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Towards improved forecasting of *Rhagoletis cerasi* (Diptera: Tephritidae) outbreaks through climate-based indicators

Подобряване на прогнозите за нападенията от черешовата муха *Rhagoletis cerasi* (Diptera: Tephritidae) чрез климатични показатели

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ABSTRACT

Rhagoletis cerasi poses a significant threat to cherry production across Europe, presenting a substantial challenge to agricultural practitioners. This study aims to enhance the techniques used for predicting seasonal pest invasions by focusing on climate factors, specifically air humidity. A comprehensive range of analytical techniques, including linear, multiple, and logistic regression, was employed to investigate the relationship between climatic variables and the incidence of substantial pest captures (defined as more than ten individuals per day). The results of the study indicated that when atmospheric humidity exceeds 70%, it is the predominant predictor of elevated *R. cerasi* activity (β=10.80, *P*=0.0302). Notably, while temperature appeared to constrain pest activity, precipitation did not demonstrate a statistically significant impact. The predictive models achieved an average explanatory power (R^2=0.41), and visual analyses supported the finding that increased flight activity correlates with higher humidity levels. This research emphasizes the crucial role of microclimatic factors, including humidity, in refining pest monitoring and management strategies. Consequently, these findings may improve predictions and mitigate economic losses in fruit agriculture. There is optimism that the insights gained will lead to more effective solutions and a prosperous future for cherry growers across Europe.

Keywords: *Rhagoletis cerasi*, humidity, population dynamics, economic threshold, forecast model, plant protection

АБСТРАКТ

Rhagoletis cerasi (Diptera: Tephritidae) е ключов неприятел по черешата в Европа, като неговата популационна динамика е силно обусловена от климатичните условия. Целта на настоящото изследване е да се подобри прогнозата за сезонните нападения чрез анализ на климатични индикатори, с акцент върху влажността на въздуха. Използвани са линейни, множествени и логистични регресионни модели за оценка на връзката между климатични фактори и надпрагови улови (>10 инд./ден). Резултатите показват, че атмосферната влажност над 70% е единственият статистически значим предиктор за повишена активност на *R. cerasi* (β=10.80, *P*=0.0302), докато температурата има гранично влияние, а валежите не са значими. Моделите демонстрират средна прогностична сила (R^2=0.41), като визуализациите потвърждават засилена летателна активност при висока влажност. Изследването потвърждава значението на интегрирането на микроклиматични показатели — особено влажността — в системите за мониторинг и управление на вредителя, с цел по-точно прогнозиране и намаляване на икономическите загуби в овощарството.

Ключови думи: *Rhagoletis cerasi*, атмосферна влажност, популационна динамика, икономически праг, прогнозен модел, растителна защита

INTRODUCTION

The European cherry fruit fly *Rhagoletis cerasi* L. (Diptera: Tephritidae) is one of the most economically important pests of sweet cherry production in Europe. Its univoltine life cycle, narrow host range, and synchronized emergence with fruit ripening make it a persistent challenge for growers. Climate variability, particularly fluctuations in winter temperatures and spring microclimatic conditions, increasingly complicates the prediction of seasonal population peaks. Improving forecasting tools is therefore essential for optimizing monitoring schedules, reducing unnecessary insecticide applications, and preventing economic losses.

A key biological feature of *R. cerasi* is its obligatory pupal diapause, the duration of which is strongly influenced by environmental cues. Temperature and humidity play central roles in diapause maintenance and termination (Higaki and Ando, 2000; Higaki, 2005; Higaki et al., 2010), while internal physiological factors such as metabolic reserves also contribute (Menu and Desouhant, 2002). Most insect species respond not to gradual cooling but to specific temperature fluctuations that signal the end of prolonged dormancy (Higaki, 2005, 2006). For univoltine species, bet-hedging strategies—spreading emergence timing across years—serve as an adaptive mechanism against unpredictable winter conditions, especially under climate-change scenarios that may reduce chilling accumulation (Moraiti et al., 2014; Moraiti and Papadopoulos, 2017). Such strategies are particularly advantageous in environments with pronounced seasonal variability (Akhund-Zade et al., 2020).

The diapause dynamics of *R. cerasi* vary across populations and are shaped by local temperature regimes, host plant characteristics, and geographic conditions (Boller and Prokopy, 1976; Kovanci and Kovanci, 2006; Ranner, 1988; Papanastasiou et al., 2011). Pupae typically terminate diapause after sufficient winter chilling, resulting in synchronized adult emergence during the fruiting period of local cherry cultivars. However, deviations from optimal chilling—such as exposure to temperatures of 3–8 °C for too short or too long a period or warming above 10 °C—may induce extended dormancy lasting more than one year (Moraiti et al., 2014; Moraiti and Papadopoulos, 2017). Extended dormancy is associated with reduced germination rates (Vallo et al., 1976) and fitness costs, including lower lifetime fecundity and shorter oviposition periods, although individuals emerging from prolonged dormancy may exhibit larger body size (Moraiti et al., 2012a). Fitness traits also differ among geographically isolated populations, reflecting local ecological pressures and limited gene flow (Moraiti et al., 2012b).

Despite extensive research on diapause mechanisms, less is known about how microclimatic factors—particularly air humidity—shape the seasonal flight activity of *R. cerasi* adults. Identifying reliable climatic indicators of increased activity could substantially improve monitoring efficiency and forecasting accuracy.

This study aimed to evaluate the winter survival and seasonal population activity of *R. cerasi* in relation to climatic conditions and varietal differences. The study specifically tested the following hypotheses: (i) air humidity is more strongly associated with daily flight activity than temperature; (ii) humidity levels above 70% increase the likelihood of high trap captures (>10 individuals/day); and (iii) temperature acts as a limiting factor for adult activity.

MATERIALS AND METHODS

The study was conducted during the winter and spring of 2024–2025 in two adjacent sweet cherry orchards located at 42.103393° N, 24.722940° E. The orchards consisted of early, mid-early, and late cultivars and were managed under standard integrated production practices. No insecticidal treatments targeting *Rhagoletis cerasi* were applied during the monitoring period, and the surrounding area consisted exclusively of cherry orchards, minimizing external population influx.

Winter assessment of pupal density

From March 5 to March 8, 2025, soil samples were collected from three cherry cultivar groups: early, mid-early, and late. A total of 16 samples were taken:

4 from early cultivars, 8 from mid-early cultivars, and 4 from late cultivars. This 4/8/4 sampling scheme reflected the proportional representation of each cultivar group within the orchards and ensured adequate replication for the dominant mid-early group.

Each sample covered an area of 0.25 m² (50 × 50 cm) and was collected at a depth of 10 cm along the canopy projection line, where pupae are most likely to accumulate. Samples were manually sifted using screens with openings of 4–5 mm, and each sample was processed twice by different observers to reduce inconsistencies. The counted pupae were recorded, and the population density was represented as the number of individuals per square meter and compared with the national economic threshold for Bulgaria (>3 pupae/m²; Ministry of Agriculture and Food, 2023), which served as a reference point for interpreting infestation pressure.

Monitoring flights during the active season

Adult activity of *R. cerasi* was monitored using two yellow Rebel® sticky traps placed in the central part of the orchard (or the tree crown) at a height of 1.5–2.0 m above ground level. The traps were positioned 20 m apart, approximately 1 m from the nearest tree canopy, to ensure unobstructed visibility and minimize edge effects. Trap inspections were conducted every five days from April to June 2025, a frequency commonly used in regional monitoring programs and sufficient to capture changes in population dynamics during the flight period. Captures were expressed as the average number of individuals per day and compared with climatic variables recorded during the same period.

Climate data

Climatic data for December 2024–March 2025 were obtained from an automatic weather station located centrally within the orchards. The station recorded hourly air temperature (minimum, maximum, and mean), soil temperature at 10 cm depth, relative humidity, and precipitation. Derived variables included the number of hours below 0 °C and −5 °C, minimum winter temperature, cumulative precipitation, and mean daily soil temperature.

Statistical processing

All analyses were performed in R (version 4.x.x; R Core Team, 2024) using RStudio. Visualizations were produced with the ggplot2 package (Wickham, 2016). Linear regression models were fitted using lm(), and logistic regression models using glm() with a binomial link function. Predictor variables included relative humidity, air temperature, soil temperature, and precipitation.

Normality of residuals was assessed using the Shapiro–Wilk test, and logarithmic transformations were applied where necessary. Model fit was evaluated using R^2 for linear models and AIC and ROC/AUC metrics for logistic models. Parameter estimates (β, SE, t, P, R^2) are reported in the Results section.

RESULTS

Observations on the overwintering population

Using the analyzed soil samples, we assessed the population density of *Rhagoletis cerasi* pupae for each variety group. Comparing samples below and above the economic threshold enables a quantitative evaluation of the overwintering population across various regions (Table 1).

The average density for early-ripening cultivars was the lowest at 3.0 pupae/m². Two of four samples were below the economic threshold, suggesting relatively low winter pressure in this category.

In medium-early ripening cultivars, an average density of 9.5 pupae per square meter was notably higher. Importantly, 87.5% of the samples (7 out of 8) surpassed the critical threshold. This suggests a substantial, uniform population overwintering, which may pose a risk of early infestations during the growing season.

The late-ripening cultivars showed the highest count at 18.0 pupae/m², with every sample (100%) exceeding the set threshold. This indicates favorable conditions for pupae survival and/or a buildup of the population from previous seasons.

Table 1. Summary data from samples by ripening cultivar groups

Ripening cultivars group	Number of samples	Average number of pupae/m²	Threshold exceeded (>3/m²)*
Early ripening	4	3.0	2 from 4 (50%)
Medium-early ripening	8	9.5	7 from 8 (87.5%)
Late-ripening	4	18.0	4 from 4 (100%)

* Economic threshold for control in Bulgaria: >3 pupae/m² (Ministry of Agriculture, 2023).

The boxplot (Figure 1) shows the distribution of pupal density for *Rhagoletis cerasi* across various variety groups, clearly demonstrating an upward trend from early to late varieties. In the early group, a low median pupal density is observed, with some values approaching the economic threshold and several samples falling below it. The medium-early varieties show a greater and more stable density, with most individual values exceeding the economic damage threshold and displaying less variability. The most considerable increase in pupal density is found in late varieties, which not only have the highest density but also exhibit a wider range of values, spanning from 12 to 24 pupae/m². The dashed red line marks the threshold value of 5 pupae/m², above which all points in the medium-early and late categories are situated. This trend suggests increased overwintering of the population in later-maturing varieties, accompanied by a higher risk of economic damage.

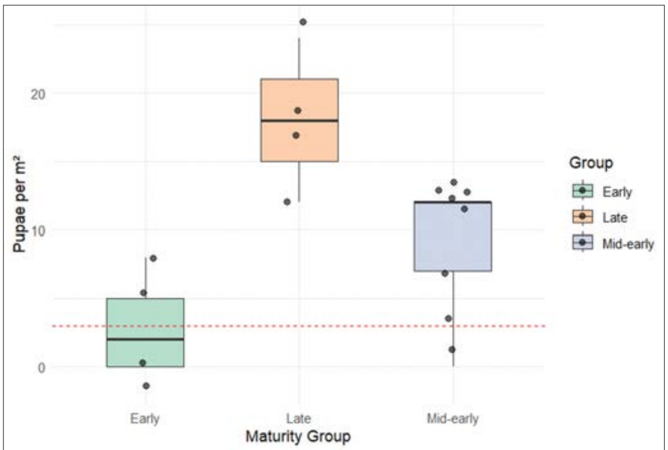

Figure 1. Distribution of *Rhagoletis cerasi* pupal density by ripening cultivar group (m²)

Throughout the winter, no snow accumulated. The total hours with temperatures falling below 0 °C were 627, with 79 hours registering -5 °C below, and the lowest temperature documented was -11.03 °C, measured 10 cm above the ground (Table 2). These circumstances might result in some level of population decline. Still, they do not suggest a complete failure.

Table 2. Cold indicators during the 2024–2025 winter

Indicator	Value	Meaning
Hours below 0 °C	627 hrs	Prolonged cold period
Hours below -5 °C	79 hrs	Potentially lethal levels
Absolute minimum	−11.03 °C	The most extreme value
Presence of snow cover	n/a	Increased thermal risk

A linear regression analysis (Figure 2) revealed a significant positive correlation between average winter soil temperature and pupal density, with an R^2 of 0.9998 ($P<0.01$).

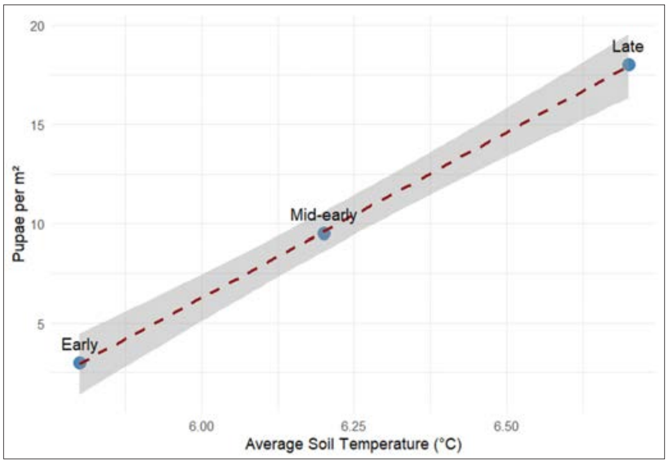

Figure 2. A linear relationship between average soil temperature and pupal density of *Rhagoletis cerasi*

The results demonstrated that soil temperature accounted for all the variability in pupal counts. The model suggested that for each 1 °C rise in soil temperature, the anticipated number of *R. cerasi* pupae increased by roughly 16.68 individuals per square meter. Despite low winter air temperatures, with a lowest recorded temperature of –11.03 °C and minimal snow cover, elevated soil temperatures in specific plots may have reduced pupal mortality and improved overwintering success.

Activation of the Rhagoletis cerasi population

The initial adult *R. cerasi* was captured on April 20, 2025, in the southern section of the area (SC2), where the soil temperature registered at 15.2 °C (Table 3). By April 24, activity was detected throughout all sections, indicating that emergence from the soil occurred simultaneously over a 4- to 5-day period.

Table 3. Dates of first trap captured adults

Soil cage	Position	Date of first catch	Soil temperature (°C)
SC2	Southern	20.04.2025	15.2
SC3	East	21.04.2025	16.1
SC4	West	22.04.2025	17.0
SC1	North	24.04.2025	17.8
SC5	Centre	25.04.2025	18.1

The daily activity patterns indicate a noticeable rise following April 22. A maximum of 21 individuals per day was recorded between April 30 and May 3, corresponding with soil temperatures reaching 17 °C or above.

The overall catch between April 19 and May 3 was highest in SC2 and SC3, suggesting a favorable microclimate in the orchard's southern and eastern regions.

The regression model (Figure 3) revealed a significant correlation between soil temperature and daily catch (R^2=0.39, P=0.0057). For each 1 °C rise, the number of individuals captured increases by 3.26.

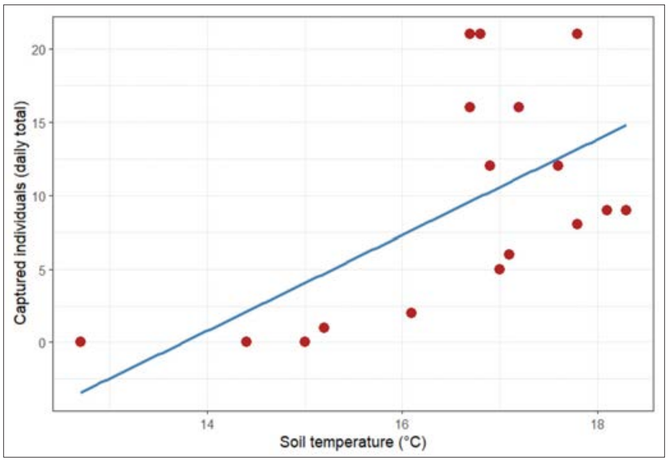

Figure 3. Linear model: soil temperature vs. daily catch

Using logistic regression (Figure 4), the impact of soil and air temperatures on the likelihood of meeting a threshold of at least 10 individuals per day was assessed. Soil temperature demonstrated a prominent positive influence (β=1.08, P=0.0618). The chance of a mass flight surpasses 50% when soil temperatures reach ≥17.5 °C and air temperatures reach ≥16 °C.

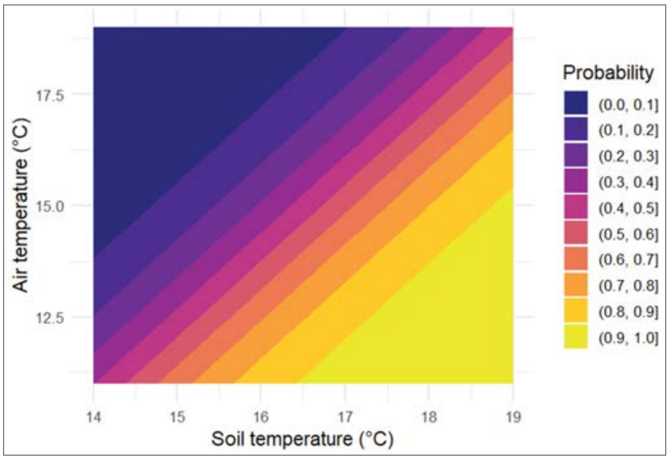

Figure 4. Predicted probability of flight (logistic surface)

Population dynamics during the vegetation season

Monitoring the activity levels of *R. cerasi* during their active season (April to June 2025) revealed clear periods in their development: initial emergence, sexual maturation, peak activity, and decline (Figure 5). The first individuals were spotted on April 25, when the temperature was 16.7 °C, and the humidity was 69%.

In the following weeks, activity steadily increased, peaking at the end of May, with 243.5 individuals recorded daily on May 25, 2025. However, following the start of June, activity began to decline significantly, and by the end of the month, the population had become almost inactive.

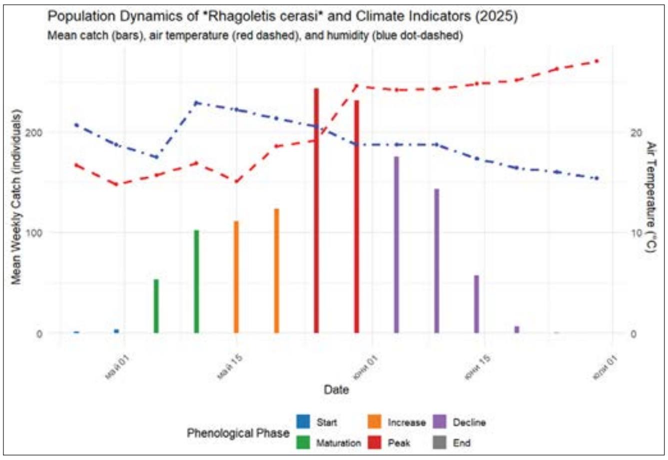

Figure 5. Diurnal activity of *Rhagoletis cerasi* and relevant climatic conditions in the 2025 season

The initial individuals were recorded on April 25, 2025, with a temperature of 16.7 °C and a humidity level of 69%. Increased activity was observed to align with higher humidity and mild temperatures, peaking at the end of May, when a maximum of 243.5 individuals per day was recorded on May 25, 2025.

The linear regression analysis between temperature and average catch did not indicate a statistically significant relationship (P=0.979; R^2=0.00006), suggesting no linear correlation between these two variables. On the other hand, the multiple linear regression model that incorporated temperature, humidity, and precipitation exhibited moderate explanatory power (R^2=0.41). In this model, humidity was identified as a statistically significant predictor (β=0.80, P=0.0302), whereas temperature was marginally significant (P=0.0853). Conversely, precipitation had no significant effect (P=0.65). Figure 6 illustrates the relationship between humidity and average catch, while Figure 7 compares the observed and predicted values from the model.

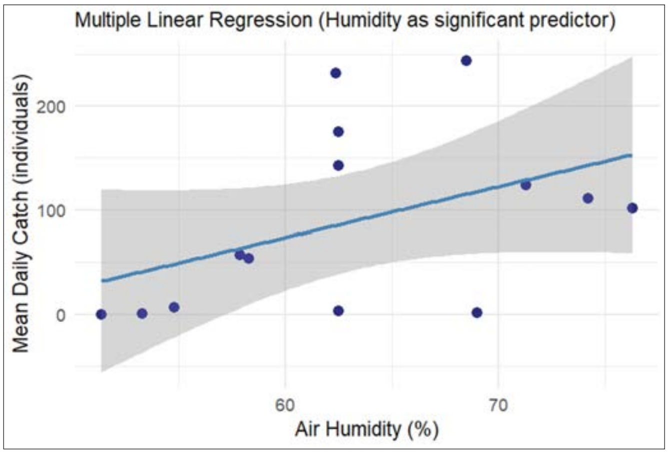

Figure 6. Relationship between air humidity and average daily catch of *Rhagoletis cerasi*

The diagram illustrates the outcomes of a multiple linear regression, highlighting a positive correlation between atmospheric humidity and population activity. The blue regression line, along with a light grey area representing the 95% confidence interval, suggests that catch rates are likely to increase as humidity levels rise. The significant coefficient value (P=0.0302) supports the notion that atmospheric moisture is crucial for aligning the species' flight patterns and peak activity.

The logistic model, which predicts the likelihood of reaching the flight threshold of at least 10 individuals per day, showed marginal significance for air humidity (β=0.270, P=0.0711). On the other hand, temperature (P=0.3490) and precipitation (P=0.9102) had no significant impact.

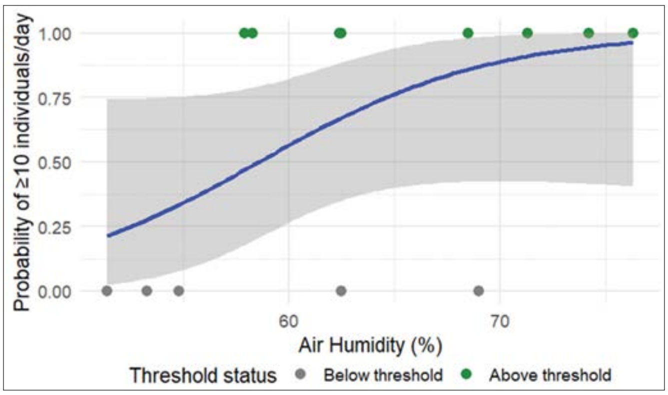

Figure 7. Predicted probability of above-threshold catch (≥10 ind./day) of *Rhagoletis cerasi* relative to air humidity

Figure 7 illustrates this relationship, showing that the probability of surpassing the catch threshold increases when humidity levels exceed 70%, although this observation lacks rigorous statistical validation.

The graph displays the findings from the logistic regression, which assesses how atmospheric humidity affects the probability of attaining a threshold of ≥10 individuals per day. The dashed blue line represents the predicted likelihood, while the grey shaded region indicates the 95% confidence interval. Observations that surpass the threshold are marked with green dots, while those that do not are shown with grey dots. The pattern suggests an increased probability when humidity exceeds 70%, but it falls short of statistical significance (P=0.0711). This supports the theory that microclimatic conditions affect population activity.

The analysis of the three models highlights that atmospheric humidity is the primary climatic factor associated with the increased activity of *R. cerasi*. Although temperature contributes positively, it is not a key factor, and precipitation is not a significant statistical predictor. This overview emphasizes the importance of incorporating humidity as a key variable in forecasting population dynamics and refining agricultural monitoring and management strategies.

The correlation between the recorded population dynamics of *Rhagoletis cerasi* and the predicted figures from a multivariate linear model (Figure 8) shows strong agreement during peak periods and a moderate level of predictability (R^2=0.41). The visual correlation between the real and estimated values supports the assertion that air humidity plays a crucial role. In contrast, the influence of other factors seems minimal.

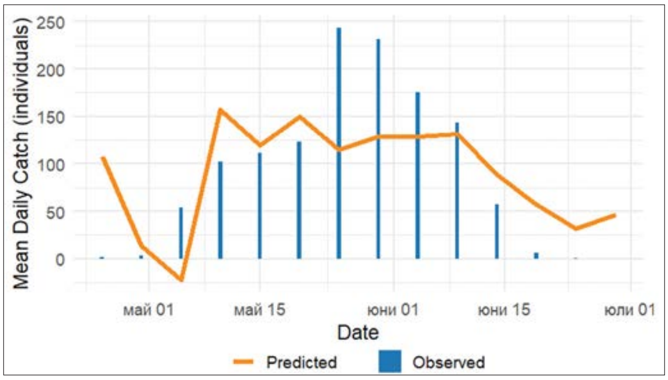

Figure 8. Comparison between observed population dynamics of *Rhagoletis cerasi* and predicted values from a multivariate linear model

To provide a clearer comparison of the regression approaches used, Table 4 presents the main statistical parameters of the three models.

To summarize, the findings from the three models suggest that atmospheric humidity is the main climatic element associated with the heightened activity of *Rhagoletis cerasi*. Although temperature contributes to the overall picture, it is not a critical factor, and precipitation has not been demonstrated to be a statistically significant predictor. The identified trends and graphical representations highlight the necessity of considering humidity as a crucial variable in forecasting population dynamics and in enhancing agricultural monitoring and management.

Table 4. Comparison between the three statistical models used to assess the activity of *Rhagoletis cerasi*

Model	Variables included	Significant factors	Coefficient (β)	Statistics	Explanatory power
Linear regression	Temperature	–	–	P = 0.979	R^2 = 0.00006
Multiple Linear Regression	Temp., humidity, precipitation	Humidity	β = 10.80	P = 0.0302	R^2 = 0.41
Logistic regression	Temp., humidity, precipitation	Humidity (limit)	β = 0.270	P = 0.0711	AIC = 21.29

DISCUSSION

The present research verifies that atmospheric humidity is a vital climatic indicator of the seasonal behavior of *Rhagoletis cerasi*. The evidence indicates that when humidity exceeds 70% and temperatures exceed 18 °C, the average daily catch increases (Figure 5) and the probability of increased flight activity increases (Figure 4). These results align with the findings of Hulshof and Van den Brink (2004), who observed that the mass activity of this species is enhanced under ideal temperature and humidity conditions. This relationship also has practical relevance, as humidity thresholds can support more precise timing of monitoring activities in commercial orchards.

The multivariate regression analysis (Table 3) reveals that humidity is the sole statistically significant predictor (β=10.80; *P*=0.0302), while temperature is marginally significant (*P*=0.0853). There is no effect observed from precipitation. These results are consistent with the findings of Daniel and Grunder (2012), which emphasized that microclimatic elements, particularly humidity, play a crucial role in flight synchronization, regardless of immediate climatic changes such as precipitation. The fact that humidity remains significant even when multiple climatic variables are included in the model further supports its dominant role in shaping adult activity.

The logistic model (Figure 7) shows marginal significance for humidity (β=0.270; *P*=0.0711) in relation to the likelihood of exceeding the threshold catches, underscoring the biological importance of this variable. While the statistical significance is not conclusive, the graph clearly shows a trend of heightened activity at humidity levels above 70%. This trend is consistent with our initial hypothesis that higher humidity increases the probability of exceeding daily capture thresholds.

The visual representations displayed (Figures 3–8) and the analytical findings (Table 3) illustrate that the models exhibit a moderately strong ability to predict outcomes, especially during the peak period. The multivariate model has an R^2 value of 0.41, which is considered satisfactory for operational forecasting. This model can function as a basis for adaptive population management in this area. Nevertheless, these predictive values should be interpreted with caution, as the study was conducted in only two orchards during a single season, which may limit the generalizability of the results.

The findings emphasize the significance of humidity as a crucial parameter for monitoring and early warning systems associated with *R. cerasi*. Rather than concentrating exclusively on temperature, it is important to enhance or reevaluate this method by integrating various climatic elements. This approach will enable more accurate planning of agricultural strategies and minimize the chance of missing critical biological stages. In practical terms, incorporating humidity-based thresholds into routine monitoring could help optimize inspection intervals and improve the timing of control measures.

CONCLUSIONS

This research highlights the importance of atmospheric humidity as a critical climatic element influencing the seasonal behavior of *Rhagoletis cerasi*. Results from three statistical models suggest that humidity levels exceeding 70% are associated with a greater likelihood of surpassing threshold catches and increased flight activity, particularly when temperatures exceed 18 °C. Although temperature influences overall population dynamics, it is not the main predictor, and precipitation is not statistically significant.

The multiple linear regression model demonstrated a satisfactory level of explanatory power (R^2=0.41), indicating its effectiveness for operational forecasting. This suggests that incorporating atmospheric humidity into the tracking and strategizing of plant protection measures can enhance the management of cherry flies.

Adjusting agricultural techniques to account for microclimatic conditions enables prompt decision-making and enhances pest management, minimizing the potential for financial loss. Adjusting agricultural practices to account for microclimatic conditions enables timely decision-making and improves pest management, thereby minimizing potential financial losses. At the same time, the conclusions should be interpreted with caution, as the study was conducted in only two orchards over a single season, highlighting the need for future multi-year and multi-location research.

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