

Research on the Flight Dynamics of *Helicoverpa armigera* Hübner in Maize Crops from the Transylvanian Plateau

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ABSTRACT

The cotton bollworm (*Helicoverpa armigera*) is a major pest of maize and other field crops, strongly affected by climatic conditions, particularly temperature, and characterized by a high potential for insecticide resistance. Therefore, reliable monitoring is essential to optimize control interventions. At the Agricultural Research and Development Station (ARDS) Turda, Romania, cotton bollworm adult flight dynamics were monitored over three consecutive years using synthetic sex pheromone-baited funnel traps. The aim was to develop and validate statistical phenological forecasting and pest warning models for cotton bollworm in maize based on climatic variables and pheromone trap catch data. Climatic conditions during 2022-2024 exhibited pronounced inter-annual variability, with 2024 characterized by higher temperature and lower minimum relative humidity, indicating warmer and drier conditions. These climatic variables significantly explained flight dynamics ($R^2 = 0.91-0.95$), with the lowest error in 2023 (MAE = 1) and the highest variability in 2024 (RMSE = 4). Adult flight activity was favored by minimum temperatures of 13-15°C and maximum temperatures of 23-28°C, while temperatures above 30°C reduced adult abundance.

Keywords: cotton bollworm, pheromone traps, climatic variables, standard metrics, phenological forecasting.

INTRODUCTION

The cotton bollworm (CBW) (*Helicoverpa armigera*, Lepidoptera: Noctuidae) is a globally widespread pest that feeds on a very broad range of host plants, such as cotton, maize, soybean, and vegetables (Zalucki et al., 1986). Depending on climate, this pest can complete from one generation per year in cold areas to as many as 11 generations per year in the tropics (Pogue, 2004). For these reasons, it is considered one of the most damaging pests of field crops worldwide (Stark and Banks, 2003; Sharma et al., 2011; Pomari-Fernandes et al., 2015; Saraf et al., 2015).

CBW is regarded as an important pest of maize, causing significant agronomic and economic losses (Riaz et al., 2021; Yadav et al., 2022). The damage caused is both direct, through larval feeding on the reproductive organs of the plant (especially silks and developing kernels), as well as through larval penetration into the ears, which reduces the

efficiency of early detection and hampers the implementation of control measures (Riaz et al., 2021; Yadav et al., 2022). In addition, infestation may lead to indirect damage by creating entry points for phytopathogenic microorganisms, thereby promoting fungal infections, particularly those caused by species belonging to the genera *Fusarium* and *Aspergillus* (Darvas et al., 2011; Negruț et al., 2019; Georgescu et al., 2025).

In order to maintain a stable and sustainable agricultural production and to reduce the losses caused by CBW, effective control strategies have been implemented over time, including chemical control (Reddy and Manjunatha, 2000; David et al., 2005), biological control (Hanafy and El-Sayed, 2013; El Fakhouri et al., 2022), and the use of genetic approaches (Dua et al., 2005; Rios et al., 2022; Kumari et al., 2024).

Beyond causing direct crop damage, CBW is also well known for its capacity to develop insecticide resistance (Ali et al., 2021;

Yogindran and Rajam, 2021; Wang et al., 2021). Therefore, implementing reliable monitoring tools, such as pheromone-baited traps, is essential to support decision-making regarding the timing and type of interventions, thereby preventing yield losses, reducing pest management costs, and minimizing environmental pollution (Reddy and Manjunatha, 2000; Pal et al., 2014; Reddy et al., 2021; Riaz et al., 2021; Costea et al., 2024; Georgescu et al., 2025). In general, pheromone traps tend to be more effective than light traps for monitoring CBW populations (Yadav et al., 2022). Moreover, pheromone trapping provides quantitative information on pest pressure, as male captures are commonly used as a proxy for the overall adult population in the field, allowing infestation levels to be estimated more accurately (Shah et al., 2015).

Knowledge of pest–climate relationships plays a key role in implementing effective pest control measures (Das et al., 2008). Changes in CBW population dynamics have been associated with key climatic variables, including maximum and minimum temperatures, relative air humidity, photoperiod, and wind speed (Yadav et al., 2022; Liu et al., 2024).

This study aimed to develop and validate statistical phenological forecasting and pest warning models for CBW in maize based on climatic variables and pheromone trap catch data collected in the Transylvanian Plateau.

$$Y = \beta_0 + \beta_1 \cdot T_{\min} + \beta_2 \cdot T_{\max} + \beta_3 \cdot RH_{\min} + \beta_4 \cdot RH_{\text{mean}} + \beta_5 \cdot D + \beta_6 \cdot T_{\min}^2 + \beta_7 \cdot T_{\max}^2 + \beta_8 \cdot RH_{\min}^2 + \beta_9 \cdot RH_{\text{mean}}^2 + \beta_{10} \cdot D^2 + \varepsilon$$

where Y represents the number of captured adults, T_{\min} and T_{\max} are the minimum and maximum air temperature, RH_{\min} and RH_{mean} are the minimum and mean relative humidity, D is the monitoring decade (10-day interval), and ε is the error term.

All statistical analyses, including model development and performance evaluation, were conducted using Microsoft Excel.

Establishing evaluation indicators for a predictive model is an important step, as it depends on the type of data and the purpose of the analysis (Hyndman and Koehler, 2006; Dumre et al., 2024). Since each metric

MATERIAL AND METHODS

The experiment was conducted at the Agricultural Research and Development Station (ARDS) Turda, Romania (46°35' N 23°48' E), over three consecutive growing seasons (2022–2024).

Adult flight of the CBW was monitored with funnel traps baited with commercial *Helicoverpa armigera* sex pheromone lures (CSALOMON®, Hungary), installed in maize fields (Fite et al., 2020; Karakasis et al., 2021; Georgescu et al., 2025). Three traps (replicates) were used each year, spaced 50 m apart. Monitoring was performed from May to October each year. The pheromone lures were replaced monthly, and trap catches were recorded weekly.

To quantify the influence of climatic conditions on CBW adult trap catches, multiple linear regression including a second-order term was applied. Predictor variables included minimum and maximum air temperature, minimum and mean relative humidity, and the monitoring decade. Starting from a multiple regression framework as proposed by Sagar et al. (2017), the model was subsequently extended by incorporating both linear and quadratic terms for each predictor to capture potential non-linear effects of weather conditions on population dynamics and improve prediction accuracy.

highlights only a specific aspect of a model's errors, evaluating performance often requires the use of a combination of metrics (Chai and Draxler, 2014).

The indicators used to evaluate the performance of the statistical phenological forecasting model were:

MAE (Mean Absolute Error) was calculated to quantify the average absolute difference between the estimated and actual values. Unlike RMSE, this indicator is less sensitive to the presence of extreme or outlying values. Therefore, when outliers occur in the dataset, MAE can provide a

more reliable assessment of the error (Willmott and Matsuura, 2005; Chai and Draxler, 2014; Dumre et al., 2024).

RMSE (Root Mean Square Error) represents the square root of the mean squared error, calculated based on the deviations between the observed and the predicted values. Through this statistical indicator, the prediction error can be understood more clearly, as it is expressed on the original scale of the analyzed data (Hyndman and Koehler, 2006; Chai and Draxler, 2014; Dumre et al., 2024).

R² (coefficient of determination) expresses the proportion of the variance in the target variable that is explained by the independent variables included in the model. Higher values of this indicator suggest a better fit of the model to the data. R² can take values between 0 and 1 and is useful for assessing the extent to which the model describes the overall variability present in the dataset (Chicco et al., 2021; Dumre et al., 2024).

RESULTS AND DISCUSSION

Meteorological data were obtained from the Turda Meteorological Station (46°35' N,

23°47' E; 427 m a.s.l.), situated approximately 2 km from the experimental site where pheromone trap monitoring was performed.

Climatic variations during 2022-2024 showed pronounced inter-annual variability, with higher minimum and maximum temperatures recorded more frequently in 2024, indicating a warming tendency (Table 1). At the same time, minimum relative humidity displayed a decreasing pattern, particularly in 2024, suggesting drier atmospheric conditions. Overall, these fluctuations reflect increasing climatic instability across the analyzed period.

This climatic pattern is also supported by data from the NARDI Fundulea field site, where temperatures during the CBW monitoring period (2020-2024) were generally above the 50-year average, while rainfall was below average in most months, confirming a warmer and drier climatic background (Georgescu et al., 2025).

Moreover, national-scale assessments indicate that 2024 was the warmest year recorded in Romania since the beginning of meteorological observations (Ionita and Nagavciuc, 2025; www.meteoromania.ro).

Table 1. Climatic conditions (10-day means/decadal means) during *Helicoverpa armigera* adult flight monitoring at ARDS Turda (2022-2024)

Month	Decade	Minimum air temperature (°C)			Maximum air temperature (°C)			Mean relative humidity (%)			Minimum relative humidity (%)		
		2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024
May	III	11.6	11.8	11.9	23.6	26.2	23.5	67.0	64.4	69.3	50.8	52.1	51.5
June	I	14.0	13.1	14.3	26.8	26.8	27.5	69.7	72.2	72.4	56.9	48.9	51.8
	II	13.6	13.6	14.6	27.5	23.7	27.4	61.6	82.9	69.1	44.2	66.7	52.7
	III	15.0	14.3	17.9	30.8	26.6	31.6	49.0	75.6	65.9	31.0	61.3	43.8
July	I	16.7	15.5	16.0	31.4	28.9	29.6	61.4	70.7	64.0	39.6	53.9	50.2
	II	13.4	17.0	19.6	28.8	31.2	36.0	46.2	67.9	55.5	27.5	51.7	33.7
	III	17.9	14.5	15.8	33.1	28.2	29.2	48.3	74.5	59.4	32.0	54.0	43.8
August	I	16.3	14.2	15.4	30.7	27.5	28.3	60.5	73.2	64.7	39.3	57.3	44.1
	II	15.8	15.2	17.8	31.3	30.0	34.0	61.2	64.8	54.7	37.2	45.1	34.1
	III	16.3	16.7	16.2	30.0	31.9	31.5	72.3	70.5	51.7	49.9	51.5	34.0
September	I	13.4	11.9	14.3	22.9	26.6	29.1	87.8	68.2	45.8	71.4	49.1	29.4
	II	10.2	13.8	11.2	19.9	27.0	21.5	79.2	75.3	75.6	64.7	56.5	57.8
	III	8.2	12.5	9.8	18.4	27.2	23.8	83.2	68.5	62.9	67.6	45.4	45.3
October	I	7.7	7.4	-	19.3	20.3	-	80.1	68.9	-	59.5	50.0	-

Source of primary data: Turda meteorological station (46°35' N; 23°4' E; 427 m a.s.l.).

In line with the previously observed climatic variations, characterized by higher temperatures and lower precipitation in 2024, a marked increase in the abundance of CBW adults was recorded. The number of captures reached 420 individuals, significantly higher than in the other two years, suggesting that warmer and drier conditions favor the development and proliferation of this pest in maize crops (Figure 1). Similar trends were observed in pheromone-trap surveys conducted at the NARDI Fundulea research station (south-eastern Romania) between

2020 and 2024, where increased CBW adult abundance coincided with warmer and drier conditions (Georgescu et al., 2025).

Consistent with these findings, long-term analyses indicate that climate warming can contribute to an increase in CBW population size, resulting in higher adult abundance in agroecosystems (Huang and Hao, 2020). Moreover, the same authors emphasized that climate change may disrupt the synchrony between crop development, CBW phenology, and climatic conditions.

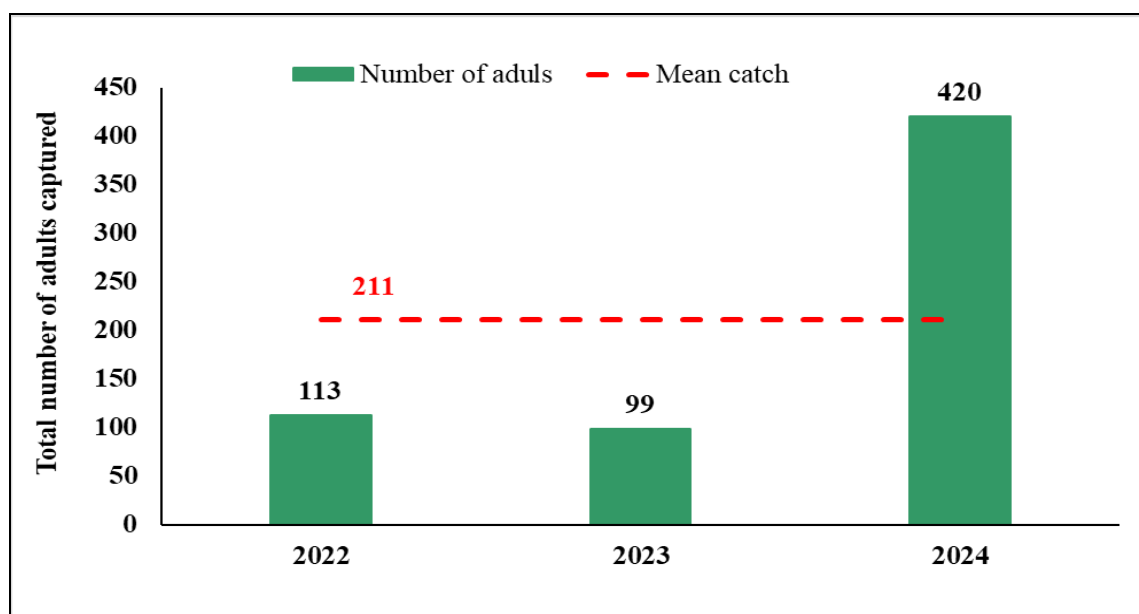


Figure 1. Abundance of *Helicoverpa armigera* adults in maize crops, ARDS Turda (2022-2024)

Across all analyzed years, a first flight peak was observed in May, corresponding to the emergence of the first generation, while in 2022 and 2023 a pronounced peak occurred in September. In 2024, the graph indicates higher flight intensity, with pronounced peaks in August and September (Figure 2).

Considering that the species can complete its biological cycle in approximately 30 days under warm conditions (Zalucki et al., 1986; Patil et al., 2017; Mahmood et al., 2021) these results suggest that the higher temperatures and lower relative humidity recorded in 2024 promoted accelerated

development and the overlap of successive generations.

A similar seasonal flight pattern was reported by Georgescu et al. (2025), who observed pronounced CBW flight peaks during late summer and early autumn (August-September), supporting intensified late-season activity in south-eastern Romania.

This interpretation is supported by long-term analyses based on light-trap monitoring, indicating that climate warming can enhance late-season generations (particularly G3), thereby increasing late summer-early autumn moth activity (Huang and Hao, 2020).

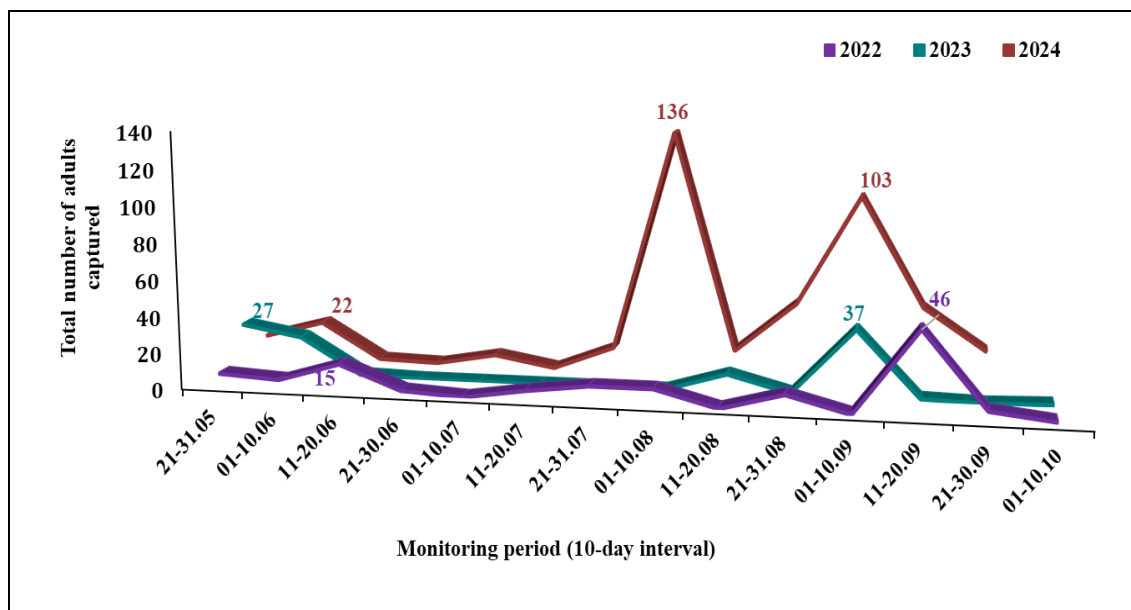


Figure 2. Flight dynamics of *Helicoverpa armigera* adults in maize crops, ARDS Turda 2022-2024

Regression models were developed to assess the relationship between CBW trap catches and climatic variables during 2022-2024 (Table 2). The developed models showed a good fit to the experimental data, with coefficients of determination (R^2) ranging between 0.92 and 0.95. Based on these regression results, 92-96% of the variation in CBW trap catches was explained by the climatic variables included in the models. The year 2023 recorded the lowest prediction error (MAE = 1), whereas 2024, under the high temperatures observed in August and September - conditions under which the pest can complete its biological cycle in only 30 days - exhibited the highest variability (RMSE = 4).

The coefficient analysis indicates that an increase in minimum air temperatures generally has a moderate positive effect, whereas maximum air temperature showed a dual effect, being positive at moderate values and negative at extremes. In addition, high relative humidity appeared to negatively affect trap catches in 2022 and 2024, while low minimum relative humidity, typical of dry periods, had a positive effect in most years. Overall, the models confirm that CBW

adult activity is closely associated with the analyzed climatic factors.

Comparable weather-based regression approaches were reported by Sagar et al. (2017), who developed prediction models for CBW pheromone-trap catches in chickpea (*Cicer arietinum*) fields using temperature and relative humidity variables. In their study, the coefficient of determination ($R^2 = 0.779$) indicated that 77.9% of the variability in male moth catches was explained by weather factors. Compared to those results, the models developed in the present study exhibited a higher explanatory power ($R^2 = 0.92-0.96$) and improved predictive performance, as reflected by lower error values (MAE = 1-3; RMSE = 1.77-4) (Table 2).

Despite differences in model accuracy, both studies highlight temperature and humidity as key drivers of adult activity, with relative humidity generally showing a negative association with trap catches.

Similarly, Fite et al. (2020), using pheromone-baited funnel and delta traps (Botrack/Femtrack lures) installed in chickpea-based agroecosystems, reported that CBW adult catches decreased with increasing average air relative humidity.

Table 2. Regression analysis of *Helicoverpa armigera* trap catches and climatic variables, ARDS Turda (2022-2024)

Year	Regression equation	MAE	RMSE	R ²
2022	$Y = 117 + 79x_1 - 44x_2 + 18x_3 - 14x_4 + 18x_5 - 3x_1^2 + 0,75x_2^2 - 0,15x_3^2 + 0,08x_4^2 - 1,26x_5^2$	2	2.75	0.94
2023	$Y = 234 - 45x_1 + 18x_2 - 0,26x_3 - 3,21x_4 + 3,22x_5 + 1,45x_1^2 - 0,33x_2^2 + 0,02x_4^2 - 0,26x_5^2$	1	1.77	0.92
2024	$Y = 4,7 - 66x_1 + 103x_2 + 0,85x_3 - 26x_4 + 31x_5 + 2x_1^2 - 2x_2^2 - 0,13x_3^2 + 0,27x_4^2 - 2,25x_5^2$	3	4	0.96

x_1 - minimum air temperature (°C); x_2 - maximum air temperature (°C); x_3 - minimum relative humidity (%); x_4 - mean relative humidity (%); x_5 - monitoring decade (10-day interval); MAE - Mean Absolute Error; RMSE - Root Mean Square Error; R² - coefficient of determination.

Model performance was further validated by comparing observed and predicted trap catches (Figure 3).

The results indicate a good fit between the observed and model-predicted values for each of the three agricultural years analyzed (2022, 2023, and 2024).

The predicted values closely follow the ideal 1:1 line ($y = x$), indicating a strong fit between observed and model-predicted trap catches. Nevertheless, slight deviations were detected, including a minor underestimation of higher values in 2022 and a small overprediction of low values in 2024. Although 2023 showed the lowest coefficient of determination, the model performance remained high ($R^2 = 0.91$).

Data points are grouped closely along the regression line, with no major systematic

deviations, indicating a high level of concordance between observed and predicted values and confirming the accuracy of the model. The most pronounced differences occur at medium-to-high trap catch levels; however, these deviations remain within statistically acceptable error limits, as further supported by the low prediction error values (MAE and RMSE) calculated previously.

A similar validation approach has been previously applied in weather-driven forecasting models for CBW adults. In chickpea (*Cicer arietinum*) fields, Sagar et al. (2017) reported good agreement between observed and predicted trap catches, although with lower predictive performance than in the present study ($R^2 = 0.751$; RMSE = 2.13; MAE = 1.51).

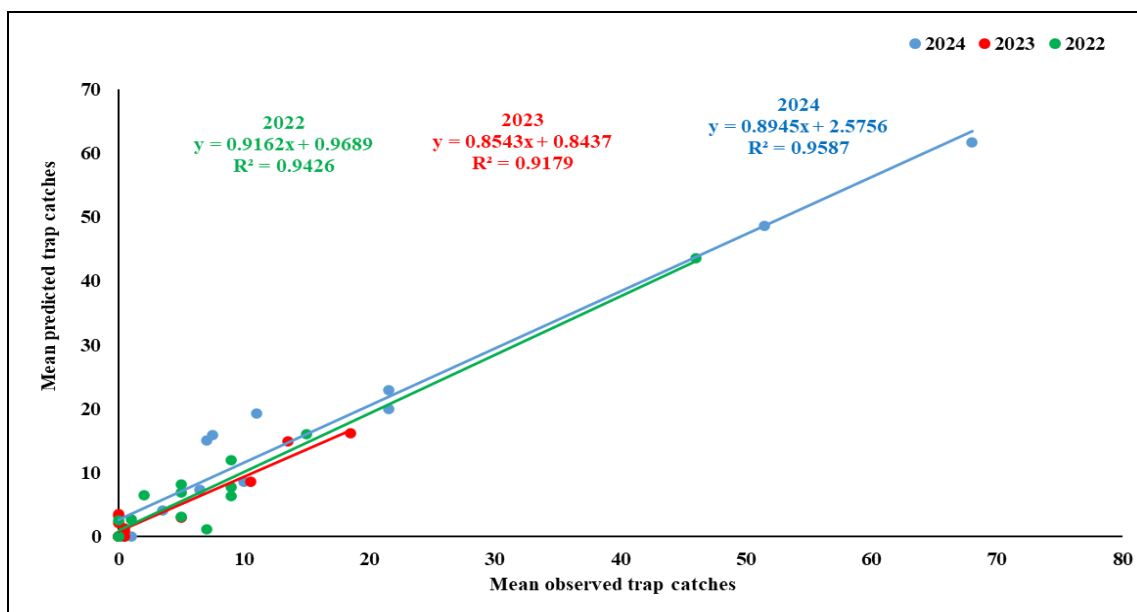


Figure 3. Mean observed and predicted trap catches of *Helicoverpa armigera*, ARDS Turda 2022-2024

The regression models were validated by comparing the observed CBW trap catches recorded during the 2022-2024 monitoring seasons with the corresponding model-predicted values. The validation results indicated high predictive performance, with coefficients of determination ranging between $R^2 = 0.92$ and 0.96 , and low prediction errors (MAE = 1-3; RMSE = 1.77-4) (Table 2). The coefficient analysis further suggests that minimum and maximum air temperatures, together with relative humidity parameters, represent key climatic factors associated with CBW trap catches in the Transylvanian Plateau (ARDS Turda, Romania).

Temperature represents one of the main abiotic factors influencing insect biology, affecting development, reproduction, and population dynamics. In general, higher temperatures speed up insect development, which may enhance population growth and increase seasonal activity (Zalucki and Furlong, 2005). To further illustrate the influence of temperature on pest activity, Figure 4 depicts the seasonal dynamics of CBW trap catches in relation to minimum

and maximum air temperatures averaged across the 2022-2024 monitoring period.

On average over the three years, during the period from the last decade of May to the first decade of October, a clear relationship was observed between minimum and maximum temperatures and the trap catch dynamics of CBW.

At the beginning of the monitoring period, when minimum and maximum temperatures are still moderate, trap catches are low or absent. As temperatures increase, particularly in July and August, the number of captured adults begins to rise. With the gradual decrease in temperatures towards the end of September, trap catches decline substantially.

The thermal regime influences the population dynamics of CBW and can be used to identify the optimal timing for phytosanitary treatments (Figure 4).

This pattern is consistent with previous studies indicating that CBW adult activity peaks within an optimal thermal range, while extreme heat reduces adult abundance (Huang and Hao, 2020; Liu et al., 2024).

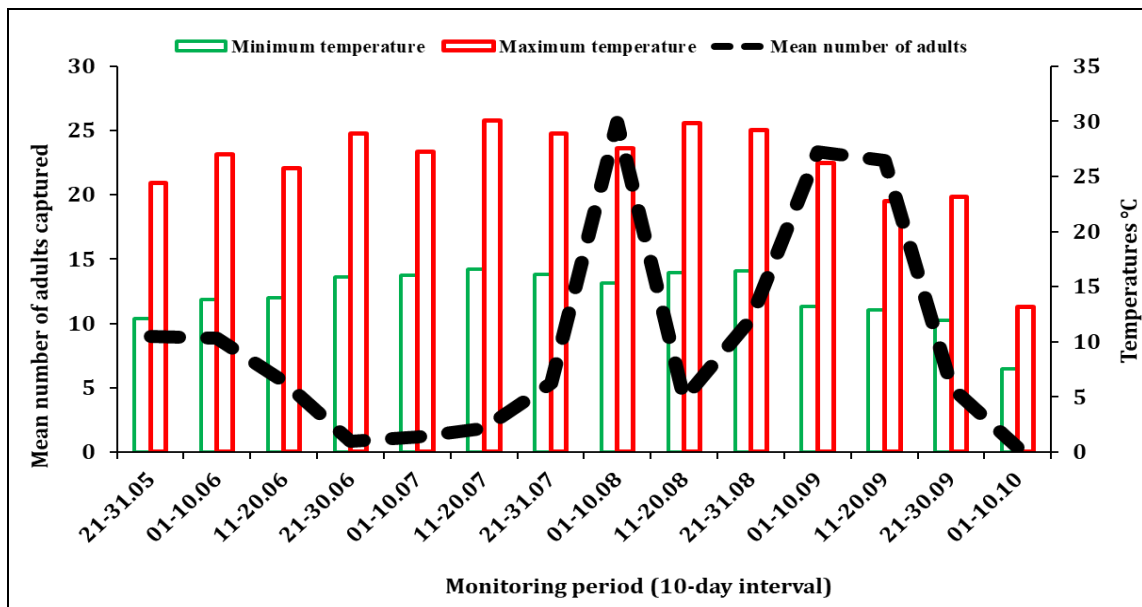


Figure 4. Flight dynamics of *Helicoverpa armigera* in relation to minimum and maximum temperature, ARDS Turda (2022-2024)

Polynomial regression analysis indicated that adult trap catches were influenced by thermal conditions, with a stronger relationship observed for minimum temperature compared with maximum temperature.

Distinct optimal thermal ranges for adult flight activity were identified, with maximum trap catches recorded at minimum temperatures of 13-15°C and maximum temperatures of 23-28°C (Figure 5).

Beyond these thresholds, adult abundance decreased markedly, particularly under higher daytime maximum temperatures (above 30°C), suggesting a limitation of flight activity under heat stress conditions. This trend is consistent with findings from a recent meta-analysis showing that CBW physiological performance peaks within a warm optimum (32-35°C), whereas temperatures exceeding 35°C may negatively affect survival and reproductive capacity (Liu et al., 2024).

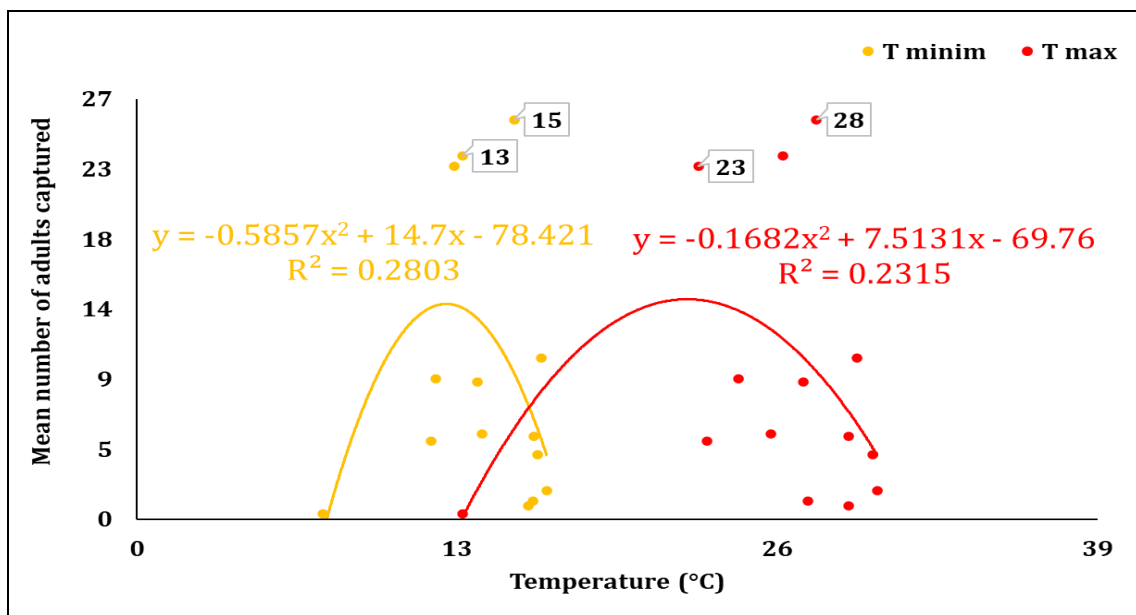


Figure 5. Relationship between *Helicoverpa armigera* trap catches and daily minimum and maximum temperatures, ARDS Turda (2022-2024)

CONCLUSIONS

In 2024, due to higher temperatures and drought conditions, a marked increase in the abundance of *Helicoverpa armigera* adults was observed, with distinct flight peaks occurring in August and September.

The high values of the determination coefficients ($R^2 = 0.91-0.95$) confirm the influence of the analyzed climatic parameters on the flight dynamics of *Helicoverpa armigera*. The year 2023 recorded the smallest error (MAE = 1), while due to the high temperatures in 2024, the largest variations were observed (RMSE = 4).

The thermal regime significantly influences the flight activity of *Helicoverpa armigera* adults, with optimal conditions observed

under minimum air temperatures of 13-15°C and maximum temperatures of 23-28°C.

When temperatures exceed 30°C, adult abundance declines, suggesting a negative impact of high temperatures on the development and activity of the species.

High relative humidity negatively affected catches in 2022 and 2024, whereas lower minimum relative humidity, typical of dry periods, had a positive influence in most years.

These results highlight the importance of climatic conditions in population dynamics. Based on the four analyzed climatic variables, warning bulletins can be developed to support the adoption of the most appropriate management decisions.

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