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ORIGINAL RESEARCH ARTICLE

Thermal requirements and development response to constant temperatures by *Sesamia cretica* (Lepidoptera: Noctuidae)

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Abstract

Corn stem borer, *Sesamia cretica* Lederer is an important pest of corn and sugarcane across the globe. The development rate and thermal constant of *S. cretica* were determined at ten constant temperatures ranging from 12 to 36 (±1) °C, 50±10% RH and a photoperiod of 16:8 (L:D) h for the Varamin and Rey populations of the pest in laboratory conditions. Two linear models (ordinary and Ikemoto) were used to determine the lower temperature threshold (T_0) and thermal constant (K) of different stages of the pest. Furthermore, the development rate at different temperatures fitted to 26 nonlinear models. No eggs were hatched at 12 °C and only the incubation period was completed at 15, 35, and 36 °C with a significant difference between the two populations. The data of both populations better fitted to the Ikemoto linear model and it estimated T_0 of the total immature stages to be 14.11 °C and 13.57 °C for the Varamin and Rey populations, respectively. The K value for the egg, larvae, pupa, and the total immature stages were estimated to be 72.74, 586.88, 141.33, and 895.36 DD in the Varamin population and 79.05, 804.36, 145.28, and 945.10 DD in the Rey population, respectively. Validation assessment of the linear and nonlinear models picked up based on Akaike information criterion (AIC) of the total immature stages showed that the development time estimated by the linear (Ikemoto) and nonlinear (Briere-1) models were close to the observed development time for the Varamin and Rey populations at the fastest developmental temperature in laboratory condition. These findings can be used to construct a forecasting model for appropriate control of *S. cretica*.

Keywords Corn stem borer · Linear and nonlinear model · Maize · Iran

Introduction

The corn stem borer, *Sesamia cretica* Lederer is an important pest of maize, sorghum, and sugarcane in Africa, the Middle East, and Mediterranean Europe (Goftishu et al. 2016). Damage of *S. cretica* estimated 16–79% in crop development time. Severe damage on maize may happen if an infestation occurs soon after plant emergence (Temerak and Negm 1979).

Temperature is one of the most important environmental factors that affects all aspects of the ecological and evolutionary life history of ectotherms (Ikemoto and Kiritani 2019). It is a major factor in determining the number of generations (Yamamura and Kiritani 1998), death in hibernation (Somme 1982), reproduction period (Kiritani 2013), distribution (Yukawa et al. 2007), and population dynamics (Kiritani 2013). The relationship between temperature and development rate is linear in most temperature ranges in which insects are exposed but is nonlinear at high temperatures and close to the low-temperature threshold (Wagner et al. 1984). Numerous linear and nonlinear models have been suggested to interpret the relationship between insect development rate and temperature (Worner 2008). Linear models are the oldest and most widely used models for describing developmental rates in linear portion, as well as estimating the lower temperature threshold (T_0) and thermal constant (K) (Ikemoto 2005). Another approach is to use nonlinear models to describe arthropod development as a nonlinear process to estimate the fastest development temperature and upper temperature threshold (T_U) (Mirhosseini et al. 2018). Various models have been suggested to describe the relationship between temperature and

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arthropod development rate (Briere et al. 1999). These models are different in the number of parameters and hypotheses of low and high-temperature threshold effects (Roy et al. 2002). Although the ability and complexity of these models differ, using models that are more complex does not mean more accuracy (Mirhosseini et al. 2017). However, thermal models are often used to predict the emergence and population fluctuations of pests and their natural enemies in field to determine the appropriate conditions for mass rearing of natural enemies, and to model the tritrophic interactions of different ecosystems with potential global warming consequences (Pakyari et al. 2011).

The study of insect response to temperature is particularly critical in climate change adaptation (Ladanyi and Horvath 2010). Temperature changes can disrupt synchronization between phenology of insect, host plant, and natural enemy (Yukawa 2000). Climate change is a major factor in pest population dynamics requires adaptive management strategies for coping with pest status changing. Various priorities can be identified for future research on the climate change effects on agricultural pests, which include improving pest management practices, monitoring climate, and pest population change, and constructing the forecasting models (Skendzic et al. 2021).

Given the crucial influence of temperature on the development and performance of pests, the current study was carried out to determine the thermal requirement and developmental response of *S. cretica* to constant temperatures, as a prerequisite for the construction of the forecasting models. Although some studies have previously been conducted to determine the effect of temperature on biological parameters of *S. cretica* (Al-Allan 2009; Soltani Orang et al. 2014), this is the first study in which two linear and 26 nonlinear models have been used to model the effect of temperature on the development of this important stem borer. The results will contribute to improve integrated pest management (IPM) programs.

Materials and methods

Plant material, rearing of *S. cretica* and experimental conditions

Plant material preparation, colonies establishment, rearing of *S. cretica* and experimental conditions were done based on Arbabtafti et al. (2021).

Thermal modeling

The lower temperature threshold (T_0) and thermal constant (K) of all immature stages were estimated for each population using the ordinary and Ikemoto linear models. Ordinary least squares (OLS) were applied in the first method while the reduced major axis (RMA) (Smith 2009; Friedman et al. 2013) was used to fit the linear section in the Ikemoto model.

Three criteria including the sum of squared error (SSE), adjusted coefficient of determination (R^2_{adj}), and Akaike information criterion (AIC) were used to evaluate the nonlinear models. All nonlinear models in each stage were ranked using AIC, as the best statistical criterion (Akaike 1974), and the model with the smallest value of AIC was considered to be the best model for describing the temperature-dependent development of *S. cretica*. According to Burnham et al. (2011), models with $\Delta > 7$ were dismissed where Δ is the difference between AIC of the best model and the i^{th} model. T_{fast}, the temperature that the maximum development rate occur was calculated directly from some of the nonlinear models (Yazdanpanah et al. 2022).

In addition to statistical criteria accuracy (Kontodimas et al. 2004), biological significance (Briere et al. 1999) were considered to select the best nonlinear model. The observed total development time of *S. cretica* in Varamin and Rey populations was compared with those estimated using the selected nonlinear models.

Data analysis

Data on development times were checked for normality using the Kolmogorov–Smirnov test and were found to be normally distributed. The one-way analysis of variance (ANOVA) was used to determine the variances and standard errors of the development time. The differences among the treatments were compared using Tukey's test ($\alpha = 0.05$). Comparison of development time of two populations was done by the Student's *t*-test. Minitab (ver. 19.2) software was used for all analyses. Excel 2016 was used for graph construction.

Evaluation of two linear and 26 nonlinear models (Table 1) was done by using ArthroThermoModel (ATM) software (Mirhosseini et al. 2017) to describe the development rate (the reciprocal of development time) of *S. cretica* as a function of temperature. The ATM software calculates criteria and parameters for all models.

Results

Development time

The development of immature stages did not take place at 12 °C. In addition, at 15, 35, and 36 °C only the incubation period was completed. However, the development of all immature stages was completed at 20, 25, 27, 30, 32, and 34 °C.

Table 1 Linear and nonlinear models for fitting to development rate of *Sesamia cretica* as a function of temperature

Model	Equation	Reference
Ordinary linear model	$R(t) = a + bT$	(Campbell et al. 1974)
Ikemoto linear model	$DT = K + T_0D$	(Ikemoto and Takai 2000)
Pradhan-Taylor	$R(T)=R_m \times exp[\frac{-1}{2}(\frac{T-Tm}{T\sigma})^2]$	(Pradhan 1945; Taylor 1981)
Davidsons logistic	$R(T)=\frac{K}{1+e^{(a-bT)}}$	(Davidson 1942, 1944)
Logan-6	$R(T)=\psi\left[e^{\rho T}-e^{(\rho T_U-t)}\right], t=\frac{T_U-T}{\Delta_T}$	(Logan et al. 1976)
Hilbert and Logan	$R(T)=\psi\left[\frac{(T-T_0)^2}{((T-T_0)^2+D^2)}\right]-e^{-(\frac{T_U-(T-T_0)}{\Delta T})}$	(Hilbert and Logan 1983)
Lactin-1	$R(T)=e^{\rho T}-e^{\left(\rho T_U-\frac{T_U-T}{\Delta}\right)}$	(Lactin et al. 1995)
Lactin-2	$R(T)=e^{\rho T}-e^{\left(\rho T_U-\frac{T_U-T}{\Delta}\right)}+\lambda$	(Lactin et al. 1995)
Logan-10	$R(T)= a[\frac{1}{1+Ke^{-\rho T}}-e^{-r}]t=\frac{T_U-T}{\Delta_T}$	(Logan et al. 1976)
Analytis-1	$R(T)=P\delta^n(1-\delta)^m, \delta=\frac{T-T_0}{T_U-T_0}$	(Analytis 1977, 1980)
Analytis-2	$R(T)=[P\delta^n(1-\delta)]^m, \delta=\frac{T-T_0}{T_U-T_0}$	(Analytis 1977, 1980)
Analytis-1/Allahyari	$R(T)=P\delta^n(1-\delta^m), \delta=\frac{T-T_0}{T_U-T_0}$	(Allahyari 2005; Zahiri et al. 2010)
Analytis-3	$R(T)=a(T-T_0)^n(T_U-T)^m$	(Analytis 1977, 1980)
Briere-1	$R(T)=aT(T-T_0)(T_U-T)^{\frac{1}{2}}$	(Briere et al. 1999)
Briere-2	$R(T)=aT(T-T_0)(T_U-T)^{\frac{1}{n}}$	(Briere et al. 1999)
Analytis-3/Kontodimas	$R(T)=a(T-T_0)^2(T_U-T)$	(Kontodimas et al. 2004)
Janisch/Kontodimas	$R(T)=\frac{2}{D_{min}(e^{K\left(T-T_{opt}\right)}+e^{-\lambda\left(T-T_{opt}\right)})}$	(Janisch 1932; Kontodimas et al. 2004)
Janisch/Rochat	$R(T)=\frac{2C}{(a^{(T-T_U)}+b^{(T_U-T)})}$	(Rochat and Gutierrez 2001)
Sharpe and DeMichele	$R(T)=T\frac{e^{(\varphi-\Delta H_A{}^{\neq}/T)/R}}{1+e^{(\Delta S_L-\Delta H_L/T)//R}+e^{(\Delta S_H-\Delta H_L/T)//R}}$	(Sharpe and DeMichele 1977)
Sharp and DeMichele/Schoolfield	$R(T)=\frac{\rho_{(25^\circ C)}\frac{T}{298}\exp[\frac{\Delta H_A{}^{\neq}}{R}(\frac{1}{298}-\frac{1}{T})]}{1+\exp[\frac{\Delta H_L}{R}(\frac{1}{T_{1/2L}}-\frac{1}{T})]+\exp[\frac{\Delta H_H}{R}(\frac{1}{T_{1/2H}}-\frac{1}{T})]}$	(Schoolfield et al. 1981)
Sharp and DeMichele/Kontodimas	$R(T)=T\frac{exp(a-b/T)}{1+\exp(c-d/T)+\exp(f-g/T)}$	(Kontodimas et al. 2004)
Polynomial (cubic)	$R(T)=a_0T^3+a_1T^2+a_2T+a_3$	(Harcourt and Yee 1982)
Sharp-Schoolfield-Ikemoto (SSI model)	$R(T)=\frac{\rho_\varphi\frac{T}{\varphi}\exp[\frac{\Delta H_A}{R}(\frac{1}{T_\varphi}-\frac{1}{T})]}{1+\exp[\frac{\Delta H_L}{R}(\frac{1}{T_L}-\frac{1}{T})]+\exp[\frac{\Delta H_H}{R}(\frac{1}{T_H}-\frac{1}{T})]}$	(Ikemoto 2005, 2008)
Performance-1	$R(T)=C(1-e^{-K_1\left(T-T_0\right)})(1-e^{-K_2\left(T-T_U\right)})$	(Shi et al. 2011)
Performance-2	$R(T)=m(T-T_0)(1-e^{K_2\left(T-T_U\right)})$	(Shi et al. 2011)
Wang	$R(T)=\frac{m\left[1-exp\left(-K_1\left(T-T_0\right)\right)\right]\left[1-exp\left(K_2\left(T-T_U\right)\right)\right]}{1+exp(-c\left(T-T_0\right))}$	(Wang et al. 1982)
Ratkowsky	$\sqrt{R(T)}=C\left(T-T_0\right)\left(1-e^{K\left(T-T_U\right)}\right)$	(Ratkowsky et al. 1983)
Beta	$R(T)=r_m(\frac{T_U-T}{T_U-T_{opt}})(\frac{T-T_0}{T_{opt}-T_0})^{\frac{T_{opt}-T_0}{T_U-T_{opt}}}$	(Yin et al. 1995)

T Temperature, R Development rate, D Development time, T_0 Lower temperature threshold, T_U Upper temperature threshold, T_{opt} Optimum temperature (equals T_{fast} in the text). Other notations are model constants. For more details on the concepts of the parameters, please see Mirhosseini et al. (2017)

Development time of different immature stages of Varamin and Rey populations of *S. cretica* at different constant temperatures and their comparison are shown in Table 2. The results showed that as temperature increased up to 34 °C, the development time decreased and then it increased again for all stages except for pupa in Varamin population (Table 2). The total development time of corn stem borer decreased with increasing temperature, i.e. it decreased from 120.55 to 45.63 days at 20 and 32 °C in the Varamin population and from 143.24 to 47.61 days at 20 and 34 °C in Rey population, respectively. The

Table 2 Development time (Mean ± SE) (days) of different stages of Varamin and Rey populations of *Sesamia cretica* at different constant temperatures

Geographical population	Temperature (°C)	Egg (day)				Larva (day)				Pupa (day)				Total (day)			
		No	Min	Max	Mean ± SE	No	Min	Max	Mean ± SE	No	Min	Max	Mean ± SE	No	Min	Max	Mean ± SE
Varamin	15	898	19	38	27.27 ± 0.10aA	-	-	-	-	-	-	-	-	-	-	-	-
	20	439	11	14	12.16 ± 0.03bA	304	60	137	83.38 ± 0.86aB	269	20	30	24.99 ± 0.11aA	264	95	172	120.55 ± 0.92aB
	25	451	5	7	5.65 ± 0.02cA	89	45	123	74.55 ± 2.07bA	79	10	14	11.99 ± 0.11bA	79	61	142	91.67 ± 2.24bA
	27	347	4	6	5.29 ± 0.03dA	93	40	110	67.00 ± 1.73cA	93	6	13	10.45 ± 0.11cB	93	55	127	82.89 ± 1.74cA
	30	467	4	5	4.16 ± 0.02eA	97	31	67	43.25 ± 0.77 dB	93	6	11	8.49 ± 0.085 dB	91	42	80	55.73 ± 0.78dA
	32	652	3	4	3.20 ± 0.01gB	81	21	60	34.71 ± 0.99eB	69	7	10	8.26 ± 0.10dA	69	32	71	45.63 ± 1.04eB
	34	629	3	4	3.61 ± 0.02fA	56	22	79	38.02 ± 1.37deA	48	6	11	8.17 ± 0.15dA	46	34	75	48.00 ± 1.33eA
	35	430	3	4	3.57 ± 0.02fB	-	-	-	-	-	-	-	-	-	-	-	-
	36	262	3	4	3.41 ± 0.03fgB	-	-	-	-	-	-	-	-	-	-	-	-
	F	-	-	-	23,595.13	-	-	-	265.37	-	-	-	4147.29	-	-	-	562.63
	df	-	-	-	8, 4563	-	-	-	5, 708	-	-	-	5, 639	-	-	-	5, 630
	P	-	-	-	≤ 0.0001	-	-	-	≤ 0.0001	-	-	-	≤ 0.0001	-	-	-	≤ 0.0001
Rey	15	427	19	36	25.20 ± 0.16aB	-	-	-	-	-	-	-	-	-	-	-	-
	20	465	10	15	12.08 ± 0.04bA	188	67	190	109.86 ± 1.84aA	173	11	35	24.80 ± 0.15aA	171	103	207	143.24 ± 1.59aA
	25	396	5	6	5.65 ± 0.02cA	81	44	117	62.95 ± 1.61bB	72	10	21	12.04 ± 0.14bA	72	61	133	81.55 ± 1.95bB
	27	313	5	6	5.22 ± 0.02dA	118	10	120	61.82 ± 1.362bB	98	9	13	10.77 ± 0.08cA	98	47	137	77.28 ± 1.41bB
	30	492	3	5	4.16 ± 0.03eA	111	37	106	50.65 ± 1.16cA	90	7	11	8.80 ± 0.08dA	89	41	81	54.18 ± 1.16cA
	32	612	3	5	4.06 ± 0.02eA	85	20	83	40.02 ± 1.48dA	68	7	10	8.28 ± 0.10deA	66	33	80	49.86 ± 1.35cA
	34	613	3	4	3.43 ± 0.02gB	57	23	67	36.68 ± 1.07dA	45	5	9	8.02 ± 0.11eA	45	35	60	47.61 ± 0.97cA
	35	1015	3	4	3.73 ± 0.014fA	-	-	-	-	-	-	-	-	-	-	-	-
	36	262	3	5	3.64 ± 0.04fgA	-	-	-	-	-	-	-	-	-	-	-	-
	F	-	-	-	17,794.61	-	-	-	314.62	-	-	-	3044.81	-	-	-	651.37
	df	-	-	-	8,4577	-	-	-	5, 623	-	-	-	5, 530	-	-	-	5, 529
	P	-	-	-	≤ 0.0001	-	-	-	≤ 0.0001	-	-	-	≤ 0.0001	-	-	-	≤ 0.0001

The means followed by different lowercase letters in the same column (for each area) are significantly different ($P < 0.05$, Tukey's test) and the means followed by different capital letters in the same column (for each temperature) are significantly different ($P < 0.05$, t-test) total development time of the Varamin population increased again at 34 °C. Analysis of variance showed a significant difference among the total development time at different temperatures (Table 2).

Thermal models

For accurate estimation of lower temperature threshold and thermal constant of different stages (except for pupa), the data of 34 °C were excluded from linear regression analysis and conformity assessment with laboratory observations. In the Rey population, an increase in development time was observed only in the incubation period at 35 °C. Other stages did not develop at this temperature (Table 2). Temperature and the interaction between the temperature and geographical population had a significant effect on total developmental time (Table 2).

The lower temperature threshold and thermal constant of each stage of *S. cretica* of Varamin and Rey populations are shown in Table 3. The results showed that the Ikemoto linear model better fitted to the data of both populations (Table 3). According to the Ikemoto model, T_0 was estimated to be 14.11 and 13.57 °C, and the K values were 895.36 and 945.10 DD for the total development time of Varamin and Rey populations, respectively (Table 3).

Nonlinear models fitted to the development rate of different immature stages of Varamin population (Table 4) and Rey population (Table 5) of *S. cretica*. According to *AIC* criterion, the best model for egg, larvae, pupa, and the total immature stages were Pradhan-Taylor, Polynomial, Analytis-3/Kontodimas and Polynomial, respectively for the Varamin population (Table 4) and Davidson logistic, Polynomial, Briere-1, and Lactin-1, respectively for the Rey population (Table 5). The thermal models were ranked based on Burnham et al. (2011) for the egg, larvae, pupa, and the total of immature stages of Varamin (Table 4) and Rey (Table 5) populations. Figures 1 and 2 depict the curves of the influence of temperature on the developmental rate of total immature stages of *S. cretica* of Varamin and Rey populations, respectively for the appropriate models. The estimated parameters by the selected models are shown in Tables 6 and 7 for the Varamin and Rey populations, respectively.

The observed fastest developmental temperature (T_{fast}) was at 32 °C for Varamin population and 34 °C for Rey population among temperatures tested (Table 2). The estimated T_{fast} by Polynomial model for total immature stages of Varamin population was 33.52 and by Lactin-1 model for total immature stages of Rey population was 33.84.

Biological significance was considered to select the best nonlinear model besides statistical criteria. Based on biological significance, the Ikemoto and Briere-1 models described the temperature-dependent developmental rates of total immature stages of the Varamin and Rey populations better than others (Table 8).

Discussion

As expected, temperature significantly affected the development time of *S. cretica*. The duration of egg, larvae, pupa, and total immature stages was negatively related

Table 3 Low-temperature threshold (T_0) and thermal constant (K) of different immature stages of Varamin and Rey populations of *Sesamia cretica* estimated by two linear models

Geographical population	Model	Developmental stage	Equation	Linear regression			T_0 (°C)	K (DD)
				R^2	R^2_{adj}	P		
Varamin	Ordinary	Egg	$R = -0.214 + 0.016\,T$	0.96	0.96	0.000	13.73	64.21
		Larva	$R = -0.019 + 0.001\,T$	0.81	0.75	0.037	13.57	716.89
		Pupa	$R = -0.073 + 0.006\,T$	0.94	0.92	0.001	12.04	165.01
		Total	$R = -0.016 + 0.001\,T$	0.89	0.85	0.016	14.17	888.06
	Ikemoto	Egg	$DT = 72.74 + 12.59D$	0.99	0.99	0.000	12.59	72.74
		Larvae	$DT = 586.88 + 15.89D$	0.79	0.73	0.013	15.89	586.88
		Pupa	$DT = 141.33 + 14.24D$	0.98	0.98	0.000	14.24	141.33
		Total	$DT = 895.36 + 14.11D$	0.89	0.85	0.004	14.11	895.36
Rey	Ordinary	Egg	$R = -0.158 + 0.013\,T$	0.98	0.98	0.000	12.25	77.64
		Larvae	$R = -0.017 + 0.001\,T$	0.96	0.95	0.000	13.33	783.36
		Pupa	$R = -0.076 + 0.006\,T$	0.97	0.96	0.000	12.36	163.32
		Total	$R = -0.014 + 0.001\,T$	0.98	0.97	0.000	13.56	944.98
	Ikemoto	Egg	$DT = 79.05 + 12.11D$	0.99	0.99	0.000	12.11	79.05
		Larvae	$DT = 804.36 + 12.98D$	0.97	0.96	0.000	12.98	804.36
		Pupa	$DT = 145.28 + 14.02D$	0.99	0.99	0.000	14.02	145.28
		Total	$DT = 945.10 + 13.57D$	0.99	0.98	0.000	13.57	945.10

T_0, K, D and R are low-temperature threshold (no measurable development is detected), thermal constant (total effective temperature), development time (day) and development rate

Table 4 Goodness of fit of 26 nonlinear models fitted to development rate of different immature stages of Varamin population of *Sesamia cretica*

Model	No. of parameters	Egg				Larvae				Pupa				Total			
		SSE	R^2_{adj}	*AIC*	Rank[1]	*SSE*	R^2_{adj}	*AIC*	Rank	*SSE*	R^2_{adj}	*AIC*	Rank	*SSE*	R^2_{adj}	*AIC*	Rank
Pradhan-Taylor	3	0.0020	0.96	-69.50	1	3.8737e-05	0.75	-65.70	4	1.2740e-05	0.99	-72.37	3	1.2787e-05	0.87	-72.35	4
Davidsons logistic	3	0.0024	0.96	-68.20	2	2.5948e-04	-0.66	-54.29	22	0.0051	-0.67	-36.44	22	1.5981e-04	-0.66	-57.19	22
Logan-6	4	0.0024	0.95	-66.12	11	3.6861e-05	0.64	-64.00	8	8.0256e-05	0.96	-59.33	20	1.0875e-05	0.83	-71.32	6
Hilbert and Logan	5	0.0021	0.94	-65.45	17	3.7584e-05	0.27	-61.88	16	1.5515e-05	0.98	-67.19	12	1.2230e-05	0.62	-68.62	15
Lactin-1	3	0.0024	0.96	-68.17	3	3.3710e-05	0.78	-66.54	3	7.5743e-05	0.97	-61.68	18	1.0362e-05	0.89	-73.61	2
Lactin-2	4	0.0025	0.95	-65.77	13	4.1770e-05	0.60	-63.25	11	1.5009e-05	0.99	-69.39	7	1.4670e-05	0.77	-69.53	11
Logan-10	5	0.0022	0.94	-64.74	19	2.5989e-05	0.50	-64.10	7	4.9164e-05	0.95	-60.27	19	6.8451e-06	0.79	-72.10	5
Analytis-1	5	0.0020	0.95	-65.67	15	3.2217e-05	0.38	-62.81	15	1.1720e-05	0.99	-68.87	9	1.1669e-05	0.63	-68.90	14
Analytis-2	5	0.0023	0.94	-64.55	20	4.7498e-05	0.08	-60.48	18	1.2621e-05	0.99	-68.43	10	1.7435e-05	0.45	-66.49	19
Analytis-1/Allahyari	5	0.0020	0.95	-65.68	14	3.0863e-05	0.41	-63.07	13	2.5915e-05	0.97	-64.11	17	1.1454e-05	0.64	-69.01	13
Analytis-3	5	0.0020	0.95	-65.58	16	4.3481e-05	0.16	-61.01	17	1.6099e-05	0.98	-66.97	14	1.4008e-05	0.56	-67.81	17
Briere-1	3	0.0025	0.95	-67.68	7	4.5385e-05	0.71	-64.75	6	1.1534e-05	0.99	-72.97	2	1.6656e-05	0.83	-70.77	7
Briere-2	4	0.0023	0.95	-66.61	10	3.8040e-05	0.63	-63.81	9	1.2586e-05	0.99	-70.45	6	1.3131e-05	0.79	-70.19	9
Analytis-3/Kontodimas	3	0.0030	0.95	-65.92	12	6.2337e-05	0.60	-62.85	14	1.1471e-05	0.99	-73.00	1	2.4328e-05	0.75	-68.49	16
Janisch/Kontodimas	4	0.0020	0.96	-67.86	5	3.1590e-05	0.70	-64.93	5	0.0086	-3.21	-31.31	23	1.2149e-05	0.81	-70.66	8
Janisch/Rochat	4	0.0019	0.96	-67.94	4	1.9122e-05	0.82	-67.94	2	2.1325e-05	0.99	-67.28	11	8.8425e-06	0.86	-72.57	3
Sharpe and DeMichele	7	0.0088	0.53	-50.40	25	-	-	-	-	-	-	-	-	-	-	-	-
Sharp and DeMichele/ Schoolfield	7	0.0037	0.80	-58.15	24	-	-	-	-	-	-	-	-	-	-	-	-
Sharp and DeMichele/ Kontodimas	6	0.0088	0.69	-50.36	26	3.6358e-05	NaN[2]	-60.08	20	6.5627e-04	NaN	-42.72	21	1.4540e-05	NaN	-65.58	21
Polynomial (cubic)	4	0.0020	0.96	-67.49	9	9.0851e-06	0.91	-72.40	1	1.1193e-05	0.99	-71.15	4	4.0419e-06	0.94	-77.26	1
Sharpe–Schoolfield–Ikemoto (SSI model)	7	0.0019	0.90	-61.97	23	-	-	-	-	-	-	-	-	-	-	-	-
Performance-1	5	0.0027	0.93	-62.98	21	4.8363e-05	0.07	-60.37	19	1.9706e-05	0.98	-65.76	15	1.4940e-05	0.53	-67.42	18
Performance-2	4	0.0027	0.94	-65.13	18	4.1879e-05	0.60	-63.23	12	1.5384e-05	0.99	-69.24	8	1.4718e-05	0.77	-69.51	12
Wang	6	0.0023	0.92	-62.51	22	3.7945e-0	NaN	-59.83	21	1.1218e-05	NaN	-67.14	13	1.3397e-05	NaN	-66.07	20
Ratkowsky	4	0.0020	0.97	-67.63	8	4.5720e-04	0.77	-48.89	23	3.3165e-05	0.99	-64.63	16	1.7586e-04	0.84	-54.62	23
Beta`	4	0.0020	0.96	-67.74	6	3.8781e-05	0.63	-63.70	10	1.1186e-05	0.99	-71.15	5	1.4387e-05	0.77	-69.64	10

[1] Rank is based on the *AIC* criteria

[2] NAN The number of model parameters is equal to or greater than the observations and cannot be calculated

- Data could not be fitted by the model

Table 5 Goodness of fit of 26 nonlinear models fitted to development rate of different immature stages of Rey population of *Sesamia cretica*

Model	No. of parameters	Egg				Larvae				Pupa				Total			
		SSE	R^2_{adj}	*AIC*	Rank[1]	*SSE*	R^2_{adj}	*AIC*	Rank	*SSE*	R^2_{adj}	*AIC*	Rank	*SSE*	R^2_{adj}	*AIC*	Rank
Pradhan-Taylor	3	4.1982e-04	0.99	-83.76	2	1.0695e-05	0.92	-73.42	4	1.4866e-05	0.99	-71.45	5	2.7590e-06	0.97	-81.55	2
Davidsons logistic	3	3.3473e-04	0.99	-85.79	1	2.2081e-04	-0.66	-55.26	23	0.005	-0.66	-36.49	22	1.4877e-04	-0.66	-57.63	23
Logan-6	4	0.0013	0.97	-71.58	22	1.6254e-05	0.82	-68.91	16	6.6335e-05	0.97	-60.47	20	5.1491e-06	0.91	-75.81	16
Hilbert and Logan	5	4.5405e-04	0.98	-79.05	11	9.4822e-06	0.78	-70.15	10	1.6590e-05	0.98	-66.79	13	3.1402e-06	0.89	-76.78	13
Lactin-1	3	0.0011	0.97	-74.72	20	1.4521e-05	0.89	-71.59	9	6.8264e-05	0.98	-62.30	19	2.2729e-06	0.97	-82.72	1
Lactin-2	4	6.0629e-04	0.98	-78.45	14	9.1775e-06	0.90	-72.34	6	1.3779e-05	0.99	-69.90	8	3.0093e-06	0.95	-79.03	8
Logan-10	5	4.7741e-04	0.99	-78.60	13	6.1743e-06	0.86	-72.72	5	3.2169e-05	0.97	-62.82	17	3.4739e-06	0.88	-76.17	15
Analytis-1	5	4.2933e-04	0.98	-79.55	9	1.1542e-05	0.74	-68.97	15	1.0662e-05	0.99	-69.44	9	2.4203e-06	0.92	-78.34	11
Analytis-2	5	4.0000e-04	0.99	-80.19	7	1.5511e-05	0.65	-67.19	19	1.4031e-05	0.99	-67.79	12	6.7824e-06	0.77	-72.16	9
Analytis-1/ Allahyari	5	4.6166e-04	0.98	-78.90	12	2.4529e-05	0.44	-64.44	20	2.3919e-05	0.98	-64.59	16	2.3979e-05	0.19	-64.58	21
Analytis-3	5	4.3423e-04	0.98	-79.45	10	2.8638e-05	0.35	-63.51	21	1.9019e-05	0.98	-65.97	15	3.0406e-06	0.90	-76.97	12
Briere-1	3	4.8138e-04	0.99	-82.52	4	1.3951e-05	0.89	-71.83	8	9.8298e-06	0.99	-73.93	1	3.7714e-06	0.96	-79.68	6
Briere-2	4	4.7641e-04	0.99	-80.62	6	7.6222e-06	0.91	-73.46	3	1.0566e-05	0.99	-71.50	4	2.9820e-06	0.95	-79.09	7
Analytis-3/ Kontodimas	3	0.0013	0.97	-73.30	21	2.8356e-05	0.79	-67.57	18	1.2828e-05	0.99	-72.33	3	7.6401e-06	0.91	-75.44	17
Janisch/Kontodimas	4	0.0130	0.65	-50.87	25	1.4500e-05	0.84	-69.60	13	0.0170	-7.43	-27.20	23	2.1665e-06	0.96	-81.00	3
Janisch/Rochat	4	5.1540e-04	0.99	-79.91	8	6.6231e-06	0.92	-74.30	2	2.4049e-05	0.99	-66.56	14	2.4912e-06	0.96	-80.17	5
Sharpe and DeMichele	7	0.4178	-27.02	-15.63	26	-	-	-	-	-	-	-	-	-	-	-	-
Sharp and DeMichele/ Schoolfield	7	0.0052	0.65	-55.14	23	-	-	-	-	-	-	-	-	-	-	-	-
Sharp and DeMichele/ Kontodimas	6	0.0053	0.76	-54.98	24	8.7268e-06	NaN[2]	-68.64	17	4.5783e-04	NaN	-44.88	21	7.9485e-06	NaN	-69.20	20
Polynomial (cubic)	4	3.7111e-04	0.99	-82.87	3	4.8654e-06	0.94	-76.15	1	8.4109e-06	0.99	-72.87	2	2.2727e-06	0.96	-80.72	4
Sharpe–Schoolfield–Ikemoto (SSI model)	7	3.5802e-04	0.98	-77.19	16	-	-	-	-	-	-	-	-	-	-	-	-
Performance-1	5	6.6280e-04	0.98	-75.65	19	9.8220e-06	0.78	-69.93	11	1.1726e-05	0.99	-68.87	11	3.1884e-06	0.89	-76.69	14
Performance-2	4	6.3493e-04	0.98	-78.03	15	9.3135e-06	0.89	-72.25	7	1.0981e-05	0.99	-71.26	6	3.0154e-06	0.95	-79.02	9
Wang	6	5.0375e-04	0.98	-76.11	17	8.1926e-06	NaN	-69.02	14	8.0681e-06	NaN	-69.12	10	3.2224e-06	NaN	-74.62	8

Table 5 (continued)

Model	No. of parameters	Egg				Larvae				Pupa				Total			
		SSE	R^2_{adj}	*AIC*	Rank[1]	*SSE*	R^2_{adj}	*AIC*	Rank	*SSE*	R^2_{adj}	*AIC*	Rank	*SSE*	R^2_{adj}	*AIC*	Rank
Ratkowsky	4	7.8647e-04	0.99	-76.11	18	8.8358e-05	0.93	-58.75	22	4.7197e-05	0.99	-62.52	18	3.5207e-05	0.97	-64.28	22
Beta	4	4.5506e-04	0.99	-81.03	5	1.3886e-05	0.84	-69.86	12	1.1230e-05	0.99	-71.13	7	3.0472e-06	0.95	-78.96	10

[1] Rank is based on the *AIC* criteria

[2] NAN The number of model parameters is equal to or greater than the observations and cannot be calculated

- Data could not be fitted by the model

to temperature up to 32 °C and then increased for the Varamin population. Similar changes were observed at 34 °C and only in the egg stage for the Rey population. The results of the present study were slightly different from the findings of Soltani Orang et al. (2014) in the longest and shortest development time and the temperature that occurred in both populations. The differences among these studies might be due to the difference in rearing techniques, experimental conditions, and diets along with differences in data analysis. In the present study, the geographical population had significant effects on the total development time of *S. cretica* by way of Trudgill and Perry (1994); Trudgill (1995) and Honek (1996a) demonstrated that geographical variation could affect development time.

The linear models only estimate lower temperature threshold, this temperature is proper for analysis of the phenology of insect populations due to simplifies the analysis (Ikemoto and Kiritani 2019). Comparison of developmental time at different temperatures showed that the linear range was up to 32 °C and 34 °C for the populations of Varamin and Rey, respectively. In the present study, lower temperature threshold and thermal constant were estimated using both ordinary and Ikemoto linear models. The R^2_{adj} coefficients used to fit the regression between temperature and the developmental rate were higher for the Ikemoto model on two populations tested. The lower temperature threshold for total immature stages was estimated by the Ikemoto model 14.11 °C and 13.57 °C, respectively for the Varamin and the Rey populations. The results of laboratory observations also confirmed the above estimates. The lower temperature threshold for the development of different immature stages of *S. cretica*, which was estimated by linear models, was in the range of 12 to 15 °C while no eggs hatched at 12 °C and only the incubation period was completed at 15 °C. The lower temperature threshold values are different from those estimated by Soltani Orang et al. (2014) (16.16 °C) and Al-Allan (2009) (15.09 °C). Based on Honek and Kocourek (1988, 1990) T_0 decreased if *K* increased therefore, the thermal constant estimated by the Ikemoto model for the Varamin and the Rey populations, respectively was 895.36 and 945.10 degree-day. Our results were higher than those reported by Soltani Orang et al. (2014) (537.43 DD) and Al-Allan (2009) (704.65 DD). The thermal characteristics may be affected by population (Lee and Elliott 1998), stage of development (Honek 1996b), and other ecological factors such as food source (Golizadeh et al. 2007) and the difference may be due to one or a set of the above factors.

Model selection is critical because of the significant differences between model predictions. Rebaudo and Rabhi (2018) point out each of the criteria for model

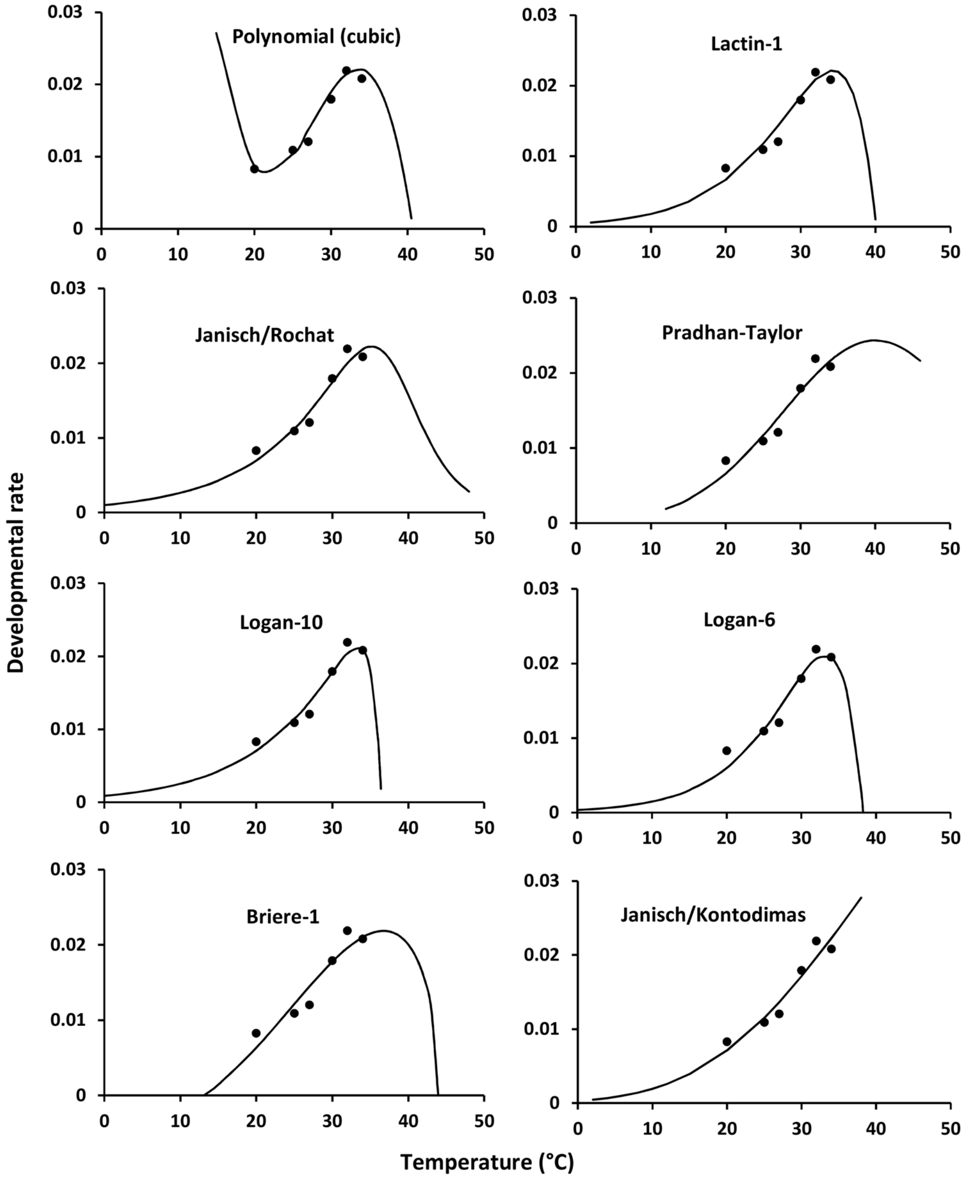

Fig. 1 Observed development rate for total immature stages of Varamin population of *Sesamia cretica* (dots) and 8 fitted nonlinear models (lines)

selection has its advantages and disadvantages therefore, a combination of different methods should be used in model selection, e.g. the *AIC* criteria can separate several models with the same R^2_{adj} and *SSE*. In most studies, the *AIC* index has been mentioned as the best statistical parameter to measure the validity of models furthermore, model selection should be performed based on observations and biological and ecological information or biological significance (Zahiri et al. 2010). A common method for evaluating the accuracy of estimated critical temperatures is based on their comparison with experimental data (Kontodimas et al. 2004; Yazdanpanah et al. 2022). In the current study, the observed development time at optimum temperature (according to the results of Arbabtafti et al. 2021 estimated 27 °C for both populations) and fastest developmental temperature (T_{fast}) which might not be suitable because of the high mortality (32 °C and 34 °C, respectively for the Varamin and the Rey populations) was compared to the estimated development time. In this evaluation, the estimations of the Ikemoto model were close to the estimations of Briere-1 as the best nonlinear model and the observed values of the total development rate of *S. cretica*.

Fig. 2 Observed development rate for total immature stages of Rey population of *Sesamia cretica* (dots) and 16 fitted nonlinear models (lines)

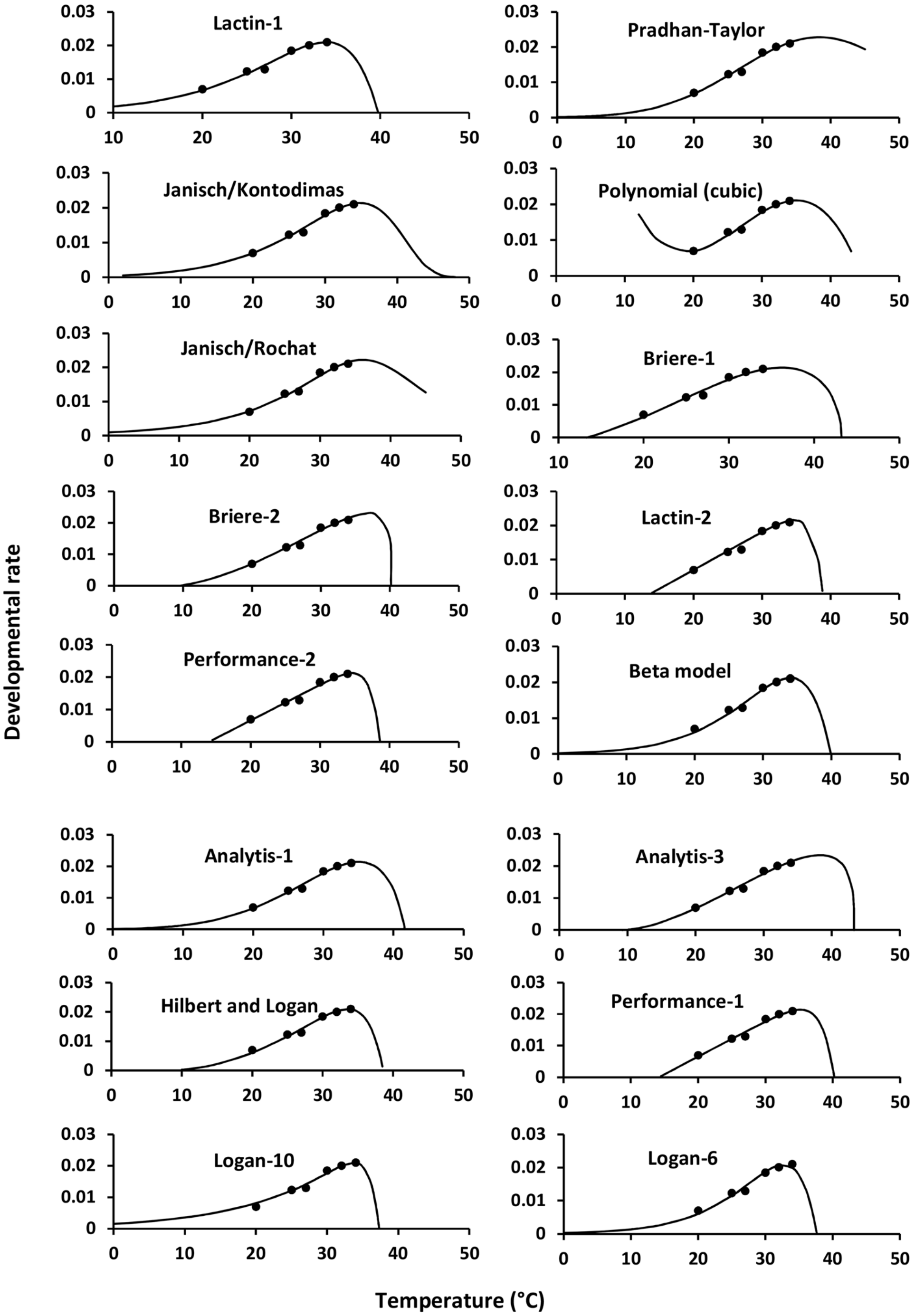

Table 6 Parameter-values (with 95% confidence bounds) for selected nonlinear models fitted to developmental rates of eggs, larvae, pupa and the total immature stages of Varamin population of *Sesamia cretica*

Model	Parameter	Egg	Larvae	Pupa	Total
Pradhan-Taylor	R_m	0.2903 (0.2659, 0.3146)	0.03071 (-0.02574, 0.08716)	0.1229 (0.1187, 0.1271)	0.02434 (-0.00878, 0.05745)
	Tm(℃)	34.91 (31.4, 38.43)	40 (-16.03, 96.03)	32.84 (31.57, 34.11)	40 (-0.01653, 80.02)
	$T\sigma$(°C)	9.451 (6.448, 12.45)	12.63 (-18.15, 43.4)	8.637 (7.448, 9.827)	12.37 (-9.289, 34.03)
Davidsons logistic	a	5.731 (2.977, 8.485	-	-	-
	b	0.2355 (0.11, 0.361)	-	-	-
	k	0.3153 (0.2549, 0.3756)	-	-	-
Logan-6	Δ_T	5.396 (-71.44, 82.23)	-	-	3.902 (-67.03, 74.83)
	ψ	0.01004 (-1.554, 1.575)	-	-	0.0003417 (-0.005623, 0.006306)
	ρ	0.1656 (-2, 2.331)	-	-	0.1508 (-1.617, 1.919)
	T_L (°C)	39.73 (34.1, 45.35)	-	-	38.28 (7.755, 68.8)
Hilbert and Logan	D	48.27 (-3.899e+04, 3.909e+04)	-	50.56 (-2.223e+06, 2.223e+06)	-
	Δ_T	4.169 (-49.86, 58.2)	-	6.715 (-3110, 3123)	-
	ψ	1.383 (-2218, 2221)	-	1.175 (-1.028e+05, 1.028e+05)	-
	T_0 (°C)	7.507 (-38.83, 53.85)	-	8.256 (-5222, 5239)	-
	T_U (°C)	35.36 (2.768, 67.96)	-	37.27 (-1297, 1371)	-
Lactin-1	Δ	5.732 (4.33, 7.134)	5.732 (-0.3287, 11.79)	-	5.732 (1.361, 10.1)
	ρ	0.1743 (0.1315, 0.2171)	0.1745 (-0.01007, 0.359)	-	0.1745 (0.0414, 0.3075)
	T_U (°C)	39.81 (37.31, 42.3)	39.72 (23.9, 55.53)	-	39.82 (28.16, 51.48)
Lactin-2	Δ	2.212 (-4.676, 9.099)	-	3.178 (-3.717, 10.07)	-
	λ	-1.166 (-1.279, -1.052)	-	-1.115 (-1.204, -1.027)	-
	ρ	0.01164 (0.007727, 0.01556)	-	0.007273 (0.003534, 0.01101)	-
	T_U (°C)	42.98 (22.35, 63.61)	-	45 (25.06, 64.94)	-
Logan-10	Δ_T	2.708 (-39.25, 44.67)	-	-	1.218 (-177.6, 180.1)
	K	100 (-229.3, 429.3)	-	-	97.62 (-2.156e+04, 2.176e+04)
	ρ	0.161 (-0.1867, 0.5087)	-	-	0.1074 (-4.302, 4.517)
	a	0.464 (-2.675, 3.603)	-	-	0.08769 (-24.95, 25.13)
	T_L (°C)	41.05 (-8.244, 90.35)	-	-	37.8 (-684, 759.6)
Analytis-1	P	2.716 (-98.13, 103.6)	-	0.8225 (-140.8, 142.5)	-
	n	4.344 (-55.25, 63.94)	-	2.318 (-142, 146.7)	-
	m	0.8022 (-13.9, 15.51)	-	0.8922 (-97.28, 99.07)	-
	T_0 (°C)	-2.645 (-255.6, 250.3)	-	10.02 (-521.8, 541.9)	-
	T_U (°C)	41.17 (-37.11, 119.5)	-	41.65 (-588.9, 672.2)	-
Analytis-2	P	7.032e+05 (-3.01e+12, 3.01e+12)	-	2.081e+05 (-3.163e+12, 3.163e+12)	-
	n	3.978 (-1.031e+06, 1.031e+06)	-	3.972 (-3.917e+06, 3.917e+06)	-
	m	4.354 (-29.94, 38.65)	-	3.113 (-65.9, 72.13)	-
	T_0 (°C)	4.023 (-93.43, 101.5)	-	9.149 (-205, 223.3)	-
	T_U (°C)	67.47 (-14, 148.9)	-	57.58 (-128.3, 243.5)	-

Table 6 (continued)

Model	Parameter	Egg	Larvae	Pupa	Total
Analytis-1/Allahyari	P	0.8436 (-15.11, 16.8)	-	-	-
	n	2.691 (-40.19, 45.57)	-	-	-
	m	4.489 (-70.31, 79.28)	-	-	-
	T_0 (°C)	3.307 (-218.5, 225.1)	-	-	-
	T_U (°C)	41.91 (19.74, 64.08)	-	-	-
Analytis-3	a	4.39e-07 (-7.846e-05, 7.934e-05)	-	1.853e-05 (-0.01525, 0.01529)	-
	T_0 (°C)	2.267 (-153.3, 157.8)	-	9.048 (-675.2, 693.3)	-
	T_U (°C)	41.23 (-37.37, 119.8)	-	40.37 (-542.1, 622.8)	-
	n	3.459 (-34.36, 41.28)	-	2.313 (-163.8, 168.4)	-
	m	0.7323 (-12.09, 13.56)	-	0.7285 (-86.74, 88.2)	-
Briere-1	a	0.0001345 (6.296e-05, 0.0002061)	1.095e-05 (-2.982e-05, 5.173e-05)	8.382e-05 (6.744e-05, 0.0001002)	9.383e-06 (-1.471e-05, 3.348e-05)
	T_0 (°C)	12.71 (8.073, 17.34)	11.98 (-17.82, 41.79)	14.45 (12.86, 16.04)	13.1 (-5.928, 32.12)
	T_U (°C)	42.68 (36.53, 48.82)	44.76 (-14.2, 103.7)	38.79 (37.3, 40.28)	43.94 (5.232, 82.65)
Briere-2	a	0.0002748 (-0.0001274, 0.0006769)	-	9.123e-05 (-0.0001772, 0.0003596)	-
	T_0 (°C)	11.71 (3.588, 19.84)	-	14.13 (8.435, 19.83)	-
	T_U (°C)	38.05 (27.25, 48.85)	-	38.4 (23.68, 53.11)	-
	n	4.147 (-7.673, 15.97)	-	2.167 (-3.152, 7.486)	-
Analytis-3/Kontodimas	a	5.656e-05 (1.703e-06, 0.0001114)	-	2.586e-05 (1.621e-05, 3.55e-05)	-
	T_0 (°C)	12.54 (8.151, 16.93)	-	11.94 (10.35, 13.53)	-
	T_U (°C)	45 (38.4, 51.6)	-	43.71 (41.09, 46.33)	-
Janisch/Kontodimas	D_{min}	3.147 (0.3779, 5.917)	-	-	8.428 (-3154, 3171)
	k	0.1885 (-0.3428, 0.7199)	-	-	0.008997 (-8.208, 8.226)
	λ	0.05081 (0.006104, 0.09552)	-	-	0.03202 (-5.251, 5.315)
	T_{opt}	39.75 (35.19, 44.3)	-	-	38.31 (-1.532e + 04, 1.54e + 04)
Janisch/Rochat	a	1.094 (0.7736, 1.415)	2.71 (-41.34, 46.76)	1.09 (0.783, 1.396)	1.298 (-7.514, 10.11)
	b	1.168 (0.9902, 1.346)	1.099 (0.9213, 1.277)	1.178 (0.9683, 1.388)	1.102 (0.7397, 1.463)
	c	0.2808 (0.1181, 0.4435)	0.01893 (-0.02818, 0.06604)	0.1172 (0.03935, 0.1951)	0.01994 (-0.1174, 0.1573)
	T_U (°C)	31.93 (16.25, 47.61)	35.16 (21.8, 48.53)	30 (14.12, 45.88)	37.94 (8.136, 67.75)
Polynomial (cubic)	a_0	-6.386e-05 (-0.0001464, 1.863e-05)	-2.98e-05 (-8.713e-05, 2.754e-05)	-2.839e-05 (-9.203e-05, 3.524e-05)	-1.745e-05 (-5.569e-05, 2.079e-05)
	a_1	0.004753 (-0.001618, 0.01112)	0.002476 (-0.002166, 0.007118)	0.001958 (-0.003194, 0.00711)	0.001448 (-0.001648, 0.004544)
	a_2	-0.09893 (-0.2566, 0.05871)	-0.06602 (-0.1891, 0.05708)	-0.0364 (-0.173, 0.1002)	-0.03822 (-0.1203, 0.04388)
	a_3	0.6678 (-0.5701, 1.906)	0.5805 (-0.487, 1.648)	0.2118 (-0.973, 1.397)	0.3335 (-0.3785, 1.046)
Performance-1	C	6.618 (-655.6, 668.8)	-	-	-
	K_1	0.002321 (-0.2343, 0.2389)	-	-	-
	K_2	0.4839 (-4.081, 5.048)	-	-	-

Table 6 (continued)

Model	Parameter	Egg	Larvae	Pupa	Total
	T_0 (°C)	13.49 (6.836, 20.14)	-	-	-
	T_U (°C)	39.9 (12.2, 67.6)	-	-	-
Performance-2	m	0.01507 (0.009267, 0.02088)	-	0.008338 (0.00406, 0.01262)	-
	K_2	0.4699 (-1.457, 2.397)	-	0.2875 (-0.4375, 1.013)	-
	T_0 (°C)	13.45 (9.567, 17.34)	-	15 (11.52, 18.48)	-
	T_U (°C)	39.91 (24.76, 55.06)	-	39.05 (29.43, 48.67)	-
Wang	m	3.967 (-505.1, 513.1)	-	7.033	-
	C	0.08294 (-5.473, 5.639)	-	0.2308	-
	K_1	0.004485 (-0.5623, 0.5713)	-	0.001204	-
	K_2	0.3495 (-8.421, 9.12)	-	0.2022	-
	T_0 (°C)	11.75 (-35.8, 59.31)	-	13.97	-
	T_U (°C)	40.45 (-11.62, 92.52)	-	40.57	-
Ratkowsky	C	0.02248 (0.0136, 0.03135)	-	-	-
	K	0.244 (-0.3239, 0.8119)	-	-	-
	T_0 (°C)	6.688 (1.741, 11.64)	-	-	-
	T_U (°C)	42.76 (29.77, 55.74)	-	-	-
Beta	r_m	0.2928 (0.2643, 0.3214)	-	0.123 (0.1162, 0.1299)	-
	T_{opt}	34.31 (31.48, 37.14)	-	32.98 (30.06, 35.9)	-
	T_0 (°C)	-6.271 (-99.77, 87.23)	-	10.68 (-10.02, 31.38)	-
	T_U (°C)	42.08 (32.33, 51.82)	-	42.9 (30.89, 54.92)	-

The values in parentheses are the parameter-values with 95% confidence bounds

- Data could not be fitted by the model

Table 7 Parameter-values (with 95% confidence bounds) for selected nonlinear models fitted to developmental rates of eggs, larvae, pupa and the total immature stages of Rey population of *Sesamia cretica*

Model	Parameter	Egg	Larvae	Pupa	Total
Pradhan-Taylor	R_m	0.2718 (0.2593, 0.2843)	0.02911 (0.0006, 0.05761)	0.124 (0.1179, 0.1301)	0.02281 (0.01257, 0.03305)
	Tm (℃)	35.43 (33.33, 37.54)	39.86 (9.396, 70.33)	33.93 (31.95, 35.91)	38.33 (24.14, 52.52)
	$T\sigma$(°C)	10.40 (8.688, 12.11)	12.68 (-4.28, 29.64)	9.426 (7.771, 11.08)	11.7 (3.247, 20.16)
Davidsons logistic	a	5.366 (4.325, 6.407)	-	-	-
	b	0.2268 (0.1779, 0.2757)	-	-	-
	k	0.2921 (0.27, 0.3141)	-	-	-
Logan-6	Δ_T	-	-	-	4.21 (-58.42, 66.84)
	ψ	-	-	-	0.0003006 (-0.0006765, 0.001278)
	ρ	-	-	-	0.1667 (-1.758, 2.091)
	T_L(°C)	-	-	-	37.66 (23.32, 52)
Hilbert and Logan	D	45.31 (-9.529e+04, 9.538e+04)	64.09 (-7.438e+05, 7.439e+05)	-	63.27 (-9.559e+05, 9.561e+05)
	Δ_T	8.142 (-249.9, 266.2)	1.55 (-697.3, 700.4)	-	2.532 (-344.5, 349.5)
	ψ	1.373 (-5726, 5728)	0.1335 (-3069, 3069)	-	0.1528 (-4584, 4585)
	T_0(°C)	5.37 (-439.9, 450.7)	4.301 (-1004, 1012)	-	7.397 (-738.6, 753.4)
	T_U(°C)	39.27 (-49.36, 127.9)	39.95 (-4820, 4899)	-	39.57 (-1908, 1987)
Lactin-1	Δ	-	5.732 (1.327, 10.14)	-	5.732 (3.778, 7.685)
	ρ	-	0.1745 (0.04033, 0.3086)	-	0.1745 (0.115, 0.2339)
	T_U(°C)	-	40.12 (27.57, 52.67)	-	39.42 (34.66, 44.19)
Lactin-2	Δ	-	0.1392	2.891 (-4.873, 10.65)	1.545 (-31.89, 34.98)
	λ	-	-1.016	-1.102 (-1.179, -1.024)	-1.015 (-1.04, 0.9906)
	ρ	-	0.001235	0.0067 (0.003515, 0.009886)	0.001088 (7.953e-05, 0.002097)
	T_U(°C)	-	44.95	45 (19.59, 70.41)	44.44 (-171.1, 260)
Logan-10	Δ_T	-	1.257 (-1955, 1957)	-	1.427 (-214.6, 217.4)
	K	-	84.23 (-4.019e+04, 4.036e+04)	-	90.45 (-4.659e+04, 4.677e+04)
	ρ	-	0.08472 (-4.083, 4.253)	-	0.08606 (-4.104, 4.276)
	a	-	0.1579 (-83.25, 83.56)	-	0.1394 (-78.67, 78.95)
	T_L(°C)	-	41.73 (-1.081e+04, 1.09e+04)	-	39.51 (-1334, 1413)
Analytis-1	P	1.519 (-25.72, 28.76)	-	0.7046 (-156, 157.4)	0.2258 (-390.1, 390.5)
	n	2.383 (-10.79, 15.56)	-	2.084 (-157.2, 161.3)	5.883 (-3719, 3731)
	m	0.7459 (-9.314, 10.81)	-	0.8244 (-133.6, 135.2)	0.7572 (-586.4, 588)
	T_0(°C)	6.519 (-45.31, 58.35)	-	10.31 (-605.5, 626.1)	-15.66 (-1.851e+04, 1.848e+04)
	T_U(°C)	44.52 (-51.61, 140.7)	-	43.3 (-1069, 1156)	41.59 (-3657, 3741)

Table 7 (continued)

Model	Parameter	Egg	Larvae	Pupa	Total
Analytis-2	P	-	-	3.381e+05 (-6.472e+12, 6.472e+12)	-
	n	-	-	4.117 (-4.922e+06, 4.922e+06)	-
	m	-	-	2.691 (-66.16, 71.54)	-
	T_0(°C)	-	-	9.823 (-229.3, 249)	-
	T_U(°C)	-	-	58.69 (-129.5, 246.9)	-
Analytis-1/Allahyari	P	0.651 (-3.267, 4.569)	-	-	-
	n	1.7113 (-6.347, 9.773)	-	-	-
	m	4.001 (-24.65, 32.65)	-	-	-
	T_0(°C)	8.289 (-35.78, 52.35)	-	-	-
	T_U(°C)	44.5 (20.75, 68.26)	-	-	-
Analytis-3	a	5.492e-05 (-0.003365, 0.003475)	-	-	4.497e-05 (-0.1679, 0.168)
	T_0(°C)	7.706 (-33.68, 49.1)	-	-	9.235 (-3315, 3334)
	T_U(°C)	44.09 (-47.01, 135.2)	-	-	43.27 (-1.098e+04, 1.107e+04)
	n	2.139 (-8.276, 12.55)	-	-	1.715 (-643.3, 646.8)
	m	0.651 (-7.852, 9.154)	-	-	0.2966 (-489.3, 489.9)
Briere-1	a	0.0001158 (8.398e-05, 0.0001477)	1.072e-05 (-1.188e-05, 3.332e-05)	7.288e-05 (5.679e-05, 8.898e-05)	9.739e-06 (-1.465e-06, 2.094e-05)
	T_0(°C)	11.42 (8.801, 14.03)	12.46 (-3.68, 28.6)	13.73 (11.92, 15.53)	13.29 (4.7, 21.88)
	T_U(°C)	43.12 (39.89, 46.36)	44.75 (10.89, 78.6)	40.12 (38.05, 42.19)	43.22 (27.09, 59.35)
Briere-2	a	0.0001579 (-0.0002292, 0.000545)	2.024e-05 (-0.001472, 0.001512)	8.188e-05 (-0.0002425, 0.0004062)	1.767e-05 (-0.0002985, 0.0003338)
	T_0(°C)	11.06 (6.244, 15.87)	6.27 (-164.4, 176.9)	13.53 (6.851, 20.21)	9.583 (-46.93, 66.1)
	T_U(°C)	41.17 (24.96, 57.38)	45 (-1820, 1910)	39.49 (17.4, 61.58)	40.18 (-190.4, 270.8)
	n	2.515 (-2.864, 7.894)	7.01 (-1131, 1145)	2.186 (-4.657, 9.028)	4.724 (-144.8, 154.3)
Analytis-3/Kontodimas	a	-	-	2.233e-05 (1.246e-05, 3.219e-05)	-
	T_0(°C)	-	-	11.56 (9.695, 13.42)	-
	T_U(°C)	-	-	44.97 (41.48, 48.47)	-
Janisch/Kontodimas	D_{min}	-	7.331 (-824.2, 838.9)	-	29.93 (-213.7, 273.6)
	k	-	0.01606 (-8.847, 8.879)	-	-0.02067 (-0.07022, 0.02888)
	λ	-	0.02599 (-4.007, 4.059)	-	-0.2241 (-2.542, 2.094)
	T_{opt}	-	46.15 (-1.247e+04, 1.256e+04)	-	44.56 (-14.67, 103.8)
Janisch/Rochat	a	-	1.013 (-4.338, 6.363)	-	1.157 (-1.671, 3.985)
	b	-	1.108 (-0.7016, 2.918)	-	1.108 (0.7906, 1.426)
	c	-	0.03348 (-1.028, 1.095)	-	0.02186 (-0.03544, 0.07916)

Table 7 (continued)

Model	Parameter	Egg	Larvae	Pupa	Total
	T_U(°C)	-	38.15 (-717.3, 793.6)	-	37.48 (9.85, 65.11)
Polynomial (cubic)	a_0	-3.953e-05 (-7.465e-05, -4.415e-06)	7.459e-06 (-3.45e-05, 4.942e-05)	-1.464e-05 (-6.981e-05, 4.052e-05)	-6.942e-06 (-3.562e-05, 2.173e-05)
	a_1	0.002857 (0.0001447, 0.005569)	-0.0005682 (-0.003965, 0.002829)	0.0009332 (-0.003533, 0.005399)	0.0005619 (-0.00176, 0.002883)
	a_2	-0.05306 (-0.1202, 0.01404)	0.01534 (-0.07475, 0.1054)	-0.01162 (-0.1301, 0.1068)	-0.01382 (-0.07538, 0.04775)
	a_3	0.3245 (-0.2024, 0.8514)	-0.1299 (-0.9111, 0.6513)	0.01675 (-1.01, 1.044)	0.1141 (-0.4198, 0.648)
Performance-1	C	-	1.238 (-6759, 6762)	2.574 (-2164, 2169)	1.111 (-5575, 5577)
	K_1	-	0.001032 (-5.698, 5.7)	0.003101 (-2.661, 2.668)	0.001018 (-5.15, 5.152)
	K_2	-	0.6238 (-2263, 2264)	0.3219 (-18.17, 18.81)	0.4809 (-167.4, 168.4)
	T_0(°C)	-	13.17 (-265.6, 292)	14.77 (-47.23, 76.77)	14.19 (-164.7, 193.1)
	T_U(°C)	-	42.35 (-2.619e+04, 2.628e+04)	39.52 (-116.6, 195.6)	40.21 (-1528, 1608)
Performance-2	m	-	0.001275 (-0.0002128, 0.002763)	0.007913 (0.004178, 0.01165)	0.001106 (0.00011, 0.002101)
	K_2	-	0.9767 (-7.381e+04, 7.382e+04)	0.2803 (-0.5162, 1.077)	0.6581 (-17.62, 18.94)
	T_0(°C)	-	13.32 (-0.6099, 27.24)	14.76 (11.52, 18)	14 (4.544, 23.45)
	T_U(°C)	-	44.68 (-7.932e+05, 7.933e+05)	39.98 (26.97, 52.98)	38.67 (-80.78, 158.1)
Wang	m	-	-	6.191	-
	C	-	-	0.2942	-
	K_1	-	-	0.001222	-
	K_2	-	-	0.2404	-
	T_0(°C)	-	-	13.7	-
	T_U(°C)	-	-	41.18	-
Beta	r_m	0.2709 (0.2596, 0.2823)	0.02702 (-0.0005097, 0.05455)	0.124 (0.1149, 0.1331)	0.02125 (0.01614, 0.02636)
	T_{opt}	34.89 (33.94, 35.83)	35 (-2.161, 72.16)	33.84 (28.94, 38.75)	33.96 (23.53, 44.39)
	T_0(°C)	3.438 (-7.038, 13.91)	-116.8 (-1.289e+04, 1.265e+04)	8.743 (-21.67, 39.15)	-115.8 (-6288, 6056)
	T_U(°C)	45 (fixed at bound)	41.32 (-43.96, 126.6)	44.1 (26.85, 61.35)	39.92 (10.87, 68.97)

The values in parentheses are the parameter-values with 95% confidence bounds

- Data could not be fitted by the model

Table 8 Biological significance of acceptable linear and nonlinear models based on *AIC* statistical criteria of the total immature stages of Varamin and Rey populations of *Sesamia cretica* at different temperatures in the laboratory

Geographical population	Model	Temperature (°C)/ Development time (day)											
		20		25		27		30		32		34	
		Observed	Estimated	Observed	Estimated	Observed	Estimated	Observed	Estimated	Observed	Estimated	Observed	Estimated
Varamin	Ordinary	120.55	250	91.67	111.11	82.89	90.91	55.73	71.43	45.63	62.50	-	-
	Ikemoto	120.55	152.01	91.67	82.22	82.89	69.46	55.73	56.35	45.63	50.05	-	-
	Polynomial (cubic)	120.55	114.94	91.67	96.68	82.89	73.08	55.73	52.77	45.63	46.71	48.00	45.34
	Lactin-1	120.55	150.31	91.67	85.08	82.89	69.66	55.73	54.09	45.63	47.90	48.00	45.17
	Janisch/Rochat	120.55	143.44	91.67	88.98	82.89	74.01	55.73	57.38	45.63	49.97	48.00	45.74
	Pradhan-Taylor	120.55	151.82	91.67	85.70	82.89	71.37	55.73	56.96	45.63	50.64	48.00	46.21
	Logan-10	120.55	141.34	91.67	87.37	82.89	72.74	55.73	56.25	45.63	48.95	48.00	47.74
	Logan-6	120.55	167.79	91.67	89.52	82.89	71.72	55.73	54.49	45.63	48.46	48.00	47.79
	Briere-1	120.55	157.84	91.67	82.31	82.89	68.99	55.73	56.30	45.63	51.00	48.00	47.57
	Janisch/Kontodimas	120.55	140.57	91.67	86.67	82.89	73.26	55.73	58.34	45.63	50.89	48.00	44.90
Rey	Ordinary	143.24	166.67	81.55	90.91	77.28	76.92	54.18	62.50	49.86	55.55	47.61	50.00
	Ikemoto	143.24	146.98	81.55	82.68	77.28	70.37	54.18	57.52	49.86	51.28	47.61	46.26
	Lactin-1	143.24	150.54	81.55	86.06	77.28	70.83	54.18	55.57	49.86	49.72	47.61	47.65
	Pradhan-Taylor	143.24	149.57	81.55	83.89	77.28	70.06	54.18	56.49	49.86	50.75	47.61	46.95
	Janisch/Kontodimas	143.24	143.67	81.55	84.91	77.28	70.77	54.18	56.22	49.86	50.24	47.61	47.16
	Polynomial (cubic)	143.24	144.42	81.55	88.35	77.28	71.71	54.18	56.25	49.86	50.58	47.61	47.78
	Janisch/Rochat	143.24	139.15	81.55	85.96	77.28	71.96	54.18	56.94	49.86	50.41	47.61	46.45
	Briere-1	143.24	158.78	81.55	82.17	77.28	68.87	54.18	56.33	49.86	51.20	47.61	48.02
	Briere-2	143.24	143.80	81.55	82.56	77.28	69.72	54.18	56.54	49.86	50.56	47.61	46.36
	Lactin-2	143.24	142.89	81.55	79.56	77.28	67.57	54.18	55.29	49.86	49.76	47.61	46.59
	Performance-2	143.24	150.69	81.55	82.21	77.28	69.58	54.18	56.70	49.86	50.86	47.61	47.40
	Beta	143.24	164.60	81.55	88.59	77.28	71.77	54.18	55.44	49.86	49.31	47.61	47.06
	Analytis-1	143.24	150.13	81.55	84.69	77.28	70.38	54.18	56.17	49.86	50.38	47.61	47.22
	Analytis-3	143.24	148.52	81.55	82.95	77.28	69.95	54.18	56.86	49.86	50.98	47.61	46.75
	Hilbert and Logan	143.24	166.11	81.55	86.17	77.28	70.32	54.18	55.06	49.86	49.37	47.61	47.92
	Performance-1	143.24	152.64	81.55	82.30	77.28	69.59	54.18	56.80	49.86	51.08	47.61	47.48
	Logan-10	143.24	123.22	81.55	82.68	77.28	70.82	54.18	56.82	49.86	50.25	47.61	47.85
	Logan-6	143.24	166.16	81.55	87.04	77.28	69.66	54.18	53.48	49.86	48.58	47.61	50.34

Observed: is the development time in laboratory and Estimated: is the development time based on the model

Nonlinear models are listed based on rate of *AIC* in the table

- Data were not fitted in nonlinear range

Conclusion

The Ikemoto and Berier-1 models were selected as the best models to determine the total development rate of *S. cretica*. The Ikemoto model is enough accurate to determine the lower temperature threshold and thermal constant in the laboratory. The insect development prediction, such as incubation time of *S. cretica*, can indicate the onset of crop damage and help to construct a forecasting model for effective pest management.

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Declarations

Conflicts of interest All authors declare that they have no conflicts of interest.

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