



Article

Effects of Climatic, Chemical, and Cultural Control Strategies on Community Composition of Auchenorrhyncha and Population Dynamics of Two Major Green Leafhopper Pests in Peach Orchards

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Academic Editor: Fajun Chen

Received: 24 November 2024

Revised: 7 January 2025

Accepted: 8 January 2025

Published: 10 January 2025

Citation: Nascimento, P.M.; Neto, A.C.; Guerreiro, V.; Barateiro, A.; Anjos, H.; Coutinho, J.P.; Antunes, M.; Rebelo, M.T. Effects of Climatic, Chemical, and Cultural Control Strategies on Community Composition of Auchenorrhyncha and Population Dynamics of Two Major Green Leafhopper Pests in Peach Orchards. *Agronomy* **2025**, *15*, 163. <https://doi.org/10.3390/agronomy15010163>

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Abstract: A three-year study in two Mediterranean peach orchards monitored Auchenorrhyncha species, including the main vectors of plant pathogens causing significant economic losses. The research focused on the management of two polyphagous leafhoppers, *Asymmetrasca decedens* and *Hebata (Signatasca) solani*. Yellow sticky traps were used to track species dynamics and assess population trends in relation to meteorological factors such as temperature, rainfall, and humidity. Chemical treatments and early green pruning were evaluated for pest control effectiveness. Fifty-five Auchenorrhyncha species were identified, including vectors of *Xylella fastidiosa*. *H. solani* appeared from spring to early summer, and was gradually replaced by *A. decedens*, which peaked in late summer. Higher temperatures favoured *A. decedens*, while rainy days significantly reduced its presence. *H. solani* responded less consistently to meteorological factors, but increased with higher minimum relative humidity, and decreased with higher total humidity. These results highlight the need for targeted chemical control strategies to manage *A. decedens* during its peak season and the benefits of early green pruning to protect susceptible trees in spring. The results emphasise the role of climate in pest dynamics and provide important insights for IPM programmes to reduce economic losses in Mediterranean peach orchards worldwide.

Keywords: Auchenorrhyncha; pest; vector; peach; *Asymmetrasca decedens*; *Hebata (Signatasca) solani*; *Xylella fastidiosa* vectors

1. Introduction

Several species of Emboascini, a tribe of leafhoppers belonging to the subfamily Typhlocybinæ (suborder Auchenorrhyncha), are known pests of economically important crops, often causing infestations in agricultural fields, orchards, and greenhouses [1].

Notable examples are *Hebata (Signatasca) vitis* (Göthe) (= *Empoasca vitis*), *Empoasca fabae* (Harris) and *Jacobiasca lybica* (Bergevin & Zanon) [2–7].

The feeding activity of several leafhopper species on leaves causes symptoms known as hopperburn. This direct injury is characterized by leaves gradually turning yellow and reddish, then curling at the edges, resulting in tissue necrosis and a dry and burnt appearance [4]. In addition, leafhoppers can act as vectors for viruses and phytoplasmas [8,9]. Together with hopperburn symptoms, these factors can be highly detrimental to various crops, causing significant production and yield losses, as well as substantial control costs [10–12]. In the Iberian Peninsula, particularly in Spain, damage has been caused to grapevines, stone fruit, and almonds, and in Portugal to vines in the Douro, Ribatejo, and Alentejo regions, and more recently to peach, apricot, and plum orchards in the Beira Interior region [3,10,13–17]. The Beira Interior region is an important production area for stone fruits in Portugal, especially peach and cherry, accounting for 47.55% and 49.05% of the national production area for these fruits, respectively [18].

The main leafhopper species recorded in the Beira Interior region associated with crop damage is *Asymmetrasca decedens* (Paoli) [17]. *A. decedens* is a highly polyphagous species, first recorded in mainland Portugal in 2013, associated with various stone fruit orchards and the surrounding common alder, *Alnus glutinosa* (L.) Gaertn. [17]. In addition to causing injury resulting in hopperburn symptoms [10,19], *A. decedens* is a vector for “*Candidatus Phytoplasma phoenicium*” which is associated with almond witches’ broom disease (AlmWB) [20,21]. It is also a potential vector for the 16SrXB phytoplasma associated with European stone fruit yellows (EFSY) [22]. Environmental factors such as temperature, photoperiod, and precipitation influence the development of immatures and the abundance of adult leafhoppers [9,16,23–25].

Control options for these leafhoppers are limited, with chemical control being the primary method, particularly for *A. decedens*, which has shown significant resistance to conventional insecticides [15]. Insecticides containing active ingredients such as azadirachtin, acetamiprid, thiacloprid, and thiamethoxam have been tested for control of this species [26,27]. Biological control methods are not available, partly due to the limited information on natural enemies of Empoascini. However, *Aphelopus* (Hymenoptera, Dryinidae), *Anagrus* (Hymenoptera, Mymaridae), and the ectoparasite *Erythraeus ankaraicus* Saboori, Cobanoglu and Bayrarn (Acari, Erythraeidae) are known to parasitise several Typhlocybinae species, although no biological control programmes exist [28–32].

Due to the lack of information of *A. decedens* and the reported injury in orchards, this species was the main focus of this study. However, emphasis was also placed on *Hebata (Signatasca) solani* over other green leafhoppers as this species was the second most abundant, due to its potential role as an emerging pest, and because it shares ecological and behavioural traits with *A. decedens*. Also, given the extensive sampling effort, all Auchenorrhyncha were identified to understand the diversity in the orchard community.

Therefore, the main objective of this study was to investigate the dynamics of the Auchenorrhyncha community in Mediterranean peach orchards, with a particular emphasis on the two main green leafhopper pests, *Asymmetrasca decedens* and *Hebata (Signatasca) solani*. Specifically, the study had three main objectives: (i) to identify the diversity of Auchenorrhyncha species present in the orchards, with particular emphasis on those species that act as vectors or potential vectors of phytopathogens; (ii) to analyse the population trends of *A. decedens* and *H. solani* in relation to environmental factors such as temperature, rainfall, and humidity, identifying seasonal patterns and ecological interactions that influence their distribution, and (iii) to evaluate the effectiveness of different pest management approaches, including chemical treatments and cultural practices such as early green pruning, in reducing pest populations and increasing the resilience of peach trees. This research should

provide valuable information that can be used to inform integrated pest management strategies, ultimately reducing economic losses due to pest damage in Mediterranean peach orchards while promoting more sustainable agricultural practices.

2. Materials and Methods

2.1. Sampling Location

Auchenorrhyncha sampling was carried out in two peach orchards located in Louriçal do Campo ($7^{\circ}30'38.92''$ W, $40^{\circ}1'45.76''$ N) and Póvoa de Atalaia ($7^{\circ}24'23.90''$ W, $40^{\circ}4'12.19''$ N), in the Beira Interior region of mainland Portugal during 2018 (16 April–15 September), 2019 (12 April to 30 October), and 2020 (8 April–26 October) (Figure 1). The Louriçal do Campo orchard covers an area of 26.8 hectares, with 23,800 trees. To the north there are other peach and apricot orchards, to the south and west there is a riparian gallery with *Alnus* sp., *Salix* sp., and other riparian vegetation, and to the east there is a natural pasture and pine forest. The Póvoa de Atalaia orchard covers an area of 15.71 hectares, with 13,960 peach trees. It is bordered to the north and south by peach and cherry orchards, to the west by another peach orchard and a pine forest, and to the east by a water line and some *Alnus* sp., *Salix* sp., and other riparian vegetation. This orchard is also characterised by the presence of some small ponds and open water reservoirs. There is a drip irrigation system in both orchards.

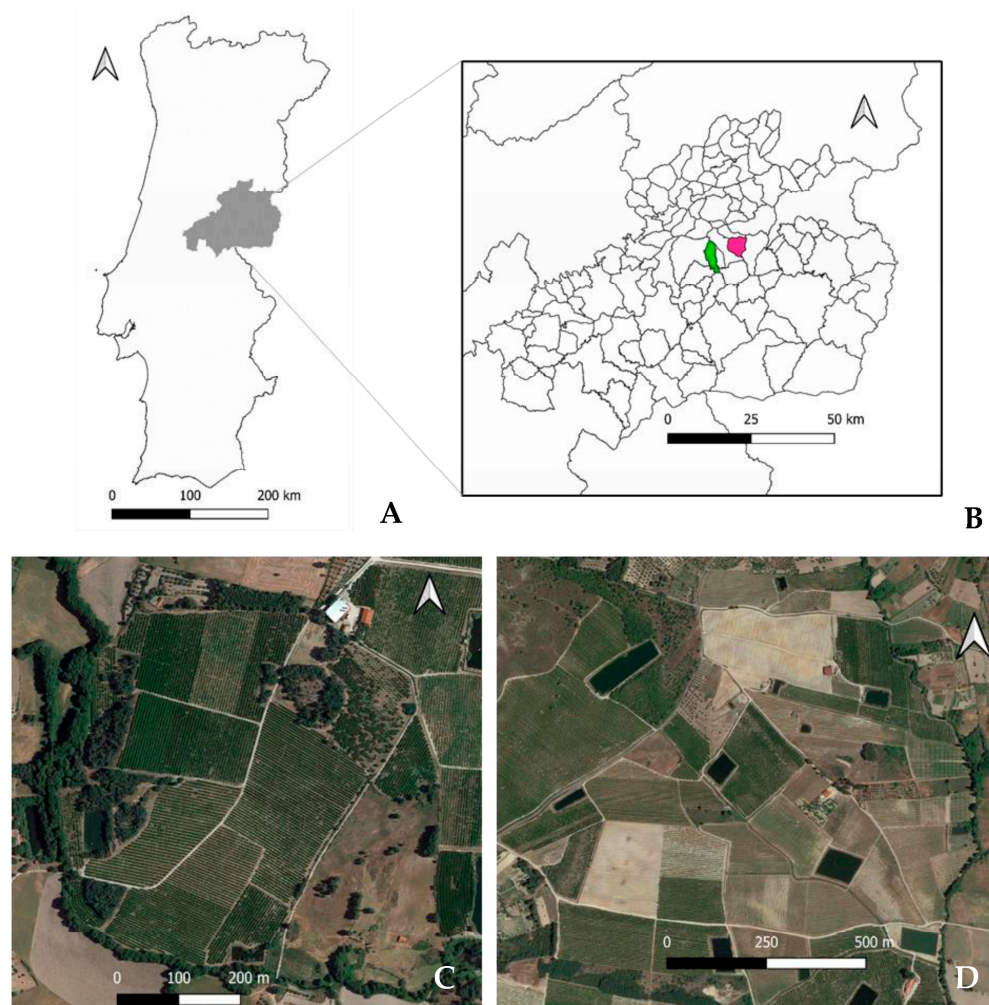


Figure 1. The location in mainland Portugal (A) encompasses the Beira Interior region (B), where the orchards Louriçal do Campo—green (C) and Póvoa de Atalaia—red (D) are situated.

2.2. Experimental Procedure

Yellow sticky traps (20 × 22.5 cm) from Biosani (Palmela, Portugal) were used to collect *Auchenorrhyncha* flying within the plot and transported to the laboratory in boxes. In 2018, four traps per orchard were placed in the middle of the plot, 50 m apart and 1.5 m above the ground, from April to September, and in 2019 and 2020, six traps per orchard were placed in the same way, from April to October, with all traps being replaced weekly. The leaves of the peach trees were observed and the progression of hopperburn symptoms was recorded each week when the traps were changed.

Green pruning is the selective removal of shoots, branches, or leaves during the active growing season, usually in late spring or summer. This process improves air circulation, light penetration, and canopy structure, thereby improving fruit quality and reducing disease pressure. Proper timing is essential to avoid stressing the plant. To assess the effect of green pruning on the susceptibility of peach trees to leafhopper attack, nine peach trees in the middle of the plot were pruned in 2018, including the monitored tree and eight adjacent trees. In 2019, pruning was expanded to 24–30 trees in three locations per orchard to increase replicates and strengthen statistical power in assessing the impact of pruning on green leafhopper activity. The dates of green pruning for 2018 and 2019 are shown in Table 1. No green pruning was carried out in 2020 to avoid further weakening of peach trees already susceptible to *A. decedens* attack.

Table 1. Green pruning in orchards of Louriçal do Campo (LC) and Póvoa de Atalaia (PA) was carried out in 2018 and 2019.

Date	Orchard
14 August 2018	Both
21 June 2019	LC
21 June 2019	PA
24 June 2019	PA
24–25 June 2019	PA
27 June 2019	LC
1 July 2019	LC
28–31 July 2019	LC

In addition to cultural practices, chemical control measures were implemented to assess their effectiveness in reducing peach pest populations. Orchards were treated with standard insecticides, acaricides, and fungicides according to manufacturers' recommended dosages and application schedules. The dates of the phytosanitary treatments for all three years are shown in Table 2.

To assess the influence of climatic factors on the population dynamics of *A. decedens* and *H. solani*, environmental data were recorded at the Póvoa de Atalaia climatological station, located approximately 10 km from Louriçal do Campo. Data included minimum, average, and maximum temperature; minimum, average, and maximum relative humidity; average solar radiation; average and maximum wind speed; total precipitation; number of cold hours (below 7 °C); and number of wet leaf hours. Since the *Auchenorrhyncha* data correspond to weekly totals, the meteorological data were aggregated into weekly minimum, average, and maximum for all daily measurements, as well as the number of days with non-zero precipitation. The interaction between climatic variables and pest abundance was analysed using the models described in Section 2.4.

Table 2. Insecticides, acaricides, and fungicides used in orchards of Louriçal do Campo and Póvoa de Atalaia in 2018, 2019, and 2020. Difenconazole, fluopyram and tebuconazole, lambda-cyhalothrin, and penconazole were applied according to the maturity of the varieties, with only one or two applications for each.

Active Ingredient	Pest	Application Date
acrinathrin	Red spider mite	2019 (29 May)
chlorpyrifos-methyl	San Jose scale	2018 (6 June)
cyprodinil	Moniliosis	2018 (20 March, 4–5 April)
copper oxychloride	Peach leaf curl, Gumspot of stone fruit	2018 (17–24 February), 2019 (7–14 February), 2020 (15–18 February)
deltamethrin + thiacloprid	Mediterranean fruit fly	2019 (29 July and 15 August)
difenconazole	Powdery mildew, Brown rot	2019 (12–14 April, 30 July–1 August), 2020 (20 July)
flonicamid	Aphids	2019 (21, 23 March), 2020 (18, 20 March)
fluopyram and tebuconazole	Moniliosis	2018 (16 April, 20, 28 June, 15 July)
fluopyram and tebuconazole	Brown rot	2019 (8, 18 July, 1, 24 August), 2020 (8, 23 June, 8, 18, 26 July, 4, 14 August)
imidacloprid	Aphids	2018 (26, 27 March)
lambda-cyhalothrin	Mediterranean fruit fly	2018 (20, 28 June, 15 July), 2019 (8, 18 July, 1, 24 August), 2020 (8, 23 June, 8, 18, 26 July, 4, 14 August)
penconazole	Powdery mildew	2018 (26–27 April), 2019 (22–26 June), 2020 (2–3 June)
spinetoram	Thrips	2018 (27 March)
spirodiclofen	Red spider mite	2018 (13 June)
sulfur	Powdery mildew	2018 (13 June), 2019 (16, 21–23 May) 2020 (3–4 May)
thiram	Peach leaf curl, Gumspot of stone fruit	2018 (9–12 March, 16 April), 2019 (2–3, 21–23 March)
ziram	Peach leaf curl, Gumspot of stone fruit	2018 (4–5 April), 2020 (27–28 February, 13, 24 March)

2.3. Morphological Identification

Specimens were individually detached from the sticky traps using a citrus oil solvent (3M, Lisbon, Portugal), sorted on the basis of morphological characteristics, and identified to the lowest possible taxonomic level according to several identification keys [8,33–47]. Most identification keys are based on male genitalia characters. Therefore, males are usually required for identification and male genitalia preparation was necessary. Females that could not be identified to species were grouped into morphospecies (i.e., taxa based on morphological similarity). The specimens preserved in labelled microtubes containing 70% ethanol are kept in the entomological collection of the FCUL. While the entire Auchenorrhyncha community was identified, the focus was on the Typhlocybinae due to the characteristic leaf injury observed in the orchards, consistent with previous reports on stone fruits [10,16,17] and almonds [13] in the Iberian Peninsula.

2.4. Data Analysis

Given the count data with excess zeros and the goal of identifying factors affecting leafhopper abundance (measured as individuals per trap over seven days), zero inflation regression models were the appropriate choice. These models account for the inflated number of zeros by allowing for two processes: one that generates structural zeros (where the result is always zero, because the species is not present at that time of the year), and another that generates zeros with some probability even though the species may be present (indicating that zero individuals were captured even though the species is present in the environment). This class of models is also suitable for dealing with overdispersion, where the variance of the data exceeds that expected from a standard counting model [48].

The experimental design involved weekly replacement of traps in the same location in two orchards over a three-year period, generating dependent data with a hierarchical structure. The inclusion of random effects in the models allows these data specific characteristics to be adequately addressed.

Zero-inflated Poisson (ZIP) and zero-inflated negative binomial (ZINB) generalised linear models with fixed and random effects components were used to model abundance. Random effects were nested by Trap within Site and crossed along Year. The choice

between Poisson and negative binomial models was based on the dispersion of the count data and the ability of the model to fit the excess of zeros. Let i, j, k , and l be the indices for the individual observations, the site (orchard), the trap within the site, and the year, respectively. We denote by Y_{ijkl} the i -th count within site j , trap k , and year l . In the zero-inflation part (Bernoulli model) models, the probability that the outcome is an excess zero is $(\pi_{ijkl}) : P(Z_{ijkl} = 0) = \pi_{ijkl}$, with π_{ijkl} being modelled as $\text{logit}(\pi_{ijkl}) = \mathbf{u}'_{ijkl}\boldsymbol{\gamma}$, where $\boldsymbol{\gamma}$ is the vector of coefficients and \mathbf{u}_{ijkl} is the vector of predictors for the zero inflation component. The count model (Poisson or Negative Binomial) is $Y_{ijkl} \sim \text{Poisson}(\mu_{ijkl}, \phi)$ or $Y_{ijkl} \sim \text{NB}(\mu_{ijkl}, \phi)$, where μ_{ijkl} is the mean of the response variable for the $ijkl$ -th observation and ϕ is the dispersion parameter. The mean relates to the linear predictor η_{ijkl} through $\log(\mu_{ijkl}) = \eta_{ijkl}$, with $\eta_{ijkl} = \mathbf{x}'_{ijkl}\boldsymbol{\beta} + b_{jk} + v_j + w_l$, where \mathbf{x}'_{ijkl} is the vector of predictors, $\boldsymbol{\beta}$ is the vector of predictors and b_{jk}, v_j , and w_l are the random effects for the trap nested within site, the site (orchard), and the year respectively. The random effects follow normal distributions with zero mean and variances equal to σ_b^2, σ_v^2 , and σ_w^2 , respectively.

The adequacy of the model in dealing with zero inflation and overdispersion was tested using DHARMA—Diagnostics for Hierarchical Regression Models—following the approach proposed by Brooks and colleagues [49]. As a starting point, a model was built including the day of the year, the meteorological and the chemical control variables. The meteorological variables (minimum, maximum, and average daily temperature, minimum, maximum, and average daily relative humidity, number of rainy days, and accumulated precipitation during the period) were included in the models with the time lags that showed the highest correlation with leafhopper abundance. The identification of such time lags was done using Pearson's correlation coefficient for the average abundance of *Asymmetrasca decedens* in 2018 (for the Lourical do Campo and Póvoa de Atalaia orchards and for the average of both orchards) and the studied meteorological variables, with lags between 0 and 7 weeks before sampling. Chemical control variables included fungicide, insecticide, acaricide, and herbicide as binary variables, indicating whether the orchards were under the effect of these treatments during the period. Pruning was included in the models as a binary variable indicating whether pruning had been carried out or not. The selection of variables for both the zero-inflation and count components of the models was performed using a top-down approach, i.e., we started by fitting models with all available variables and discarded one variable at a time, starting with the least statistically significant variable, until the model contained only statistically significant variables plus the variables we decided to keep in the model for discussion purposes. Nested models were compared using likelihood ratio tests.

For *Asymmetrasca decedens*, chemical control variables were retained in the model for discussion purposes, even if they were not statistically significant. The persistence of the pesticides' active substances was considered in the model. Insecticide information was entered into the models as a binary variable indicating whether the insecticide would be active during the period of each capture. For fungicide, due to its short duration of action, we considered the proportion of days of the period under fungicide action for each capture. We wanted to assess if our data would confirm farmers' empirical knowledge that insecticides are not effective, and that fungicide favours the presence of green leafhoppers. Results are presented for both parts of the fitted models.

Statistical analyses were performed using R and RStudio (version 4.3.1 and version 2023.09.1 respectively) [50]. The glmmTMB (version 1.1.10) [49] and DHARMA (version 0.4.6) [51] packages were used for model fitting and model validation, respectively. In the analysis, p -values < 0.05 were considered significant.

3. Results

3.1. Auchenorrhyncha Community and Known Vectors or Potential Vectors of Phytopathogens

The Auchenorrhyncha community collected in the two orchards during the three years is shown in Table 3. A total of 27,037 individuals of 55 species were captured, with Typhlocybinae being the most abundant subfamily (25,421 specimens). *Asymmetrasca decedens* and *Hebata solani* were the dominant species, accounting for 82%, 93%, and 92% of the captures in 2018, 2019, and 2020, respectively.

Table 3. Auchenorrhyncha species collected in orchards of Louriçal do Campo (LC) and Póvoa de Atalaia (PA) in 2018, 2019, and 2020. The specimens of the two species marked with * were found loose on the trap boxes in 2018, making it unclear which orchard they came from, and are considered to be from both sites. Species in bold are known vectors or potential vectors of phytopathogens.

Infraorder	Family	Subfamily	Genus/Species	2018		2019		2020	
				LC	PA	LC	PA	LC	PA
Cicadomorpha	Aphrophoridae	Aphrophorinae	<i>Neophilaenus campestris</i> (Fallén)	0	0	1	3	3	0
			<i>Philaenus spumarius</i> (Linnaeus)	2	3	3	1	3	5
	Cercopidae	Cercopinae	<i>Cercopis intermedia</i> Kirschbaum	1	0	0	0	0	0
			<i>Aphrodes makarovi</i> Zachvatkin	23	20	12	15	16	39
	Cicadellidae	Cicadellinae	<i>Cicadella viridis</i> (Linnaeus)	1	0	0	0	0	0
			<i>Balclutha punctata</i> (Fabricius)	0	0	0	0	2	2
	Deltoccephalinae		<i>Cicadula persimilis</i> (Edwards)	0	0	0	0	1	0
			<i>Euscelidius variegatus</i> (Kirschbaum)	5	22	2	6	10	11
			<i>Euscelis incisus</i> (Kirschbaum)	0	0	0	0	0	2
			<i>Fieberiella florii</i> (Stål)	0	0	1	0	0	6
			<i>Macrostelus sordidipennis</i> (Stål)	0	0	0	0	2	1
			<i>Neoliturus fenestratus</i> (Herrich-Schäffer)	4	3	4	0	2	0
			<i>Phlepsius intricatus</i> (Herrich-Schäffer)	1 *	1 *	0	0	0	0
			<i>Platymetopius guttatus</i> Fieber	0	0	2	0	1	0
			<i>Psammotettix striatus</i> (Linnaeus)	0	0	0	0	0	1
			<i>Sardius argus</i> (Marshall)	1	1	0	0	2	1
	Dorycephalinae		<i>Eupelix cuspidata</i> (Fabricius)	0	0	4	0	1	2
			<i>Sophonia orientalis</i> (Matsumura)	1 *	1 *	0	0	0	0
	Evacanthinae		<i>Macropsis cerea</i> (Germar)	0	0	1	1	0	0
			<i>Macropsis scutellata</i> (Boheman)	0	0	0	0	0	1
	Megophthalminae		<i>Agallia consobrina</i> Curtis	225	113	93	70	289	264
			<i>Anaceratagallia glabra</i> Dmitriev	18	16	42	35	25	28
			<i>Austroagallia sinuata</i> (Mulsant & Rey)	0	0	10	4	2	0
			<i>Megophthalmus scabripennis</i> Edwards	3	1	1	0	0	0
	Typhlocybinae		<i>Alebra coryli</i> Le Quesne	0	0	0	0	0	1
			<i>Alnetoidia alneti</i> (Dahlbom)	4	0	0	0	1	0
			<i>Arboridia parvula</i> (Boheman)	0	4	0	0	2	6
			<i>Asymmetrasca decedens</i> (Paoli)	1913	603	3716	2754	6930	4775
			<i>Edwardsiana gratiosa</i> (Boheman)	0	0	0	0	1	0
			<i>Edwardsiana rosae</i> (Linnaeus)	0	0	0	0	2	1
			<i>Eupteryx filicum</i> (Newman)	0	0	0	1	0	0
			<i>Fruticidia bisignata</i> (Mulsant & Rey)	1	1	1	0	3	2
			<i>Fruticidia sanguinosa</i> (Rey)	0	0	1	0	1	0
			<i>Hauptidia marocanna</i> (Melichar)	2	6	0	0	29	10
			<i>Hauptidia provincialis</i> (Ribaut)	0	0	0	0	4	15
			<i>Hebata decipiens</i> Paoli	22	26	1	2	2	0
			<i>Hebata solani</i> (Curtis)	796	622	710	398	621	875
			<i>Jacobiasca lybica</i> (Bergevin & Zanon)	0	5	0	0	0	0
			<i>Lindbergina aurovittata</i> (Douglas)	0	1	0	0	0	0
			<i>Ribautiana cruciata</i> (Ribaut)	1	1	1	1	1	0
			<i>Ribautiana debilis</i> (Douglas)	0	1	3	1	6	2
			<i>Ribautiana tenerrima</i> (Herrich-Schäffer)	0	0	0	0	5	3
			<i>Zygina lunaris</i> (Mulsant & Rey)	14	1	5	1	8	1
			<i>Zygina nivea</i> (Mulsant & Rey)	10	7	2	2	1	0
			<i>Zygina ordinaria</i> (Ribaut)	115	84	61	45	3	22
			<i>Zygina schneideri</i> (Gunthart)	0	0	0	0	1	3
			<i>Zyginidia scutellaris</i> (Herrich-Schäffer)	15	17	26	52	17	12
			<i>Hyalesthes obsoletus</i> Signoret	0	2	0	0	0	0
Fulgoromorpha	Cixiidae	Cixiinae	<i>Conomelus lorifer</i> Ribaut	0	0	0	0	0	1
			<i>Laodelphax striatella</i> (Fallén)	8	13	1	3	26	18
	Delphacidae		<i>Metadelphax propinqua</i> (Fieber)	14	7	6	0	1	14
			<i>Dictyophara europaea</i> (Linnaeus)	0	0	0	1	0	0
	Dictyopharidae	Dictyopharinae	<i>Tettigometra griseola</i> (Fieber)	0	0	0	0	1	1
			<i>Tettigometra impressopunctata</i> (Dufour)	0	0	0	0	1	1
	Tettigometridae		<i>Tettigometra virescens</i> (Panzer)	0	0	0	0	0	1

It is noteworthy that 28 species are known vectors or potential vectors of phytopathogens (Tables 3 and 4) including three vector species of *Xylella fastidiosa* Wells et al.,

namely *Philaenus spumarius* (Linnaeus), *Neophilaenus campestris* (Fallén), and *Cicadella viridis* (Linnaeus). *P. spumarius*, considered to be the main vector of *X. fastidiosa* in Europe [52], was trapped on all three years of the study, although at low abundance.

Given the small size of Typhlocybae, most of the damage caused to crops is direct leaf injury resulting from their feeding. However, the most common captured species, *A. decedens*, has also been described as a competent vector for ‘*Candidatus Phytoplasma phoenicium*’ and a potential vector for ‘*Candidatus Phytoplasma prunorum*’ [20,21] and European stone fruit yellows (EFSY) [22]. *Hebata decipiens* is a vector for ‘*Candidatus Phytoplasma aurantifolia*’, ‘*Candidatus Phytoplasma asteris*’, and can cause almond witches’ broom disease (AlmWB) [20,53,54].

Other diseases caused by some of the captured Auchenorrhyncha species are: Aster Yellows (AY), Barley Yellow Stripe Mosaic Cytorhabdovirus (BYSMV), Bois Noir (BN), ‘*Candidatus Phytoplasma solani*’ (=Stolburn), Cynodon Chlorotic Streak Virus (CCSV), Chrysanthemum Yellow (CY), European Stone Fruit Yellow (ESFY), *Flavescence Dorée* of Grapevine (FD), Grape Yellow (GY), Lettuce Phyllody (LP), Maize Mosaic Virus (MMV), Maize Rough Dwarf Virus (MRDV), Mulberry Dwarf Phytoplasma (MDP), Northern Cereal Mosaic Virus (NCMV), Rice Black-Streaked Dwarf Virus (RBSDV), Rice Stripe Virus (RSV), Winter Wheat Virus (WWV), Western X-Disease (WXD), and X-Disease (XD) [7,10,14,20–22,38,52–106]—see Table 4.

Table 4. Auchenorrhyncha vectors or potential vectors of plant pathogens found in peach orchards. The list is in the same order as in Table 3.

Species	Pests/Vectors/Direct Injury	References
<i>Neophilaenus campestris</i> (Fallén)	<i>Xylella fastidiosa</i>	[55–57]
<i>Philaenus spumarius</i> (Linnaeus)	AY, Ca <i>P. solani</i> , <i>Xylella fastidiosa</i>	[52,58–61]
<i>Anaceratagallia glabra</i> Dmitriev	AY, BN	[62–65]
<i>Austroagallia sinuata</i> (Mulsant & Rey)	AY, Ca <i>P. aurantifolia</i> , Ca <i>P. solani</i>	[66–68]
<i>Aphrodes makarovi</i> Zachvatkin	FD, Ca <i>P. solani</i>	[22,69]
<i>Cicadella viridis</i> (Linnaeus)	Ca <i>P. solani</i> , <i>Xylella fastidiosa</i>	[61,70]
<i>Balclutha punctata</i> (Fabricius)	MDP	[71]
<i>Euscelidius variegatus</i> (Kirschbaum)	AY, Ca <i>P. solani</i> , CY, FD, WXD	[59,61,72–74]
<i>Euscelis incisus</i> (Kirschbaum)	AY, Ca <i>P. solani</i> , CY, FD, XD	[59,61,69,75]
<i>Fieberiella florii</i> (Stål)	Ca <i>P. mali</i> , Ca <i>P. prunorum</i> , XD	[65,76,77]
<i>Neoliturus fenestratus</i> (Herrich-Schäffer)	AY, Ca <i>P. solani</i> , GY, SP, LP	[64,78–80]
<i>Psammotettix striatus</i> (Linnaeus)	WWV, Ca <i>P. solani</i> (potential vector)	[61,63,81]
<i>Eupelix cuspidata</i> (Fabricius)	Ca <i>P. solani</i> (potencial vector)	[62]
<i>Megophthalmus scabripennis</i> Edwards	AY (potencial vector)	[64]
<i>Asymmetrasca decedens</i> (Paoli)	Ca <i>P. phoenicium</i> , Ca <i>P. prunorum</i> , direct injury, EFSY	[10,20–22,82]
<i>Edwardsiana rosae</i> (Linnaeus)	Direct injury	[83–85]
<i>Fruticidia bisignata</i> (Mulsant & Rey)	Direct injury	[83,87]
<i>Hauptidia marocanna</i> (Melichar)	Direct injury	[88]
<i>Hauptidia provincialis</i> (Ribaut)	Direct injury	[89]
<i>Hebata decipiens</i> Paoli	Alm WB, Ca <i>P. asteris</i> , Ca <i>P. aurantifolia</i>	[20,53,54,86]
<i>Hebata solani</i> (Curtis)	Direct injury	[14]
<i>Jacobiasca lybica</i> (Bergevin & Zanon)	Direct injury	[7,90–92]
<i>Ribautiana tenerrima</i> (Herrich-Schäffer)	Direct injury	[93]
<i>Zyginidia scutellaris</i> (Herrich-Schäffer)	Direct injury	[94]
<i>Hyalesthes obsoletus</i> Signoret	AY, BN	[64,95–98]
<i>Laodelphax striatellus</i> (Fallén)	AY, BN, BYSMV, Ca <i>P. solani</i> , MMV, MRDV, NCMV, RBSDV, RSV	[59,61,99–102]
<i>Metadelphax propinqua</i> (Fieber)	CCSV, MMV, MRDV	[38,68]
<i>Dictyophara europaea</i> (Linnaeus)	Ca <i>P. solani</i> , FD	[61,104–106]

3.2. Population Dynamics of the Two Main Leafhopper Species, *Asymmetrasca decedens* and *Hebata solani*

Injury observed in orchards ranged from severe wrinkling and curling of leaves with a dry and burnt appearance (Figure 2) to shortening of internodes and growth retardation of branches and shoots. Young trees showed weaker and slower growth. This type of injury has been described previously [10,19] and was also reported in the Beira Interior region in 2015 [17]. The injury coincided with periods of higher numbers of captures of the green leafhopper *Asymmetrasca decedens*, especially in August and September (Figure 3).



Figure 2. Injuries coincident with the periods of higher numbers of *Asymmetrasca decedens* in peach orchards include leaf curling and wrinkling (A), often accompanied by a dry and burned appearance (B).

Four species of Empoascini were identified among the collected individuals: *Asymmetrasca decedens*, *Hebata solani*, *H. decipiens*, and *Jacobiasca lybica*. The last two species were observed occasionally, representing 0.2% and 0.02% of the Empoascini species caught during the sampling period. Only *A. decedens* and *H. solani* were present in both orchards (Louriçal do Campo and Póvoa de Atalaia) in all three years of the study, as shown in Figure 3.

As shown in Figure 3, the majority of *H. solani* captures occurred from April to July each year, while *A. decedens* captures were significantly higher from August to October. For *H. solani* in 2018, the relative maximum was reached on 27 April and 29 June in the Louriçal do Campo orchard, and on 29 June in the Póvoa de Atalaia orchard. In 2019, the maximum was reached on 18 April, and in 2020 on 20 July in both orchards. For *A. decedens* the maximum capture occurred on 14 September 2018, on 20 September 2019, and on 20 July and 10 September 2020 in the Póvoa de Atalaia and Louriçal do Campo orchards, respectively. Notably, the 2018 sampling period ended on 14 September, so it is unclear whether the observed maximum was the actual peak. In general, the Louriçal do Campo orchard had a higher number of captures of Empoascini species than the Póvoa de Atalaia orchard.

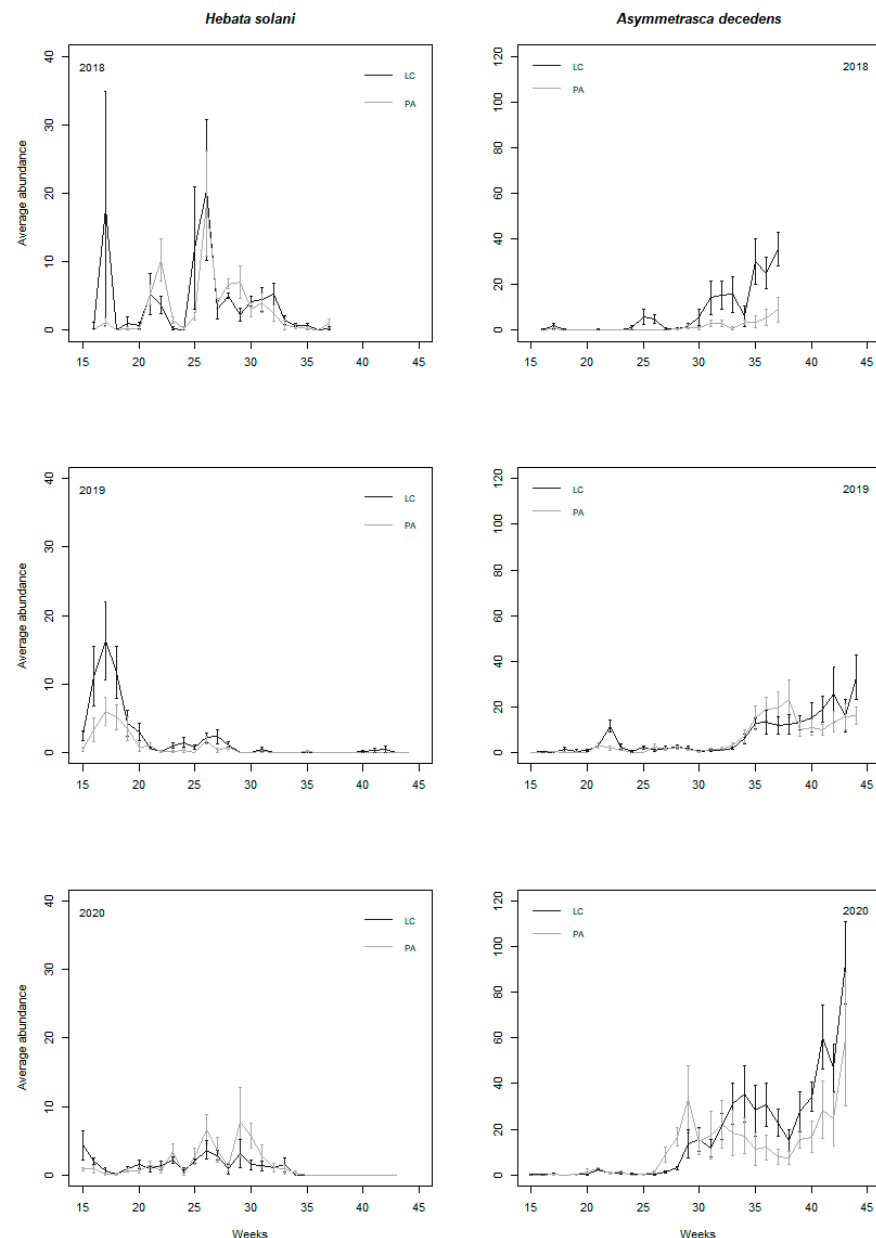


Figure 3. Mean abundance of *Hebata solani* and *Asymmetrasca decedens* males during 2018, 2019, and 2020 in the orchards of Lourical do Campo (LC) and Póvoa de Atalaia (PA). Weeks 15–24 (spring), 25–38 (summer), 39–45 (autumn).

3.3. Analysis and Modelling of Climate Conditions and Management Measures

The influence of climate conditions on the distribution of *Asymmetrasca decedens* and *Hebata solani* in both orchards was analysed (Tables 5 and 6). Details of all correlations, respective lags, and meteorological data are given in the Supplementary Materials (Tables S1–S9).

For *Asymmetrasca decedens*, a zero-inflated negative binomial (ZINB) regression model with fixed and random effects was fitted to the counts. Day of the year (DayOfYear), maximum temperature (MaxTemp), and the number of non-null precipitation days per week (NrRainyDays) were the variables found to be significantly associated with the presence of structural zeros, i.e., the absence of the species in the environment. Later days of the year and higher maximum temperature favoured the presence of the species, while a higher number of rainy days favoured its absence. Specifically, the odds of the species being absent decreased 2.8% per day and by 10.8% per unit increase in daily maximum

temperature, while rain increased the odds of absence by 50% for each additional rainy day. Once present, the abundance of the species (reflected by the number of individuals caught in the traps) increased daily by 1.8% per week over time (DayOfYear), as shown in Figure 4. No significant effect of insecticide use was found, but higher fungicide exposure, expressed by the proportion of time under the fungicide (variable FungProp), resulted in a 39.5% decrease in abundance (estimate = -0.502 , IRR = 0.605 , p -value = 0.0175). However, the effect of the fungicide is reduced by the presence of rain (interaction term NrRainyDays \times FungProp), which favours an increase in abundance of 38.7% per rainy day in the presence of the fungicide (estimate = 0.327 , IRR = 1.387 , p -value = 0.0558), meaning that a single day of rain is sufficient to eliminate the reducing effect of the fungicide on the number of individuals caught in the traps. By itself, the number of rainy days is associated with a lower number of captured specimens. None of the remaining meteorological variables contributed significantly to the explanation of abundance, once the above variables were included in the model. Details are given in Table 5.

Table 5. Summary of the zero-inflated negative binomial (ZINB) model for *Asymmetrasca decedens* abundance. OR = Odds Ratio, IRR = Incident Risk Ratio, CI = Confidence Interval.

Structural Zeros Component	Estimate	OR	OR 95% CI	p-Value
(Intercept)	5.263	--	--	0.0012
DayOfYear	-0.029	0.972	(0.956, 0.987)	0.0003
MaxTemp	-0.114	0.892	(0.809, 0.984)	0.0231
NrRainyDays	0.406	1.500	(1.071, 2.101)	0.0181
Count Component	Estimate	IRR	IRR 95% CI	p-Value
(Intercept)	-1.970	--	--	<0.001
DayOfYear	0.018	1.018	(1.016, 1.021)	<0.001
NrRainyDays	-0.107	0.989	(0.847, 0.953)	<0.001
FungProp	-0.502	0.605	(0.400, 0.916)	0.0175
Insecticide = yes	-0.024	0.977	(0.798, 1.195)	0.8192
NrRainyDays \times FungProp	0.327	1.387	(0.992, 1.940)	0.0558

Table 6. Summary of the Zero-Inflated Negative Binomial (ZINB) model for *Hebata solani* abundance. OR = Odds Ratio, IRR = Incident Risk Ratio, Confidence Interval = CI.

Structural Zeros Component	Estimate	OR	OR 95% CI	p-Value
(Intercept)	7.192	--	--	0.0010
DayOfYear	-0.035	0.966	(0.942, 0.990)	0.0055
MaxRelHum	-0.071	0.932	(0.899, 0.966)	<0.001
Count Component	Estimate	IRR	IRR 95% CI	p-Value
(Intercept)	1.154	--	--	0.3242
DayOfYear	-0.005	0.995	(0.983, 1.007)	0.4222
AvgTemp	0.405	1.499	(1.294, 1.737)	<0.001
MinRelHum	0.018	1.018	(1.002, 1.034)	0.0287
MaxRelHum	-0.021	0.980	(0.970, 0.990)	<0.001
NrDaysInsecticide	0.031	1.031	(0.980, 1.085)	0.2342
DayOfYear \times AvgTemp	-0.002	0.998	(0.998, 0.999)	<0.001

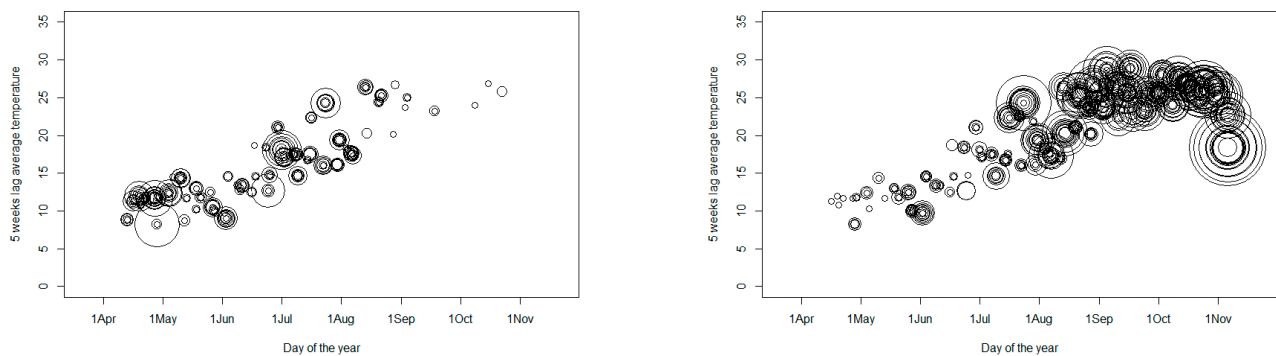


Figure 4. Plot of *Hebata solani* (left) and *Asymmetrasca decedens* (right) abundance over time as a function of mean temperature with a five-week lag. Abundance, expressed as the number of captures per trap, is proportional to the bubble size.

For *Hebata solani*, a zero-inflated negative binomial (ZINB) regression model with fixed and random effects was fitted to the counts. Day of the year (DayOfYear) and maximum relative humidity (MaxRelHum) were the only variables significantly associated with the presence of structural zeros, i.e., the absence of the species. Specifically, the probability of absence decreased 3.4% per day and by 6.8% per unit increase in maximum relative humidity. Once the species was present, abundance (reflected by the number of individuals caught in traps) increased with higher average temperatures (AvgTemp), but this effect diminished over time, as reflected by the negative sign of the interaction term (DayOfYear \times AvgTemp) (Figure 4). Relative humidity played different roles in the model. Higher minimum relative humidity favoured higher abundance, while higher maximum relative humidity decreased it (1.8% increase and 2% decrease per unit increase, respectively). Insecticide exposure was entered into the model as the number of days per week under insecticide effect in the week (NrDaysInsecticide). No significant effect of insecticide use was found. Details are given in Table 6.

4. Discussion

Recently, Xu et al. [1] reclassified the tribe Empoascini, renaming *Empoasca solani* and *Empoasca decipiens* as *Hebata (Signatasca) solani* and *Hebata (Alboneurasca) decipiens*, respectively, based on molecular analyses. Nevertheless, male genital characters remain sufficient for the systematic classification of Typhlocybae [38,46,47]. Accordingly, this paper adopts the genus *Hebata* for the former *Empoasca* species.

The identification of the Auchenorrhyncha community has improved our understanding of the ecological diversity in these agroecosystems and identified pests or potential pests that could negatively impact these orchards and other areas. This includes the first record of the invasive leafhopper, *Sophonia orientalis* (Matsumura), in these studied peach orchards [107].

The number of captures of *A. decedens* was very high in both orchards over the three years, which is particularly worrying in view of the tree injury observed. The characteristic hopperburn injury caused by this green leafhopper species can lead to significant production losses, slower development of younger trees, weaker growth, and delayed fruit production [10]. Monitoring of this species is crucial due to its impact on Portuguese stone fruit production, particularly peach and cherry, and other areas in the Mediterranean region where it is already widespread. Monitoring is essential to evaluate the impact of *A. decedens* and the presence of phytoplasmas, which could further increase production losses and have significant economic impact, as reported by others [20,22].

The asynchronous distribution of *H. solani* and *A. decedens* is noteworthy, with *H. solani* appearing earlier in spring and early summer, and *A. decedens* peaking in late summer and

early autumn, as reported by others [15,108,109]. This distribution may reduce competition between the two species.

Both *H. solani* and *A. decedens* showed similar distributions in both orchards in all years, probably due to their proximity. However, captures of *A. decedens* were still increasing at the end of the sampling period ended, making it impossible to determine when this species leaves the orchards to overwinter in the surrounding vegetation. A longer sampling period might have helped to determine this.

Several meteorological variables showed significant and consistent correlations with the distribution of *A. decedens* over the three years, especially temperature, as previously described [16,24,110]. According to our study, both temperature and relative humidity influence the distribution of this species, but in opposite ways. Temperature had a positive effect on *A. decedens*, whereas relative humidity had a negative effect. Conversely, the abundance of *H. solani* increased with higher relative humidity, in agreement with other studies [111].

Captures of *A. decedens* were significantly higher than *H. solani*, and the proportion of captures increased over the three years of the study, possibly due to rising temperatures (the average increase in minimum, mean, and maximum temperature that occurred over the three years—see Supplementary Materials) favouring *A. decedens* and negatively affecting *H. solani*. This suggests that ongoing global temperature increase, particularly in the Mediterranean region, could lead to even higher numbers of *A. decedens*. Given its positive association with temperature and its polyphagous nature, *A. decedens* could become a serious threat to a wide range of crops and expand its current distribution.

None of the pesticides used in the orchards specifically targeted *A. decedens* or had a significant or consistent effect on its distribution over the three years. This study highlights that fungicides can have unintended secondary effects on non-target pests. Specifically, the results show that the presence of fungicides significantly reduced *A. decedens* populations by almost 40% when the fungicide was active (FungProp = 1), when weather conditions were dry and there were no rainy days (NrRainyDays = 0). Although fungicides are primarily used to control fungal diseases, they may inadvertently alter insect population dynamics [112]. This is because many fungicides are broad-spectrum biocides, as their mode of action often involves inhibition of cellular respiration or division, which is common to all organisms [113]. Supporting evidence for these secondary effects can be found in previous studies, e.g., [114,115], which discuss the effects of chemical treatments on non-target insects and highlight the complexity of managing arthropod pests within an IPM framework. In addition, research by other authors [112] has discussed that insecticide-resistant pest individuals may be better able to resist adverse fungicide effects if their ability to detoxify chemicals is generally higher, highlighting the need to carefully consider the effects of fungicides on both beneficial and pest insect communities, and therefore all agrochemicals should be considered together in management strategies.

Green pruning did not affect the abundance of *A. decedens*, but as this technique can weaken trees, carrying it out earlier, preferably in June or July, may help to minimise additional stress on trees already susceptible to leafhopper attack.

Despite the lack of a control programme for *A. decedens*, targeting nymphs during an earlier application period is recommended. The lack of a control programme further emphasises the importance of monitoring this species and conducting further research into potential control options [10,15,27].

This study highlights the importance of continuous monitoring of the green leafhopper *A. decedens*, given the injury it causes, the lack of control methods, and its resistance to common insecticides. It also highlights the need to monitor other Auchenorrhyncha species, especially those that are vectors or potential vectors of phytoplasmas, viruses, or bacteria.

In addition, the study confirmed the influence of certain meteorological variables on Empoascini species and provided insights into the optimal timing of green pruning.

5. Conclusions

The current study identified a community of 55 Auchenorrhyncha species, with *Asymmetrasca decedens* and *Hebata (Signatasca) solani* being the most abundant, highlighting their potential threat to crop health through their role as vectors of plant pathogens. The research has demonstrated the significant influence of climate, chemical treatments and cultural control strategies on the population dynamics of the two main important green leafhopper pests. The results suggest that temperature and humidity have significant effects on the abundance and seasonal patterns of these pests, highlighting the importance of understanding climatic effects in integrated pest management frameworks. Chemical control measures, particularly insecticide applications, did not consistently reduce *A. decedens* populations, suggesting the need to explore alternative strategies. In addition, early green pruning proved to be a beneficial practice, increasing tree resistance during vulnerable periods. Overall, this research provides important insights into the ecology of leafhoppers and their management, informing growers and agronomists in the pursuit of sustainable practices that mitigate economic losses in peach production under changing climatic conditions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15010163/s1>, Table S1. Meteorological data from Póvoa de Atalaia station, from 11 April 2018 to 14 September 2018 grouped weekly. Table S2. Pearson's correlation coefficient for the average abundance of *Asymmetrasca decedens* in 2018. Table S3. Pearson's correlation coefficient for the average abundance of *Hebata solani* in 2018. Table S4. Meteorological data from Póvoa de Atalaia station, from 4 April 2019 to 31 October 2019 grouped weekly. Table S5. Pearson's correlation coefficient for the average abundance of *Asymmetrasca decedens* in 2019. Table S6. Pearson's correlation coefficient for the average abundance of *Hebata solani* in 2019. Table S7. Meteorological data from Póvoa de Atalaia station, from 6 April 2020 to 31 October 2020 grouped weekly. Table S8. Pearson's correlation coefficient for the average abundance of *Asymmetrasca decedens* in 2020. Table S9. Pearson's correlation coefficient for the average abundance of *Hebata solani* in 2020.

Author Contributions: Conceptualization, A.C.N., J.P.C. and M.T.R.; methodology, A.B., A.C.N., H.A., J.P.C., M.A., M.T.R., P.M.N. and V.G.; investigation, A.C.N., M.A., M.T.R., P.M.N. and V.G.; resources, A.B., J.P.C. and M.T.R.; formal analysis, A.C.N., H.A., M.A., M.T.R., P.M.N. and V.G.; software, A.C.N., H.A., M.A., M.T.R., P.M.N. and V.G.; validation, A.C.N., M.A., J.P.C. and M.T.R.; data curation, A.C.N., M.T.R., P.M.N. and V.G.; writing—original draft preparation, A.C.N., P.M.N. and V.G.; writing—review and editing, A.C.N., J.P.C., M.A., M.T.R., P.M.N. and V.G.; supervision, M.T.R.; project administration, A.B., J.P.C. and M.T.R.; funding acquisition, A.B., J.P.C. and M.T.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FCT/MCTES with financial support to the Centre for Ecology, Evolution and Environmental Changes (cE3c) (ref—UIDB/00329/2020, <https://doi.org/10.54499/UIDB/00329/2020>), the Centre for Environmental and Marine Studies (CESAM-Ciências) (ref—UIDB/50017/2020, <https://doi.org/10.54499/UIDB/50017/2020>; ref—UIDP/50017/2020, <https://doi.org/10.54499/UIDP/50017/2020>; and ref—LA/P/0094/2020, <https://doi.org/10.54499/LA/P/0094/2020>), the Centro de Estatística e Aplicações da Universidade de Lisboa (CEAUL) (<https://doi.org/10.54499/UIDB/00006/2020>), the Operational Group Prunus-Fito (PDR2020-101-031707), and co-funding by the European Regional Development Fund, within the Portugal 2020 Partnership Agreement and Compete 2020.

Data Availability Statement: Data is contained within the article and Supplementary Materials.

Acknowledgments: The authors are grateful to the peach orchard growers associated with Appizêzere for allowing access to their properties. The authors would also like to thank the reviewers and the journal editor for their comments and suggestions, which helped to improve the first version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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