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Using Accumulated Heat Units to analyze Climate Impacts on Fall Armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Larval Development in Response to Climate Change Scenarios

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ABSTRACT

The study evaluates the impact of climate change on the larval development duration of *Spodoptera frugiperda* (fall armyworm) across three Egyptian governorates; Ismailia (Lower- Egypt), El Fayoum (Middle Egypt), and New Valley (Upper Egypt) Governorates, between 2022 and projected scenarios for 2030 and 2050. Climate change data from the HadCM3 model was utilized, focusing on A1 scenarios recommended by the Intergovernmental Panel on Climate Change (IPCC). In 2022, larval development durations ranged from 26.75 ± 8.53 days in Ismailia (365.23 ± 3.16 Degree Days Units [DDUs]) to 22.8 ± 4.12 days in El Fayoum (369.55 ± 4.57 DDUs), and 17.12 ± 2.03 days in New Valley (371.06 ± 3.52 DDUs). With rising temperatures, by 2030, development times are projected to decrease to 23.36 ± 8.02 days, 20.45 ± 4.25 days, and 16.86 ± 3.36 days in these regions, respectively, while DDUs slightly increase. By 2050, larval development will further accelerate, with durations of 21.33 ± 5.63 days in Ismailia, 19.36 ± 3.44 days in El Fayoum, and 17.06 ± 3.94 days in New Valley. Seasonal data highlight the shortest development times during peak summer months (e.g., 14 days in July in New Valley, 15–18 days in other regions) and longer durations during cooler periods. Degree-day analyses reveal higher thermal unit accumulation in New Valley, reflecting its hotter climate. Projected climate scenarios show faster development times, particularly in hotter regions, with implications for increased pest generations and heightened crop damage risk. The study underscores regional differences in pest behavior, highlighting the need for localized pest management strategies under changing climatic conditions.

INTRODUCTION

Spodoptera frugiperda, commonly known as the fall armyworm (FAW), is a significant agricultural pest that has rapidly spread globally, particularly affecting maize

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crops. Its adaptability to various climates and extensive host range has facilitated its invasion into regions such as Africa and Asia since 2016 (Tahir *et al.*, 2020). The pest is known for its polyphagous feeding habits, primarily targeting graminaceous crops like maize, leading to substantial reductions in crop yields and recorded as eating 186 plant species from 42 families (Chen *et al.*, 2023 and FAO, 2019). *S. frugiperda*, or the fall armyworm, has significantly impacted maize yields in Egypt since its introduction in 2019. Research indicates that this pest can cause yield losses ranging from 20% to 100%, with specific studies reporting damage levels of approximately 78.89% in untreated maize crops. (Kandil and Abd Kader, 2023) The infestation typically intensifies as maize plants mature, leading to a direct correlation between plant age and the severity of damage inflicted by the larvae. According to Day *et al*. (2018), FAW significantly impacts maize yield on the continent, causing losses of $2,481 million to $6,187 million annually. Its economic significance is influenced by its high reproduction rate, migratory behavior, rapid dispersal, and flight speed. (Prasanna *et al*., 2018) After making its debut in Nigeria in 2016, it quickly spread to over 28 nations in southern and eastern Africa, causing serious harm (Goergen *et al*., 2016; Day *et al*., 2017; Cock *et al*., 2017 and FAO, 2018). It rapidly spread to more than 28 countries in southern and eastern Africa after making its debut in Nigeria in 2016, severely impairing more than 70% of maize production (Goergen *et al*., 2016; Day *et al*., 2017; Cock *et al*., 2017 and FAO, 2018). According to NPPO (EPPO A1 List), FAW was initially found on maize fields at a village in Kom-Ombo city, Aswan Governorate, Upper Egypt, in May 2019 (Dahi *et al*., 2020). It then expanded to the governorates of Sohag, Qena, and Luxor, according to the Ministry of Agriculture's Agricultural Pesticide Committee (APC). Later, in 2021, it spread into the Assiut Governorate, causing damage to corn plantations (IPPC 2019, Mohamed *et al*., 2022). Khalil *et al*. (2010) emphasize the importance of understanding temperature's impact on insect species development to aid in risk analyses, forecasting, and pest management strategies, as temperature fluctuations differ from constant conditions, affecting insect population dynamics differently (Hagstrum and Hagstrum, 1970). Research indicates that the optimal temperature range for the growth and survival of *S. frugiperda* is between 28°C and 30°C. At these temperatures, the insect exhibits the best fitness, with a notable increase in both developmental rates and survival across its life stages (Malekera *et al*., 2022). However, environmental and climatic variables, as well as landscape management features such as the suitability and prevalence of the host insect and its host plants, are important determinants for a candidate parasitoid's success in a given ecology (Escobar-Ramrez *et al*., 2019; Harrison *et al*., 2019).

According to Montezano *et al*. (2018), Chormule *et al*. (2019), Liao *et al*. (2019), and Huesing (2018), the mean incubation period was 6.9, 3.4, and 2.1 days at 20°C, 25°C, and 30°C, respectively, while the larval duration was 38.5, 23.7, and 18.6 days at the same temperatures. The average pupa durations were 22.5 days at 20°C, 9.4 days at 25°C, and 7.7 days at 30°C. For the adult stage, the mean time required for ovulation maturation and egg-laying decreased as temperature increased, from 4.8 days at 20°C to 2.1 days at 30°C. At 20°C, 25°C, and 30°C, the mean generation durations for *S. frugiperda* were 72.7, 40.1, and 30.5 days, respectively, (Du Plessis *et al*., 2020). The lower developmental threshold (t_0) and average thermal units in degree-days (DDs) were 15.79°C and 30.0 DDs for the egg stage, 10.39°C and 360.2 DDs for the larval stage, 14.05°C and 129.8 DDs for the pupal stage, 12.95°C and 37.73 DDs for the pre-oviposition period, and 12.49°C and 527.3 DDs for a complete generation, (Dahi *et al*., 2020). The lower thermal threshold for development is approximately 13.51°C, while the upper threshold is around 34.13°C. Below 15°C, *S. frugiperda* fails to develop, indicating that this temperature is unsuitable for its lifecycle. Conversely, temperatures exceeding 30°C can negatively impact larval development duration, leading to longer times to reach maturity, although some development still occurs at higher temperatures. Additionally, studies show that larval survival peaks between 26°C and 30°C, with significant mortality observed at lower temperatures like 18°C. The duration of various life stages—eggs, larvae, and pupae—varies significantly with temperature changes; for instance, the egg-to-adult cycle can last from 23.43 days at 32°C to 50.46 days at 20°C. Overall, understanding these temperature-dependent dynamics is crucial for effectively managing this pest in agricultural settings, (Tanaka and Matsukura, 2023). This study aims to predict the larval development duration of the Fall Armyworm, *S. frugiperda* (Lepidoptera: Noctuidae), in Egypt under varying climate change conditions. This prediction will be achieved by utilizing thermal heat units, enabling a comprehensive understanding of how future climatic variations may impact the growth and proliferation of this agricultural pest.

MATERIALS AND METHODS

1- Estimate degree-days units:

1-1- Under current climate:

These experiments were performed on *S. frugiperda* at Ismailia (Lower- Egypt), El Fayoum (Middle Egypt), and New Valley (Upper Egypt) Governorates – Egypt as shown in Figure 1, these represent three different agroecological zones in Egypt, from January- December for successive seasons in 2021-2022. Average temperatures (daily maximum and minimum) were calculated according to the data recorded and obtained from CLAC, Egypt.

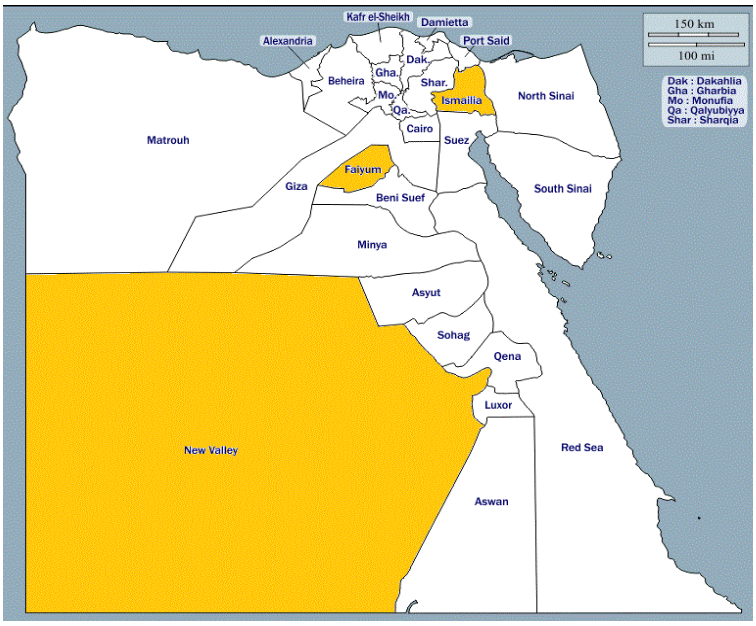

Fig. 1: Geographic Locations of the Study Sites Analyzed for Climate-Induced Changes in Fall Armyworm (*S. frugiperda*) Larval Development.

1-2- Under future climate:

This study was performed to predicate the numbers and durations of Larval Stages of *S. frugiperda* (Fall Armyworm) and ADDU (accumulated Degree Day units) in expected future climatic changes in the 2030-2040s and 2050-2060s. Future climatic data have been obtained based on the GHG emissions scenarios (SSP-4.5), increase the temperature (1.5 °C) near term 2030-2040 (2.0°C) med term 2050 -2060 (IPCC 2021) as shown in Figure 2.

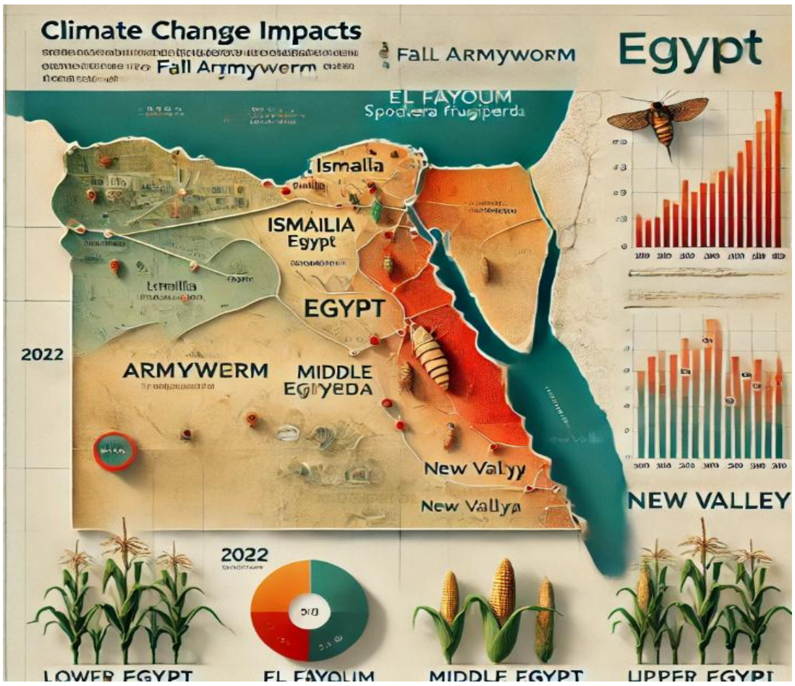

Fig. 2: Predicting Climate-Induced Changes in Fall Armyworm (*S. frugiperda*, Lepidoptera: Noctuidae) Larval Development Using Thermal Heat Units.

2- Determination of the Thermal Units Required for FAW Development as Degree-Days Units (DDU):

Daily maximum and minimum temperatures recorded and obtained from climate change information center data station were transformed to heat units using the lower threshold temperature of *S. frugiperda* (where, t_0 was 10.3° C with 360.2 DD's for generation according to Dahi *et al*., (2020) and the lower Degree-days units (DDU) were calculated by applying the Richmond *et al*., (1983) formula as follows (El Kenawy *et al*., 2024).

$$H = \sum H J$$

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

- H J = {(max + min)/2 – °C} (If max. > °C and min. > °C).
- H J = {(max. – °C)^{2} / (max.-min.)} (If max. > °C and min. < °C).
- H J = 0 (If max. < °C and min. < °C).
- C = threshold temperature (t_0).

3- Data Analysis:

Assumptions for parametric tests were assessed, with continuous variables tested for normality using the Shapiro-Wilk and Kolmogorov-Smirnov tests. The statistical software package SPSS version 22 was used. Descriptive statistics were reported as means and standard deviations. Analysis of variance (ANOVA) was conducted to examine differences in the calculated generation durations and the required days and degree-days (DDUs). These analyses were performed with multiple replicates for each group. Post-hoc comparisons were conducted using Tukey's pairwise comparison test, with statistical significance set at $p < 0.05$. The Pearson correlation coefficient was calculated to examine the relationship between the days and DDUs required for each generation or developmental stage across seasons. This analysis aimed to predict the days required for generations in 2030-2040 and 2040-2060 based on DDUs, compared to the baseline of the 2021 season. These calculations were performed using MiniTab version 14. Data visualization, where applicable, was conducted using RStudio version 2022.02.4.

RESULTS

The presented data indicated that climate change will significantly impact the developmental biology of *S. frugiperda*, referring to the presented data, the larval development times decreased and thermal heat unit requirements slightly increased. These changes may affect the pest's population dynamics, potential for outbreaks, and the effectiveness of pest management strategies. The regional variations in development times and DDUs also underscore the need for localized pest management approaches as climate impacts will differ depending on the geographic location.

Referring to the results recorded in Table 1, 2021-2022 seasons recorded the highest development period and the lowest thermal requirements, followed by the 2030 -2040 season and the 2050-2060 seasons. In the 2021-2022 season, it was found that the Ismailia Governorate recorded the highest larval development times (26.75 ± 8.53 days) and the lowest thermal heat unit requirements (365.23 ± 3.16 DDUs), followed by El Fayoum Governorate (22.8 ± 4.12 Days & 369.55 ± 4.57 DDUs) and New Valley Governorate (17.12 ± 2.03 Days & 371.06 ± 3.52 DDUs). The same trend was recorded for 2030-2040 season and 2050-2060 season following the same sequence of governorates, for 2030-2040 season, Ismailia Governorate recorded (23.36 ± 8.02 Days & 369.55 ± 4.99 DDUs) larval development, El Fayoum Governorate recorded (20.45 ± 4.25 Days & 370.24 ± 6.59 DDUs)larval development and New Valley Governorate recorded (16.86 ± 3.36 Days & 371.84 ± 6.18 DDUs) larval development. Finally, for 2050-2060 seasons recorded larval developments follow Ismailia Governorate (21.33 ± 5.63 Days & 370.35 ± 4.61DDUs), El Fayoum Governorate (19.36 ± 3.44 Days & 371.04 ± 5.98 DDUs) and New Valley Governorate (17.06 ± 3.94 Days & 372.33 ± 6.31 DDUs).

A notable distinction was observed in Table 1 that the time needed to complete larval duration across various governorates (reflecting different weather conditions) and seasons (f = 1.31, p = 0.270), as well as in the Degree-Day Units (f = 1.88, p = 0.120), was not statistically significant. This indicates that while there are observable variations in larval development time and DDUs between regions and across years, these differences are not substantial enough to suggest a strong effect of weather variations on the development period, as indicated by the non-significant P-values (P > 0.05). Thus, the trends highlighted may reflect general climate-related changes but lack the statistical backing to confirm significant distinctions in these metrics across the studied periods.

Table 1. Current and Projected Changes in Fall Armyworm Larval Development (Days and DDUs) Across Different Climate Scenarios for 2021-2060 in Selected Egyptian Governorates.

Season		**2021- 2022**	**2030-2040** (1.5 °C)	**2050-2060** (2 °C)
Ismailia Governorate	**Days**	26.75 ± 8.53[a]	23.36 ± 8.02[a]	21.33 ± 5.63[a]
	DDUs	365.23 ± 3.16[a]	369.55 ± 4.99[ab]	370.35 ± 4.61[a]
El Fayoum Governorate	**Days**	22.8 ± 4.12[b]	20.45 ± 4.25[a]	19.36 ± 3.44[a]
	DDUs	369.55 ± 4.57[b]	370.24 ± 6.59[a]	371.04 ± 5.98[a]
New Valley Governorate	**Days**	17.12 ± 2.03[c]	16.86 ± 3.36[a]	17.06 ± 3.94[a]
	DDUs	371.06 ± 3.52[c]	371.84 ± 6.18[a]	372.33 ± 6.31[a]

Current Climatic Conditions (Season 2022):

The data presented in Table 2, depicts the initial analysis of current climate conditions across three governorates in Egypt: Ismailia, El Fayoum, and New Valley. Indicate significant average values of observed days and Degree Day Units (DDUs) (*f*=12.2) (*P*=.0000) calculated for the larval duration of *S. frugiperda* across three governorates in Egypt: Ismailia, El Fayoum, and New Valley (*f*=64.1) (*P*=.0000). The data reflects the seasonal variations in larval development of the pest species in these regions during the specified study period spanning from April to November.

Table 2: Monthly (Mean ± SE) Accumulated Heat Units (DDUs) and Larval Development Days for Fall Armyworm (*S. frugiperda*) Across Governorates in Egypt under 2021-2022 Season climate conditions.

Season 2021-2022									
Governorates		**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**
Ismailia	**Days**	31±3.1	28±2.9	26±2.4	23±1.8	22±1.7	21±1.6	25±2.1	30±4.2
	DDUs	359.1 ±4.1	364.7 ±4.5	365.5 ±5.1	368.2 ±4.2	369.6 ±3.1	367.3 ±3.8	367.4 ±4.2	361.4 ±3.1
El Fayoum	**Days**	26±2.7	24±1.9	20±1.7	20±1.5	20±1.6	21±1.8	25±1.9	28±1.7
	DDUs	364.1 ±3.1	366.4 ±2.9	373.6 ±2.7	371.5 ±3.2	367.8 ±3.1	375.6 ±2.7	367.6 ±2.8	364.4 ±2.7
New Valley	**Days**	18±1.1	17±1.7	15±1.4	15±1.5	16±1.4	16±1.4	19±1.5	22±1.9
	DDUs	367.6 ±2.6	370.1 ±2.7	372.4 ±2.9	377.5 ±2.8	376.6 ±2.8	371.7 ±3.2	368.9 ±3.1	367.9 ±3.5

From the data in Figure 3, it is apparent that there is a significant difference between data recorded in November while there is no significant difference between data recorded in July, August, and September respectively. Across the months, the DDUs remain relatively consistent, ranging from approximately 366 to 374 DDUs, indicating that the thermal energy required for larval development does not vary significantly throughout the year. The lowest DDU values are observed in April and November (approximately 366 DDUs), while the highest values occur in July (approximately 374 DDUs).

In contrast, the development duration in days shows notable variation across the months, reflecting the influence of fluctuating environmental temperatures on the rate of larval development. The development duration is longest in April and November, exceeding 25 days and shortest during July and August, with durations close to 20 days. This inverse relationship suggests that warmer months, such as July and August, accelerate larval development, while cooler months, such as April and November, prolong it.

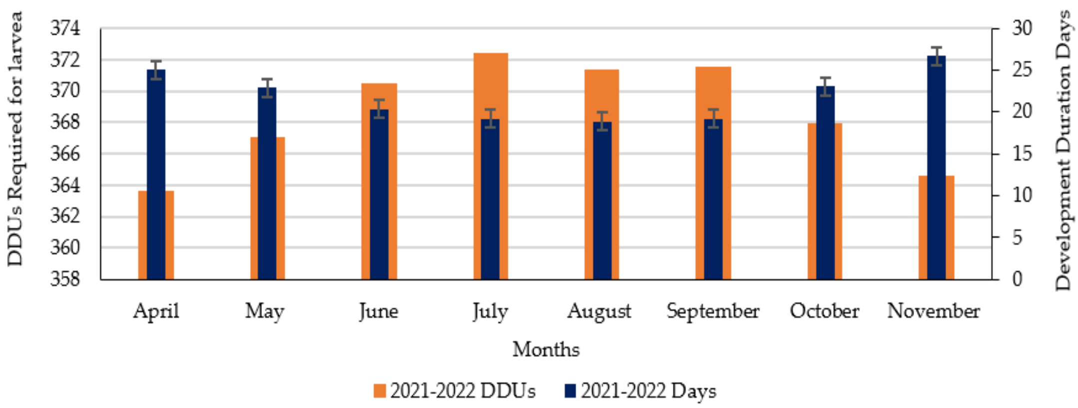

Fig. 3: Depicts the average DDUs and duration Days required for *S. frugiperda* larvae to complete their development throughout the observed months in the 2021-2022 seasons under current climatic conditions.

Expected Future Climate Change (2030-2040) and (2050-2060):

In an analysis of future climate scenarios for the Ismailia, El Fayoum, and New Valley Governorates, projected for the (2030-2040) and (2050-2060) seasons and compared with the 2022 season, the data from Tables 3-4 and Figures 4-5 show a decrease in the duration of *S. frugiperda* larvae.

The provided Table 3 and Figure 4 shows the predicted effects of climate change on the development of the fall armyworm (*S. frugiperda*), specifically focusing on larval development using degree-days (DDUs) for different regions of Egypt (Ismailia, El Fayoum, and New Valley Governorates) across the months of April to November in the 2022-2030 period. Degree-days (DDUs) represent the accumulation of heat required for the insect's developmental stages, calculated based on daily temperatures exceeding a certain threshold, essential for predicting climate impacts on pest lifecycles.

In Ismailia (Lower Egypt), the data indicates that in April, larvae take approximately 29 days to complete their development, accumulating 364.5 DDUs. As the temperature increases during May and June, the development time shortens to 25 and 21 days, respectively, with a corresponding rise in DDUs to 371.8 and 367.5. During the hottest months (July and August), development further accelerates, with the larvae taking just 18 and 17 days, and DDUs increase to 376.3 and 372.1.

However, as temperatures decrease in September through November, the development period begins to lengthen again, requiring 16 to 36 days for full development, while DDUs fluctuate between 363.8 and 366.2. These trends suggest that temperature significantly influences larval growth, with faster development in warmer months and slower progress as temperatures cool.

In El Fayoum (Middle Egypt), a similar trend is observed. The development time in April is 25 days with 375.9 DDUs. As the temperature increases, the development time decreases to 22 days in May and 19 days in June, with DDUs being 365.0 and 368.8, respectively. The fastest development period occurs in July and August, with the larvae taking 18 days each month and DDUs reaching a high of 377.1 in July and 366.6 in August.

September through November sees a reversal of this pattern, with development times lengthening to 32 days in November as the temperature decreases, and DDUs drop to 361.5 by the end of the season. These data imply that while Middle Egypt follows a similar pattern to Lower Egypt, the overall heat accumulation (DDUs) and development durations are slightly different due to regional climatic variations.

In New Valley (Upper Egypt), the warmer climate results in even shorter larval development times across all months. In April, larvae require only 22 days with a heat accumulation of 360.2 DDUs. The development time drops to 16 days in May and 15 days in June, with DDUs rising to 370.2 and 373.3, respectively. The shortest development time is observed in July, where larvae complete their development in 14 days with 365.2 DDUs.

August through November sees a gradual lengthening of the development period, from 15 days in August to 22 days in November, while DDUs fluctuate between 366.6 and 372.2. This pattern highlights the intense heat in Upper Egypt, leading to accelerated pest development, potentially increasing the number of generations per year, which could result in greater pest pressure on crops.

Table 3: Means ± SE for observed Days and DDUs for *S. frugiperda* larval duration through studied season 2030-2040 and governorates under future conditions.

Season 2030-2040									
Governorates		**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**
Ismailia	**Days**	29±2.1	25±2.1	21±1.9	18±1.7	17±1.5	16±1.5	22±1.7	36±2.4
	DDUs	364.5	371.8	367.5	376.3	372.1	374.6	363.8	366.2
El Fayoum	**Days**	25±1.3	22±1.4	19±1.3	18±1.5	18±1.4	18±1.4	19±1.3	32±1.4
	DDUs	375.9	365.0	368.8	377.1	366.6	371.3	368.6	361.5
New Valley	**Days**	22±1.4	16±1.5	15±1.4	14±1.4	15±1.3	12±1.6	18±1.3	22±1.8
	DDUs	360.2	370.2	373.3	365.2	373.5	366.6	369.4	372.2

The updated Table 4, projects the effect of climate change on the development of fall armyworm (*S. frugiperda*) larvae in Egypt for the period 2040-2060. The table focuses on three key regions: Ismailia (Lower Egypt), El Fayoum (Middle Egypt), and New Valley (Upper Egypt), detailing both the days required for larval development and the corresponding Degree Day Units (DDUs) across months from April to November. The data shows that in hotter regions like New Valley, the development time for larvae is consistently shorter compared to the cooler Lower Egypt, represented by Ismailia. This faster development means that more generations of fall armyworm will emerge within the growing season, particularly in Upper Egypt, intensifying pest pressure. The projected shortening of development time is particularly concerning for pest management, as it suggests a potential for increased pest activity during the hottest months, making July and August critical periods for control measures.

In Ismailia (Lower Egypt), the larvae are projected to take 30 days to develop in April, accumulating 371.4 DDUs. As the months progress and temperatures increase, development speeds up, with larvae taking only 26 days in May and 18 days in June, while DDUs remain stable at around 370-371. The warmest months, July and August, show the most rapid development, with larvae needing just 17 and 16 days, respectively, as DDUs increase slightly, particularly in August when they rise to 377.1. Moving into autumn, larvae take longer to develop, with 18 days in September, 21 days in October, and 23 days in November, as temperatures cool, and DDUs drop to around 367.7 by November.

In El Fayoum (Middle Egypt), larval development is faster from the outset, with larvae taking 23 days in April, accumulating 364.4 DDUs. Development accelerates in May and June, reducing to 22 and 18 days, respectively, with DDUs increasing to around 372- 376 during this period. Similar to Ismailia, July and August see the shortest development times of 17 days each, with DDUs varying between 361.0 and 374.5. As the months get cooler, larval development stabilizes at 18 days in September and October, before dropping to 18 days in November. DDUs also follow this cooling trend, decreasing to 364.7 by the end of the season.

New Valley (Upper Egypt), being the hottest region, experiences the fastest larval development. In April, larvae take only 22 days to develop, with 368.3 DDUs. Development times drop even further in May, June, and July, with larvae needing just 16, 15, and 14 days, respectively, as temperatures rise and DDUs peak at 374.0 in July. From August onward, development slows slightly, with larvae taking 15 days in August, 18 days in October, and 20 days in November, while DDUs remain high, ranging from 367.9 to 371.1.

Table 4: Means ± SE for observed days and DDUs for *S. frugiperda* larval duration through studied season 2040-2060 and governorates under future conditions.

Season 2040-2050									
Governorates		**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**
Ismailia	**Days**	30±2.1	26±2.2	18±1.9	17±1.7	16±2.5	18±1.7	21±1.6	23±2.6
	DDUs	371.4	370.1	371.5	371.5	377.1	371.2	364.4	367.7
El Fayoum	**Days**	23±2.3	22±2.3	18±2.1	17±1.8	17±1.5	18±1.4	18±1.9	18±2
	DDUs	364.4	376.0	372.1	361.0	374.5	369.6	362.8	364.7
New Valley	**Days**	22±2.4	16±1.9	15±1.6	14±1.8	14±2.4	15±1.6	18±1.8	20±1.8
	DDUs	368.3	363.3	366.7	374.0	367.9	378.8	376.3	371.1

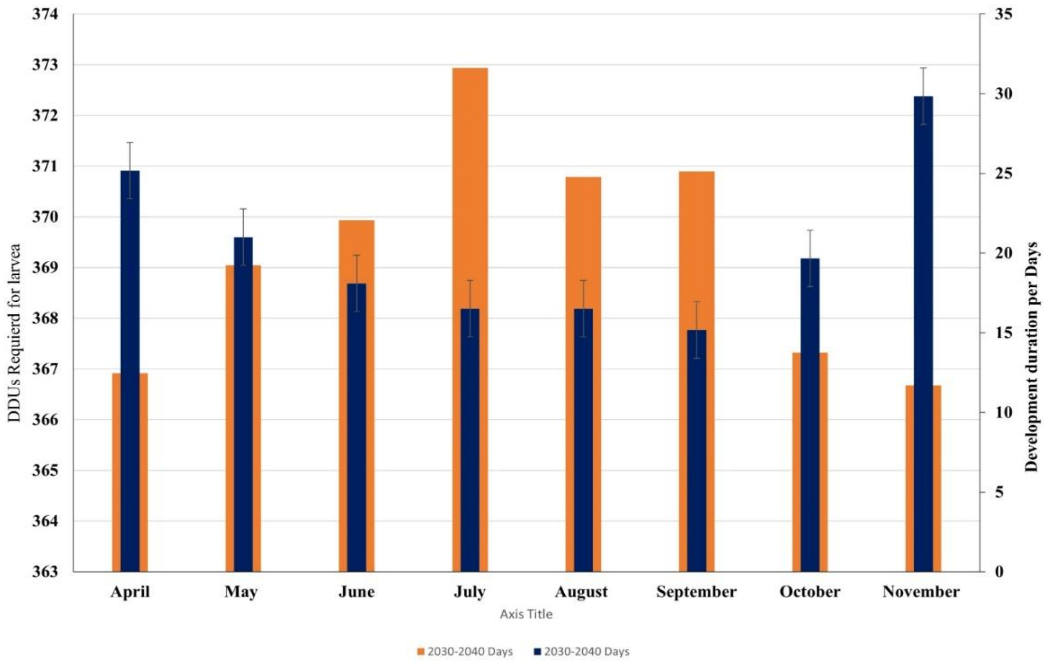

Fig. 4: Depicts the average DDUs and duration Days required for *S. frugiperda* larvae to complete their development throughout the observed months in the 2030-2040 seasons under future climatic conditions.

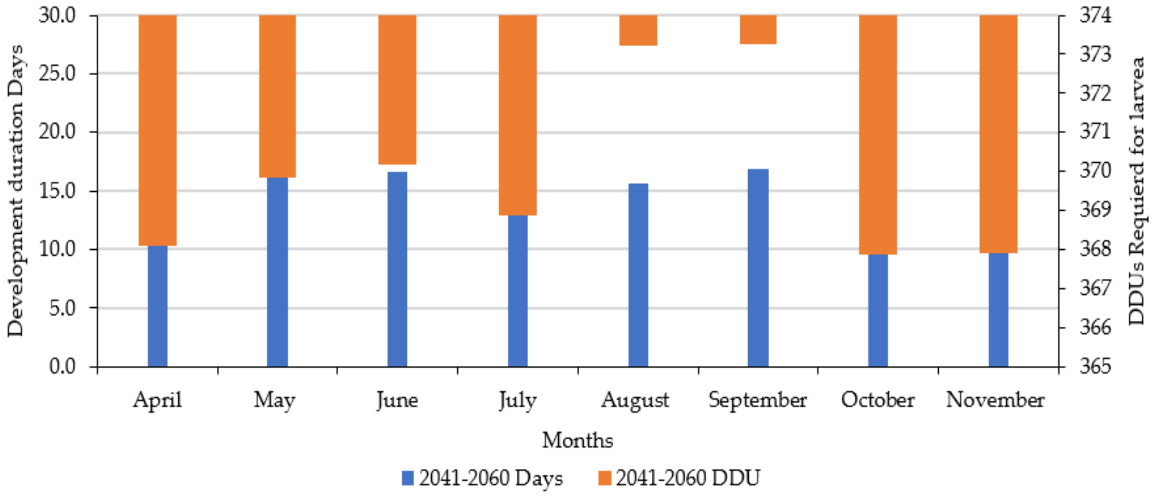

Fig. 5: Depicts the average DDUs and duration Days required for *S. frugiperda* larvae to complete their development throughout the observed months in the 2050-2060 seasons under future climatic conditions.

DISCUSSION

The results of this study on *S. frugiperda* larval development revealed significant variations in larval duration across different months and governorates during the 2021 season. These findings are consistent with previous studies that have highlighted the role of temperature in influencing the development of insect pests. The longer larval durations observed in April, May, June, October, and November, and shorter durations in the summer months of July, August, and September, reflect the complex interaction between environmental temperature and insect physiology. Specifically, Ismailia Governorate exhibited the longest larval duration, followed by El Fayoum, with the shortest duration recorded in New Valley. These regional differences can be attributed to varying climatic conditions across the governorates.

The accumulated thermal heat units, a critical metric for predicting insect development rates, peaked at different times depending on the governorate, with Ismailia Governorate recording the highest on July 19, El Fayoum on July 7, and New Valley on August 27. This temporal and geographic variation in thermal heat accumulation underscores the importance of local climate conditions on the developmental rates of *S. frugiperda*. These findings align with the observations of Dahi *et al.* (2020), who emphasized the role of temperature extremes and degree days in shaping insect population dynamics. High temperatures, as noted by Fye and Poole (1971), can limit pest development, indicating that temperature is a key determinant in regulating insect life cycles (Gilioli *et al.*, 2022). Temperature plays a pivotal role in insect development, with deviations from optimal temperature ranges significantly affecting developmental rates (Bakry & Abdel-Baky, 2023). Insects like *S. frugiperda* are poikilothermic, meaning their physiological processes are highly dependent on external temperatures. Research by Joworsk *et al.* (2013) has shown that near-optimal temperatures lead to increased metabolic activity, which accelerates insect development. Conversely, Aguilon and Velasco (2015) highlighted that deviations from these temperatures impede developmental rates, either slowing down metabolism at lower temperatures or disrupting physiological functions at excessively high temperatures.

The quantitative analysis conducted in this study, using velocity constants and thermal summation, provides a framework for understanding the relationship between temperature and developmental speed (Gilioli *et al*., 2022). This approach not only aids in forecasting pest behavior but also offers a basis for developing effective pest management strategies. Studies by Calvo and Molina (2005) suggest that this method can be integrated into risk analysis models to predict pest outbreaks and inform management decisions. Future climate projections suggest significant shifts in *S. frugiperda* larval duration and thermal heat units, with the potential for shorter developmental periods and an increase in the number of generations per year as global temperatures rise. This is supported by the physiological findings of Chiang (1985), who emphasized the importance of temperature on insect development. Woiwod (1997) further argued that climatic changes could directly alter insect physiology and indirectly influence interactions with host plants and natural enemies. These projected changes raise concerns about the potential expansion of *S. frugiperda*'s geographic range and the intensification of its impact on agricultural productivity. As temperatures rise, the pest may exploit crops more aggressively during critical growth periods, increasing the risk to food security (Wang *et al.*, 2020). Moreover, altered precipitation patterns could complicate pest management by influencing the availability of host plants. The work of Parmesan (2007) and Merril *et al.* (2008) further highlights the potential for climate change to alter pest interactions with the environment, particularly through changes in crop-pest dynamics and overwintering survival.

In light of these findings, it is crucial to incorporate climate change considerations into pest management strategies for *S. frugiperda*. Integrated Pest Management (IPM) offers a comprehensive approach that can be tailored to account for shifting climate conditions. Effective IPM strategies include monitoring pest populations, applying biological controls such as natural predators, and utilizing cultural practices like crop rotation and intercropping to disrupt pest life cycles (Montezano *et al.*, 2018). Mechanical controls, such as the use of physical barriers, and biological controls, like parasitoid introduction, can also help reduce pest pressure without increasing reliance on chemical pesticides. Incorporating future projections into management strategies is essential for preparing for potential shifts in *S. frugiperda* behavior and distribution. With anticipated changes in temperature, the time required for larvae to reach maturity could decrease by 10-20%, as suggested by climate models. This would result in greater pest pressure on crops, necessitating the adaptation of management approaches. Understanding these dynamics will be critical for developing adaptive strategies to mitigate risks to agricultural productivity and ecosystem health, as highlighted by Woiwod (1997) and Bale *et al.* (2002).

Conclusion:

The study investigated the impact of varying weather conditions on the larval duration and Degree-Day Units (DDUs) required for insect development across different governorates in Egypt (Ismailia, El Fayoum, and New Valley) for the years 2022, 2030, and 2050. Results show that while there were observable trends in the reduction of larval duration over time, particularly between 2022 and 2050, these changes were not statistically significant. This suggests that despite anticipated climate changes, the developmental period for insects, as reflected in DDUs, will remain relatively stable across these regions over the study period. Moreover, the analysis points to regional variations in weather patterns, with governorates like New Valley showing the shortest larval development time, likely due to its higher temperatures. However, the differences in larval duration and DDUs across governorates and seasons were also not statistically significant, indicating that other factors, such as insect adaptation or other environmental variables, may play a role in modulating insect development under changing climatic conditions.

Declarations

Ethical Approval: Not applicable.

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ARABIC SUMMARY

استخدام الوحدات الحرارية المتجمعة لتحليل التأثيرات المناخية على تطور يرقات دودة الحشد الخريفية *Spodoptera frugiperda* (Lepidoptera: Noctuidae) استجابة لسيناريوهات تغير المناخ

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اعتمدت الدراسة الحالية علي تقيم تأثير تغير المناخ على مدة نمو يرقات *Spodoptera frugiperda* (دودة الحشد الخريفية) في ثلاث محافظات مصرية – الإسماعيلية و الفيوم و الوادي الجديد - بين عامي -2021-2022 والسيناريوهات المتوقعة لاعوام 2030 - 2050. تم استخدام بيانات تغير المناخ من نموذج HadCM3، مع التركيز على سيناريوهات A1 التي أوصت بها الهيئة الحكومية الدولية المعنية بتغير المناخ (IPCC). في عام 2022، تراوحت مدة نمو اليرقات من 75. 26 ±8.53 يومًا في الاسماعيلية (365.23± 3.16 وحدة حرارية [DDUs]) إلى 22.8± 4.12 يومًا في الفيوم (369.55 ± 4.57 وحدة حرارية)، و17.12 ± 2.03 يومًا في الوادي الجديد (371.06 ± 3.52 وحدة حرارية). مع ارتفاع درجات الحرارة، من المتوقع أن تنخفض معدلات النمو بحلول عام 2030 إلى 23.36 ± 8.02 يومًا و20.45 ± 4.25 يومًا و16.86 ± 3.36 يومًا في هذه المناطق على التوالي، بينما تزداد الوحدات الحرارية قليلاً. وبحلول عام 2050، سوف يتسارع نمو اليرقات بشكل أكبر، مع فترات زمنية تبلغ 21.33 ± 5.63 يومًا في الاسماعيلية، و19.36 ± 3.44 يومًا في الفيوم، و17.06 ± 3.94 يومًا في الوادي الجديد، وتسلط البيانات الموسمية الضوء على أقصر أوقات النمو خلال أشهر الذروة في الصيف (على سبيل المثال، 14 يومًا في يوليو في الوادي الجديد، و15-18 يومًا في مناطق أخرى) وفترات زمنية أطول خلال الفترات الأكثر برودة. وتكشف تحليلات درجة اليومية عن تراكم أعلى للوحدات الحرارية في الوادي الجديد ، مما يعكس مناخها الأكثر حرارة. وتُظهر سيناريوهات المناخ المتوقعة أوقات نمو أسرع، وخاصة في المناطق الأكثر حرارة، مع ما يترتب على ذلك من زيادة أجيال الآفات وزيادة خطر تلف المحاصيل. وتؤكد الدراسة على الاختلافات الإقليمية في سلوك الآفات، مما يسلط الضوء على الحاجة إلى استراتيجيات محلية لإدارة الآفات في ظل الظروف المناخية المتغيرة. وتشير هذه النتائج إلى أن التأثيرات المناخية المتصاعدة من شأنها أن تعقد مكافحة الآفات وتؤثر علي النظم الزراعية في مصر.

الكلمات المفتاحية:
ديناميكيات نمو اليرقات، نماذج وحدات الحرارة، تأثيرات تغير المناخ، بيئة الحشرات