sciendo DOI: 10.2478/ats-2025-0004 AGRICULTURA TROPICA ET SUBTROPICA, 58 OV, 33–44, 2025

Original Research Article

Influence of temperature on the population dynamics of *Parlatoria ziziphi* and potential for biological control by the parasitoids *Aphytis* and *Encarsia* in citrus orchards

Farid **Mezerdi**[1], Kamila **Gacem**[2]

[1] *Laboratory Promotion of Innovation in Agriculture in Arid Regions (PIARA), Department of Agronomic Sciences, University of Biskra, Algeria; f.mezerdi@univ-biskra.dz; (https://orcid.org/0000-0002-4388-2520)*
[2] *Laboratory of Ecosystem Diversity and Agricultural Production System Dynamics in Arid Zones (DEDSPAZA), Department of Agronomic Sciences, University of Biskra, Algeria*

Correspondence to:
K. Gacem, Laboratory of Ecosystem Diversity and Agricultural Production System Dynamics in Arid Zones (DEDSPAZA), Department of Agronomic Sciences, University of Biskra, Algeria,
e-mail: kamila.gacem@univ-biskra.dz; (https://orcid.org/0000-0002-0800-110X)

Abstract

The black scale, *Parlatoria ziziphi* (Lucas, 1853), is a significant citrus pest that weakens trees, reduces fruit quality, and significantly lowers production, thereby affecting profitability. Parasitoids play a key role in its biological control, parasitizing *P. ziziphi* at different developmental stages. This study aimed to examine the population fluctuations of *P. ziziphi* in citrus orchards in the Kadiria region (Bouira, Algeria). Additionally, we investigated the influence of temperature on its development and mortality and identified potential biological control agents. Weekly monitoring was conducted in a citrus orchard to assess *P. ziziphi* populations on orange and mandarin trees. Leaf and fruit samples were collected for identification. The pest was also reared under controlled laboratory conditions to determine its life cycle. The study found that *P. ziziphi* was more frequently present on leaves and fruit, and laboratory observations identified two parasitoids from the genera *Aphytis* and *Encarsia*, though the parasitism rate was low. Moderate temperatures favored *P. ziziphi* infestations, particularly during the citrus harvesting phase. Regression analysis showed that temperature variations significantly influenced the pest development and mortality. For mandarin orchards, temperature accounted for 33% of the variation in *P. ziziphi* development/mortality ($R^2 = 0.330$, $p = 0.020$). For orange orchards, the correlation was stronger, with temperature explaining 48.5% of the variation ($R^2 = 0.485$, $p = 0.001$). The findings highlight the role of temperature in influencing *P. ziziphi* population dynamics. While the natural parasitoids were identified, their impact on controlling the pest remains limited. These insights contribute to understanding the pest behaviour and improving management strategies for sustainable citrus production.

Keywords: dynamics; infestation; Kadiria; mealybugs; mandarin; orange, parasitoid; *Parlatoria ziziphi*.

INTRODUCTION

The Rutaceae family includes three genera: *Citrus*, *Poncirus*, and *Fortunella*. *Citrus* is the most important since the orange tree represents it, as well as the lemon, the mandarin, the clementine, and the pummelo (Uzun and Yesiloglu, 2012). However, *Citrus* cultivation faces significant challenges due to various pests and diseases; for example, the Diaspididae family includes several species detrimental to *Citrus*. This family includes the commonly called "protected" or "shield" mealybugs of economic importance as agricultural pests very well adapted to parasitic life; they are characterised by a marked sexual dimorphism and are the most numerous and specialised group within the Coccoidae (Taibi et al., 2016). Currently, approximately 2,650 species are known, distributed among around 400 genera (Harsur et al., 2019). Several species of the Diaspididae family have been detected on *Citrus*; three species belong to the genus *Parlatoria*: *P. cinerea*, *P. pergandii*, and *P. ziziphi* (Almeida et al., 2018). These mealybugs are difficult to detect as they are well hidden and have been identified in most citrus-growing regions worldwide. High population densities can lead to total loss of production and cause spots that affect the fruit's commercial value, both for export and the local market (Gravena et al., 1992).

The development of *Citrus* cultivation, sensitive to infestations caused by several hidden diseases and pests that cause serious damage, poses several issues, not only technical and economic but also commercial. Diaspididae mainly cause damage throughout the northern strip of Algeria (Aroua et al., 2020). *P. ziziphi* affects twigs, leaves, and fruit. Sap withdrawals lead to a decrease in host vigor, and foliage and fruit may show yellow discoloration. Severe infestations can end in premature leaf and fruit drops (Haddad et al., 2019).

Mealybugs generally cause considerable damage to crops despite their numerous natural enemies that are likely to limit their outbreak. Only predators and parasitoids have been investigated in several cases (Jendoubi and Suma, 2021).

This study is based on the following hypotheses.

Citrus orchards in Kadiria have high populations of *Parlatoria ziziphi*, which could damage production and, in particular, fruit quality.

This black scale attacking *Citrus* in the region is the most abundant during the harvest season and, therefore, the most damaging.

This research had the following objectives.

Identify the phases of the black scale by morphological characteristics. Determine the layout of the tree (leaves, fruit, and branches).

Establish the life cycle of the species found between November 2021 and February 2024 in the laboratory.

Understand the relationship between its life cycle and environmental conditions, particularly temperature.

Parasitoid detection has two other objectives: to recognise parasitoid species under the microscope and to obtain information on population abundance and biological aspects of the species, which could be considered a biological control for this pest.

MATERIAL AND METHODS

Presentation of the study orchard

The sampling took place from November 2021 to February 2024 in a *Citrus* orchard of 6 hectares at the edge of a highway (Highway A1. East-West; 36°31′32″ N, 3°41′30″ E, altitude 1.33 km) in the agricultural area of the commune of Kadiria (Bouira: Algeria) that has a semi-arid climate, with a dry summer season lasting most of the year and a wet season, with low rainfall in the latter years, this orchard is divided into two parts, with orange trees in the first, and mandarin trees in the second. It is moderately maintained in winter and pruned for formation during the spring-summer period. No phytosanitary treatments against insect pests were performed during the study period.

Non-biological materials

Pruning shears and paper bags for collecting leaves and fruits, labelled with sampling date, orchard number, and direction, following the manual sampling methodology described in Mezerdi and Gacem (2022).

A refrigerator to store samples to stop the development of stages during the counting period. A binocular magnifying glass was used to count the individuals of the scale insect with pins. Petri dishes were used to monitor the emergence of mealybug parasitoids.

Morphology of black scale *Parlatoria ziziphi*

The scale insect appears as black oval spots, the back shield covering the body of the female measures 1.25 mm broad by 2 mm in length, the second exuviae is the most developed and has four longitudinal carinae which occupy much of the shield, in the posterior part of the same is a white serous appendage. The body of the adult female is oval with two lobe-shaped projections in the cephalic region and a membranous cuticle. The average body length is 0.67 mm, and the width is 0.58 mm. The pygidium is rounded, and on the edge, it presents three pairs of lobes, L4 in the form of a sclerotised point. Perivulvar pores (16) are arranged in four groups (Claps and Wolff, 2003).

The black portion is the exuviae of the second larval stage. It is rectangular with rounded corners. In the front is the exuviae of the first instar larva, also black but oval. A thin, whitish waxy production extends posteriorly to the exuviae of the second stage. The male shield is elongated, 1.0 mm long, white-grayish, and waxy with black exuviae of the first stage at the interior part. The nymph's body is violet and elongated, carrying two large dark spots on the cephalic segment (Krache and Bendenia, 2018).

Figure 1. Different developmental stages of the mealybug *Parlatoria ziziphi*

The living female is purplish, occupying only the anterior third of the shield, and the rest of the space is reserved for eggs. The body of the female is subcircular in shape. Microscopic examination of adult females mounted on slides is relatively easy to distinguish from those of other species of the genus *Parlatoria* by the presence of ear-like lobes on each side of the head.

The egg of *P. ziziphi* is arranged transversely in two parallel series and from 0.18 to 0.25 mm long. It has an oval shape and purple colour with a perfectly smooth and transparent chorion (Monastero, 1962).

Figure 1. continued. Different developmental stages of the mealybug *Parlatoria ziziphi*

The larvae of the first-stage future males settle and undergo a first larval molt after a short period, giving rise to a second-stage individual recognisable with two red cephalic anterior masses (Chapot and Delucchi, 1964).

Parlatoria ziziphi is immediately distinguished macroscopically from all other diaspines by the colour and shape of its shield, which is small, black, and rectangular (0.6 to 0.75 mm × 1.25 to 1.4 mm for adults) (Figure 1).

Sampling method

The sampling was conducted from November 2021 to February 2024. The study station was divided into two orchards, the first with 560 orange trees and the second with 400 mandarin trees. From each orchard, ten leaves and twigs were randomly selected and cut with shears at weekly intervals, and two fruits were collected at the height of a man in the four directions and the centre of the trees (Gacem and Mezerdi, 2022).

Method for counting mealybugs in the laboratory

The collected leaves and twigs were carefully examined under a binocular magnifying glass. We counted the different mealybug stages present on the fruits and both faces of the leaves, and a twig was taken at random and studied in each direction. The number of individuals of each developmental stage was then determined (Gacem et al., 2022).

The different biological states of the mealybugs were quantified and noted on cards bearing the date of the collection trip. The number of the tree, the direction of sampling, and parasitising individuals of *Parlatoria ziziphi* were also noted to appreciate the state of the infestations of the insect and the evolution of their parasitoids over time.

The two parasitoids, *Aphytis* and *Encarsia,* were also counted, as well as the shields with holes. The active parasitoids of these species were counted by lifting the shields of the mealybugs.

Data analysis

To examine the influence of temperature on *P. ziziphi* development and mortality, regression analysis and ANOVA were done using Microsoft Excel 2019's Data Analysis ToolPak. Regression analysis assessed the relationship between temperature variables (maximum, average, and minimum) and pest development/mortality rates, while ANOVA determined the statistical significance of temperature fluctuations and seasonal population differences.

Regression model:

The regression model follows the form:

$$Y = a + b_1*X_1 + b_2*X_2 + b_3*X_3$$

Y represents the number of *Parlatoria ziziphi* not parasitized

X_1(T °C Max), X_2(T °C Moy), and X_3(T °C Min) are the independent variables (temperature metrics)

a is the intercept

b_1, b_2, and b_3 indicate the effect of each respective temperature variable on Y.

ANOVA (Analysis of Variance) data is structured into:

Regression (Sum of Squares (*SS*), Mean Square (*MS*), F-statistic, and significance (*p-value*))

Residual (error component, *SS* and *MS*)

Total (sum of regression and residual *SS*)

This structure helps assess how well the independent variables explain the variation in Y.

The significance F value helps determine whether the model is statistically significant.

RESULTS

This work focused on monitoring mealybugs and assessing the parasitic incidence of two parasitoids found in populations of *Parlatoria ziziphi*. Additionally, this study evaluated the effect of temperature variables on the development and mortality of *Parlatoria ziziphi* (not parasitized) in mandarin and orange trees.

Total fluctuation temporal of *Parlatoria ziziphi* dynamics

Parlatoria ziziphi coexisted in the same substrate (mandarin and orange trees), they were present in different parts of the tree (fruit, leaf, etc.), and their abundance varied according to the climatic factors. The climate in the Kadiria study area is semi-arid. The average temperature over the year is 16.1 °C, and annual rainfall averages 652 mm. The increase in the number of mealybugs seen in the period after the end of autumn was a result of the heavy rains causing the flight of the auxiliaries. For mealybugs, their shields protect them from both the weather and phytosanitary treatments. We studied the fluctuations of the population dynamics of *P. ziziphi* on the leaves and fruits of mandarin and orange in the region of Kadiria, and by trying to gather the maximum information concerning some factors (period, orientations, and organs) which can act on the distribution of this mealybug on its host plant, to have a clearer perception on the behaviour of this last one and get an idea on what allows it to evolve during a period from November 2021 to February 2024.

The results obtained are shown in the graph (Figure 2). We noted a total of 7047 individuals in the mandarin trees and 5933 individuals throughout the study period in the orange grove distributed over 28 months. The number was low in November and then rose and stabilised at a peak during the period from January to the end of February.

The population of *P. ziziphi* did not exist in the months following the end of fruit harvesting, as climatic conditions were inadequate. The most important of them was the high temperature, after which a new generation emerged in September, which continued to increase until the second peak in December, followed by a second decline in the early months.

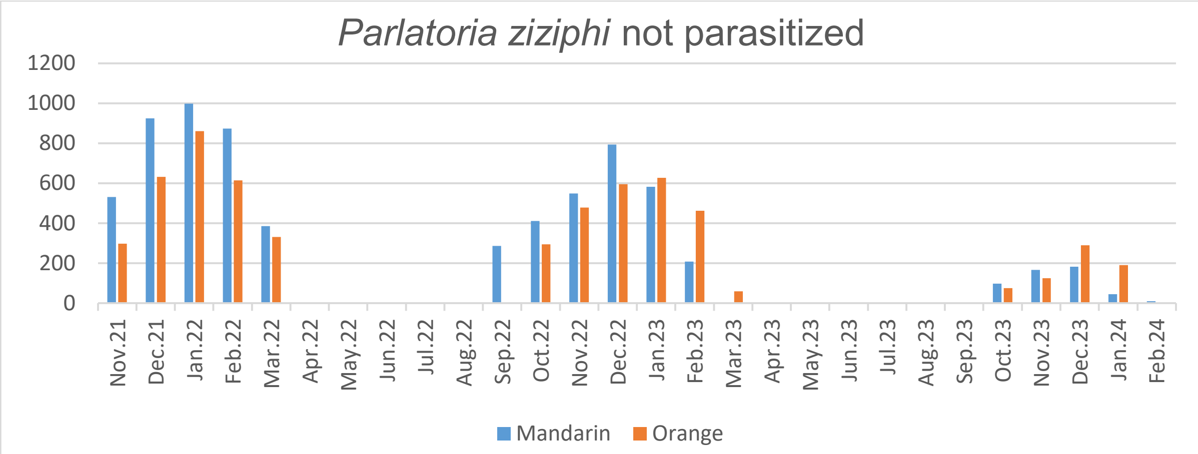

Figure 2. Evolution of *Parlatoria ziziphi* infestation on orange and mandarin trees as a function of time

The counting of *P. ziziphi* dynamics in *Citrus* clearly shows that winter and spring periods seem most suitable for its development. The highest peaks were recorded there. However, at the beginning of the fruit ripening each year, we observed an average population of *P. ziziphi* increasing until the end of December and January and then decreasing thereafter during the period until the end of February, after the end of the reap.

The summary of recorded results has shown that infection fluctuations were prevalent over the entire study period on orange and mandarin trees. It was clear that the mealybugs go through periods of activity. The largest number of individuals was observed in December and January, corresponding to the winter period, followed by a marked decline until the end of March. The second peak was recorded at the beginning of winter in 2023 and 2024.

Biological control of *P. ziziphi* dynamics

The study was carried out on adult parasitoids emerging from the shield of sampled mealybugs parasitized, and it aimed to reveal the impact of the parasitoids. The two parasitoids living on the shield, related to *Parlatoria ziziphi*, genus *Encarsia* (endoparasite) and *Aphytis* (ectoparasite), have been identified as the main biological control agents of the *P. ziziphi* populations (Figure 3).

The female parasitoids lay their eggs in the mealybugs. At the end of larval development, the adult parasitoids escape by piercing an opening in the mealybug shield.

As shown in the results illustrated above, the fluctuations in *Encarsia* and *Aphytis* parasitism exhibit two distinct peaks throughout the entire experimental period.

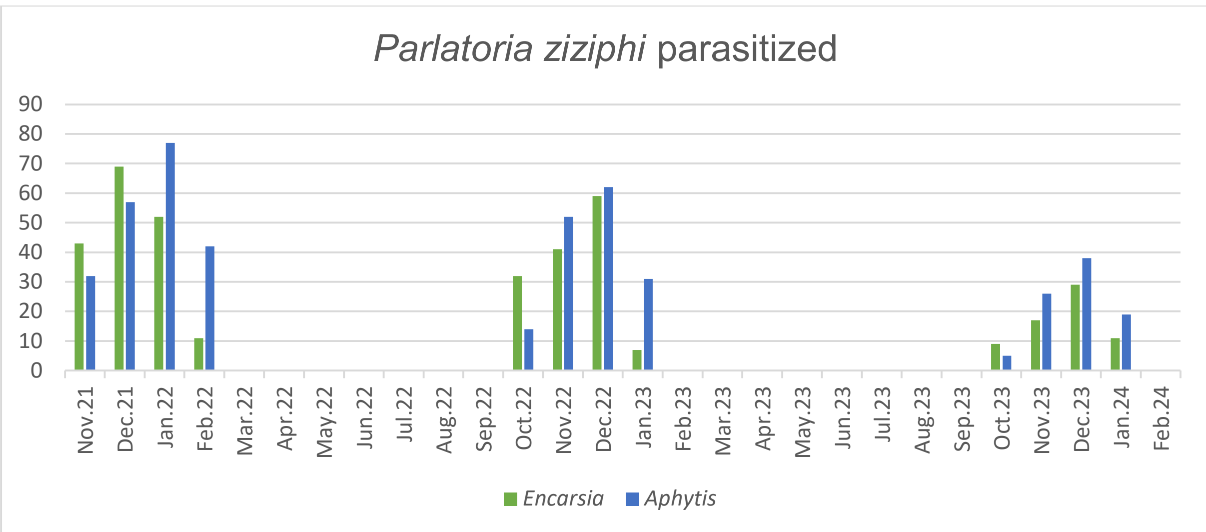

Figure 3. Population dynamics of *Parlatoria ziziphi* parasitized

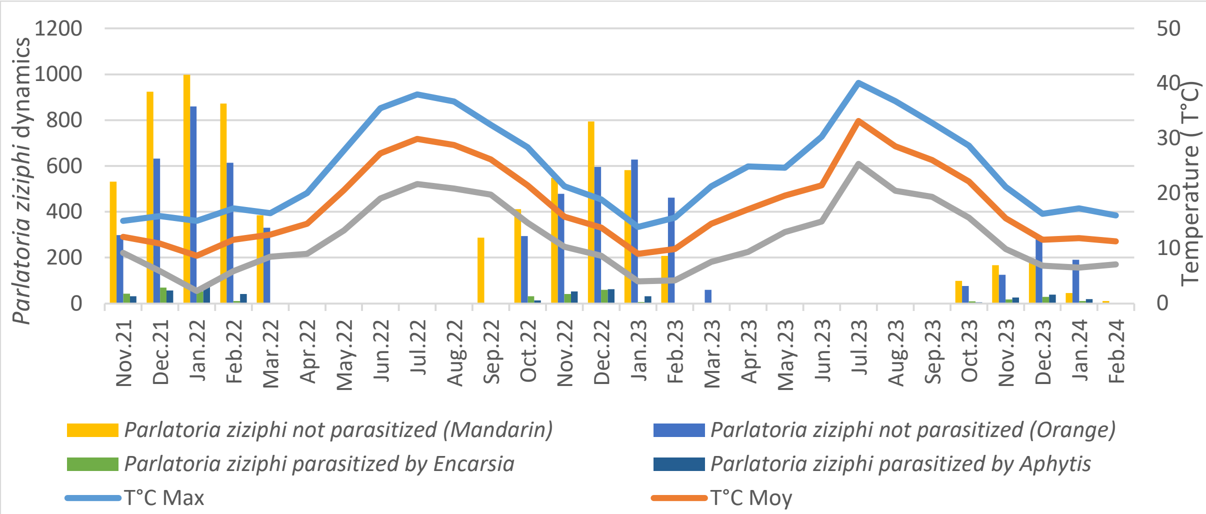

Figure 4. Impact of temperature on the dynamics of *Parlatoria ziziphi*

Impact of temperature on the dynamics of *Parlatoria ziziphi*

Temperature affects the rate of development of eggs, larvae, and adults. Optimal temperatures can accelerate the life cycle, while extreme temperatures (either too high or too low) can slow it down or inhibit reproduction. High summer temperatures can lead to increased mortality, particularly among immature stages. The total number of *P. ziziphi* was influenced by thermal variables (minimum, average, and maximum). Among the results obtained, the abiotic factor temperature had a significant impact on the black scale population, with a peak in winter with the availability of fruit hosts, followed by a continuous decline due to the negative impact of high temperatures on black scale population dynamics (Figure 4).

The average number of eggs laid per female was 34.3, and the females that fed on fruit laid more eggs than those fed on branches or leaves. Under controlled conditions, the shortest incubation period (4.4 days) was recorded at 27 °C and 65% relative humidity. Under natural temperature conditions (8.4–34.6 °C), the incubation period varied from 5.4 to 12.1 days. Larval stages lasted from 23.5 to 34.8 days for females and from 28.6 to 49.4 days for males.

The development and mortality of non-parasitised *Parlatoria ziziphi* in mandarin and orange trees were analysed using multiple linear regression to assess the influence of temperature variables (T °C Max, T °C Moy, T °C Min).

Mandarin regression model

The Mandarin regression model is:

$$Y = 808.87 - 56.18X_1 + 64.35X_2 - 30.11X_3$$

The intercept (808.87) represents the expected number of non-parasitized *Parlatoria ziziphi* when all temperatures are zero. The coefficient for T °C Max (−56.18) suggests that a 1 °C increase in maximum temperature decreases the count by approximately 56.18, though this effect is not statistically significant (P-value = 0.58). The coefficient for T °C Moy (+64.35) indicates that a 1 °C increase in the mean temperature increases the count by about 64.35, but this effect is also not significant (P-value = 0.76). The coefficient for T °C Min (−30.11) implies that a 1 °C increase in minimum temperature decreases the count by around 30.11, and it remains statistically insignificant (P-value = 0.80).

Model performance

The R^2 value for this model is 0.33 (33%), meaning the model explains 33% of the variation in non-parasitized counts. The significance F value is 0.02, indicating that the model is statistically significant overall.

ANOVA analysis

For the Mandarin model, the F-statistics is 3.94, with a significant F value of 0.02, which means that the model is statistically significant (Table 1).

Orange regression model

The Orange regression model is:

$$Y = 592.56 - 50.80X_1 + 94.31X_2 - 71.69X_3$$

The intercept (592.56) represents the baseline count when all temperature variables are zero. The coefficient for T °C Max (−50.80) suggests that a 1 °C increase in maximum temperature decreases the count by about 50.80, though this effect is not statistically significant (P-value = 0.48). The coefficient for T °C Moy (+94.31)

Table 1. Influence of temperature variables on the development and mortality of *Parlatoria ziziphi* (not parasitized) in Mandarin

Regression Statistics model: $Y = a + b_1*X_1 + b_2*X_2 + b_3*X_3$	
Multiple R	0.57464229
R Square	**0.330213762**
Adjusted R Square	**0.246490482**
Standard Error	284.909079
Observations	28

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	960467.7	320155.9	3.944109	0.020257
Residual	24	1948156	81173.18		
Total	27	2908624			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	808.874645	268.4834	3.012754	0.00602	254.7521	1362.997	254.7521	1362.997
T°C Max	–56.1774666	99.56716	–0.56422	0.577842	–261.674	149.3191	–261.674	149.3191
T°C Moy	64.34883584	204.1676	0.315177	0.755352	–357.032	485.73	–357.032	485.73
T°C Min	–30.10855315	116.5025	–0.25844	0.798273	–270.558	210.3407	–270.558	210.3407

implies that a 1 °C increase in mean temperature increases the count by roughly 94.31, but this is not significant (P-value = 0.52). The coefficient for T °C Min (–71.69) indicates that a 1 °C increase in minimum temperature decreases the count by approximately 71.69, although this effect is not statistically significant (P-value = 0.39).

Model performance

The R^2 value for this model is 0.48 (48%), meaning the model explains 48% of the variation in non-parasitized counts. The significance F value is 0.001, indicating that the model is statistically significant overall.

ANOVA ANALYSIS

For the Orange model, the F-statistic is 7.52, with a significance F value of 0.001, suggesting that the model is more significant than the Mandarin model (Table 2).

Overall, the temperature moderately influenced the *P. ziziphi* dynamics, with a stronger effect observed in orange trees compared to mandarin trees. Despite the significance of the regression models, the lack of significance in individual temperature predictors highlights the complexity of ecological interactions affecting *P. ziziphi* populations.

DISCUSSION

Our results confirmed the observations of Podsiadlo and Bugila (2007), who regard *Parlatoria ziziphi* as a pest of *Citrus*. The insect causes twig dieback, premature fruit, and leaf drop. It is usually part of the fruit that cannot be removed, leading to heavy infestation, which reduces its commercial value and may render it unfit for human consumption. According to Cocuzza and Rapisarda (2017), ecological factors act on living beings by modifying their fertility and mortality rates, as well as the development cycles of *Citrus* mealybugs and, subsequently, population densities. Our complete examination of *Parlatoria ziziphi* populations on orange trees during the study period clearly shows that the spring period and the foliage of the trees, as well as the center orientation of the trees, are the most preferred elements by this scale because we recorded the highest peaks there.

The low abundance of individuals at the start of the study could be attributed to the activity of natural enemies, as suggested by Jendoubi (2018) and Githae (2021). Spring sap surges allowed *Parlatoria ziziphi* populations to peak, while the decline coincided with the return of natural enemies as weather conditions improved. Nutritional preferences also play a decisive role. As Abrol (2015) points out, the leaves richer in nutrients serve as preferred sites for *P. ziziphi*. Our

Table 2. Influence of temperature variables on the development and mortality of *Parlatoria ziziphi* (not parasitized) in Orange

Regression Statistics model: $Y = a + b_1{*}X_1 + b_2{*}X_2 + b_3{*}X_3$	
Multiple R	0.696189174
R Square	**0.484679367**
Adjusted R Square	**0.420264287**
Standard Error	200.9187485
Observations	28

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	911232.4	303744.1	7.524315	0.001023
Residual	24	968840.2	40368.34		
Total	27	1880073			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	592.5554588	189.3353	3.129661	0.004551	201.7865	983.3244	201.7865	983.3244
T°C Max	−50.79605243	70.21507	−0.72344	0.476405	−195.713	94.12072	−195.713	94.12072
T°C Moy	94.30837929	143.9796	0.655012	0.518689	−202.851	391.4677	−202.851	391.4677
T°C Min	−71.68766455	82.15789	−0.87256	0.391549	−241.253	97.87789	−241.253	97.87789

observations corroborate those of Ouzzani (1984), who reported a higher density of leaves compared to twigs. Regarding the tree orientation, also during our study period, the highest number of *P. ziziphi* at all developmental stages was recorded in the centre of the tree (Takarli 2012). According to Meziane (2007), northern and central exposures are the most favourable for scale development and female egg-laying as they provide shade and protection from direct sunlight.

The temporal and spatial distribution of the populations studied shows similarities with the results obtained by Adil and Bennia (2020), namely that the abundance of individuals of the same evolutionary stage differs on leaves and twigs for all orientations, while the distribution over time for each orientation is much greater in the north/south direction of the tree and in the centre. According to Chelghoum (2014), the species *Parlatoria ziziphi* was found in the south of the tree. The shade creates favourable microclimatic conditions with very low evaporation and higher humidity, influencing the mealybug population (Smirnoff, 1957).

Humidity had a greater influence than temperature on the population abundance of this species, with higher peaks in the summer-autumn seasons. Population density was positively influenced by high temperatures and negatively by low relative humidity and, to a lesser extent, precipitation. The highest population density was generally found in the lower part of the canopy. Most mealybugs were found on the upper leaf surface; the lower leaf surface was only infected when population density was very high. The black scale attacked lemons and oranges but had a strong preference for mandarins. Adult longevity varies between 50.8 and 88.2 days for females and 1.4 and 3.4 days for males (Medjdoub, 2014).

Our study aimed at determining the number of generations on orange leaves, showing two generations under Algerian conditions, one winter and the other spring.

The abundance of parasitoids and insect predators directly affects the abundance of phytophagous insect species. So, it is useful to follow the parasitism study in a mealybug population by determining the parasite incidence in the population (Belguendouz et al., 2017).

Mbieji et al. (2020) note that the genus *Parlatoria* affects young shoots, foliage, and fruit. Sap withdrawals decrease the host's vigor, and foliage and fruit may show yellow discoloration; these symptoms may be confused with those caused by other scale insects. Severe infestations can cause premature leaf and fruit drops, with the tiny black scales formed by the shields of adult females visible and covering large areas (Bugila, 2006). Leaves are the preferred feeding sites, but mealybugs also attack fruits and branches. This scale is found on both sides (Mansour et al., 2017). The results show that orientation did not influence the fertility of *Parlatoria ziziphi* at our study site. Therefore, we assume that the adult female cannot choose her oviposition site due to her fixation since the L2 stage. Nevertheless, the time factor indirectly affects the mealybug's fertility through the quantity and quality of the sap, which varies according to the season. In France, it is described as a potential pest and is listed as a pest of great economic importance in that country (Foldi, 2001).

Excessive concentrations of nitrogen or phosphorus applied to sweet orange seedlings caused an increase in the population density of *P. ziziphi*, applied calcium had no effect but potassium and magnesium had some impact, which varied according to *Citrus* variety. Studies conducted in Egypt, in low fields and under laboratory conditions, *P. ziziphi* reproduced sexually and had two generations per year on sour orange (Sweilem et al., 1984), and three generations per year on grapefruit. In Egypt, it was considered a secondary pest until 1972 when, with the increase in population, it became a major pest affecting *Citrus*. Studies on oranges reveal that the average number of *P. ziziphi*/leaf is 216.7; this density was recorded between August 1978 and July 1979 (Salama et al., 1985). In China, *P. ziziphi* has three to four overlapping generations yearly, overwintering in the adult stage. Mortality of the 1st stage larvae due to climatic factors, where some larvae have left the maternal shield and have not yet secreted their shield to protect themselves against the effects of climatic conditions, causing the larvae to dry out. Mealybugs are most vulnerable as young larvae when they are barely protected by their waxy secretion. We also noted high mortality among the populations of L1 and L2 female larvae and mature males and females in the summer months from April to August; the summer period is characterised by high natural mortality. This mortality is particularly due to the high drying temperatures that have characterised the scale insects' destruction. The oviposition period lasted 79–135 days, and eggs averaged 7.8–11.6 days to hatching, with 89.7–99.7% hatching (Huang et al., 1988). In Brazil, in the municipalities located in the north of the state of São Paulo, it was found that *Aphytis hispanicus* in a low percentage of *Parlatoria cinerea*, the highest parasitism was observed in January, and the lowest in December, was also found a higher frequency of mealybugs with signs of parasitism on the fruit peduncle, but the maximum emergence of parasitoids occurred in the superficial roots of the tree (Pazini and Gravena, 1994).

CONCLUSION

This study confirms the presence of *Encarsia* and *Aphytis* parasitoids in *Parlatoria ziziphi* populations, emphasising their role in natural pest control. Temperature influences *P. ziziphi* dynamics, explaining 33% of its variation in mandarin orchards ($R^2 = 0.330$, $p = 0.020$) and 48.5% in orange groves ($R^2 = 0.485$, $p = 0.0010$), though other environmental and biological factors also contribute. With peak pest activity from November to February, aligning with sap-rich host availability, monitoring Diaspididae populations is crucial. Given the limitations of chemical control due to the strong adhesion of *P. ziziphi* shields, biological control presents a sustainable alternative for improving *Citrus* pest management.

CONFLICT OF INTEREST

The authors declared no conflicts of interest concerning the research, authorship, and publication of this article.

ETHICAL COMPLIANCE

The authors have followed ethical standards in conducting the research and preparing the manuscript.

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Received: March 17, 2024
Accepted after revisions: March 31, 2025