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Monitoring the Bud Mite Pest in a Hazelnut Orchard of Central Italy: Do Plant Height and Irrigation Influence the Infestation Level?

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Abstract: Mite pests are a serious threat for hazelnut cultivations, causing economic losses every year. At least two species of big bud mites, *Phytoptus avellanae* (Acari: Phytoptidae) and *Cecidophyopsis vermiformis* (Acari: Eriophyidae), are involved in severe hazelnut bud infestations, even though few studies report *P. avellanae* as the most present and harmful. Great steps forward have been made in monitoring and management strategies of these mite pests, but a plethora of questions remains unanswered about their ecology and behaviour and how agronomical practices impact populations. Given this precondition, we conducted a four-year monitoring in an experimental hazelnut orchard located in the Viterbo hazelnut district, Central Italy, to: (i) explore the potential effect that irrigation has on mite infestations, (ii) assess if mites locate in a particular band height of hazelnut plants; and (iii) assess the overall field infestation over the years. This study showed that not-irrigated plants and plants irrigated by underground pipe systems were similarly infested. Mites tend to locate in the middle band of the plant, namely from 1.5 to 3 m from the ground. The four-year survey showed an overall increasing infestation trend, with a peak in 2021 for irrigated plants and 2022 for not-irrigated. These results are a milestone for further exploration of the biology and ecology of this pest and to formulate ad hoc monitoring and control strategies as well.

Keywords: Eriophyoidea; agronomic practices; pest monitoring; pest ecology; *Corylus avellana*

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1. Introduction

The economic relevance of hazelnut production leads to an even wider distribution of several species belonging to the *Corylus* L. (Betulaceae) genus in the Northern hemisphere. Among the species, the European hazelnut *C. avellana* L. is gaining significant importance in the Mediterranean basin and in Italy, the world's second largest producer behind Turkey. The Italian average hazelnut production is 140, 000 t/year, mostly concentrated in Piedmont, Latium, Campania, and Sicily (from north to south) [1,2].

Historically, hazelnut is acknowledged for its resilience to adverse environmental conditions, but in recent years it faces aggression by a plethora of biotic entities [3–5]. The causal agents of infestations and diseases are manifold: insects, mites, fungi, and bacteria pests lead to heavy production losses or, in the worst cases, even to the death of plants [4,6–9].

Curbing phytosanitary emergencies in hazelnut orchards is of great importance to harvest a quantitatively satisfactory production with high organoleptic characteristics [10]. The starting point for the formulation of a successful and efficient control strategy is the knowledge of the biology and the infestation mechanisms of the noxious agents [11,12]. This knowledge becomes even more important for the species where information is still fragmented, as in the case of mite pests.

Among the different threats, the hazelnut mite pests strongly demand our attention, given the still partially understood biology and epidemiology. At least two species, the big bud mite, *Phytoptus avellanae* Nalepa (Acari: Phytoptidae), and *Cecidophyopsis vermiformis* (Nalepa) (Acari: Eriophyidae) are involved in severe hazelnut bud infestations with the formation of bud galls [13–16].

Although these two species can be observed together in the galls, *C. vermiformis* has never been proved to induce the bud deformations. It plays a secondary role in the damage onset [17]. Alternatively, *P. avellanae* is reportedly the most harmful of the two species [13].

Cvrković et al. [15] demonstrated that two cryptic species lie under the umbrella name of *P. avellanae*: a first one inducing galls within it lives (that should be called *P. avellanae*), and a second one having a vagrant behaviour on the green organs. The vagrant species is unnamed and needs to be studied in its biological and ecological aspects. Given the complexity of the taxonomic status of the *P. avellanae* name species, in what follows we refer to *P. avellanae sensu latu*, indicating both gall-living and vagrant taxa.

Several studies [13,15,18] reported that *P. avellanae* migrates as nymph during the spring months either to new generative or vegetative axillary buds. The individuals subsequently infest new hazelnut plant buds, where the mite lives until the following spring. Alternatively, the mite's vagrant form, which slightly differs from the form inhabiting the buds, colonizes other parts of the plant such as leaf undersurfaces, shoots, or young nut clusters, not only during the spring but also in the summer and autumn [13].

Once infested, buds offer protection and food to mites. Within buds, mite populations increase causing, in winter, a localized growth reaction of the plant (usually defined as "big buds" or "galls") [13,19] and the buds lose their viability, becoming swollen, fleshy, and reddish. A considerable disturbance in hazelnut plant growth patterns can occur [13,19].

The typical big bud symptoms are easily discriminated from non-deformed buds during winter. This is why infestation level is assessed in winter by visual inspections when the ratio between the number of big buds and the number of healthy buds per branch is considered the parameter related to the intervention threshold above which treatments against the mites have to be carried out. For the Italian hazelnut orchards, Viggiani and Bianco [20] reported an economic threshold at 15 to 20% of infested buds.

Pest monitoring, including visual inspections, is time-consuming and requires qualified personnel [21]. To overcome this issue, Lippi et al. [22] introduced an innovative system to automatically detect insect pests in hazelnut orchards. This strategy consists of a data-driven approach based on Convolutional Neural Networks (CNNs) and of a You Only Look Once (YOLO) architecture. Application of this system for the detection of *P. avellanae* showed an average reliability of 82.5% in identifying the presence of big buds on the plants [23].

Although great steps forward have been made in monitoring and management strategies of hazelnut mite pests such as *P. avellanae*, questions remain unanswered. For instance, we may wonder the potential role that agronomic practices, such as artificial water supply carried out during the dry season, have on big buds' incidence. Accordingly, this study aims to assess if artificial irrigation provokes differences in terms of big buds' presence on irrigated and not-irrigated plants. A second relevant question relates to the localization of the infestation at the plant level. The second aim of this study is to understand in which parts of the hazelnut plant mites are most likely to be found. This information supports the winter monitoring of the populations, especially if population abundance is assessed by automated systems. Knowing which is the most infested "band height" of the plant is beneficial for speeding up the data acquisition and maximizing, and at the same time, the amount of information collected.

This study aims to explore these two relevant open questions through a multi-year study conducted in an experimental hazelnut orchard fully inserted into the "Viterbo Hazelnut District", an area of circa 21,000 hectares where hazelnut is the main cultivation. Besides the agronomic and behavioral information, this study also aimed to provide the scenario of mite infestations in a four-year survey carried out in the hazelnut orchard.

2. Materials and Methods

2.1. Study Site

The study was carried out in the framework of the H2020 "Pantheon" project and conducted in "Vignola" farm (42°17′23.86″ N–12°17′00.51″ E), located in the municipality of Caprarola, in the province of Viterbo (Italy).

The hazelnut orchard where experimentation was carried out covers a surface of 3.1 hectares and contains about 1200 plants. The land is mainly flat, and the predominant cultivar is Tonda Gentile Romana, pollinated by specimens of Nocchione cultivar. All the observations of the present study were carried out on Tonda Gentile Romana specimens.

The field is composed of plants about 30 years old, cultivated in multi-stemmed bush with an average number of 5 to 7 branches per plant. Only standard pruning practices (e.g., winter pruning providing for removal of the drying or weakened branches; spring/summer pruning providing for removal of suckers) were carried out on the plants. Hazelnuts are distributed in a regular layout of 5 × 5 m and their average height is circa 5 m. All plants grew under similar conditions of temperature, relative humidity, sunlight exposition, and rain.

The field was equipped with an irrigation system except for 5 lines where, for the sake of this study, water was not provided during all the four years of the survey. An underground irrigation drip line between each planting row provided a water supply in July and August (2019, 2020, 2021, and 2022), during which each plant was irrigated for 5 days a week with an average amount of about 80 L per day.

2.2. Monitoring

2.2.1. Infestation over the Years and Plant Irrigation

Monitoring was carried out in January 2019, 2020, 2021, and 2022. It focused on the main aims of this study: (i) evaluating the infestation level over the years, (ii) evaluating the infestation level between irrigated and not-irrigated plants; and (iii) identifying band heights most affected by mite infestations on plants.

Differences related to water management were assessed by considering 10 irrigated plants selected on the same row interspersed by 2 plants (considered as buffer) on which no observations were conducted. Ten plants from the non-irrigated part of the field were selected with the same criteria, additionally leaving 2 lines per side as a buffer zone. All plants were selected and labeled with a code in the first year of the survey, so that they would also be considered in the subsequent 3 years. Given that the plants were irrigated through an underground pipe system, we are positive there are no mechanical effects that may interfere with *P. avellanae* populations, as it is reasonable to suppose in case of rain-like irrigation systems. Accordingly, we suppose that differences in infestation levels between irrigated and non-irrigated plants are directly related to the impact that water supply has on *P. avellanae*'s capability to infest the buds.

The presence of mite-induced big buds was assessed every year in January, when plants were in winter dormancy. From each plant, 3 50-cm portions of branches were randomly selected, and the number of both non-deformed buds and big buds was counted. As previously stated, while we have considered the same selected plants of both the irrigated and not-irrigated part of the field for each year of the survey, the sampled branches were randomly chosen during each yearly sampling. The non-infested buds were counted to calculate an infestation index according to Viggiani and Bianco [20] to evaluate the overall infestation trend of the field as detailed in Section 2.2.3.

According to the monitoring protocol, the 10 plants for each irrigated/non-irrigated thesis are considered as repetitions, while the single plant is a block with random effects. The branches randomly selected for the inspection in each plant were considered as replicates of a sample.

2.2.2. Infestation over Plant Height Bands

Differences of big buds in plant band heights were assessed in 2021 and 2022 based on a pre-evaluation carried out during 2019 and 2020. From visual inspections, we noticed that there were apparent different distributions of mite populations depending on plant height, which deserved an accurate measurement. This part of the survey involved the same plants labeled at the beginning of the experimentation but provided for a slightly different sampling technique. More specifically, each plant was conceptually divided into 3 band heights: 0–1.5 m, 1.5–3 m and >3 m. For each band, 3 50-cm portions of branch per plant were randomly selected and the number of both non-infested buds and big buds were counted.

2.2.3. Calculation of the Overall Infestation Threshold over the Years and Irrigation

Besides statistical analysis, collected data was also used to calculate the threshold level according to Viggiani and Bianco [20]. To date, it is the most common index to assess the infestation level in Italian hazelnut orchards, as usually indicated by the Regionals technical bulletin. More specifically, the ratio R is defined as follows:

$$R = \frac{N_{BB}}{N_B} \cdot 100 \tag{1}$$

where N_{BB} is the number of big buds and N_B is the number of non-infested buds. Equation (1) can be considered as an infestation index indicating the entity of mite attacks into the field. Given that this index is purely indicative in the context of this study, for each year of survey and for irrigated/non-irrigated plants was calculated: (i) the number of non-infested buds N_B by averaging the values of all irrigated and non-irrigated plants, respectively; and (ii) the number of big buds N_{BB} by averaging the values of all irrigated and non-irrigated plants, respectively. Accordingly, as already introduced in Section 2.2.1, for each year of survey we obtained an index for the overall irrigated and non-irrigated plants.

2.3. Statistical Analysis

2.3.1. Differences in Infestation over the Years and Plant Irrigation

This part of the analysis considered the overall 4-year survey and provided for a two-factor analysis to assess: (i) differences among the years of the overall mite infestation level, without considering the effects of irrigation; and (ii) differences in mite infestation level between irrigated and non-irrigated plants. This analysis was carried out through a Generalized Linear Mixed-Effects Model (GLMM) with a negative binomial distribution and the Bonferroni adjusted as *post hoc* test (α = 0.05), in an analogous way to Di Sora et al. [24]. The year of the survey and irrigation were considered as independent variables, while the plant was considered as a random variable.

Overall, the sampling method was the same, but while in 2019 and 2020 we had only 3 50-cm portions of branches inspected in each plant, in 2021 and 2022 we had 9 per plant, 3 for each height band. This led to an unbalanced design, but it did not affect the data analysis introduced with this section because GLMMs are methods valid also in case of unbalanced designs.

2.3.2. Differences in Infestation over Plant Height Bands

This second part of the analysis considered only 2021 and 2022 to assess differences among the infestation observed in each plant band height and between the 2 years involved in this part of the experimentation. Irrigation in this part of the analysis was not considered given that the first part did not provide significant differences. This analysis was carried out analogously to the abovementioned first part, using a GLMM with a negative binomial distribution and the Bonferroni adjusted as post hoc test (α = 0.05). The year of the survey and plant band height were considered as independent variables, while the plant was considered as random variable.

2.3.3. Software for Data Analysis

Calculations were carried out through R software (vers. 3.6.0, R Foundation for Statistical Computing, Vienna, Austria) [25] using the functions *glmer.nb()* contained in *lme4* package, *cld()* contained in *multcomp* package, and *emmeans()* and *pairs()* contained in the packages *multcompView* and *emmeans*, respectively. All the scripts, as well as the raw data ensuring the full reproducibility of the results of the present study, are publicly available at https://github.com/lucaros1190/Phytoptus-avellanae (accessed on 17 July 2022).

3. Results

3.1. Infestation over the Years and among Different Plant Irrigation Systems

The survey carried out during the four years of observation highlighted a significant variation in presence of big buds in the hazelnut plantation (Figure 1). In particular, an increasing number of big buds was recorded over the years, with a peak of presence observed in 2021, followed by a reduced presence in 2022. As shown in Figure 1, 2019 had the lower presence of big buds in the overall orchard, even though the number of big buds counted was not statistically different from 2020 (GLMM, Z = −2.333, p = 0.1180). Additionally, 2021 had the highest infestation, significantly different from 2019 and 2020 (GLMM, Z = −7.442 and Z = −5.081, respectively, $p < 0.0001$) and from 2022 (GLMM, Z = 3.417, p = 0.0038). Furthermore, 2022 was different from 2019, 2020 (GLMM, Z = −5.211, $p < 0.0001$ and Z = −2.682, p = 0.044, respectively), and 2021 (GLMM, Z = 3.417, p = 0.0038).

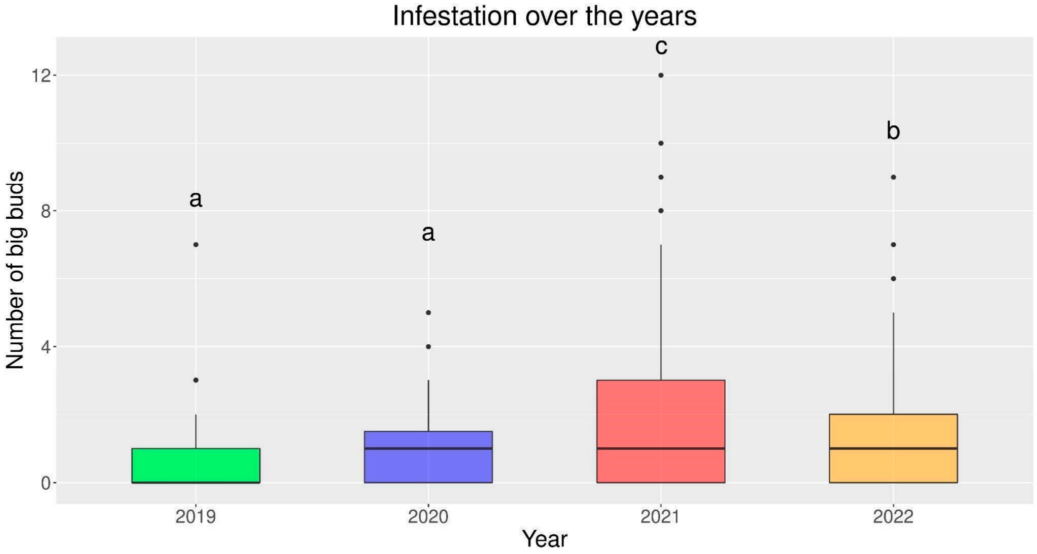

Figure 1. Overall infestation of hazelnut plants (number of big buds per plant) over the four years of survey, with no distinction between irrigated and not-irrigated plants. Different letters indicate significant difference between the year of survey after Bonferroni post hoc test at $p < 0.05$.

The differences assessed among irrigated and non-irrigated plants over the years, instead, are shown in Figure 2. No differences between irrigated and non-irrigated plants in the same year of the survey were observed despite the differences emerging among the years. In particular, the GLMM analysis did not report a difference between irrigated and non-irrigated plants in 2019, 2020, 2021, and 2022 with Z = 2.235 and p = 0.7116.

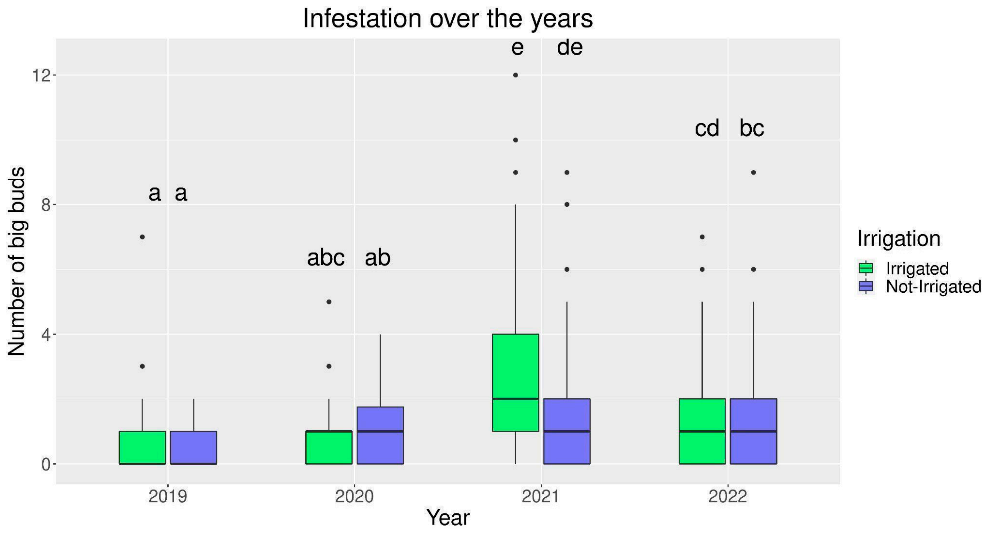

Figure 2. Overall infestation of hazelnut plants over the four years of survey, distinguishing between irrigated and not-irrigated plants. Different letters indicate significant difference between the year of survey, irrigated and not-irrigated plants after Bonferroni post hoc test at $p < 0.05$.

3.2. *Infestation over Plant Height Bands*

The overall results of the infestation over height ranges assessed in 2021 and 2022 are depicted in Figure 3. Given that the results shown in Section 3.1 did not report differences between irrigated and non-irrigated plants, irrigation was not considered in analyzing infestations among height ranges. Considering both 2021 and 2022, differences in the number of big buds were reported between the band 1.5 to 3.0 m (the most infested) and the bands 0 to 1.5 (GLMM, Z = −9.508, $p < 0.0001$) and >3.0 (GLMM, Z = 8.907, $p < 0.0001$). There was no difference between the band height 0 to 1.5 and >3.0 (GLMM, Z = −0.767, $p = 1$).

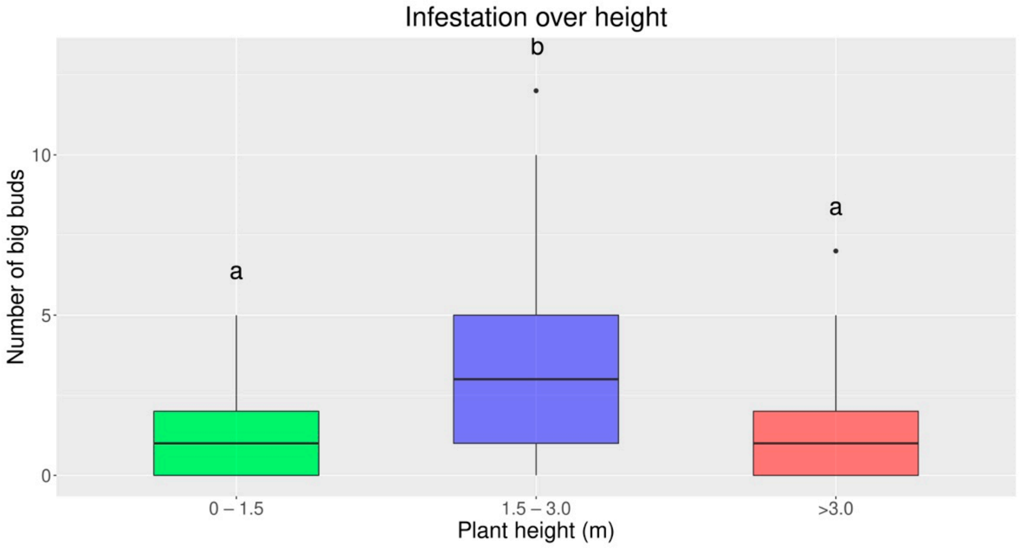

Figure 3. Overall infestation of hazelnut plants over the band heights, with no distinction between 2021 and 2022. Different letters indicate significant difference between the height ranges after Bonferroni post hoc test ($p < 0.05$).

The detailed situation of 2021 and 2022 is depicted in Figure 4. In particular, we found the same difference between the overall infestation depicted in Figure 1, but each year the difference between the height ranges shown in Figure 3 is coherently retrieved. In particular, in 2021, there is a difference between the band height 1.5 to 3.0 and 0 to 1.5

(GLMM, Z= −9.508, $p < 0.0001$) and >3.0 (GLMM, Z = 8.907, $p < 0.0001$), while there was no difference between the band height 0 to 1.5 and >3.0 (GLMM, Z = 0.767, $p = 1$). In 2022, the situation was similar since there was a difference between the band height of 1.5 to 3.0 and 0 to 1.5 (GLMM, Z = −9.508, $p < 0.0001$) and >3.0 (GLMM, Z = 8.907, $p < 0.0001$), while there was no difference between the band height 0 to 1.5 and >3.0 (GLMM, Z = 0.767, $p = 1$).

Figure 4. Overall infestation of hazelnut plants over the band heights, distinguishing between 2021 and 2022. Different letters indicate significant difference between the year of survey and height ranges after Bonferroni post hoc test at $p < 0.05$.

3.3. Infestation Ratio (Big Buds on Non-Infested Buds) over the Years and Plant Irrigation

The infestation index, calculated according to Equation (1), increased over the years, coherently with the variation of the number of big buds previously reported. All the values calculated for each year and distinguishing between irrigated and non-irrigated plants are listed in Table 1. The highest value of the index was observed in 2021 for the irrigated plants and 2022 for the non-irrigated plants.

Table 1. Infestation index for the irrigated and not-irrigated plants over the years, calculated according to Equation (1). N_B is the average number of not deformed buds per plant (mean ± SE), N_{BB} is the average number of big buds per plant (mean ± SE), R is the infestation index (%).

Year of Survey	Infestation Index (R) on Irrigated Plants	Infestation Index on Not-Irrigated Plants
2019	$N_B = 79 \pm 3$ $N_{BB} = 0.7 \pm 0.1$ $R = 0.89$	$N_B = 61 \pm 4$ $N_{BB} = 0.3 \pm 0.1$ $R = 0.54$
2020	$N_B = 49 \pm 2$ $N_{BB} = 1.0 \pm 0.1$ $R = 1.86$	$N_B = 34 \pm 2$ $N_{BB} = 1.0 \pm 0.2$ $R = 2.79$
2021	$N_B = 46 \pm 3$ $N_{BB} = 3.0 \pm 0.2$ $R = 5.86$	$N_B = 45 \pm 2$ $N_{BB} = 2.0 \pm 0.2$ $R = 3.85$
2022	$N_B = 36 \pm 2$ $N_{BB} = 1.4 \pm 0.2$ $R = 3.97$	$N_B = 36 \pm 2$ $N_{BB} = 1.5 \pm 0.2$ $R = 4.21$

4. Discussion and Conclusions

The results of the study show an overall increase, in recent years, of big bud mite infestation in the monitored hazelnut orchard located in central Italy. Although the percentage of affected buds persisted below the damage threshold determined by Viggiani and Bianco [20], the attention to the incidence of this phytophagous pest must be addressed to assess the impact that climate change may have on its populations and to set up the proper control strategy. This pest exhibits its harmfulness on several cultivars grown in Europe, becoming one of the main pests in hazelnut plantations and causing remarkable commercial losses [18,26,27]. Several studies highlighted differences in susceptibility, between cultivars commonly grown in Europe, to *P. avellanae* [3,28]. Based on the literature available, “Tonda Gentile Romana”, the main cultivar in Viterbo hazelnut district, showed a low susceptibility if compared to the other common Italian cultivars [29,30]. Our observations confirmed the lower susceptibility of “Tonda Gentile Romana”, but the situation is different in other relevant hazelnut districts of northern Italy, such as the Piedmont region. In this area, “Tonda delle Langhe” is the main cultivar and the presence of *P. avellanae* that periodically exceeds damage thresholds is controlled by the use of sulfur-based pesticides during the mite migration phase.

Besides the susceptibility level that different cultivars may have to mite infestations, some ecological and biological aspects of the species involved and its relationship with the host plant are still missing or partially explored. According to our results, underground irrigation does not seem to be a relevant factor of the infestation level since no differences were observed in the number of big buds between irrigated and non-irrigated plants. To the best of our knowledge, it is the first time that a dedicated experiment investigated the effects of irrigation on big buds’ mite populations in hazelnut orchards. However, our results raise another interesting question that further experiments should investigate. One may ask if watering impacts the plant’s physiological mechanisms regulating pest–host relationships with implications for mite penetration and colonization activity within buds. Based on what we observed, i.e., the absence of differences in big buds on irrigated and non-irrigated hazelnut plants, irrigation does not impact the capability of *P. avellanae* to penetrate and colonize the buds. This could be explained because irrigation by underground pipe systems provides water in dry months (i.e., mainly July and August in our focus areas), when mite penetration within the bud may have already occurred. As already stated, although several unclear aspects of mite pest biology persist, the timing and dynamics of migration from big buds to colonize healthy buds are sufficiently ascertained. Migration and bud penetration occurs mainly in April and May [13] when watering relies only on natural rainfall and resetting, de facto, the differences between irrigated and non-irrigated plants.

The appropriate water management, particularly in the Mediterranean area, has increasingly become a necessity, firstly because of its availability, which in the future will be more limited. In Central Italy, in particular, extreme droughts in association with rising temperatures mandate extremely careful management of water for crop irrigation [31]. Additionally, water is crucial in contrasting phytophagous agents, as already stated by González-Zamora et al. [32]. Both the amount and the method of supplying water may help in a more sustainable control of mite populations. In our experimental field, water was provided by an underground pipe system, but it has been observed that rainfall may impact *P. avellanae* populations migrating from colonized to healthy buds [13]. This leads to supposing that irrigation systems having similar effects to the rain may negatively impact the population density. This hypothesis is suggested by studies conducted on spider mites in several crops, even with the different bioethology of the species with respect to big bud mites. On grapevines, for example, an increased damage activity of *Tetranychus* spider mites on portions of plants exposed to high temperatures and low humidity has been assessed [33,34]. Additionally, a knockdown effect on populations of these phytophagous species occurred in plants sprayed with water [34], showing a detrimental impact on predatory mites [35]. The rain-like effect of irrigation caused a significant reduction of spider mite populations.

This precondition may explain why we have not observed significant differences in infestation levels between the irrigated and non-irrigated plants. Underground pipe systems have the advantage of being localized and never wetting the leaves. Accordingly, this irrigation method does not act as an artificial rain that may mechanically remove mites from plants. This supposition is confirmed by the results obtained by Chandler et al. [36] on corn plants infested by the spider mites *Oligonychus prarensis* (Banks) and *Tetranychus cinnabarinus* (Boisduval) whose populations have been affected by controlled irrigations as well as prolonged rain and thunderstorms.

Alternatively, the main result of this study concerns the mostly infested part of the plant considering its subdivision in height bands. As it has been demonstrated, in fact, the most infested band is central, namely 1.5 to 3.0 m. Starting from the ground, the first height band (0 to 1.5 m) may be not preferred by mites because of the low availability of buds, above all in cultivated fields where agronomic practices provide for removal of suckers through pruning. The higher band, >3.0 m, may be the least suitable because of the higher temperatures and lower humidity consequential to a higher exposure to sun rays. Moreover, the higher part of the canopy is also more susceptible to the action of rain, which, as stated above, can wash the plant surface from mite pests. Given this precondition, it may be logical to suppose that the central band height is a good compromise between availability of buds, optimal microenvironmental conditions, and sheltering from meteorological adversities. The vertical distribution we observed in this study is in line with the more general review published by Ulyshen [37] describing the arthropod vertical stratification in temperate deciduous forests.

The choice of the central band height can be justified considering the migration strategy of mites. The morphological characteristics of eriophyoids considerably compromise the active search for a new host plant, so that dispersal is generally passive [38,39]. As mentioned for the rust mite *Calepitrimerus vitis* (Nalepa), in vineyards [40,41], for instance, migration is mainly due to wind transportation or by exploiting other organisms, such as other arthropods or even humans with the common agricultural field management activities [42]. However, it is conceivable that under these conditions it becomes extremely difficult for the mite to have any decision-making ability in choosing the host [43]. At this point, both the mite's ability, albeit limited, to move and its capability to be transported by rainwater may play a role in the short-range dispersal of mites on the plant, providing a reasonable explanation of the concentration of the big buds in the plant's mid-belt.

Understanding the dispersal strategies of this phytophagous as well as a deeper knowledge of its biology can be very helpful in defining effective monitoring and control strategies. As stated in the introduction, there are at least two species involved in infestations, but their role has not yet been thoroughly delineated. Nonetheless, *P. avellanae* has been defined as a complex of two cryptic species: one living in the buds and responsible for gall formation and one present on several plant organs, in particular on the lower page of the leaves [15].

In light of the results obtained, this work adds some bricks to the knowledge about *P. avellanae*, but at the same time is a starting point for further aspects to deeply explore. Recently, the YOLO technique to automatically detect big buds has been introduced [23], but progress is still needed in the discrimination between big buds and healthy buds. An improvement of the YOLO application toward this direction will contribute to the automatic assessment of the infestation level in the field according to the common thresholds that are used in the management of this pest. The common trend in the management of this pest is to inspect as much as possible of the whole plant. This issue is relevant above all if the automated detection is entrusted to camera-equipped robots or drones with a limited battery capacity [44]. The identification of the most infested plant band height is of crucial importance since it will enable automated detection systems to monitor as many plants as possible in a limited time range. Additionally, further studies will need to be conducted to develop automated systems to control hazelnut major pests, in particular *P. avellanae*, at the granularity level of the single plant, which would reduce pesticide use, making hazelnut cultivation more sustainable.

This study provides information to (i) better cater the definition of monitoring and low-impact control strategies of a pest that will potentially be among the most injurious for hazelnut cultivations; and (ii) better understand the role of water in controlling this mite species, fundamental information in a context of increasing drought, above all in the Mediterranean basin.

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References

1. ISTAT. Available online: http://agri.istat.it/jsp/dawinci.jsp?q=plC190000010000011000&an=2017&ig=1&ct=270&id=15A%7C21A%7C30A (accessed on 17 July 2022).
2. FAO. FAOSTAT. Available online: http://www.fao.org/faostat/en/#data (accessed on 17 July 2022).
3. AliNiazee, M.T. Ecology and management of hazelnut pests. *Annu. Rev. Entomol.* **1998**, *43*, 395–419. [CrossRef]
4. Bosco, L.; Moraglio, S.T.; Tavella, L. *Halyomorpha halys*, a serious threat for hazelnut in newly invaded areas. *J. Pest Sci.* **2018**, *91*, 661–670. [CrossRef]
5. Turan, A.; Erdoğan, V. Spread and damage of citrus longhorned beetle [*Anoplophora chinensis* (Forster, 1771) (Coleoptera: Cerambycidae)] to hazelnut orchards in Turkey. *Turk. J. Agric.-Food Sci. Technol.* **2022**, *10*, 531–535. [CrossRef]
6. Mazzaglia, A.; Drais, M.I.; Turco, S.; Silvestri, C.; Cristofori, V.; Aymami, A.; Casadó, V.; Rovira, M. First report of *Erysiphe corylacearum* causing powdery mildew on *Corylus avellana* in Spain. *New Dis. Rep.* **2021**, *44*, 2–4. [CrossRef]
7. Mezzalama, M.; Guarnaccia, V.; Martano, G.; Spadaro, D. Presence of powdery mildew caused by *Erysiphe corylacearum* on hazelnut (*Corylus avellana*) in Italy. *Plant Dis.* **2021**, *105*, 1565. [CrossRef]
8. Sezer, A.; Dolar, F.S.; Lucas, S.J.; Köse, Ç.; Gümüş, E. First report of the recently introduced, destructive powdery mildew *Erysiphe corylacearum* on hazelnut in Turkey. *Phytoparasitica* **2017**, *45*, 577–581. [CrossRef]
9. Turco, S.; Zuppante, L.; Drais, M.I.; Mazzaglia, A. Dressing like a pathogen: Comparative analysis of different *Pseudomonas* genomospecies wearing different features to infect *Corylus avellana*. *J. Phytopathol.* **2022**, *170*, 1–13. [CrossRef]
10. Memoli, A.; Albanese, D.; Esti, M.; Lombardelli, C.; Crescitelli, A.; di Matteo, M.; Benucci, I. Effect of bug damage and mold contamination on fatty acids and sterols of hazelnut oil. *Eur. Food Res. Technol.* **2017**, *243*, 651–658. [CrossRef]
11. Rossini, L.; Contarini, M.; Speranza, S. A novel version of the Von Foerster equation to describe poikilothermic organisms including physiological age and reproduction rate. *Ric. Mat.* **2021**, *70*, 489–503. [CrossRef]
12. Rossini, L.; Contarini, M.; Giarruzzo, F.; Assennato, M.; Speranza, S. Modelling *Drosophila suzukii* adult male populations: A physiologically based approach with validation. *Insects* **2020**, *11*, 751. [CrossRef]
13. Özman, S.K.; Toros, S. Life cycles of *Phytoptus avellanae* Nal. and *Cecidiopyopsis vermiformis* Nal. (Eriphyoidea: Acarina). *Acta Hortic.* **1997**, *445*, 493–502. [CrossRef]

14. Ozman-Sullivan, S.K. Do the contradictory life cycles of the hazelnut big bud mite, *Phytoptus avellanae* (Nal.) (Acari: Phytoptidae) imply two species? In Proceedings of the Abstract book, XIV International Congress of Acarology, Kyoto, Japan, 13–18 July 2014; p. 62.
15. Cvrković, T.; Chetverikov, P.; Vidović, B.; Petanović, R. Cryptic speciation within *Phytoptus avellanae* s.l. (Eriophyoidea: Phytoptidae) revealed by molecular data and observations on molting tegonotus-like nymphs. *Exp. Appl. Acarol.* **2016**, *68*, 83–96. [CrossRef] [PubMed]
16. Vacante, V. *The Handbook of Mites of Economic Plants: Identification, Bio-Ecology and Control*; CABI: Wallingford, UK, 2015.
17. Ozman-Sullivan, S.K.; Akça, I. Efficiency of pesticides against big bud mites [*Phytoptus avellanae* Nal. and *Cecidophyopsis vermiformis* Nal. (Acarina: Eriophyoidea)] on hazelnut. *Acta Hortic.* **2005**, *686*, 393–400. [CrossRef]
18. Stamenkovic, S.; Milenkovic, S.; Pesic, M.; Mitrovic, M. Population dynamics, harmfulness and control of *Phytoptus avellanae* (Nalepa) in Western Serbia. *Acta Hortic.* **1997**, *445*, 521–526. [CrossRef]
19. Westphal, E.; Manson, D.C.M. 1.4.6 Feeding effects on host plants: Gall formation and other distortions. In *World Crop Pests*; Elsevier: Amsterdam, The Netherlands, 1996; pp. 231–242.
20. Viggiani, G.; Bianco, M. Osservazioni ed esperienze per una lotta chimica razionale contro *Phytoptus avellanae* Nalepa (Acarina: Eriophyidea). *Boll. Lab. Entomol. Agrar.* **1974**, *31*, 3–26.
21. Rossini, L.; Bono Rosselló, N.; Speranza, S.; Garone, E. A general ODE-based model to describe the physiological age structure of ectotherms: Description and application to *Drosophila suzukii*. *Ecol. Model.* **2021**, *456*, 109673. [CrossRef]
22. Lippi, M.; Bonucci, N.; Carpio, R.F.; Contarini, M.; Speranza, S.; Gasparri, A. A YOLO-based pest detection system for precision agriculture. In Proceedings of the 2021 29th Mediterranean Conference on Control and Automation (MED), Bari, Italy, 22–25 June 2021; pp. 342–347.
23. Lippi, M.; Carpio, R.F.; Contarini, M.; Speranza, S.; Gasparri, A. A data-driven monitoring system for the early pest detection in the precision agriculture of hazelnut orchards. In Proceedings of the 7th IFAC Conference on Sensing, Control and Automation Technologies for Agriculture, Munich, Germany, 14–16 September 2022.
24. Di Sora, N.; Rossini, L.; Contarini, M.; Chiarot, E.; Speranza, S. Endotherapic treatment to control *Toumeyella parvicornis* Cockerell infestations on *Pinus pinea* L. *Pest Manag. Sci.* **2022**, *78*, 2443–2448. [CrossRef]
25. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2008.
26. Abramishvili, T.; Gaganidze, D.; Ozman-Sullivan, S.K.; Abashidze, E. Phylogenetic analysis of hazelnut big bud mite—*Phytoptus avellanae* Nal. in the black sea region of Georgia. *Bull. Georgian Natl. Acad. Sci.* **2018**, *12*, 113–118.
27. Kereselidze, M.; Goderdzishvili, G.; Khidesheli, Z. Monitoring damage caused by harmful pests in hazelnut orchards in Samegrelo Region, Georgia. *Acta Hortic.* **2018**, *1226*, 373–378. [CrossRef]
28. Gantner, M. Susceptibility of large-fruited hazel cultivars grown in Poland to major pest and their crop productivity. *Acta Hortic.* **2005**, *686*, 377–384. [CrossRef]
29. Mehlenbacher, S.A. Genetic improvement of hazelnut. *Acta Hortic.* **1994**, *351*, 23–38. [CrossRef]
30. Tuncer, C. Arthropod management in organic hazelnut growing. *Acta Hortic.* **2009**, *845*, 571–578. [CrossRef]
31. Vergni, L.; Todisco, F. Spatio-temporal variability of precipitation, temperature and agricultural drought indices in Central Italy. *Agric. For. Meteorol.* **2011**, *151*, 301–313. [CrossRef]
32. González-Zamora, J.E.; Alonso-López, M.T.; Gómez-Regife, Y.; Ruiz-Muñoz, S. Decreased water use in a super-intensive olive orchard mediates arthropod populations and pest damage. *Agronomy* **2021**, *11*, 1337. [CrossRef]
33. Flaherty, D.L.; Huffaker, C.B. Biological control of Pacific mites and Willamette mites in San Joaquin Valley vineyards: I. Role of *Metaseiulus occidentalis*. *Hilgardia* **1970**, *40*, 267–308. [CrossRef]
34. Kinn, D.N.; Joos, J.L.; Doutt, R.L. Influence of overhead sprinkler systems on spider mite populations in north coast vineyards of California. *Environ. Entomol.* **1972**, *1*, 795–796. [CrossRef]
35. Opit, G.P.; Fitch, G.K.; Margolies, D.C.; Nechols, J.R.; Williams, K.A. Overhead and drip-tube irrigation affect twospotted spider mites and their biological control by a predatory mite on impatiens. *HortScience* **2006**, *41*, 691–694. [CrossRef]
36. Chandler, L.D.; Archer, T.L.; Ward, C.R.; Lyle, W.M. Influences of irrigation practices on spider mite. Densities on field corn. *Environ. Entomol.* **1979**, *8*, 196–201. [CrossRef]
37. Ulyshen, M.D. Arthropod vertical stratification in temperate deciduous forests: Implications for conservation-oriented management. *For. Ecol. Manag.* **2011**, *261*, 1479–1489. [CrossRef]
38. Sabelis, M.W.; Bruin, J. 1.5.3. Evolutionary ecology: Life history patterns, food plant choice and dispersal. In *World Crop Pests*; Elsevier: Amsterdam, The Netherlands, 1996; Volume 6, pp. 329–366.
39. Valenzano, D.; Bari, G.; Valeria, M.; de Lillo, E. Off-host survival of *Eriophyoidea* and remarks on their dispersal modes. *Exp. Appl. Acarol.* **2019**, *79*, 21–33. [CrossRef]
40. Duffner, K.; Schruft, G.; Guggenheim, R. Passive dispersal of the grape rust mite *Calepitrimerus vitis* Nalepa 1905 (Acari, Eriophyoidea) in vineyards. *Anz. Fur Schent Glyphadlingskunde* **2001**, *74*, 1–6. [CrossRef]
41. Galvão, A.S.; Melo, J.W.S.; Monteiro, V.B.; Lima, D.B.; de Moraes, G.J.; Gondim, M.G.C. Dispersal strategies of *Aceria guerreronis* (Acari: Eriophyidae), a coconut pest. *Exp. Appl. Acarol.* **2012**, *57*, 504–516. [CrossRef] [PubMed]
42. Rossini, L.; Bono Rosselló, N.; Contarini, M.; Speranza, S.; Garone, E. Modelling ectotherms' populations considering physiological age structure and spatial motion: A novel approach. *Ecol. Inform.* **2022**, *70*, 101703. [CrossRef]

43. Calvet, É.C.; Lima, D.B.; Melo, J.W.S.; Gondim, M.G.C., Jr. Host plant discrimination through mobility parameters by eriophyoid mites. *Syst. Appl. Acarol.* **2020**, *25*, 1541–1551. [CrossRef]
44. Rossello, N.B.; Garone, E. Carrier-vehicle system for delivery in city environments. *IFAC-PapersOnLine* **2020**, *53*, 15253–15258. [CrossRef]