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Mealybugs in Mediterranean persimmon: fruit infestation, seasonal trend and effect of climate change

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With 4 figures

Abstract: Mealybugs (Hemiptera: Pseudococcidae) are the main pest of persimmon in Spain, the second producer in the world. In order to develop an Integrated Pest Management (IPM) program, it is necessary to identify the main mealybug species, determine their phenology, and develop tools to predict damage. To do this, we sampled 17 orchards from the main persimmon producing area in Spain over two years. *Pseudococcus longispinus* (Targioni-Tozzeti) was the most abundant and widely distributed species. This mealybug species completed three generations per year and reached peak density just before harvest. Fruit infestation at harvest was highly correlated with mealybug density in spring and summer. The estimated thermal constants to complete development and one generation were 512.5 and 956.3 degree days, respectively. Based on climate change predictions, crop damage caused by the third generation of *P. longispinus* will increase in 2040 and the mealybug will complete a fourth generation by 2080. *Pseudococcus longispinus* has become the main pest for Mediterranean persimmon and damage produced by this mealybug may be exacerbated by climate change. This work provides essential data to design a sampling protocol and determine intervention times and thresholds against this mealybug.

Keywords: degree-days; Pseudococcidae; phenology; *Pseudococcus longispinus*; climate warming

1 Introduction

Pest pressure tends to increase after the first years of planting a new crop in a new area (Panizzi & Correa-Ferreira 1997). This trend has also occurred with the expansion of persimmon in Spain. The area dedicated to growing persimmons has increased sixfold in the last 25 years in this country, that has become the largest producer of persimmon in the Mediterranean basin and the second producer in the world (FAO 2022). In the last decade, the density of some pests has increased, and mealybugs stand out among these pests (Fernandez-Zamudio et al. 2020; García-Martínez 2019).

Mealybugs represent the main threat for Spanish persimmons. In 2021, farmers reported a 20–25% decrease in production that represented 40€ million losses due to the damage produced by mealybugs (ASAJA 2021). The damage is caused by the honeydew excreted by mealybugs which supports the growth of sooty mold, depreciating the fruits (García-Martínez 2019). Additionally, persimmon fruits can lose commercial value due to the mere presence of mealybug at harvest. The three most abundant mealybug species in Spanish persimmon orchards are *Pseudococcus longispinus* (Targioni-Tozzeti), *Pseudococcus viburni* (Signoret) and *Planococcus citri* (Risso) (García-Martínez et al. 2017; Prieto 2016). The cryptic behavior of mealybugs and their difficult identification make their management problematic. In order to develop Integrated Pest Management (IPM) programs against mealybugs, it is important to identify the mealybug species that are currently causing the damage in the main persimmon producing area and to study their seasonal trend and phenology.

As with other insects, temperature is the driving abiotic factor for mealybug development, and can strongly alter mealybug phenology (Martínez-Ferrer et al. 2003; Walton et al. 2013). Although other abiotic factors such as humidity may also affect mealybug development, the magnitude of their effect seems to be lower than temperature (Gillani et al. 2009). From the mid-20th century to the present, there has been a global increase in the average annual temperature and most models predict that greenhouse gas emissions will accelerate this warming during the 21st century (IPCC 2014). The Mediterranean basin is especially susceptible to this phenomenon (IPCC 2014; Zittis et al. 2019). Consequently, insects can be pervasively affected by climate change and the incidence of several insect pests can increase (Jactel et al. 2019; Skendžić et al. 2021). In the case of mealybugs,

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temperature increase can expand their distribution, decrease their generation time, and increase their fecundity and survival in winter (Fand et al. 2014; Jara et al. 2013; Ji et al. 2020). Therefore, it is necessary to study mealybug responses under the projected climate scenarios to predict future damages.

The aims of this work were to: i) determine the spatio-temporal dynamics of mealybug species in the main persimmon producing area of the Mediterranean basin; ii) determine seasonal trend, phenology, and fruit infestation of the main mealybug species; and, iii) predict the effect of climate change on mealybug phenology. To achieve the third aim, the thermal constant necessary to complete a generation for the main mealybug species identified was estimated under field conditions.

2 Material and methods

2.1 Spatio-temporal dynamics of mealybugs

Seventeen persimmon orchards located in Valencia, Spain, were selected. All persimmon orchards were managed under IPM guidelines, details of which are provided in Supplementary materials: Table S1. Within each orchard, a plot consisting of 40 trees (8 × 5) was established. This standardized size was used because it was the maximum area that could be applied to all the orchards of our study (Table 1). From each 40-trees plot, nine alternate trees were sampled (Supplementary materials: Fig. S1) in spring (between May 10 and 22), summer (between July 14 and July 27) and early-autumn (between September 27 and October 10) across two consecutive years (2020 and 2021). For each tree and date, 120 leaves (30 per cardinal direction), 40 fruits (10 per cardinal direction) and the surface of the trunk (from the base to a 50 cm height) were surveyed. Fruits and leaves were randomly chosen from those closest to the ground up to a height of 2 meters and from the external and internal part of the tree, and the trunk was inspected for 30 seconds. All mealybugs were counted and identified to species using taxonomic keys (Miller & Giliomee 2011; Williams & Granara 1992). When necessary, insects were collected and transported to the laboratory for identification under stereo- or compound- (young nymphs of mealybugs) microscopy. All field observations were made between 9 a.m. and 4 p.m.

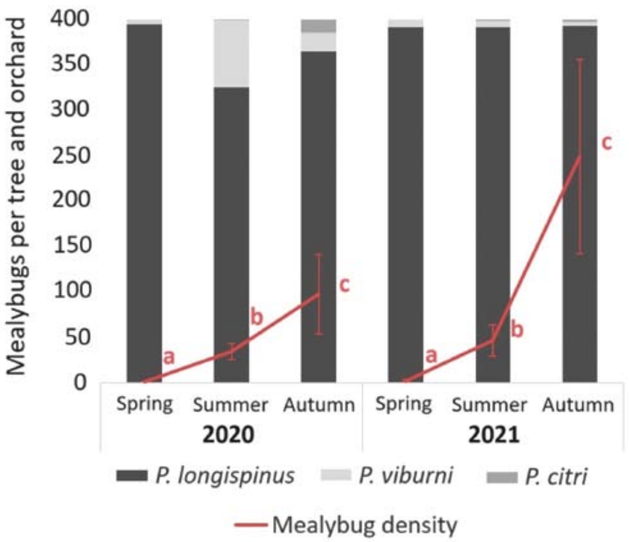

Fig. 1. Seasonal mealybug density in the 17 persimmon orchards in Valencia during 2020 and 2021. Presented as the mean number of mealybugs sampled per tree per orchard (± SE). Different letters represent significant differences between the mean densities of mealybugs in the three seasons of each year (Tukey test, $P < 0.05$). Bars represent the seasonal relative abundance of each mealybug species.

To study the seasonal trend of mealybugs, mealybug density was calculated for each mealybug species as the mean number of mealybugs (sum of mealybugs observed in 120 leaves, 40 fruits, and trunk) per orchard (mean of nine trees) and sampling date. To evaluate whether mealybug density was affected by season and year, a factorial generalized linear model (GLM) with Poisson distribution was used, with mealybug density (all mealybug species together) as the response variable and season (spring, summer and autumn) and year (2020 and 2021) as explanatory variables. Multiple comparisons to assess differences among seasons were based on Tukey's post hoc tests.

To study the geographical distribution of mealybugs, the relative abundance of each mealybug species for each orchard and year was calculated.

2.2 Fruit infestation of *P. longispinus*

To estimate the damage caused by the most abundant mealybug species, *P. longispinus*, the proportion of fruit infested by this mealybug at harvest was calculated. The proportion of fruit infested by mealybugs at harvest can provide a good estimation of damage because these fruits lose commercial value due to mealybug presence. This proportion was calculated for each orchard (mean of 9 trees; 40 fruits per tree) and year as the number of fruits infested by *P. longispinus* divided by the number of sampled fruits. To determine whether the proportion of fruits infested by *P. longispinus* at harvest (autumn) can be predicted with early season sampling, in spring or summer, two GLMs with binomial distribution were used. The proportion of fruits infested in autumn was the response variable, while the proportion of fruits infested in spring or summer were the explanatory variables. Year (2020 and 2021) was also included as fixed factor in both models. The assumed error structures were then assessed using a heterogeneity factor equal to the residual deviance divided by the residual degrees of freedom. If an over- or an underdispersion was detected, we re-evaluated the significance of the explanatory variables using an F-test after re-scaling the statistical model by a Pearson's $\chi 2$ divided by the residual degrees of freedom. Significance was assessed by the change in deviance when a variable was removed from the model using a $\chi 2$ test with binomial error. Significant values are given for the minimal model, while the non-significant values are those obtained before we deleted the variable from the initial model (Crawley 2007).

2.3 Seasonal trend and phenology of *P. longispinus*

An orchard that had high density of *P. longispinus* (39°48′12.1″N 0°09′58.7″W 15 m. a.s.l) was selected to study the seasonal trend and phenology of this mealybug species over 2021 and 2022. In this orchard, 16 trees were selected and sampled twice per month. The same trees were sampled over the two years. From each tree, 40 leaves (ten per cardinal direction), 20 fruits (five per cardinal direction) and the surface of the trunk (from the base to a 50 cm height) were sampled, and the number of *P. longispinus* was recorded.

The mean number of mealybugs per tree and sampling date was recorded, as well as the developmental instar of each mealybug individual. Adult males were rarely seen and were not considered. The phenology was described based on the proportion of each mealybug instar per sample, and it was recorded only when more than 10 mealybugs were observed per sampling date. The number of generations per year was estimated by counting the number of peaks of first instar nymphs (herein after “peak of nymphs”).

2.4 Degree-days necessary to complete a generation and reach adulthood

Based on the calculated temperature thresholds for development under laboratory conditions (Costa et al. 2011; Raja et al. 2011), the degree-day curve of *P. longispinus* for the two study years was determined. For this, the daily mean temperature recorded in the closest weather station was used (SIAR Carlet, 6.5 km from the sampled orchard). Each day, the number of degrees above the lower threshold temperature for development of *P. longispinus* (8°C) was accumulated, up to 27°C, which is the optimal development temperature (Costa et al. 2011; Raja et al. 2011; Fig. S2). The upper temperature threshold is unknown for *P. longispinus*, but it is known that is above 32°C (Costa et al. 2011; Raja et al. 2011). As daily mean temperature in the study area does not exceed this temperature in any of our models, it was assumed that the development rate decreased linearly above the optimum temperature. Therefore, when the daily mean temperature exceeded 27°C, each degree above was subtracted from the optimal 19 degree-days (see supplementary materials: Fig. S2 for details).

The number of accumulated degree-days from January 1st until the first peak of nymphs was determined for the two years. January 1st was taken because the lowest temperatures in the area are reached in January (see supplementary materials: Fig. S3).

To calculate the degree-days necessary to complete a generation, the degree-days between consecutive peaks of nymphs within a year were calculated. Therefore, the degree-days between the first and second peaks of nymphs and between the second and the third peaks of nymphs for both years were calculated. Then, the mean for the four generations, two from each year, was calculated.

To calculate the degree-days necessary to reach adulthood, the number of accumulated degree-days between the peaks of nymphs and the subsequent peak of adult females was estimated. Then, the mean accumulated degree-days for four generations, two from each year, was calculated.

2.5 Effect of climate change on *P. longispinus* phenology

Different degree-day curves were generated with the temperature thresholds of *P. longispinus*, described in the previous section, but assuming changes in the daily mean temperature. Firstly, a degree-day curve that represents the current annual temperature trend was generated. To do this, the climate data from the last 10 years in the closest weather station was used (Carlet, 6.5 km from the sampled orchard; MAPAMA database). For each day, the average daily mean temperature in the last 10 years was calculated. Secondly, three additional curves were generated to simulate different scenarios. One degree-day curve was generated to simulate a recent past scenario (1972–1996), when this mealybug species was not problematic to Spanish persimmon. This curve was calculated with a daily mean temperature 1.1°C below the current temperature (i.e. each day was considered 1.1°C cooler than the average daily mean temperature in the last 10 years). This 1.1°C was the difference between the annual average temperature of the last 25 years (1997–2021) and the previous 25-year series (1972–1996) from the closest station recording temperatures in 1972. This was the Meteorological station #8416 of Valencia, 35 km from the sampled orchard (MAPAMA database).

Then, two degree-day curves with the most probable scenarios of temperature in the short-medium (2040–2060) and medium-long term (2080–2100) were generated. The curves were based on the predictions of the IPCC 2014 for the Mediterranean basin: an increase of ~1.5°C for the period 2040–2060 and ~3°C for 2080–2100 (IPCC 2014; Zittis et al. 2019). As the models agree that the temperature will increase more in summer than in winter in the Mediterranean area (Cos et al. 2022), the 2040–2060 curve was calculated with a daily mean temperature 1°C above the current temperature from December to February; +1.5°C from March to May; +2°C from June to August; and +1.5°C from September to November. The curve for the 2080–2100 scenario was based on the predictions of the IPCC 2014 for the Mediterranean basin (an increase of ~3°C) (IPCC 2014; Zittis et al. 2019). The 2080–2100 curve was calculated with a daily mean temperature 2°C above the current temperature from December to February; +3°C from March to May; +4°C from June to August; and +3°C from September to November.

Based on the number of degree-days necessary to reach the first peak of nymphs, to complete a generation and to reach adulthood under field conditions, which had been previously estimated, the number of generations per year and when they would occur under the three climate scenarios were estimated.

3 Results

3.1 Spatio-temporal dynamics of mealybugs

To study the geographical distribution and seasonal trend of the main mealybug species, 17 persimmon orchards were sampled in spring, summer and autumn of 2020 and 2021. A total of 66,065 mealybugs were counted and identified during the two years, 20,465 in 2020 and 45,600 in 2021. Of these mealybugs, 131 were observed on trunk (0.2%), 15,855 (24%) on leaves and 50,079 (75.8%) on fruit. Mealybug density, measured as mean number of mealybugs per tree per orchard, was higher in 2021 than in 2020 ($F_{1, 98} = 5.17$, $P = 0.025$) and was strongly affected by season ($F_{2, 99} = 6.6$, $P < 0.001$), independently of the year (Interaction season × year: $F_{2, 96} = 0.26$, $P = 0.77$) (Fig. 1). Mealybug density was significantly higher in summer than in spring, and in autumn than in summer.

Three species of mealybugs were identified: *P. longispinus, P. viburni* and *P. citri*. *Pseudococcus longispinus* was the most abundant species over the two-year study: 88.8% of the sampled individuals in 2020 and 98.2% in 2021. Moreover, *P. longispinus* was also the species with the widest distribution. It was present in 14 and 16 out of the 17 sampled orchards in 2020 and 2021, respectively (Fig. 2). *Pseudococcus viburni* was the second species in relative abundance (8.5% in 2020 and 1.4% in 2021). In both years, it was present across all seasons. *Pseudococcus viburni* was observed in nine and eight orchards in 2020 and 2021, respectively, but two of these orchards had very low abundance. *Planococcus citri* was present only in summer and autumn in both years and observed in seven orchards, but with low relative abundance (2.6% in 2020 and 0.4% in 2021).

3.2 Fruit infestation of *P. longispinus*

The proportion of fruit infested by *P. longispinus* was calculated in spring, summer and autumn of 2020 and 2021. These data were used to determine whether the infestation at harvest (autumn) can be predicted with the infestation

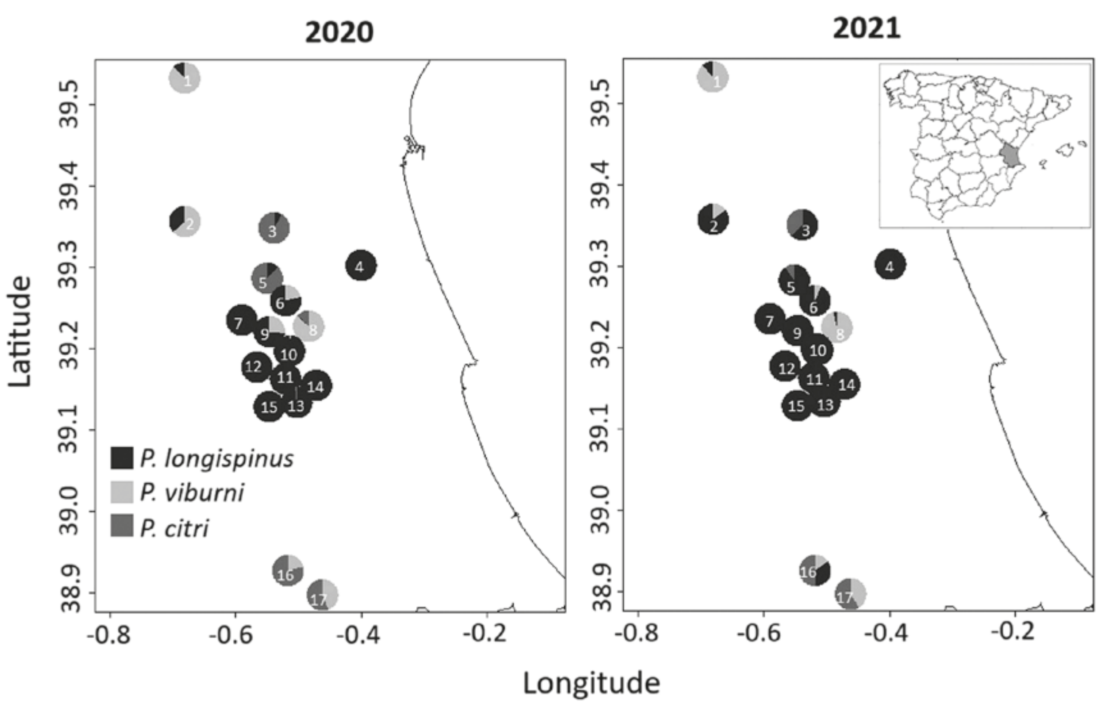

Fig. 2. Complex of mealybug species in the 17 persimmon orchards sampled in the main persimmon producing area of the Mediterranean basin (eastern Spain). The different shades represent the relative abundance of each mealybug species in each orchard and year (including the three sampling seasons: spring, summer and autumn). Geographical reference system: WGS84.

levels in spring or summer. The proportion of fruit infested by *P. longispinus* per tree and orchard in spring averaged 0.017 ± 0.006 in 2020 and 0.03 ± 0.015 in 2021. In summer, this proportion increased to 0.067 ± 0.048 in 2020 and 0.217 ± 0.064 in 2021. During the harvest period in autumn, the proportion of fruit infested by *P. longispinus* averaged 0.206 ± 0.053 in 2020 and 0.341 ± 0.093 in 2021.

The proportion of fruit infested by *P. longispinus* in autumn was positively correlated with the proportion in spring ($F_{1, 32}$ = 9.98, P < 0.001), without a significant effect of the year ($F_{1, 31}$ = 1.44, P = 0.24) nor a significant interaction ($F_{1, 30}$ = 0.39, P = 0.54). The model explained 43.8% of the total deviance (Fig. 3A and Table S2). Likewise, the proportion of fruit infested by *P. longispinus* in autumn was positively correlated with this proportion in summer ($F_{1, 32}$ = 60.18, P < 0.001), without a significant effect of the year ($F_{1, 31}$ = 2.4, P = 0.13) nor a significant interaction ($F_{1, 30}$ = 0.57, P = 0.46). The model explained 65% of the total deviance (Fig. 3B and Table S2).

3.3 Density and phenology of *P. longispinus*

To describe the density and phenology of *P. longispinus* in detail, a persimmon orchard was sampled twice per month in 2021 and 2022. *Pseudococcus longispinus* density was extremely low during the winter (Fig. 4). The few individuals observed between December and May were mostly adult females hidden under the bark of the trunk. At the beginning of May, when persimmons are setting, female adults of *P. longispinus* were observed moving towards the tree canopy and settling under the sepals of the newly set fruits. Then, *P. longispinus* density increased exponentially until harvest, reaching a maximum in October. In 2022, there was a slight decrease in *P. longispinus* density during mid-August, but then it grew exponentially again until October.

Three discrete generations of *P. longispinus* were observed per year, as shown by peaks of nymphs (Fig. 4). The first peak of nymphs was observed in mid-June of both years, with a proportion of first nymph instars of 0.64 in 2021 and 0.76 in 2022. The second peak of nymphs was observed in mid-August, when the proportion of first instar nymphs was 0.62 in 2021, and 0.49 in 2022. During 2022, the second peak of nymphs was taken as the intermediate date between two consecutive sampling dates, as the proportion of first instar nymphs and adults was similar on both dates. The third peak of nymphs was observed in early October both years, with a proportion of first instar nymphs of 0.73 in 2021, and 0.5 in 2022. The highest density of *P. longispinus* was reached at this third peak of nymphs both years (Fig. 4).

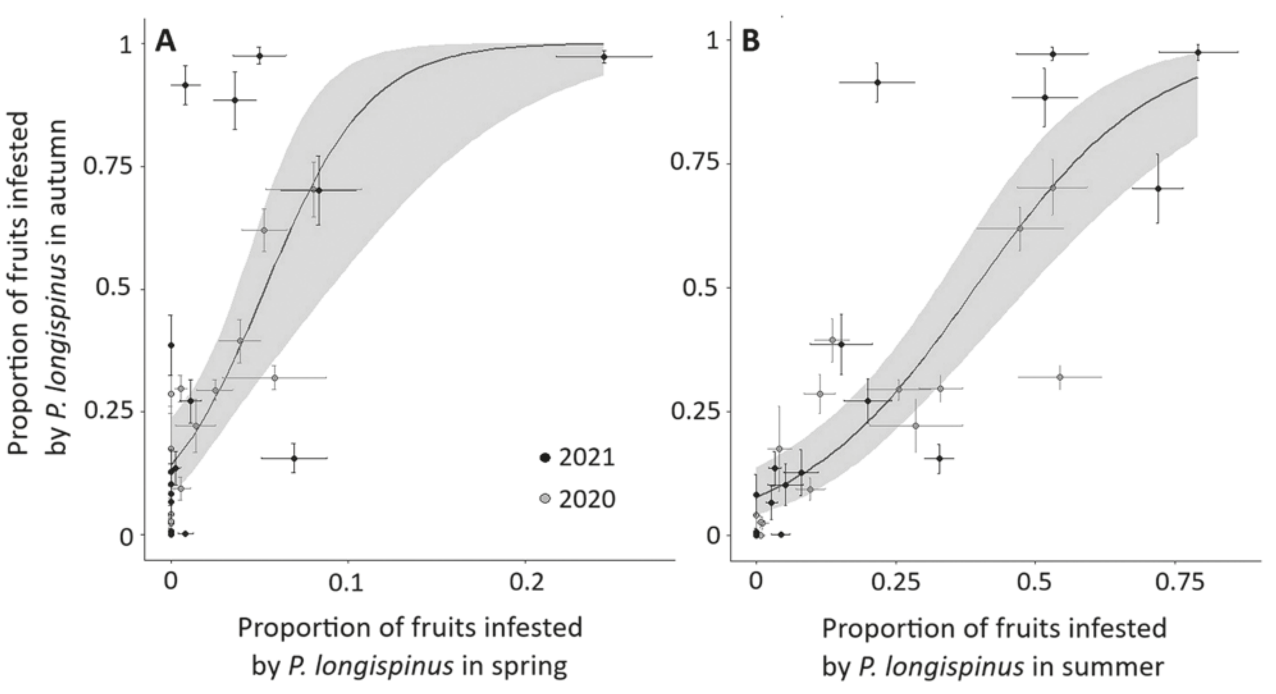

Fig. 3. The proportion of fruit infested by *P. longispinus* in spring **(A)** and in summer **(B)** to the proportion of fruit infested by *P. longispinus* in autumn. Each point represents the mean (± SE) proportion per tree and orchard in 2020 and 2021. Tree was the sampling unit for each orchard and there were nine trees per orchard. Lines represent the generalized linear models (GLMs) with binomial distribution. The year was not included as a factor in the model as neither the year nor its interaction with season were significant.

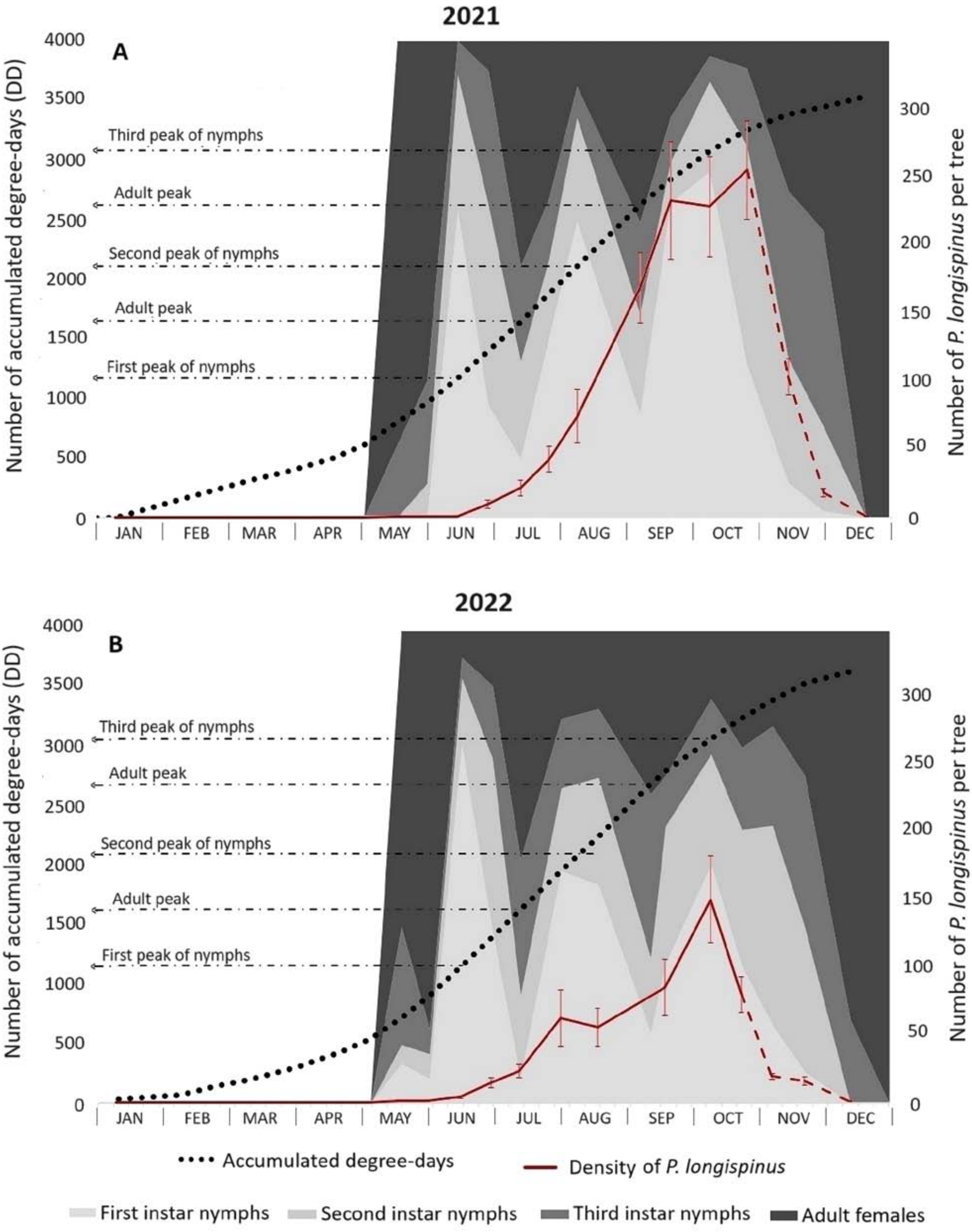

Fig. 4. Red lines represent the seasonal density of *Pseudococcus longispinus* in the persimmon orchard throughout 2021 and 2022, represented by the number of mealybugs per tree (Mean of 16 trees ± SE). The trunk surface, 40 leaves and 20 fruits were sampled in each tree. The dashed line represents the trend after fruit harvest, when only the trunk and leaves were sampled because the trees had no fruit. Grey scale represent the seasonal phenology of *Pseudococcus longispinus* in the persimmon orchard throughout 2021 **(A)** and 2022 **(B)**. The black dotted line represents the number of accumulated degree-days as of January 1st, considering the temperature thresholds for development of *P. longispinus*. Dashed horizontal lines represent the number of accumulated degree-days when the different peaks of first instar nymphs and adult females were reached.

3.4 Degree-days necessary to complete a generation and reach adulthood

The degree-days necessary to complete a generation and reach adulthood were calculated using the previous data. The first peak of nymphs was reached at 1176.7 and 1166.7 degree-days in 2021 and 2022, respectively (Fig. 4). Therefore, the mean degree-days (herein after "DD") for the first peak of nymphs was 1171.7 ± 5 DD. In 2021, the second and third peaks of nymphs were reached at 2112.4 and 3081.8 DD (Fig. 4A). In 2022, these peaks were reached at 2116.2 and 3086.9 DD (Fig. 4B). Therefore, in 2021 there were 935.7 DD and 969.4 DD between peaks of nymphs, while in 2022 there were 949.5 DD and 970.7 DD between these peaks. These values averaged a thermal constant of 956.3 ± 8.4 DD to complete each generation.

In 2021, the first peak of adult females was reached at 1651.1 DD and the second at 2626.1 D (Fig. 4A). In 2022, these peaks were reached at 1644 DD and 2702.2 DD, respectively (Fig. 4B). Therefore, there were 474.4 and 512.3 DD between the peaks of nymphs and the subsequent peaks of adults in 2021, and 477.3 and 586 DD in 2022. These values averaged a thermal constant of 512.5 ± 26 DD to reach adulthood.

3.5 Effect of climate change on *P. longispinus* phenology

To evaluate the effect of climate change on *P. longpispinus* phenology, we generated three models. These models represent the temperature between 1972–1996, when *P. longispinus* was not considered a pest in persimmon, and the most probable scenarios of temperature in the short-medium (2040–2060) and medium-long term (2080–2100) based on the predictions of the IPCC 2014 for the Mediterranean basin.

3.6 1972–1996 scenario

The generated model shows that *P. longispinus* would reach the two first nymphal peaks approximately two weeks later under the 1973–1996 scenario (Fig. S4; blue line vs. black line). The second generation would reach adulthood 20 days later (in late September instead of early September). The third peak of nymphs would be 40 days later, in November instead of October. This third generation would not reach the adulthood.

3.7 2040–2060 scenario

The generated model shows that *P. longispinus* will reach the three nymphal peaks approximately two weeks earlier under the 2040–2060 scenario (Fig. S4; orange line vs. black line). The second generation will reach the adulthood 12 days earlier. The third generation will reach the adulthood 56 days earlier, in late October instead of late December.

3.8 2080–2100 scenario

The generated model shows that *P. longispinus* will reach the three nymphal peaks approximately three weeks earlier under 2080–2100 scenario (Fig. S4; red line vs. black line). The second generation will reach adulthood 18 days earlier. The third generation will reach adulthood 70 days earlier (early October instead of late December). A fourth peak of nymphs will occur in November, so there will be one more generation.

4 Discussion

The number and density of pests has increased in persimmon after its expansion within the Mediterranean basin. This work demonstrates that *P. longispinus* was the main mealybug species in the main Mediterranean persimmon-producing area, and can cause high crop damage. In this manuscript, we have described the fruit infestation levels, the seasonal trend and the phenology of *P. longispinus*. We have also related these observations with current and expected temperature in the coming years under global warming. Finally, we used these data to suggest potential sampling protocols and management strategies against *P. longispinus* in persimmon.

The long-tailed mealybug *P. longispinus* was the most abundant and widely distributed mealybug species across the 17 persimmon orchards sampled in our two-year study. Previous studies had shown that *P. longispinus, P. viburni* and *P. citri* were equally abundant in this area until 2015 (García-Martínez et al. 2017; Prieto 2016). Our results showed that *P. longispinus* has become the predominant mealybug species. In our study, more than 20% of the fruit was infested by *P. longispinus* at harvest and this percentage increased from 2020 to 2021. The second year of the study, four of the 17 sampled orchards exceeded 80% of fruit infested by this mealybug at harvest. These infestation levels of *P. longispinus* are strongly higher than those reported five years earlier (García-Martínez 2019). Several factors could explain why *P. longispinus* has become the most abundant and damaging mealybug species in persimmon. Below, we discuss the effect of temperature and climate warming on the phenology and density of this mealybug.

Pseudococcus longispinus completed three annual generations per year in persimmon and reached the maximum density in the third generation that occurred in autumn, when persimmons are harvested. Field studies from other crops and countries with Mediterranean climate also observed three annual generations for *P. longispinus* (Furness 1976; Charles 1981). The thermal constants estimated in the present study could be useful to predict the peaks of young nymphs of *P. longispinus*, which are susceptible to insecticides. Many active ingredients have low efficacy against adult females because they are protected by wax (Ulusoy et al. 2022). If it is necessary to spray with insecticides, we recommend spraying against the first nymphal peak (1200 DD from January 1st) because persimmon fruit is not fully developed, and mealybug developmental stages are more exposed and susceptible to insecticides. Another strategy to improve the control of *P. longispinus* could be the release of natural enemies. The main natural enemy of *P. longispinus* in Mediterranean persimmon is the encyrtid parasitoid *Anagyrus fusciven-*

tris (Plata et al. 2023). This species parasitizes third instar nymphs and adult females of *P. longispinus*. Therefore, the optimal times for inoculative or inundative releases of this parasitoid would be when the proportion of adults is high (1650 and 2650 DD from January 1st).

To calculate the intervention thresholds against *P. longispinus*, it is first necessary to develop a sampling protocol. Our results demonstrate that fruit infestation at harvest can be predicted at the end of spring or mid-summer. Therefore, we suggest a binomial sampling based on direct observations of persimmon fruit in late spring (June) and repeat it in August, when the deviance explained by our model was higher. Monitoring the presence/absence of mealybugs by direct observation of fruit has been widely used in IPM programs of other mealybug species and in other crops (Pérez-Rodríguez et al. 2017). For Mediterranean persimmon, economic and environmental cost analysis must next be carried out to determine intervention thresholds.

Our models suggest that crop damage caused by the third generation of *P. longispinus* will increase in 2040 and the mealybug will complete a fourth generation by 2080 under the predicted climate models. Under the assumption of 1.5°C increase in the annual average temperature, predicted in the short-medium term (2040–2060), our models showed that the third generation will reach adulthood two months earlier, in late October instead of late December, so it would develop and cause damage (honeydew excretion) before harvest. Under the assumption of 3°C increase in the annual average temperature, predicted by the end of the century (2080–2100), *P. longispinus* will complete one more generation and a fourth peak of nymphs will occur in November. On the other hand, although the predicted average daily mean temperature does not exceed 32°C (Fig. 2), a high level of unpredictability is expected regarding heatwave events. *Pseudococcus longispinus* tolerates high temperatures (up to 39°C) for a limited time (Hollingsworth & Armstrong 2005), but prolonged periods above 36°C can increase mortality of *P. longispinus* nymphs (Costa et al. 2011). Our models also show that the temperature increase over the two hottest months, July and August, will slightly slow down *P. longispinus* development by exceeding its optimum temperature for development (Fig. S4). The effect of climate warming on mealybugs have been studied for several species (Fand et al. 2014; Jara et al. 2013; Ji et al. 2020). However, this is the first time that this question is addressed for *P. longispinus*. This mealybug species is present in most regions of the world and can affect a wide variety of crops. Our findings showed that climate warming may be a key factor causing outbreaks of *P. longispinus* and facilitating its pest status in some crops from temperate ecosystems such as the Mediterranean basin. Further research should evaluate how the effect of climate warming on *P. longispinus* can be modulated by the interactions between the mealybug, its natural enemies, and mutualistic ants, as temperature related biological and behavioral changes of these organisms can be contrasting (Gutierrez et al. 2008; Zhou et al. 2017).

5 Conclusion

Pseudococcus longispinus has become the most damaging pest in the main persimmon-producing area of the Mediterranean basin. The abundance and damage produced by *P. longispinus* may increase in the coming years because it might have a fourth generation due to rising temperatures. There is, therefore, an urgent need to develop an IPM program against this mealybug. Essential data to design a sampling protocol and determine intervention thresholds are provided in this manuscript. Our data show that fruit infestation at harvest can be predicted by sampling fruit infestation in late spring or mid-summer. The critical times to: i) spray insecticides against insecticide-susceptible instars; and ii) release the parasitoid *A. fusciventris* have also been determined. Further research should identify and evaluate the efficacy of this parasitoid in Mediterranean persimmon orchards, as well as the potential mutualistic relationship between *P. longispinus* and ants.

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References

ASAJA (2021). AVA-ASAJA y AEKAKI redoblan la reivindicación a la conselleria por el Cotonet que ya causa 40 millones de pérdidas en el caqui. https://www.asaja.com/publicaciones/ava-asaja_y_aekaki_redoblan_la_reivindicacion_a_la_conselleria_por_el_cotonet_que_ya_causa_40_millones_de_perdidas_en_el_caqui_9398

Charles, J. G. (1981). Distribution and life history of the long-tailed mealybug, *Pseudococcus longispinus* (Homoptera: Pseudococcidae), in Auckland vineyards. *New Zealand Journal of Zoology, 8*(2), 285–293. https://doi.org/10.1080/03014223.1981.10427968

Cos, J., Doblas-Reyes, F., Jury, M., Marcos, R., Bretonnière, P. A., & Samsó, M. (2022). The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. *Earth System Dynamics: ESD, 13*(1), 321–340. https://doi.org/10.5194/esd-13-321-2022

Costa, L., Prado, E., Viana de Sousa, M., Viana de Sousa, A. L., & Baptist, L. (2011). Effect of temperature on development and survival of the mealybug cochineal *Pseudococcus longispinus* (Targioni Tozzetti, 1867) (Hemiptera: Pseudococcidae) in coffee. *Coffee Science, 6*(2), 1–7.

Crawley, M. J. (2007). *The R book*. New York: John Wiley. https://doi.org/10.1002/9780470515075

Fand, B. B., Tonnang, H. E. Z., Kumar, M., Bal, S. K., Singh, N. P., Rao, D. V. K. N., … Minhas, P. S. (2014). Predicting the impact of climate change on regional and seasonal abundance of the mealybug *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) using temperature-driven phenology model linked to GIS. *Ecological Modelling, 288*, 62–78. https://doi.org/10.1016/j.ecolmodel.2014.05.018

FAO (2022). Crop and livestock product data. https://www.fao.org/faostat/es/#data/QCL

Fernandez-Zamudio, M. A., Barco, H., & Schneider, F. (2020). Direct measurement of mass and economic harvest and post-harvest losses in spanish persimmon primary production. *Agriculture, 10*(12), 581. https://doi.org/10.3390/agriculture10120581

Furness, G. O. (1976). The dispersal, age-structure and natural enemies of the long-tailed mealybug, *Pseudococcus longispinus* (Targioni-Tozzetti), in relation to sampling and control. *Australian Journal of Zoology, 24*(2), 237–247. https://doi.org/10.1071/ZO9760237

García-Martínez, O. (2019). Bases para una gestión integrada de plagas en el cultivo de caqui en la Comunidad Valenciana. PhD thesis, Universidad de Alicante.

García-Martínez, O., Urbaneja, A., Beitia, F., & Pérez-Hedo, M. (2017). Especies de cotonet y su dinámica poblacional en cultivo de cagui en la Comunidad Valenciana. *Phytoma, 286*, 52–55.

Gillani, W. A., Copland, M. J. W., & Raja, S. (2009). Effect of Different Humidity Levels on the Biology of Longtailed Mealy Bug *Pseudococcus longispinus* (Targioni and Tozzetti) (Homoptera: Pseudococcidae): Humidity Effects on *P. longispinus. Biological Sciences-PJSIR, 52*(5), 270–274.

Gutierrez, A. P., Daane, K. M., Ponti, L., Walton, V. M., & Ellis, C. K. (2008). Prospective evaluation of the biological control of vine mealybug: Refuge effects and climate. *Journal of Applied Ecology, 45*(2), 524–536. https://doi.org/10.1111/j.1365-2664.2007.01356.x

Hollingsworth, R. G., & Armstrong, J. W. (2005). Potential of temperature, controlled atmospheres, and ozone fumigation to control thrips and mealybugs on ornamental plants for export. *Journal of Economic Entomology, 98*(2), 289–298. https://doi.org/10.1093/jee/98.2.289

IPCC (2014). IPCC. In *Climate Change 2014 Synthesis Report Contribution of working groups I, II and III to the Fifth assessment report of the Intergovernmental Panel on Climate Change*, Core Writing Team, R.K. Pachauri and L.A. Meyer.

Jactel, H., Koricheva, J., & Castagneyrol, B. (2019). Responses of forest insect pests to climate change: Not so simple. *Current Opinion in Insect Science, 35*, 103–108. https://doi.org/10.1016/j.cois.2019.07.010

Jara, V., Meza, F. J., Zaviezo, T., & Chorbadjian, R. (2013). Climate change impacts on invasive potential of pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green), in Chile. *Climatic Change, 117*(1–2), 305–317. https://doi.org/10.1007/s10584-012-0542-1

Ji, W., Han, K., Lu, Y., & Wei, J. (2020). Predicting the potential distribution of the vine mealybug, *Planococcus ficus* under climate change by MaxEnt. *Crop Protection (Guildford, Surrey), 137*, 105268. https://doi.org/10.1016/j.cropro.2020.105268

Martínez-Ferrer, M. T., García-Marí, F., & Ripollés Molés, J. L. (2003). Population dynamics of *Planococcus citri* (Risso) (Homoptera: Pseudococcidae) in citrus groves in Spain. *IOBC/WPRS Bulletin, 26*(6), 149–161.

Miller, D. R., & Giliomee, J. H. (2011). Systematic revision of the mealybug genus *Delottococcus* Cox & Ben-Dov (Hemiptera: Pseudococcidae). *African Entomology, 19*(3), 614–640. https://doi.org/10.4001/003.019.0306

Panizzi, A. R., & Correa-Ferreira, B. S. (1997). Dynamics in the insect fauna adaptation to soybean in the tropics. *Trends in Entomology, 1*(1), 71–88.

Pérez-Rodríguez, J., Martínez-Blay, V., Soto, A., Selfa, J., Monzó, C., Urbaneja, A., & Tena, A. (2017). Aggregation Patterns, Sampling Plan, and Economic Injury Levels for the New Citrus Pest *Delottococcus aberiae* (Hemiptera: Pseudococcidae). *Journal of Economic Entomology, 110*(6), 2699–2706. https://doi.org/10.1093/jee/tox258

Plata, A., Gómez-Martínez, M., Beitia, F. J., & Tena, A. (2023). Do hyperparasitoids disrupt the biological control of *Pseudococcus longispinus* in persimmon? *Biological Control, 185*, 105310. https://doi.org/10.1016/j.biocontrol.2023.105310

Prieto, J. (2016). Plagas del caqui y enemigos naturales en la comarca de la Ribera Alta: abundancia y evolución estacional en el año 2015. Masther Thesis. Universidad Politécnica de Valencia.

Raja, S., Gillani, W., & Copland, M. (2011). Effect of different temperatures and host plants on the biology of the long-tailed mealy bug *Pseudococcus longispinus* (Targioni Tozzetti) (Homoptera: Pseudococcidae). *Pakistan Journal of Scientific and Industrial Research. Series B: Biological Sciences, 54*(3), 142–151. https://doi.org/10.52763/PJSIR.BIOL.SCI.54.3.2011.142.151

Skendžić, S., Zovko, M., Živković, I. P., Lešić, V., & Lemić, D. (2021). The impact of climate change on agricultural insect pests. *Insects, 12*(5), 440. https://doi.org/10.3390/insects12050440

Ulusoy, S., Kahya, D., Bilgin, M. G., & Apalak, A. (2022). The effectiveness of wax secretion on chemical control in some mealybug species. *Journal of Asia-Pacific Entomology, 25*(3), 101954. https://doi.org/10.1016/j.aspen.2022.101954

Walton, V. M., Dalton, D. T., Daane, K. M., Kaiser, C., & Hilton, R. J. (2013). Seasonal phenology of *Pseudococcus maritimus* (Hemiptera: Pseudococcidae) and pheromone-baited trap survey of four important mealybug species in three wine grape growing regions of Oregon. *Annals of the Entomological Society of America, 106*(4), 471–478. https://doi.org/10.1603/AN12152

Williams, D. J., & Granara de Willink, M. C. (1992). Mealybugs of Central and South America. 635 pp. Wallingford: CAB International. ISBN 0-85198-791-5.

Zhou, A., Qu, X., Shan, L., & Wang, X. (2017). Temperature warming strengthens the mutualism between ghost ants and invasive mealybugs. *Scientific Reports, 7*(1), 959. https://doi.org/10.1038/s41598-017-01137-0

Zittis, G., Hadjinicolaou, P., Klangidou, M., Proestos, Y., & Lelieveld, J. (2019). A multi-model, multi-scenario, and multi-domain analysis of regional climate projections for the Mediterranean. *Regional Environmental Change, 19*(8), 2621–2635. https://doi.org/10.1007/s10113-019-01565-w

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