Journal of Insect Science OPEN ACCESS

RESEARCH

Effect of Temperature on Developmental Rate of *Sesamia cretica* (Lepidoptera: Noctuidae) Immature Stages

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Subject Editor: Xinzhi Ni

J. Insect Sci. 14(197): 2014; DOI: 10.1093/jisesa/ieu059

ABSTRACT. Effect of temperature on development of pink stem borer, *Sesamia cretica* Lederer, was studied at eight constant temperatures (15, 18, 20.5, 24, 27, 30, 34, and 38°C), a photoperiod of 16:8 (L:D) h, and 50–60% rela\tive humidity. The larvae of pink stem borer were reared on cutting stems of maize. The results showed that temperature had statistically significant effect on developmental times of the all developmental stages. The most commonly used six nonlinear models applied for modeling developmental rate of immature stages as a function of temperature. Evaluation of the models fit to data took place based on the coefficient of determination, residual sum of squires, adjusted coefficient of determination, and Akaike information criterion. Besides statistical criteria, biological significance was used to determine the best model. All the examined models statistically fit the data well. In addition, Briere-2 was selected as the best model considering biological significance of the estimated values for the biologically interpretable parameters of models. Based on the results, the values of the lower temperature threshold were 10.82, 11.81, 9.35, and 10.67°C, the optimal temperature were 35.50, 31.80, 33.35, and 32.22°C, and the upper temperature threshold were 38.93, 39.19, 37.41, and 36.55°C, for incubation period, larva, pupa, and overall immature stages of pink stem borer, respectively.

Key Words: pink stem borer, nonlinear model, development, temperature threshold

Maize follows wheat and barley is the most important nutrient in the world. The origin of maize backs to America continent (southern Mexico) and harvest history of maize is more than 8,000 to 10,000 years ago (Tollenaar and Dwyer 1999). The most important producing countries are Northern America, China, and Latin America, whereas Northern America has a bit less than half of world maize production through 14% world production area (Pinthus 1973). Pink stem borers are as the main pest insects of maize in the fields throughout the world. Sugarcane and maize fields are damaged seriously by the stem borers belonging to the genus *Sesamia*. These stem borers are considered as the most important pest insect in the mentioned crop fields especially in southern parts (e.g., Khuzestan and Fars provinces) of Iran (Ranjbar Aghdam 1999). The main species of mentioned pests are belonging to the families Pyralidae and Noctuidae. In addition to the maize, *Zea mays*, host plants of the stem borers, *Sesamia* spp. are: *Avena sativa*, *Hordeum vulgare*, *Oryza sativa*, *Pennisetum typhoideum*, *Saccharum* spp., *Sorghum bicolor*, *So. halpense*, *Triticum aestivum*, unidentified bamboo, unidentified bulrush, and unidentified palms (Tams and Bowden 1953; Rao and Nagaraja 1969; Leslie 1994; Meijerman and Ulenberg 1996; Zaki et al. 1997; Heinrichs 1998; Polaszek and Khan 1998).

Temperature is a critical abiotic factor influencing the dynamics of mite and insect pests and their natural enemies (Huffaker et al. 1999). Temperature sets the limits of biological activities in arthropods, such that lower and upper temperature threshold and optimum temperature can be estimated for all major life processes (Roy et al. 2002). Thermal characteristics may vary between species, populations, development stages, and with other ecological factors such as food source (Gilbert and Raworth 1996, Roy et al. 2003).

All biology, or biological development, is dependent on chemical reactions. The rate at which chemical reactions occur is dependent on the amount of heat received at the reaction site. The more heat received, the faster the rate of the reactions; and, in the case of biological organisms, the faster their development within limits (Zalom et al. 1983).

Developmental rate, expressed as the reciprocal of time taken to change from one developmental stage of an arthropod to another (Cossins and Bowler 1987). Value of development rate is nil at the low temperature threshold, increases with temperature before leveling off at the optimum, and then decreases rapidly as the high threshold is approached (Roy et al. 2002). The relationship between temperature and developmental rate is curvilinear near extremes, but approximately linear at moderate temperatures (Wagner et al. 1984). In order to describe the developmental rate more realistically over a wider temperature range, several nonlinear mathematical models have been applied (e.g., Briere et al. 1999; Roy et al. 2002; Kontodimas 2004; Arbab et al. 2006; Ranjbar Aghdam et al. 2009, 2011). These models provide estimations for lower and upper temperature thresholds and optimal temperature of a given stage in addition to description of developmental rate at different temperatures. In comparison, the linear models are able to estimate low temperature threshold, and thermal constant in a limited thermal range (Roy et al. 2002, Kontodimas 2004, Ranjbar Aghdam et al. 2009). It should be noticed that the estimation of low temperature threshold by linear models has a difference from nonlinear estimation and the estimations of nonlinear models are more accurate (Ranjbar Aghdam et al. 2009). However, linear models are mostly used to calculate thermal requirement of arthropods, because they are simple and easy to calculate (Roy et al. 2002, Ranjbar Aghdam et al. 2009). By the linear models, it is assumed that there is a linear relation between development rate of insect and temperature. Linear model cannot present a real description of relationship between temperature and development rate over a wider range of temperature.

The objectives of this study were to develop knowledge of the temperature-dependent development and thermal indices of the pink stem borer, *Sesamia cretica* Lederer, by using mathematical nonlinear modes. The results can help us to provide precise phenological model to forecast the pest status in the maize field.

Materials and Methods

Laboratory-Rearing Procedure. The larvae of the pink stem borer, *S. cretica*, were originally collected from maize fields of Rey region located in Tehran province, during the year 2010. The larvae were reared in growth chamber at temperature 25 ± 2°C, 60 ± 10% relative humidity (RH), and a photoperiod of 16:8 (L:D) h. Collected larvae were transferred to transparent plastic jars (15 cm by 25 cm in height by diameter) for rearing. Larvae were reared on the cutting stems of commonly cultivated maize cultivar, SC-740, in Rey region. Developmental process of the larvae and food quality were checked 2–3 times per week. The old cutting stems were replaced by the fresh cutting every 4–5 days. After pupation, pupae were picked up and translocated to pupal containers in the similar environmental conditions. All the isolated pupae were located on a cotton substrate in transparent plastic jars (15 cm by 25 cm in height by diameter) until emergence of the adults. Emerged moths were translocated to that. Mating and oviposition containers were made from transparent plastic in cubic form (61 by 41 by 50 cm^3 in length, width, and height). Feeding the moth was carried out by using 10% water–honey solution. A piece of rolled cotton was passed from a hole in the upside of the food solution containers to provide food for feeding moth during mating and oviposition. The volume of the solution containers was about 15 cm^3. To provide a suitable oviposition substrate, fresh maize stems with leaf sheath were put in oviposition containers. During oviposition period, maize stems were replaced daily by fresh stems and the eggs were picked up by an artistic fine brush from the inner side of the leaf sheath. The eggs were located in test tubes that were 1.5 cm in diameter and 10 cm in height. Open side of the tubes was closed by compressed cotton to prevent exit of neonate larvae. The tubes were checked daily for hatching eggs. When the color of eggs was changed and became darker, cutting of maize fresh stems with leaf sheath (~5 cm), that was cut from the upper parts of the maize stems, were put inside tubes for feeding neonate larvae. When the larvae were developed to the second instar, they were isolated from each other and reared separately.

Experimental Conditions. Developmental rate was studied at eight constant temperatures 15, 18, 20.5, 24, 27, 30, 34, and 38 (±0.5)°C, 50 ± 10% RH and a photoperiod of 16:8 (L:D) h in growth chambers.

Temperature-Dependent Development. Developmental time of the pink stem borer immature stages including incubation period, larval, pupal, and overall immature stages were determined under mentioned experimental conditions.

In order to the study of incubation period, 200–400 eggs, each less than 24-h old were incubated in each experimental condition. All eggs were checked daily for hatching and the number of hatched eggs was recorded. Newly emerged larvae were translocated individually to test tubes. Test tubes were 1.5 cm in diameter and 10 cm in height. Following incubation period, larval and pupal developmental time were recorded in each experimental condition. The larvae were reared in plastic dishes with 6.5 cm diameter in opening side and 3 cm height. The larvae were placed singly in larval rearing containers using a fine brush. Larval rearing containers were inspected for pupating daily. The date of pupation was recorded. All the pupae were kept in the same larval rearing containers until emergence moths. Based on the recorded data, larval period and pupal period were determined for each studied individual. In addition, the developmental time of overall immature stages from the date of oviposition to the date of moth emergence were calculated based on observations at examined temperatures.

Nonlinear Mathematical Models. Developmental rate is the reciprocal of developmental time in days. These rates are used in evaluated mathematical models where data are added daily (Arbab et al. 2006). Development id completed when the sum of daily developmental values equals 1 (Curry et al. 1978). Therefore, the integral of the developmental rate function along time can be used to simulate the development of an organism exposed to different temperatures (Arbab et al. 2006). Due to intrinsic disabilities of linear models to estimate critical temperatures and real description of relationship between temperature and development rate, six commonly used nonlinear models were applied to describe temperature-dependent development of the pink stem borer over a wide range of temperature. Nonlinear models were Briére-1, Briére-2, Logan-6, Logan-10, Polynomial -third order (Harcourt equation), and Lactin (Table 1).

Standard Temperature Indices. Developmental rate of the insects is depend on the amount of heat unites received at the reaction site between two critical point of temperature for development, lower, and upper temperature thresholds. The more heat received, the faster the rate of the reactions and the faster developmental rate. These critical points of temperature and optimal temperature are referred as standard temperature indices in some of the literatures (Ranjbar Aghdam et al. 2009).

Lower Temperature Threshold (T_{min}*)*. This temperature is often referred as the lower developmental threshold (Kontodimas et al. 2004) or the zero development temperature (Howell and Neven 2000). However, at the lower temperature threshold, measurable development is not detected or the rate of development is zero. Among evaluated nonlinear modes, Briére-1, Briére-2, and Lactin could estimate this temperature index for development of the pink stem borer immature stages.

Optimal Temperature (T_{opt}*)*. At the optimal temperature (T_{opt}), developmental time is the lowest and developmental rate is in the highest value. It may be estimated directly from the equations of some nonlinear models, or as the parameter value for which their first derivatives equals zero (Kontodimas et al. 2004). All of the evaluated models gave estimated values for optimal temperature of the pink stem borer developmental stages.

Upper Temperature Threshold (T_{max}*)*. At the upper temperature threshold, the rate of development is zero or life cannot be maintained for a long time (Kontodimas et al. 2004). All of the evaluated nonlinear models estimated this critical temperature for development of the pink stem borer.

Experimental Design and Data Analysis

The effect of temperature on developmental time of pink stem borer immature stages was examined based on completely randomized design (CRD). Collected data were analyzed using General Linear Model (GLM) procedure. If significant differences among developmental time were confirmed, the means of developmental time were compared using Ryan's Multiple Range Test. All the statistical analysis was carried out by using SAS Ver. 9.1 software (SAS Institute 2004).

Parameters of the Nonlinear Models

In each evaluated nonlinear model, there are two types of parameters. 1) Fitted coefficients ($a, b, c, d, \Delta, \rho, \lambda, \Psi$) that are not directly calculated but estimated as coefficients of nonlinear regression (Kontodimas et al. 2004). Each nonlinear model may have intrinsically different number of this type of the parameters. 2) Measurable parameters (Kontodimas et al. 2004) including, lower temperature threshold, optimal temperature, and upper temperature threshold. Most of the models enable the estimation of two or more parameters of the later group. The standard temperature indices have biological interpretation.

Model Evaluation

In order to select the best nonlinear models, all of the examined models were evaluated based on statistical criteria and biological significance.

Statistical Criteria. Four statistical criteria were used to assess the performance of evaluated nonlinear models; the coefficient of determination, R^2 (Kontodimas et al. 2004, Arbab et al. 2006). The residual sum of square, RSS (Kontodimas et al. 2004, Arbab et al. 2006), The Akaike information criterion, AIC (Akaike 1974, Burnham and Anderson 2002, Vucetich et al. 2002, Angilletta 2006, Ranjbar Aghdam et al. 2009), and the adjusted coefficient of determination, R^2_{adj} (Rezaei and Soltani 1998). Higher values of R^2 and R^2_{adj} and lower values of RSS and AIC indicate a better fit. The coefficient of determination and RSS were commonly used for model evaluation. However, the R^2 value is not appropriate for discriminating between models with different numbers of parameters because models with more parameters always provide a better fit. Therefore, AIC and R^2_{adj} were used because that are parameter-independent (Ranjbar Aghdam et al. 2009).

Biological Significance. Biological significance or accuracy at estimation of thermal indices of pink stem borer was carried out based on their comparison with experimental data. The lower temperature threshold should be lower than 15°C. The optimal temperature should lie between 30 and 34°C, where maximum value of developmental rate was measured. Similarly, the true value of upper temperature threshold should be located between 34 and 38°C for pupal and overall immature stages. However, mentioned critical temperature for incubation period and larval stage should be more than 38°C as the temperature 38°C was not lethal for individuals in egg and larval stages.

The analysis of regression and estimation of model parameters were carried out by using the JMP, Ver. 4.0.2, (SAS Institute 2000) and SPSS, Ver. 13 (SPSS Institute 2004) software.

Table 1. Mathematical models used to describe temperature-dependent development of pink stem borer

Model	Equation	Reference
Briére-1	$\frac{1}{D} = aT(T - T_{min})(T_{max} - T)^{1/2}$	Briére et al. (1999)
Briére-2	$\frac{1}{D} = aT(T - T_{min})(T_{max} - T)^{1/d}$	Briére et al. (1999)
Lactin-2	$\frac{1}{D} = e^{\rho T} - e^{\left(\rho T_{max} - \frac{T_{max}-T}{\Delta T}\right)} + \lambda$	Lactin et al. (1995)
Logan-6	$\frac{1}{D} = \psi\left[e^{\rho T} - e^{\left(\rho T_{max} - \frac{T_{max}-T}{\Delta T}\right)}\right]$	Logan et al. (1976)
Logan-10	$\frac{1}{D} = \alpha\left[\frac{1}{1+Ke^{-\rho T}} - e^{\left(-\frac{T_{max}-T}{\Delta T}\right)}\right]$	Logan et al. (1976)
Polynomial third order	$\frac{1}{D} = aT^3 + bT^2 + cT + d$	Harcourt and Yee (1982)

Results

Temperature-Dependent Development. Development of immature stages of pink stem borer could be completed at 15, 18, 20.5, 24, 27, 30, 34, and 38°C, except pupal stage at 38°C. Incubation period and developmental times of larval, pupal and overall immature stages of pink stem borer were presented in Table 2. There were significant effects of temperature on developmental time for all the pink stem borer immature stages. Mean incubation period (egg developmental time) decreased with increasing temperature up to 34°C and then increased at 38°C. Incubation periods were statistically different at examined temperatures ($F = 23695.51$, df = 7,976, $P < 0.001$). The shortest value for the incubation period observed at 34°C and the longest period occurred at 15°C. Similarly, the larval period was affected significantly by temperature ($F = 53245.79$, df = 7,475, $P < 0.001$). Although, the shortest value of larval period was observed at 30°C. There was no statistically significant difference between the values of larval period at 30 and 34°C. The longest larval period was observed at 15°C (Table 2). None of the examined pupae could complete its development at 38°C. Therefore, analysis of variance of pupal period was conducted from temperature, 15–34°C. However, same as incubation and larval periods, pupal period was statistically different at examined temperatures

Table 2. Comparison developmental time of the immature stages of pink stem borer at eight constant temperatures

Developmental stage	Temperature (°C)	Number of individuals	Developmental time (days)		
			Min.	Max.	Mean ± SE
Egg (incubation period)	15	133	24	27	25.94 ± 0.06g
	18	68	14	17	15.44 ± 0.10f
	20.5	146	11	13	12.03 ± 0.03e
	24	178	6	8	6.55 ± 0.05d
	27	138	5	6	5.05 ± 0.02c
	30	157	4	6	4.37 ± 0.05b
	34	121	3	4	3.62 ± 0.04a
	38	43	4	5	4.21 ± 0.06b
Larva	15	31	103	150	127.97 ± 2.49g
	18	45	65	88	75.35 ± 0.97f
	20.5	60	32	50	38.18 ± 0.55d
	24	77	28	39	32.69 ± 0.29c
	27	83	20	42	25.58 ± 0.44b
	30	91	15	34	20.58 ± 0.35a
	34	75	18	33	23.16 ± 0.41ab
	38	21	29	51	41.52 ± 1.60e
Pupa	15	20	42	57	46.80 ± 0.95f
	18	41	24	31	26.71 ± 0.22e
	20.5	49	12	22	15.48 ± 0.29d
	24	70	7	15	12.71 ± 0.12c
	27	69	9	12	10.14 ± 0.07b
	30	75	4	10	8.11 ± 0.11a
	34	73	6	9	7.70 ± 0.08a
	38	–	–	–	–
Overall immature stages	15	20	169	228	197.60 ± 3.11f
	18	41	107	129	117.58 ± 1.09e
	20.5	49	55	83	65.34 ± 0.83d
	24	70	48	58	51.57 ± 0.29c
	27	69	35	57	40.90 ± 0.48b
	30	75	28	39	32.45 ± 0.32a
	34	73	29	45	34.23 ± 0.48a
	38	–	–	–	–

The means of developmental time in the same developmental stages followed by different letters are statistically different. Ryan's multiple range test $P < 0.05$.

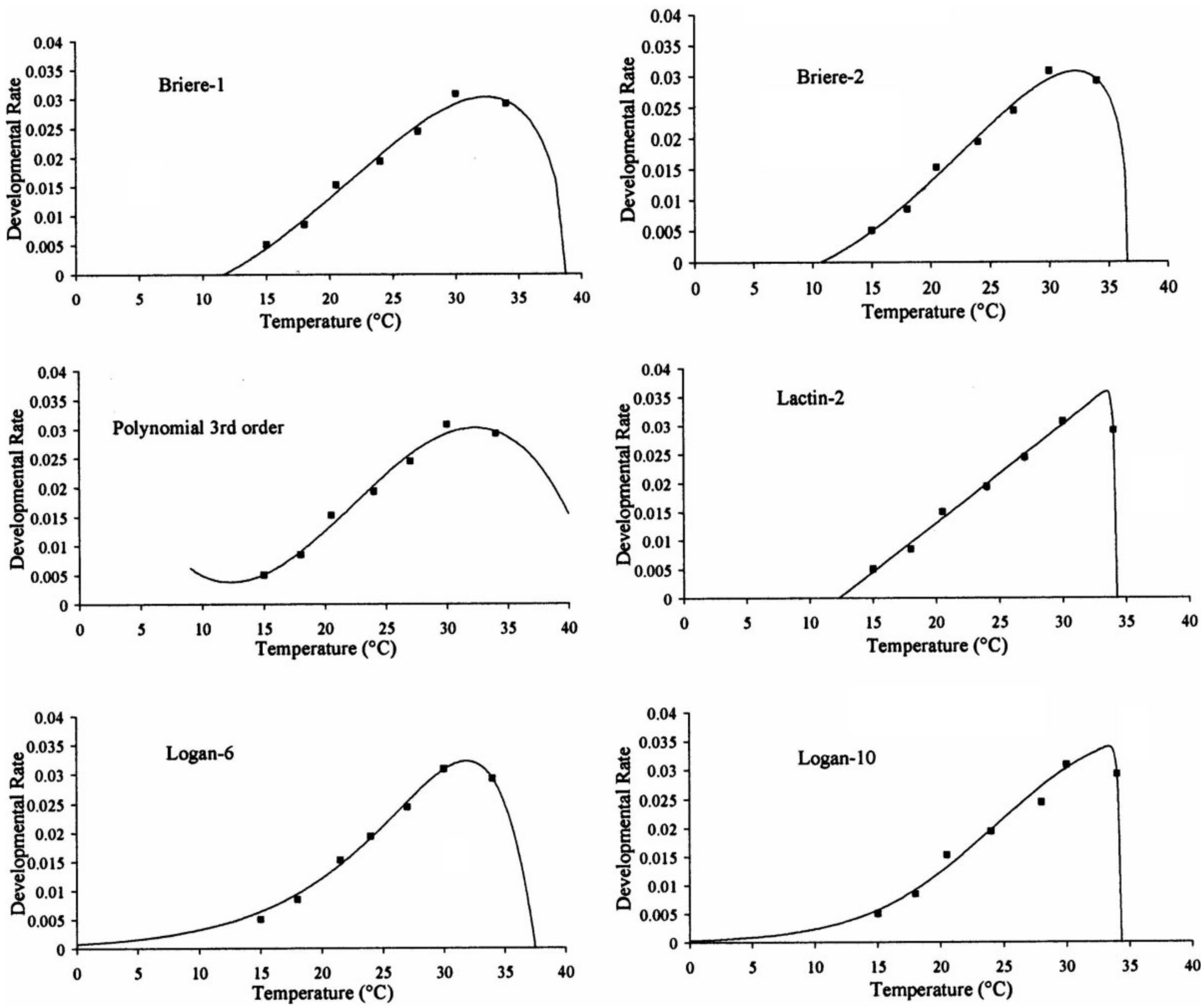

Fig. 1. Fitting six nonlinear models to observed values of developmental rates (1/day) of overall immature stages of pink stem borer at examined temperatures. Black squares are observed data.

($F = 5815.09$, df $= 6, 390$, $P < 0.001$). In addition, pupal periods were the shortest at temperatures 30 and 34°C (Table 2). Due to death of all examined individuals in pupal stage at 38°C, the value of developmental time for overall immature stages could not be estimated at mentioned temperature. Totally, the values of overall immature stages were statistically different at examined temperatures ($F = 108497.12$, $df_t = 6, 390$, $P < 0.001$). The shortest value of developmental time of overall immature stages was 32.45 days at 30°C and the longest was 197.60 days at 15°C. There was no statistically significant difference between the values of developmental time at 30 and 34°C (Table 2).

Evaluation of Nonlinear Models.

Based on Statistical Criteria. All of the evaluated nonlinear models fit the data well (Fig. 1). The curves of the influence of temperature on developmental rate of overall immature stages fitted by each model are presented in Fig. 1. The values of statistical criteria, R^2, RSS, AIC, and R^2_{adj} used to evaluate goodness-of-fit the models (Table 3). Based on the mentioned criteria, Briere-2 and Logan-10 with the highest values for R^2 and R^2_{adj} and the lowest values for RSS and AIC had the best fit to data among all evaluated nonlinear models for incubation period. Briere-1, Briere-2, and Lactin were the best fitted models for larval, pupal, and overall immature stages, considering estimated criteria, especially AIC, and R^2_{adj}. The values of fitted coefficients, measurable parameters, and critical points of temperature for development of pink stem borer are presented in Table 4.

Biological Significance. Briere-2 and Logan-10 were the best fitted models to data among all evaluated nonlinear models for incubation period. Logan-10 could not estimate the lower temperature threshold, because it was asymptotic to the left of the temperature axis. In addition, the estimated value for the optimal temperature was higher than those assumed, based on laboratory observations. Therefore, Logan-10 was rejected and Briere-2 was selected as the best descriptive model for temperature-dependent development of the incubation period. Similarly, based on observed developmental rate in studied temperatures, among selected models considering statistical criteria, Briere-2 was selected as the best descriptive model for temperature-dependent development of larval, pupal, and overall immature stages of pink stem borer.

Discussion

This study was the first attempt to examine the effect of temperature on development of *S. cretica*. The results confirmed that the temperature was an effective factor that influenced developmental rate of pink stem borer. Most of the cited references (Thanopoulos and Tsitsipis 1987, Lopez et al. 2001, Argyro et al. 2003) have been focused on sugar

Table 3. Comparison of six nonlinear models based on R^2, RSS, AIC, and R^2_{adj} for description of temperature-dependent development of pink stem borer at examined constant temperatures

Developmental stage	Model	Statistical criteria			
		R^2	RSS (10^{-4})	AIC	R^2_{adj}
Incubation period	Briére-1	0.989	6.130	−69.812	0.985
	Briére-2	0.994	3.364	−105.949	0.992
	Lactin-2	0.991	4.926	−58.931	0.984
	Logan-6	0.985	8.160	−65.524	0.974
	Logan-10	0.996	2.122	−74.296	0.991
	Polynomial third order	0.994	3.327	−72.700	0.989
Larva	Briére-1	0.972	0.399	−91.662	0.961
	Briére-2	0.975	0.359	−92.521	0.965
	Lactin-2	0.974	0.363	−77.188	0.954
	Logan-6	0.939	0.860	−83.527	0.893
	Logan-10	0.976	0.334	−45.104	0.944
	Polynomial third order	0.973	0.390	−89.856	0.953
Pupa	Briére-1	0.990	0.074	−71.700	0.986
	Briére-2	0.990	0.037	−71.843	0.986
	Lactin-2	0.992	0.780	−71.835	0.986
	Logan-6	0.982	1.814	−65.925	0.969
	Logan-10	0.987	1.318	−66.158	0.970
	Polynomial third order	0.989	1.113	−69.342	0.981
Overall immature stages	Briére-1	0.987	0.074	−90.276	0.982
	Briére-2	0.988	0.066	−93.630	0.982
	Lactin-2	0.993	0.039	−92.856	0.988
	Logan-6	0.986	0.084	−87.472	0.976
	Logan-10	0.990	0.060	−87.821	0.677
	Polynomial third order	0.987	0.077	−88.017	0.977

Table 4. Values of fitted coefficients and measurable parameters of six developmental rate models to describe temperature-dependent development of pink stem borer

Model	Parameters	Incubation period	Larva	Pupa	Overall immature stages
Briere-1	a	1.30×10^{-4}	2.66×10^{-5}	6.00×10^{-5}	1.78×10^{-5}
	t_{min}	14.44	10.87	10.27	11.58
	t_{max}	41.62	38.74	41.29	38.74
	t_{opt}	35.12	32.55	34.27	32.40
Briere-2	A	2.30×10^{-4}	2.16×10^{-5}	1.09×10^{-4}	2.72×10^{-5}
	t_{min}	10.82	11.81	9.35	10.67
	t_{max}	38.93	39.19	37.41	36.55
	t_{opt}	35.50	31.80	33.35	32.22
	D	3.97	1.65	3.43	2.99
Lactin-2	Δ	2.15	4.39	0.18	0.17
	P	0.01	0.00	0.01	0.00
	Λ	−1.15	−1.04	−1.07	−1.02
	t_l	43.56	51.25	34.74	34.82
	t_{min}	12.70	12.76	11.58	12.29
	t_{max}	40.57	39.86	34.36	34.26
	t_{opt}	35.25	32.00	34.00	33.62
Logan-6	Ψ	0.05	0.02	0.02	0.00
	P	0.16	0.15	0.16	0.17
	t_{max}	41.11	39.46	38.73	37.49
	Δ	6.17	6.63	5.96	5.53
	t_{opt}	34.91	32.76	32.71	32.90
Logan-10	A	0.31	1.67	0.16	0.04
	P	0.21	0.08	0.19	0.20
	t_{max}	38.26	40.25	34.46	34.35
	Δ	0.16	17.60	0.16	0.19
	K	178.32	23.60	94.14	113.44
	t_{opt}	37.34	31.55	33.59	34.33
Polynomial third order	A	-5.80×10^{-5}	-1.30×10^{-5}	-1.10×10^{-5}	-6.61×10^{-6}
	B	0.04×10^{-1}	0.01×10^{-1}	0.01×10^{-1}	4.43×10^{-4}
	C	−0.09	−0.02	−0.01	−0.01
	D	0.58	0.09	0.02	0.05
	t_{max}	44.94	40.77	50.04	42.90
	t_{opt}	34.30	32.21	36.10	32.50

cane or corn stem borer, *Sesamia nonagrioides* (Lefebvre). Thanopoulos and Tsitsipis (1987) reported a lower temperature threshold for larva *S. nonagrioides* of 10.85°C for a population from Greece. Lopez et al. (2001) have reported the estimated value of the lower temperature threshold of *S. nonagrioides* is 12°C. Based on the findings of Argyro et al. (2003), the values of lower temperature threshold of sugarcane stem borer, *S. nonagrioides* were 10.57, 8.89, and 10.75°C for egg, larva, and pupa stages, respectively. All the mentioned estimations for lower temperature threshold were carried out by using common linear model.

Based on the findings of Allan et al. (2010), estimated values of lower temperature threshold for egg, larva, pupa, and overall immature stages of pink stem borer, *S. cretica*, were 12.27, 13.89, 7.69, and 15.09°C, respectively. However, our findings showed estimated values of lower temperature threshold for egg, larva, pupa, and overall immature stages of pink stem borer were 10.82, 11.81, 9.35, and 10.67°C, respectively, by using Briere-2 as the best descriptive nonlinear model. Except pupa stage, all the estimated values of lower temperature threshold were lower than those estimated by Allan et al. (2010). This difference observed due to intrinsic difference between the abilities of linear and nonlinear models to present a real relationship between developmental rate and temperature over a wide range of temperature. In the most cases, the linear models cannot estimate an accurate value for temperature thresholds in out of linear region of relationship between developmental rate and temperature.

Argyro et al. (2003) estimated thermal indices for the developmental stages of *S. nonagrioides* by using Lactin nonlinear model. Based on the findings of Argyro et al. (2003), optimal developmental temperature for egg, larval, and pupal stages were 29.50, 41.25, and 29.25°C under constant temperatures rearing, and 38.00, 44.25, and 27.75°C under alternating temperatures rearing, respectively. The study of Argyro et al. (2003) had been conducted over a limited temperature range. Therefore, they had not enough observations on developmental rate at lower and upper temperatures for fitting on nonlinear models. Current study was conducted at a wider range of temperature from 15 to 38°C. Observations at 15 and 18°C as the temperature points near the real lower temperature threshold and at 34 and 38°C as the temperature points near the real optimal and upper temperature threshold help us to make a better fit and provide an accurately estimated values for critical temperatures.

The estimated value of upper temperature threshold for overall immature stages of *S. nonagrioides* was 36°C using Logan-6 nonlinear model by Lopez et al. (2001). The estimated value of the upper temperature threshold by using the same nonmodel for overall immature stages of pink stem borer was 37.49°C (Table 4). Although, we examined six nonlinear models to find the best descriptive model for temperature-dependent development of pink stem borer and Logan-6 was one of the poorest models among examined nonlinear models, the estimated value of upper temperature threshold was not more different from findings of Lopez et al. (2001). However, the difference in species or thermal adaptations in different climates cause this difference.

All of the examined nonlinear models fit the data well. All the examined nonlinear models can be introduced as suitable model to describe temperature-dependent development of the pink stem borer, considering statistical criteria. Despite this, only Briere-2 has biologically interpretable estimations.

The data presented here show that pink stem borer can complete its development under the broad range of temperature. In addition, the results can be used to forecast accurately the occurrence of the pest life stages in maize fields and enable us to determine the best time for controlling with better performance.

Acknowledgments

We are grateful to the head of Biological Control Research Department (BCRD) of Iranian Research Institute of Plant Protection. This project was carried out in BCRD and was supported by research grant provided by Shahed University, Tehran, Iran.

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Received 14 November 2011; accepted 12 July 2014.