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IMPACTS OF CLIMATE CHANGE ON THE NUMBER OF DAYS PER GENERATION OF THE EGG-PARASITOID *TELENOMUS REMUS* NIXON, 1937 (HYMENOPTERA: SCELIONIDAE) IN EGYPT

[a]Ahmed Hamed El Kenawy, [b]Hassan Ahmed Hassan, [c]Mohamed Kamel Abdel-samed Hamza, [d]Wael El-zaher Abd El-Hafeez El-Sheikh

[a] *Biological Control Research Department, Plant Protection Research Institute, Agricultural Research Center, Giza, Egypt.*

[b] *Central Laboratory for Agriculture Climate, Agriculture Research Center, Dokki, Giza, Egypt*

[c] *Plant Protection Department, Faculty of Agriculture, AL-Azhar University, Nasr City, Cairo, Egypt.*

[d] *Department of Plant Protection, Faculty of Agriculture, Beni-Suef University, Egypt, Beni Suef 62511, Egypt.*

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ABSTRACT

In this research, we forecasted both the degree-day units and annual generations of the egg parasitoid *Telenomus remus* Nixon, which parasitizes fall armyworm (*Spodoptera frugiperda*). The aim was to comprehend its potential spread across diverse agro-climatic zones, considering both current conditions and potential future climates. This was achieved by examining the correlation between degree-day units and population fluctuations. Climate change data from the HadCM3 model was utilized, focusing on A1 scenarios recommended by the Intergovernmental Panel on Climate Change (IPCC). We aimed to evaluate how temperature projections are anticipated to impact the annual generations in three Egyptian governorates. The investigation revealed that *T. remus* populations in Aswan, an Upper Egyptian governorate, exhibited a higher number of generations compared to other regions, namely El Sharkia and Beni Suef governorates, in the current climate. The completion of generations by *T. remus* in El Sharkia, Beni Suef, and Aswan took 13.42, 12.6, and 10.08 days, respectively. The results highlighted that the average generation period in 2021 was the longest, reaching 13.42 ± 6.17 days in El Sharkia governorate. Predictions suggest that *T. remus* is anticipated to undergo 23 generations between 2040 and 2060, indicating a two-generation increase from 2021. Conversely, in the Beni Suef governorate, where *T. remus* completed generations in 10.86 ± 5.72 days, the generation period was the longest in 2021. Projections indicate that *T. remus* is expected to have 24 generations in 2040 and 28 generations in 2060, compared to 22 generations in 2021. Additionally, Aswan's *T. remus* is forecasted to experience 32 generations in 2040 and 35 generations in 2060, up from 29 generations in the 2021 climate. The duration of the first generation took 13, 11, and 12 days in the years 2021, 2040, and 2060, respectively. A comprehensive understanding of thermal requirements and biological factors is crucial for accurately predicting generation duration, serving as a valuable reference for the mass production and preservation of parasitoids.

Corresponding Author: Ahmed Hahmed El Kenawy

Email: ahmed.elkenawy@arc.sci.eg

INTRODUCTION

Worldwide climate changes, resulting from increased greenhouse gas emissions, are predicted to have a wide range of consequences on agro-ecosystems, the outcome of which is determined by synergistic impacts of climatic factors, such as temperature and precipitation, in conjunction with other relevant worldwide changing components (Kalinkat and Rall, 2015). The study of individual species' physiology and ecology, as well as their interactions within networks, community structure, and the functioning of (agro) ecosystems, will be profoundly altered because of these changes (Abdala-Roberts et al., 2019). Climate change can potentially have adverse effects on natural predators and parasitoids that serve as the primary adversaries through extrinsic and internal systems (Cornelissen, 2011). Imported predators and parasitoids, in addition to the target and non-target species, will be impacted due to the rate of climate change and the number and magnitude of changing climate factors. Directly, these changes will have an impact on their developmental periods, survival, and reproduction. Indirectly, these changes will have an impact on their dispersal and colonization through their impact on landscapes (Evans et al., 2007). Over the past few years, abiotic factors connected to climate change have been the subject of comprehensive studies to assess their direct effects on herbivores' natural enemies. For instance, it has been reported that temperature is a significant factor in the development, survival, fecundity, parasitism, and dissemination of parasitoids (Selvaraj et al., 2013).

The rate of development, according to Zalom and Wilson (1982), is dependent on the accumulation of heat assessed in physiological rather than chronological time. Chiang (1985) defines "optimal range" as the temperature range between the lower and upper thresholds, where development is exactly proportional to temperature. Outside of these boundaries, activity comes to a halt but does not necessarily result in death. Zalom et al. (1983) describe the thermal unit as a valuable tool for insect pest control in forecasting infestations, monitoring, and scheduling insecticide applications. Cumulated thermal units have been used to predict the seasonal development and emergence of several insects (Daoud et al., 1999; Khalil et al., 2010).

To calculate degree-days (°D), first compute degree-hours (°H) for each hour of the day. The number of °H is derived by subtracting the lower threshold from the mean hourly temperature or the upper threshold, whichever is less. To calculate °D, add °H over 24 hours and divide it by 24 (Snyder, 1985).

The degree-day calculation processes differ in complexity. Season and climatic areas also influence how closely these methods reflect actual degree days. It is critical to utilize the same strategy as that employed in constructing the organism's biological growth relationships. The area under the diurnal temperature curve and between the thresholds is used to calculate and accumulate degree days. Degree days can be calculated using single-sine, double-sine, single-triangle, or double-triangle methods. Huber's approach is a horizontal cutoff version of the single-sine method. Because the rate of development is assumed to be a straight line directly proportional to temperature, all these approaches are linear. Nonlinear approaches exist as well; however, they are now mostly used in research (Baskerville and Emin, 1969).

Due to natural enemies' role in the initial phases of pest development, before any detrimental impact occurs to the crop, egg parasitoids are one of the most significant classes of biological control agents utilized in augmentative biological management (Postali Parra and Coelho, 2019). The egg parasitoid *Telenomus remus* Nixon (Hymenoptera: Scelionidae) is a lepidopterous egg parasitoid that lives originally in peninsular Malaysia and Papua New Guinea (Wengrat et al., 2021). Because of the significant level of reproduction and simplicity of mass rearing, *T. remus* seems a tremendous biological control agent for lepidopterous pests, especially those of the genus *Spodoptera* (Noctuidae) (Pomari et al., 2012). This egg parasitoid's biology and ecology were previously investigated and discussed by Cave (2000). Throughout its lifespan, its female produces about 270 eggs, which are typically laid individually in each host egg to prevent superparasitism. The phase of laying eggs lasts ten hours at 30°C (Hernández and Daz, 1996) and 18-24 hours at 15.5°C (Gómez, 1987). Females have the most eggs in the ovary at 2-3 days of age (van Welzen and Waage, 1987) and generate over 76% of their offspring within the five early days of adulthood. The progeny sex ratio is generally 60-70% females, which decreases to 22% as the females age (Schwartz and Gerling, 1974). The 1st male egg is normally deposited when the 2nd host is assaulted; the following male eggs are given at varying intervals between female egg depositions. When the number of females of this parasitoid is substantially more than those of hosts, increased proportions of male eggs are produced (van Welzen and Waage, 1987), which could be owing to superparasitism and differential mortality. Pomari et al. (2012) investigated the effects of temperature on *T. remus* parasitism and development in the eggs of four *Spodoptera* species. The thermal requirements of *T. remus* have been estimated to have a thermal constant (K) of 125.39 degree-days (DD) and a base temperature (Tbase) of 15.139°C. For *S. cosmioides*, the estimated thermal requirements are 125.56 DD and 14.912°C. *S. frugiperda* has thermal requirements of 142.98 DD and 14.197°C, while *S. albula* has requirements of 149.16 DD and 13.846°C. Lastly, *S. eridania* has estimated thermal requirements of 149.16 DD and 13.846°C.

Thus, the present study aimed to explore the potential relationship between degree-day values and the number of days per generation in *T. remus*. In the 1st stage, generations were divided into 3 periods: the average current temperature effect (2021), the near future (2040), and the far future (2060).

MATERIALS AND METHODS

Climate change data from three governorates of Egypt representing Aswan (Upper Egypt), Beni-Suef (Middle Egypt), and El Sharkia (Delta- Lower Egypt) were chosen. These represented three different agroecological zones in Egypt whose classification depends on calculating the yearly potential evapotranspiration (PET) in each governorate. If the difference in the PET of many governorates decreased below 5%, the governorates were grouped in one area.

Determination of degree-days units (DDU)

Under the current climate temperature

The daily highest and lowest readings were received from the Center Laboratory for Agriculture Climate (CLAC). These temperatures were then converted into heat units by utilizing the lower threshold temperature for aphids (where t_0 was 10.8° C with 336.7 units per generation based on the study of Oktaviani et al., (2022). The calculation of lower degree-day units (DDU) was performed using the formula proposed by Richmond et al. (1983) as outlined below:

H =Σ H J

(Where: H = number of degree-days units).

H J = {(max + min)/2} – C (If $_{max}$. > C and min. > C)

H J = {(max. – C) 2 /2 (max.-min.)} (If $_{max}$. > C and min. < C)

H J = 0 (If max. < C and min. < C)

C = t_0

Influence of contemporary climate change on *T. remus*

The study was performed on *T. remus* at the three governorates, namely El Sharkia, Beni-Suef, and Aswan, Egypt, from January to December, starting the successive seasons in 2021. The average temperature, including both daily maximum and minimum values, was computed based on the recorded data provided by CLAC, Egypt.

Influence of expected future climate change on *T. remus*

Current research was carried out to predict the numbers and durations of generations and DDU (accumulated thermal heat units) in expected future climate change in the 2040s and 2060s. Future data about the climate were received according to the scenarios of GHG emissions (SSP-4.5), the rise of the temperature (1.5 °C) near term 2040 (2.0°C) mid-term 2060 and (2.7 °C) (Allan et al., 2021).

Data Analysis

Data were coded and entered using the statistical package SPSS V.22. Data were tested for satisfying assumptions of parametric tests, and continuous variables were subjected to Shapiro- Wilk, and Kolmogorov-Smirnov test for normality. Data were presented as means, and standard deviations. ANOVA analyses were done regarding the calculated generation and stages needed days and DDUs, analysis evaluated using multiple replicates at least for each group; post-hoc analysis evaluated using Tukey pairwise comparison; P-values were considered significant at<0.05. Pearson correlation coefficient was done between days and DDUs needed for every generation or stage regarding seasons to reveal how would predict 2040 and 2060 generations needed days would depend on DDUs in comparison to the current 2021 season, the analysis became available using MiniTab V 14. Data were visualized when possible, using R studio V 2022.02.4.

RESULTS

The findings emphasize the limited understanding of how the forthcoming impact of climate change may affect the function and effectiveness of natural enemies. A notable distinction was observed in the time needed to complete generations across various governorates (reflecting different weather conditions) and seasons (F = 1.31, P = 0.268), as well as in the Degree-Day Units (F = 0.25, P = 0.907).

Current climate

The data presented in Figure 1 and Table 1 depicts the initial analysis of current climate conditions gathered during the study period spanning from April to November. The mean values of thermal units required for the completion of *T. remus* generations were 161.05 ± 4.46, 162.3 ± 4.21, and 161.69 ± 6.62 units in El-Sharkia, Beni-Suef, and Aswan Governorates, respectively. As a result, given 2021 climatic conditions, generations were successfully completed at El-Sharkia, Beni-Suef, and Aswan in 13.42, 12.6, and 10.08 days, respectively.

Table 1: Mean ± SD for observed days and DDUs for *T. remus* through studied seasons and governorates.

	Sharkia Governorate		Beni Suef Governorate		Aswan Governorate	
	Days	**DDUs**	**Days**	**DDUs**	**Days**	**DDUs**
2021	13.42 ± 6.17[a]	161.05 ± 4.46[a]	10.86 ± 5.72[a]	162.3 ± 4.21[a]	7.47 ± 1.49[a]	161.69 ± 6.62[a]
2040	12 ± 6.73[a]	157.89 ± 4.2[a]	9.04 ± 3.22[a]	157.16 ± 5.12[b]	6.84 ± 1.12[a]	157.22 ± 5.64[b]
2060	10.08 ± 2.7[a]	158.53 ± 5.21[a]	8.32 ± 2.4[a]	158.01 ± 5.24[b]	7.45 ± 1.96[a]	157.66 ± 6.06[ab]

*Means that do not share a letter are significantly different within the column.

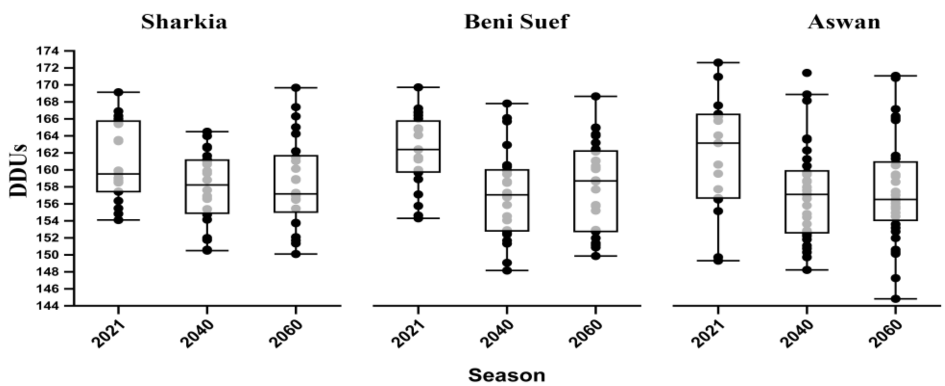

Figure 1. Box and whisker plot of DDUs uptaken during observed seasons and governorates.

Expected future climate

In the examined regions (El-Sharkia, Beni-Suef, and Aswan Governorates), both the degree days and the duration required for a generation to complete decreased between 2040 and 2060 when compared to the data from 2021 (Figures 1 and 2). The outcomes depicted in Figure 3 indicated that the summer (June-August) and autumn (September-October) seasons exhibited the most substantial alterations in degree days. Conversely, the winter and spring (April-May) seasons experienced only minor changes in 2040 and 2060 compared to the 2021 data.

Number of generations and DDUs under El-Sharkia climate conditions

Compared to the anticipated climate conditions in 2040 (12 ± 6.73 days) and 2060 (10.08 ± 2.7 days), there were no significant differences between the values (T = -1.51, P = 0.306) and (T = -1.28, P = 0.419), respectively. However, a significant difference was observed only between the values of 2040 and 2060 (T = 0.23, P = 0.972). The longest average generation period occurred in 2021, lasting 13.42 ± 6.17 days.

Table 2 indicates that *T. remus* is projected to undergo 23 generations from 2040 to 2060, representing an increase of two generations each year compared to 2021. The initial generation's longest durations in April were 29, 25, and 12 days in 2021, 2040, and 2060, respectively. The time taken for generations in 2040 and 2060 was 4 and 17 days less than in 2021, respectively.

Number of generations and DDUs under Beni-Suef climate condition

In contrast to the projected climate conditions for 2040 (9.04 ± 3.22 days) and 2060 (8.32 ± 2.4 days), there was no statistically significant difference between the values of 2040 - 2021 (T = -2.42, P = 0.061) and for 2060 - 2040 (T = -0.45, P = 0.893). The generation period in 2021, with a mean duration of 10.86 ± 5.72 days, exhibited the lengthiest duration.

Table 2: Degree-days and generation numbers of *T. remus* under climate season 2021 and Future climate 2040, 2060 at El-Sharkia, Beni Suef, and Aswan Governorates.

	El Sharkia						Beni Suef						Aswan					
No.	**2021**		**2040**		**2060**		**2021**		**2040**		**2060**		**2021**		**2040**		**2060**	
Gen.	Days	DDUs	Days	DDUs	Days	DDUs	Days	DDUs	Days	DDUs	Days	DDUs	Days	DDUs	Days	DDUs	Days	DDUs
1	29	154.1	25	156.9	12	151	26	164.1	19	167.8	12	155.9	13	159.6	11	154.4	12	159.4
2	28	154.8	13	159.6	14	157	25	164.8	9	148.2	9	151.1	8	149.3	9	161.3	10	161.7
3	25	159	10	154.7	10	157	10	154.6	8	162.9	8	168.7	8	160.6	7	154.8	7	165.9
4	10	155.5	10	162.6	10	159	10	159.7	9	160.6	7	164.2	7	156.7	7	158.6	7	155.7
5	14	165.8	10	152	9	160	10	154.3	9	160.4	9	165	7	156.5	6	152.9	6	152
6	12	159.9	9	157.6	9	159	19	164.9	8	154.1	8	162.2	8	164.1	7	152.2	7	161.3
7	11	163.4	9	156.6	8	157	9	161.5	8	149.1	8	160.3	8	166.6	7	151.1	7	159.2
8	11	166	9	154.1	8	150	0	167.2	7	158.5	7	157.7	7	166.3	7	168.2	7	160.5
9	10	165.4	8	161.2	8	162	8	161.4	7	151.7	7	151.4	7	165.8	7	171.4	6	157.4
10	9	166.9	8	156.6	8	170	8	166.4	7	158.5	7	150.9	7	157.7	6	157.9	6	147.3
11	9	157.4	8	162.6	8	166	8	166.8	7	154.5	7	164.9	7	163.2	7	163.7	6	157
12	9	156.4	8	160.7	8	165	8	169.7	7	156.8	7	152.9	6	149.7	6	150.3	6	144.8
13	9	166.4	8	151.8	8	157	7	161.2	6	152.4	6	160.1	7	171	6	158.7	6	152.7
14	9	169.1	8	164.5	8	167	8	162.4	7	156.8	6	160.4	7	166.5	6	155.8	6	166.3
15	9	158.6	9	161	8	152	8	155.8	7	166.1	6	158.8	6	155.2	6	153.6	6	155.6
16	10	163.5	9	161.7	9	164	8	160	7	151.3	6	155.7	7	167.6	6	157.2	6	155
17	10	159.5	9	151.8	9	156	9	166.7	8	165.7	7	161.1	7	172.6	6	157.1	6	167.2
18	12	165.7	9	162.7	9	154	9	166	8	159.5	7	149.9	7	161.2	6	152.7	6	155.6
19	13	158.8	9	159.9	11	161	10	162.4	8	152.6	7	152.7	7	162.4	6	163.6	6	156.4
20	14	157.4	10	164	10	152	11	158.9	9	158.6	7	152	7	155.8	6	157.6	6	170.8
21	19	158.5	11	160.7	12	162	13	164.8	10	152.9	8	164	8	160	6	150.8	6	156.1
22			12	155.4	12	157	15	157.1	11	157.3	8	163.2	8	166.7	6	148.2	6	150.1
23			13	156.6	15	157			13	159.9	9	162.4	8	166	6	160.5	6	155.4
24									18	155.9	9	161	9	162.4	6	162.3	6	166.1
25											10	152.8	9	158.9	7	168.9	9	153.2
26											11	155.2	10	164.8	7	151.8	7	156.5
27											13	151.4	11	164.8	7	159.5	10	158.6
28											17	158.6	12	164.8	8	152.4	8	154.5
29													12	162.8	7	149.7	10	171.1
30															7	158	8	153.6
31															9	159.7	8	159.2
32															8	156.6	8	150.3
33																	9	150.6
34																	12	159.5
35																	13	161.4

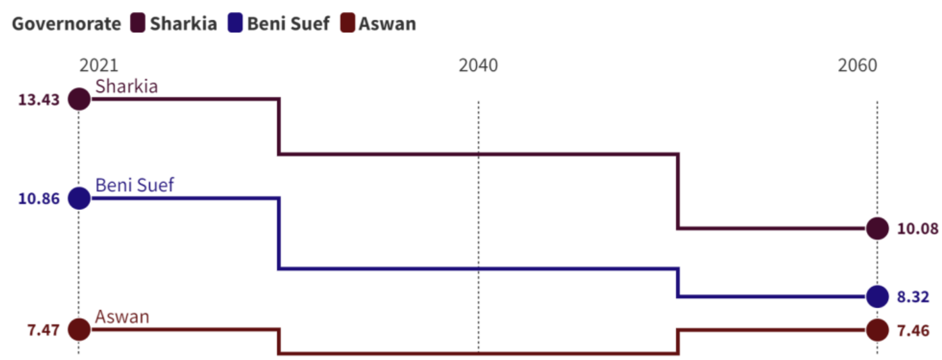

Figure 2. Slope chart of days needed for a generation to complete during observed seasons and governorates

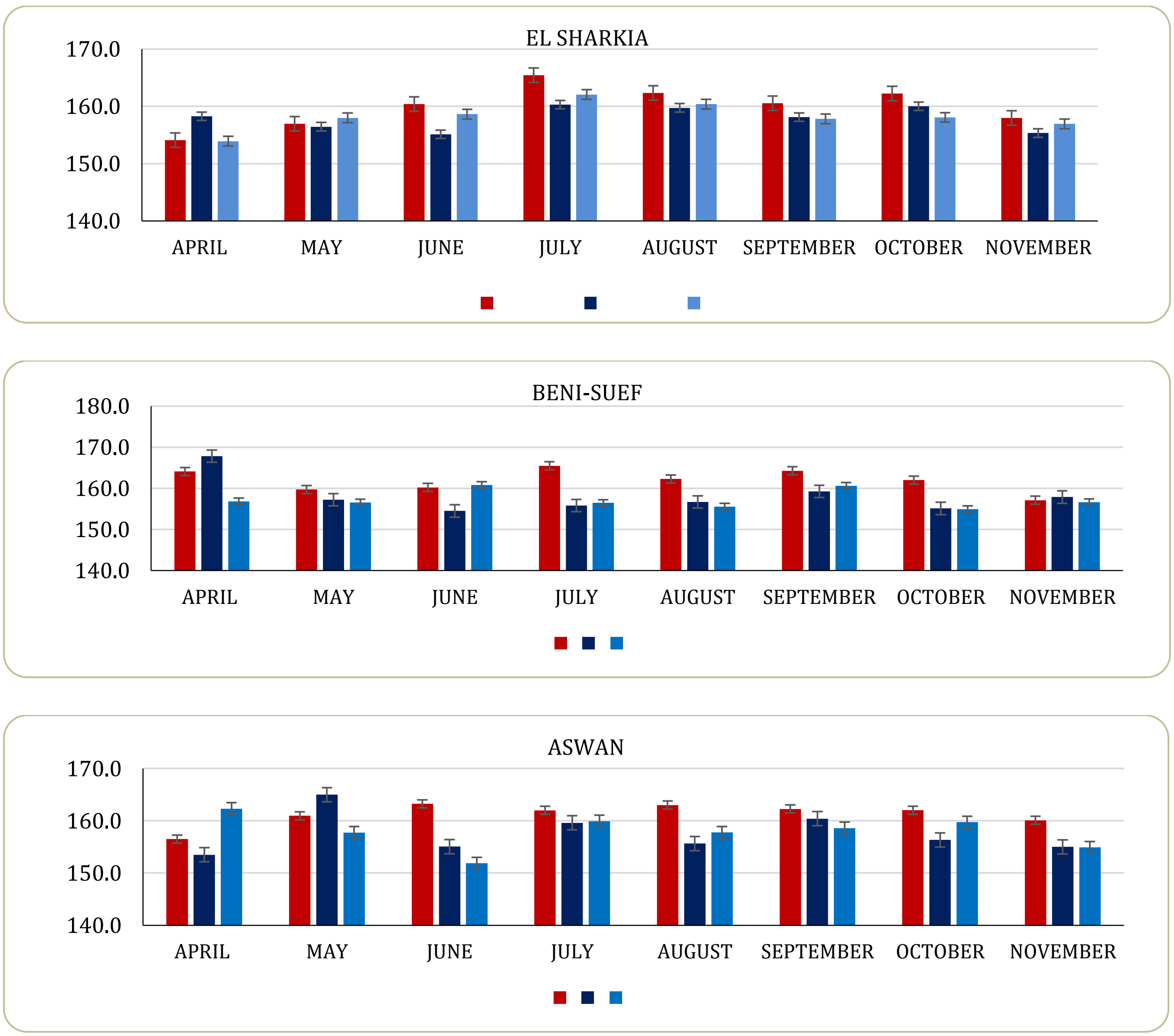

Figure 3. Comparison between Monthly degree days of *T. remus* under 2021 and expected future climate conditions (2040 and 2060) at El-Sharkia, Beni Suef, and Aswan Governorates.

As per Table 2, *T. remus* is anticipated to undergo 24 generations in 2040 and 28 generations in 2060, representing an increase of two and six generations, respectively, compared to the 22 generations in the 2021 climate. The initial generation's longest duration was 26, 19, and 12 days in 2021, the future climates of 2040, and 2060, respectively, all occurring in April. In 2040 and 2060, the durations were 7 and 19 days earlier than in 2021, respectively.

Number of generations and DDUs under Aswan climate conditions

In comparison to the anticipated future climate conditions in 2040 (6.84 ± 1.12 days) and 2060 (7.45 ± 1.96 days), where there were no significant differences observed between 2040 - 2021 (T = -2.34, P = 0.071), 2060 - 2021 (T = -2.16, P = 0.102), and 2060 - 2040 (T = 0.19, P = 0.981), the average generation period in 2021 endured longer, totaling 7.47 ± 1.49 days. According to Table 2, *T. remus* is projected to have 32 generations in 2040 and 35 generations in 2060, marking an increase from 29 generations in the 2021 climate by 3 and 5 generations, respectively. The longest duration of the first generation was 13, 11, and 12 days in 2021 and the anticipated future climates of 2040 and 2060, all occurring in April. In 2040 and 2060, the durations were 2 days earlier and one day longer than in 2021, respectively.

The results revealed a significant, strong, positive correlation (Figure 4) between the degree days of *T. remus* in 2021 and the expected future climate conditions (2040 and 2060) in El-Sharkia, Beni-Suef, and Aswan governorates, with correlation coefficients of r = 0.840, p < 0.00, r = 0.840, p < 0.00, r = 0.724, p < 0.00, r = 0.769, p < 0.00, r = 0.888, p < 0.00, r = 0.879, p < 0.00, respectively.

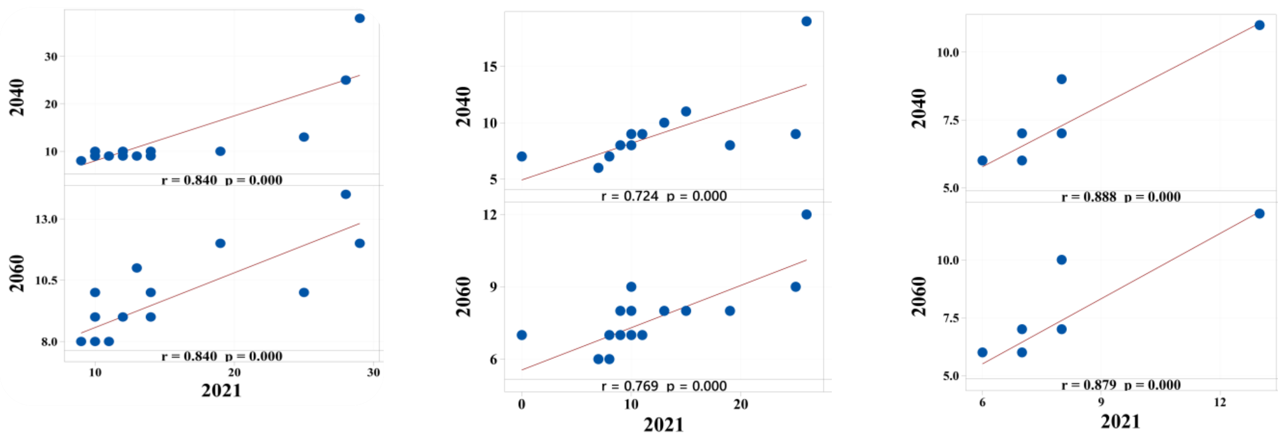

Figure 4. Correlation matrixes between degree days of *T. remus* under 2021 and expected future climate conditions (2040 and 2060) at El-Sharkia, Beni Suef, and Aswan Governorates.

DISCUSSION

There are significant findings in terms of understanding the expected future climate impact using the relationship between degree-day units and *T. remus* population fluctuations. The current study corroborated the findings of Bueno et al. (2008), who found that a temperature difference of 8.3 ± 0.01 to 47.2 ± 0.01 days for *T. remus* females and 8.1 ± 0.01 to 46.8 ± 0.01 days for males at 31 and 15°C, respectively, influenced the life cycle (egg to adult). The females of *T. remus* had a higher 196 thermal constant (K) and a lower thermal threshold (Tb) than the males (154.12 degree-days and 12.6°C), respectively. *T. remus* generations were expected, under 2021 climate conditions, to be 21, 22, and 28. In comparison, El Sharkia, Beni-Suef, and Aswan governorates will have 23, 24, and 32 in 2040 and 23, 28, and 35 in 2060. To ascertain the number of generations considering field circumstances, it is necessary to utilize the monthly 2021 average temperature for each area. The development rates of *T. remus* were influenced by the amplitude of the average variation in temperature. These rates are faster or slower than those reported in the laboratories (Torres et al., 1997). According to Pomari et al. (2012), the estimated thermal requirements of *T. remus* for the thermal constant (K) and the base 206 temperature (*Tbase*) were: 125.39 DD and 15.139°C; 125.56 DD and 14.912°C; 142.98 DD and 207 14.197°C; and 149.16 DD.

Concerning the limitations of *T. remus* thermal requirements research, according to Bueno et al. (2008), a similar pattern of results was obtained in various egg parasitoids when the parasitoid was reared on *Photedes* including eggs, the lower temperature threshold (Tb) and thermal constant (K)were 10.65 °C and 151.25 degree-days, respectively, and 11.64 °C and 127.60 degree-days in the event of rearing on *Anticarsia gemmatalis* eggs.

When the parasitoid was grown on *Photedes,* including *A. gemmates* eggs, the number of monthly generations rose with temperature, from 1.45 to 4.23 and from 1.49 to 4.79, respectively. Several studies discovered a link between the thermal constant (K) according to the period of parasitoid development at various temperatures, starting with a lower temperature threshold (Tb), and the insect's thermal requirements (Pratissoli et al., 2005). *Trichogramma pretiosum* RV grown on *A. gemmates* eggs had a lower thermal constant (127.6 degree-days) than *T. pretiosum* reared on *Heliothis virescens, Sitotroga cerealella, Anagasta kuehniella,* and *Galleria mellonella* eggs, according to the results of Goodenough et al. (1983). These findings are like those of Bleicher and Parra (1989). The adaptability of the parasitoid to each unique host egg, as well as the quantity and quality of nutrients present in the host egg, all play a role in these variations. According to the literature, the insect diet influences K and Tb values (Haddad et al., 1999). *Nasonia vitripennis* (Walker) (Hymenoptera: Pteromalidae) has an overall thermal constant (K) of 224.3 ± 1.7degree days, according to Grassberger and Frank (2003). According to the findings of the development of 226 requirements from oviposition to adult eclosion were 273.1 ± 5.9 degree days above a threshold of 4.5 ± 0.4°C. These findings agree with previous studies on the development of *Aphidius matricide* depending on temperature (Hymenoptera: Aphidiidae) and the host *Diuraphis noxia*.

The findings are consistent with those of Jacas et al. (2007). For development from egg to adult, *Fidiobia dominica* had an upper development threshold (UDT) of 30.0°C, a maximum development rate (MDR) of 27.6°C, a lower development threshold (LDT) of 9.6°C, and a thermal constant (K) of 293.1 DD. The UDT for *Haeckeliania* separately recorded 35.0°C, the MDR was 31.0°C, the LDT recorded 15°C, and the K recorded 188.1 DD.

CONCLUSIONS

The study found that the number of generations of *T. remus* increased with rising temperatures, with the highest number observed in Aswan. The duration to complete generations in El-Sharkia, Beni-Suef, and Aswan was 13.42, 12.6, and 10.08 days, respectively. The mean generation period was longest in 2021, lasting 13.42 ± 6.17 days. El-Sharkia and *T. remus* are projected to have 23 generations between 2040 and 2060, an increase of two generations annually compared to the 21 generations in 2021. This finding is essential for developing field biological control programs for this parasitoid strain, although variations in study scenarios should be considered beyond constant laboratory temperatures.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

Ahmed Hahmed El Kenawy, Hassan Ahmed Hassan, Wael El-zaher Abd El-hafeez El-Sheikh conceived the idea; curated the data, prepared the original draft, reviewed and edited the manuscript. All researchers read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

The data reported in this study are contained within the article.

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