and photoperiod responses of spring wheat. *Field Crops Research* **4**, 269-283

Davidson JL, Christian KR (1984) Flowering in wheat. In: Pearson CJ (Ed) *Control of Crop Productivity*, Academic Press, Sydney, pp 112-126

Eshraghi-Nejad M (2009) Predicting of phenological development in millet. MSc thesis, Gorgan University of Agricultural Sciences and Natural Resources, 151 pp

Fischer RA (1979) Growth and water limitation to dryland wheat yield in Australia: A physiological framework. *Australian Journal of Agriculture Science* **45**, 83-94

Forcella F (1993) Seedling emergence model for velvefleaf. *Journal of Agronomy* **85**, 929-933

Grimm SS, Jones JW, Boote KJ, Hasketh JD (1997) Parameter estimation for predicting flowering date of soybean cultivars. *Crop Science* **33**, 137-144

Hammer GL, Vaderlip RL, Gibson G, Wade LJ, Henzell RG, Younger DR, Warren J, Dale AB (1989) Genotype-by-environment interaction in grain sorghum. II. Effect of temperature and photoperiod on ontogeny. *Crop Science* **29**, 376-384

Hodges T (1991) Crop growth simulation and the role of phenological models. In: Tom H (Eds) *Predicting Crop Phenology*, CRC Press, Boca Raton, FL, pp 3-6

Horie T (1994) Crop ontogeny and development. In: Boote KJ, Bennett JM, Sinclair TR, Paulsen GM (Eds) *Physiology and Determination of Crop Yield*, ASA, CSSA, and SSSA, Madison, USA, pp 153-180

Kamkar B (2005) Application of a system approach for evaluation of potential yield and yield gap of cumin and three millet genus (a case study in Northern, Razavi and Southern Khorasan provinces). PhD thesis, Ferdowsi University of Mashhad, 177 pp

Kamkar B, Ahmadi M, Soltani A, Zeinali E (2008) Evaluating non-linear regression models to describe response of wheat emergence rate to temperature. *Seed Science and Biotechnology* **2**, 53-57

Kamkar B, Jami Al-Ahmadi M, Mahdavi-Damghani AM, Villalobos FJ (2012) Quantification of the cardinal temperatures and thermal time requirement of opium poppy (*Papaver somniferum* L.) seeds to germinate using non-linear regression models. *Industrial Crops and Products* **35 (1)**, 192-198

Kamkar B, Koocheki A, Nasiri Mahallati M, Teixeira da Silva JA, Rezvani

Moghaddam P, Kafi M (2011) Fungal diseases and inappropriate sowing dates, the most important reducing factors in cumin fields of Iran, a case study in Khorasan provinces. *Journal of Crop Protection* **30**, 208-215

Jame YW, Cutforth HW (2004) Simulating the effects of temperature and seeding depth on germination and emergence of spring wheat. *Agriculture and Forest Meteorology* **124**, 207-218

Manupeerapan T, Person CJ (1993) Apex size, flowering and grain yield of wheat as affected by sowing date. *Field Crops Research* **32**, 41-57

Narciso G, Ragni P, Venturi A (1992) *Agrometeorological Aspects of Crops in Italy, Spain and Greece*, Joint Research Centre, Commission of the European Communities, Brussels, Luxembourg, 440 pp

Olsen JK, McMahan CR, Hammer GL (1993) Predication of sweet corn phenology in subtropical environments. *Journal of Agronomy* **54**, 410-415

Richards RA (1991) Crop improvement for temperate Australia: Future opportunities. *Field Crops Research* **26**, 141-169

Ritchie JT (1991) Wheat phasic development. In: Hanks RJ, Ritchie JT (Eds) *Modelling Plant and Soil Systems*, Agronomy Monograph No **31**, American Society of Agronomy, Madison, Wisconsin, USA, pp 31-54

Robertson MJ, Carberry PS, Huth NI, Turpin JE, Probert EM, Poulton PL, Bell M, Wright GC, Yeaters SJ, Brinsmead RB (2002a) Simulation of growth and development of diverse legume species in APSIM. *Australian Journal of Agriculture Research* **53**, 429-446

Robertson MJ, Watkinson AR, Kirgekaard JA, Holland JF, Potter TD, Burton W, Walton GH, Moot DJ, Wratten N, Farre I, Asseng S (2002b) Environmental and genotypic control of time to flowering in canola and Indian mustard. *Australian Journal of Agriculture Science* **53**, 793-809

SAS Institute (1997) SAS/STAT user's guide. SAS Institute Inc., Cary. NC, USA, 220 pp

Slafer GA, Rawson HM (1994) Sensitivity of wheat phasic development to major environmental factors: a re-examination of some assumptions made by physiologists and modelers. *Australian Journal of Plant Physiological* **21**, 393-426

Slafer GA, Rawson HM (1996) Responses to photoperiod change with phenophase and temperature during wheat development. *Field Crops Research* **46**, 1-13

Soltani A, Hammer GL, Torabi B, Robertson MJ, Zeinali E (2006) Modeling chickpea growth and development: Phenological development. *Field Crops Research* **99**, 1-13

Stapper M, Fischer RA (1990) Genotype, sowing date and plant spacing influence on high-yielding irrigated wheat in southern New South Wales: I. Phasic development canopy growth and spike production. *Australian Journal of Agriculture Research* **41**, 997-1019

Sterk NA, Weiss A, Xue Q, Baenziger PS (2003) Improving predictions of developmental stages in winter wheat: A modified Wang and Engel model. *Agriculture and Forest Meteorology* **115**, 139-150

Syme JR (1968) Ear emergence of Australian, Mexican and European wheat in relation to time of sowing and their response to vernalization and daylength. *Australian Journal of Experimental Agriculture* **8**, 578-581

Peter J (Ed) (1991) *Weather and Yield*, Elsevier, Amsterdam, 288 pp

Wallach D, Makowski D, Jones J (2006) Evaluating crop models. *Field Crops Research* **97**, 11-52

Whitechurch EM, Slafer GA, Miralles DJ (2007) Variability in the duration of stem elongation in wheat genotypes and sensitivity to photoperiod and vernalization. *Journal of Agronomy Science* **193**, 131-137

Weir AH, Bragg PL, Porter JR, Rayner JH (1984) A winter wheat crop simulation model without water on nutrient limitations. *Journal of Agriculture Science* **102**, 371-382

Xue Q (2000) Phenology and gas exchange in winter wheat (*Triticum aestivum* L.). PhD thesis, University of Nebraska-Lincoln, 123 pp

Yin X, Kropff MJ, Horie T, Nakagawa H, Genteno HGS, Zhu D, Goudriaan J (1997) A model for photothermal responses of flowering in rice. I: Model description and parameterization. *Field Crops Research* **51**, 189-200

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. *EUCARPIA Bulletin* **7**, 42-52