Crop Protection 187 (2025) 106968

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Soft soap and linalool as potential management tools for *Philaenus spumarius* (Hemiptera: Aphrophoridae), vector of *Xylella fastidiosa*

Linda Abenaim [a,1], Priscilla Farina [a,1], Alessandro Mandoli [b], Giuseppe Conte [a,c], Barbara Conti [a,c,d,*]

[a] University of Pisa, Department of Agriculture, Food and Environment, Via del Borghetto 80, 56124, Pisa, PI, Italy
[b] University of Pisa, Department of Chemistry and Industrial Chemistry, Via Giuseppe Moruzzi 13, 56124, Pisa, PI, Italy
[c] University of Pisa, Nutrafood, Research Center Nutraceuticals and Food for Health-Nutrafood, Via del Borghetto 80, 56124, Pisa, PI, Italy
[d] University of Pisa, Cirsec, Centre for Climatic Change Impact, Via del Borghetto 80, 56124, Pisa, PI, Italy

ARTICLE INFO

Keywords:
Spittlebug
Xylella fastidiosa
Potassium salts of fatty acids
Olfactometer
IPM

ABSTRACT

Philaenus spumarius (Hemiptera: Aphrophoridae) is one of the most polyphagous xylem-feeding pests. It recently acquired bad fame when it was identified as the main vector of the bacterium *Xylella fastidiosa*, the causal agent of the Olive Quick Decline Syndrome that, within ten years, has affected and led to the death of more than 21 million olive trees in the Southern Italian region Apulia alone. Despite the agricultural practices and synthetic insecticides available, as not sufficiently effective, more strategies to target all the developmental instars of the pest and eco-friendly formulations, especially in organic orchards, are urgently needed. Therefore, the main goals of this work were to test the toxicity of a solution of potassium salts of fatty acids (soft soap) on *P. spumarius* juveniles and assess the attractiveness exerted by linalool on adults in a planar olfactometer. According to our results, the average neanids/nymphs' mortality was 82.2 ± 10.4% 24h after spraying the soft soap on them at the labelled dose. Regarding the adults, linalool was significantly attractive to both sexes in a concentrations range between 0.01 and 0.12 μL linalool L^{-1} air. Our purpose is to potentially suggest a dual, integrated control approach against *P. spumarius*, with the soft soap as a biopesticide to reduce the immature stages of the pest and attractive, linalool-activated traps to numerically cull the population of the meadow spittlebug as part of a broader management system.

1. Introduction

Philaenus spumarius (Linné, 1758) (Hemiptera: Aphrophoridae), known as the meadow spittlebug, is a species of Palearctic origin and distribution, but it is also established in North America after an accidental introduction (Whittaker 1973).

It is considered one of the most polyphagous xylem-feeding pests, reported on over 1300 host plants belonging to 117 families (Thompson et al., 2023). Juveniles prefer herbaceous plants of the families Asteraceae and Fabaceae, while adults, especially over Summer, migrate to woody host plants to find more succulent and tender shoots and a shaded shelter.

The name "spittlebug" derives from the characteristic production of a frothy nest by neanids and nymphs, where they live protected until adult development. This froth is supposed to shield juvenile spittlebugs, characterised by a soft cuticle, from excessive evaporation (Evans 1940), UV radiation (Chen et al., 2018), and/or against predators and pathogens (Chang et al., 2019).

Philaenus spumarius recently acquired bad fame when it was identified as the main vector of the xylem-inhabiting bacterium *Xylella fastidiosa* Wells et al., 1987 (Saponari et al., 2014), the causal agent of, among others, Pierce's disease of grapevine (subsp. *fastidiosa*) and Olive Quick Decline Syndrome (OQDS) (subsp. *pauca*). Within the last ten years, in the Southern Italian region of Apulia alone, more than 21 million olive trees were infected by *X. fastidiosa*, with severe ecological and economic repercussions (Coldiretti 2023). The bacterium is acquired and transmitted by xylem-feeding Auchenorrhyncha only: its cells attach to and multiply in the stomodeum (precibarium and cibarium) of the vectors (Hill and Purcell, 1995). Therefore, the juvenile instars that acquire *X. fastidiosa* from infected plants can only transmit it

* Corresponding author. University of Pisa, Department of Agriculture, Food and Environment, Via del Borghetto 80, 56124, Pisa, PI, Italy.
E-mail address: barbara.conti@unipi.it (B. Conti).
[1] Linda Abenaim and Priscilla Farina should be considered joint first author.

https://doi.org/10.1016/j.cropro.2024.106968
Received 7 August 2024; Received in revised form 26 September 2024; Accepted 30 September 2024
Available online 1 October 2024
0261-2194/

until their moult, as the latter involves the change of the foregut cuticle and, consequently, the loss of the epicuticle-associated bacteria. Instead, positive adults can persistently transmit it for the rest of their lives (Almeida and Purcell 2006). As this species has never been considered a major crop threat, biological data, often dependent on environmental conditions, are currently lacking and scattered. Nowadays, however, this knowledge has become crucial, given the role of this pest in the transmission of the *X. fastidiosa* bacterium.

To try to reduce *P. spumarius* populations, the juveniles' control through soil tilling remains the most useful and sustainable approach, even if not fully effective (Sanna et al., 2021). Conversely, adult management requires several applications of insecticides, mainly pyrethroids and neonicotinoids (Dongiovanni et al., 2018), before they reach the canopies of olive and other trees and bushes of agricultural interest. The use of such chemicals has certainly helped but not solved the problem and, undoubtedly, brought side effects. The meadow spittlebug control, therefore, must benefit from the integration of all the available strategies to target its different developmental stages and reduce the massive use of chemical insecticides, in favour of eco-friendly formulations, especially in organic orchards.

Potassium salts of fatty acids (soft soap) are prepared from plant oil or animal fat through saponification by adding potassium hydroxide (Betsy et al., 2013), so different commercial formulations are available. They have been used since the 1700s to control soft-bodied insects (*e.g.*, aphids, psyllids, scales, thrips, whiteflies) and mite pests. The first pesticide containing soft soap was officially registered in 1947 in the US (RED, 1992). Its insecticidal and miticidal properties are related to the length of the carbon-based fatty acid chains (from 8 to 12 or 18-carbon chains are preferable) (Puritch 1981). Soft soap has low acute toxicity on humans when accidentally taken orally or with prolonged skin contact, and its half-life in the environment is estimated to be less than one day. Some potassium salts of fatty acids used as food additives are even listed as generally recognized as safe (GRAS) by the United States Food and Drug Administration (CFR 2023a). In the European Union, soft soap is authorised as a pesticide in organic farming under Council Regulation (EEC) No 2092/91 (EEC, 1991) carried over by Council Regulation (EC) No 834/2007 (EC, 2007).

Racemic linalool ((±)-3,7-dimethyl-1,6-octadien-3-*ol*) is an acyclic monoterpene alcohol. It is one of the most common secondary metabolites in monocotyledonous and dicotyledonous; indeed, it is part of the floral scent emitted by 70% of the seed plants (Knudsen et al., 2006). In this regard, linalool attracts a broad spectrum of insect pollinators (*e.g.*, bees, butterflies, moths, beetles), herbivores, and parasitoid wasps (Raguso and Pichersky 1999). Considering its flowery, spicy, citrusy, and fresh aroma, linalool extracted from essential oils or industrially synthesised is abundantly used in perfumery and cosmetics (Kamatou and Viljoen 2008). It is, as well as the soft soap, listed as a GRAS substance (CFR 2023b), so it can be employed by the food industry as a flavouring agent and adjuvant. Its relaxing, sedative, anxiolytic (Cline et al., 2008; Linck et al., 2010), analgesic (Batista et al., 2008), and anti-inflammatory (Peana et al., 2002) properties on humans and animals have been assessed in numerous *in vitro* and *in vivo* trials (Aprotosoaie et al., 2014). Furthermore, linalool is registered as a biopesticide to control fleas, mites, spiders, and ticks and inhibits mosquitoes (EPA 2018).

Therefore, the aims of this work were: I. to study the biology of *P. spumarius* in Central Italy; II. to evaluate the toxicity of a soft soap solution on its juveniles when protected by their foam nests; III. to assess the bioactivity of linalool on its adults. Our purpose is to potentially suggest a dual, integrated control approach for *P. spumarius,* using soft soap as a biopesticide and attractive, linalool-activated traps to numerically cull the *P. spumarius* population as part of a broader management system.

2. Materials and methods

2.1. Biological observations on Philaenus spumarius in central Italy

Due to the difficulties encountered in rearing *P. spumarius* under laboratory conditions (Cornara et al., 2018), biological observations were conducted by collecting the species in fallow fields, near an olive grove in Central Italy (Pisa, Tuscany), starting from February 2023. Each week, residues of the previous year's vegetation of *Artemisia vulgaris* L., belonging to the Asteraceae family and known to host *P. spumarius* juvenile instars, were collected to record the presence of eggs. Beginning in April, only the parts of the new plants with frothy nests were sampled, and the neanids/nymphs from these nests were used for the toxicity tests. Additional rooted plants with foam nests were planted in pots and then placed in cages to allow the development of adults for taxonomical identification. These adults were also subsequently used for the laboratory behavioural tests. Further adults were then collected starting from May in the olive tree orchard, using an entomological net (Cornara et al., 2018), with the aim of using them in the behavioural tests and recording their presence in the environment considered. All adults were randomly identified taxonomically using the EPPO (2020) Diagnostic Protocol (PM 7/76(5)).

2.2. Chemicals

We used a commercial soft soap (Sapone molle Zapi Garden, ZAPI S. p.A., Conselve, Italy) obtained from vegetal oil and containing 35% of potassium salts of fatty acids. The concentrations recommended on the label, for prevention and to dissolve honeydew, are 7 mL L^{-1} of water (0.7%) for flowers and ornamental plants and 9 mL L^{-1} (0.9%) for horticultural crops and fruits.

Racemic (±)-linalool was purchased from Sigma-Aldrich (St. Louis, MO, USA).

2.3. Insecticidal activity of soft soap against Philaenus spumarius juveniles

The neanids/nymphs protected in their foam nests placed at the top of the *A. vulgaris* plants were selected for the soft soap toxicity bioassays by establishing the presence of only one nest per plant and only one juvenile in each nest, according to the protocol of Sevarika et al. (2022). All the additional specimens found in the nests were carefully transferred to the adult development cage using a fine-tipped, wet brush. Ten flasks filled with water (25 mL of volume), each one containing the *A. vulgaris* segment with a juvenile protected inside its nest, were randomly distributed in BugDorm-4M4590DH cages (47.5 × 47.5 × 93 cm manufactured by Mega View Science Co., Ltd. in Taichung, Taiwan). Six cages were assigned to soft soap, six to water, and six to the negative control groups, so that each group was composed of six replications for a total of 60 frothy nests/juveniles. The soft soap group consisted of administering two sprays of a soft soap solution to each nest using a spray dispenser, employing the lowest dose indicated on the label of the commercial product (namely 7 mL of the concentrated soft soap solution, density 1.03 kg L^{-1}, in 1000 mL of water, corresponding to 0.25% by weight of dry soap; the pH of the solution was 8.6 ± 0.05 (mean pH ± standard deviation SD, $n = 3$) as measured with a pH-meter). Each spray had an average weight of 0.082 ± 0.02 g (mean weight ± SD, $n = 20$) that, assuming a density around 1 kg L^{-1} for the diluted solution, corresponds to approximately 82 μL. Therefore, each nest received approximately 1.15 μL of concentrated soap solution or 415 μg on dry soap basis. The water group received two sprays of water only (approximately 164 μL), while the negative control received no spraying.

The cages were maintained under environmental conditions (20 ± 2 °C temperature, 70–72% relative humidity) in an outdoor netted and covered tunnel greenhouse. The full experiment was repeated four times (namely, on the 12th, 19th, and 26th of April and 3rd of May), and the mortality was assessed after 24 h from the beginning of each test.

Other control experiments with $NaHCO_3$, $KHCO_3$, and Tween 80 were conducted on the 3rd of May to evaluate the differences in mode of action against *P. spumarius* juveniles. The trials were performed with the same methodology as the previous ones, and three cages were assigned to $NaHCO_3$ (9.8 mM), $KHCO_3$ (9.8 mM), 1.28 wt% of Tween 80, 0.7% of soft soap, and water alone each. All the frothy nests were sprayed with an assigned treatment, and the mortality was assessed after 24 h from the beginning of the test.

2.4. Behavioural impact of linalool on Philaenus spumarius adults

The adults used for the behavioural assay with linalool were obtained by gently transferring juveniles collected in the open field into a polyester and knitted mesh cage (BugDorm-4M4590DH) provided with an *A. vulgaris* potted plant. The cage was maintained under the same above-mentioned environmental conditions until the emergence of the adults.

The behavioural impact exerted by linalool on *P. spumarius* adults was assessed in a two-way planar olfactometer, as reported by Abenaim et al. (2022). The device consists of a polymethylmethacrylate arena (15 × 15 × 1 cm) with three circular chambers (4.0 cm Ø, volume 12.56 cm^3). The two lateral chambers are connected to the central one (release chamber) by linear paths (length 2.0 cm), forming a 90° angle between them. The top and bottom of the arena are removable glass panels. One lateral chamber represents the control (C) and contains a square (side 1.0 cm) of Whatman no. 1 filter paper treated with 3.0 μL of ethanol. The other chamber contains an identical square of filter paper treated (T) with 3.0 μL of ethanol solutions of linalool at different concentrations (namely, 0.005, 0.01, 0.025, 0.05, 0.075, and 0.1%, corresponding to the concentrations of 0.01, 0.02, 0.06, 0.12, 0.18, and 0.24 μL linalool L^{-1} air). Before use, the solvent was let to evaporate.

At the beginning of the observation, one unsexed *P. spumarius* adult was gently placed on the floor of the release chamber, and the top glass panel of the arena was closed. The choice was considered valid when the insect entered the C or T chamber after at least 20 s from the release and stayed in it for at least 30 s. The total observation time was 360 s. Specimens unable to choose after 331 s were discarded. For each linalool concentration, the test was replicated until 10 adults made a valid choice; each full experiment was repeated 3 times for a total of 30 valid tests. All the observations were conducted in a quiet room at a temperature of 25 ± 1 °C, 65% relative humidity, and illuminated only with a daylight fluorescent tube (Philips 30 W/33, 10,000 lux) placed right over the arena.

After each test, the planar olfactometer was rotated 90° clockwise to avoid positional biases, and the squares of filter paper were renewed. After four consecutive tests, the arena and the glass panels were wiped for about 30 s with ethanol, washed in a water bath with mild soap, rinsed first with hot water for about 30 s, then with distilled water, and dried.

2.5. Data analysis

For the effectiveness of the soft soap toxicity tests, the percentage of juveniles' mortality was calculated as the average of the mortality for water, soft soap, $NaHCO_3$, $KHCO_3$, and Tween 80 groups. Before the statistical analysis, the observed mortality was corrected with Abbott's formula (1925). The Shapiro-Wilk normality test (JMP software, JMP Pro®, Version 17. SAS Institute Inc., Cary, NC, USA, 1989–2021) indicated that the data were not normally distributed, so the nonparametric Kruskal-Wallis test, followed by the Wilcoxon post-hoc test ($p = 0.05$), was performed to evaluate the mortality between the treatments over time.

For the bioactivity of linalool, the proportion of *P. spumarius* adults choosing a specific chamber of the two-way olfactometer was compared through a likelihood-ratio chi-square (χ^2) test, with a null hypothesis of a 50:50 chance of insects choosing the control (C) chamber *vs* the treated chamber (T). We postulate that, in normal conditions, the distribution of the insects would be 50% in the C chamber and 50% in the T chamber (Germain et al., 2020).

3. Results

3.1. Biological traits of Philaenus spumarius in central Italy

From our observations, in Central Italy, *P. spumarius* (Fig. 1a) is confirmed as a monovoltine species, having its overwintering eggs (Fig. 1b) hatching in March, juveniles' development during the Spring through five stages (two neanids and three nymphs) (Fig. 1c and d), and adults' presence from late April/early May to November (Table 1).

During the biological observations, we also examined the foam nests produced by the nymphs. The foam is composed of honeydew deriving from the filter chamber and a mixture of proteins from the epithelium of the distal segment of Malpighian tubules and mucopolysaccharides from the proximal one (Marshall 1964, 1973). To "whip" it, nymphs blow in air from their thoracic and abdominal stigmas and repeat movements of union and separation of the paratergal lobes of the urites (Farina et al., 2022) shown in Fig. 2.

3.2. Toxicity of soft soap on Philaenus spumarius juveniles

The soft soap solution led to mortality the *P. spumarius* juveniles after 24 h of treatment in the four different application times from April to May. Mortality data were adjusted using Abbott's formula (1925) to consider the natural mortality of the neanids/nymphs that occurred in the negative control group (6.5 ± 0.9%).

The average percentage of juveniles' mortality in each replicate with soft soap was always higher than 60%. The highest percentage of mortality reached was 93.3 ± 8.2%, observed on the 19th of April. The overall mean neanids/nymphs' mortality over time was 82.2 ± 10.4%.

Conversely, the water-sprayed juveniles exhibited significantly lower mortality percentages (overall mean of 11.2 ± 3.5%) after 24 h from the beginning of the experiments. Indeed, a statistically significant difference in mortality was observed between the soft soap and water-sprayed specimens ($\chi^2 = 41.05$; DF = 7; $p < 0.0001$), as displayed in Fig. 3.

The mortality of *P. spumarius* juveniles after 24 h in the additional control treatments is reported in Fig. 4.

The highest percentage of mortality reached was 40 ± 1.73% observed for the soft soap treatment. The lowest mortality was obtained with water (3.3 ± 0.57%). $NaHCO_3$, $KHCO_3$, and Tween 80 accounted for 10 ± 1, 20 ± 1, and 6.6 ± 0.5% mortality, respectively.

The statistical analysis reported a statistically significant difference in mortality only between the soft soap and water-sprayed neanids/nymphs ($\chi^2 = 9.73$; DF = 4; $p < 0.0452$).

3.3. Bioactivity of linalool on Philaenus spumarius adults

At the lowest concentrations tested, linalool showed a clear effect on *P. spumarius* adults' behaviour (Fig. 5). In detail, in the concentrations range between 0.01 and 0.12 μL L^{-1} air, linalool was significantly attractive on males and females of the species [0.01 μL L^{-1} air: χ^2 (1, n = 15) = 16.13, $p = 0.00006$; 0.02 μL L^{-1} air: χ^2 (1, n = 15) = 13.33, $p = 0.00026$; 0.06 μL L^{-1} air: χ^2 (1, n = 15) = 10.80, $p = 0.00102$; 0.12 μL L^{-1} air: χ^2 (1, n = 15) = 4.80, $p = 0.028$], and, in particular, its attractive effect increased as the concentration decreased.

Conversely, at the concentrations of 0.18 and 0.24 μL L^{-1} air, linalool did not influence *P. spumarius*' behaviour (Fig. 5).

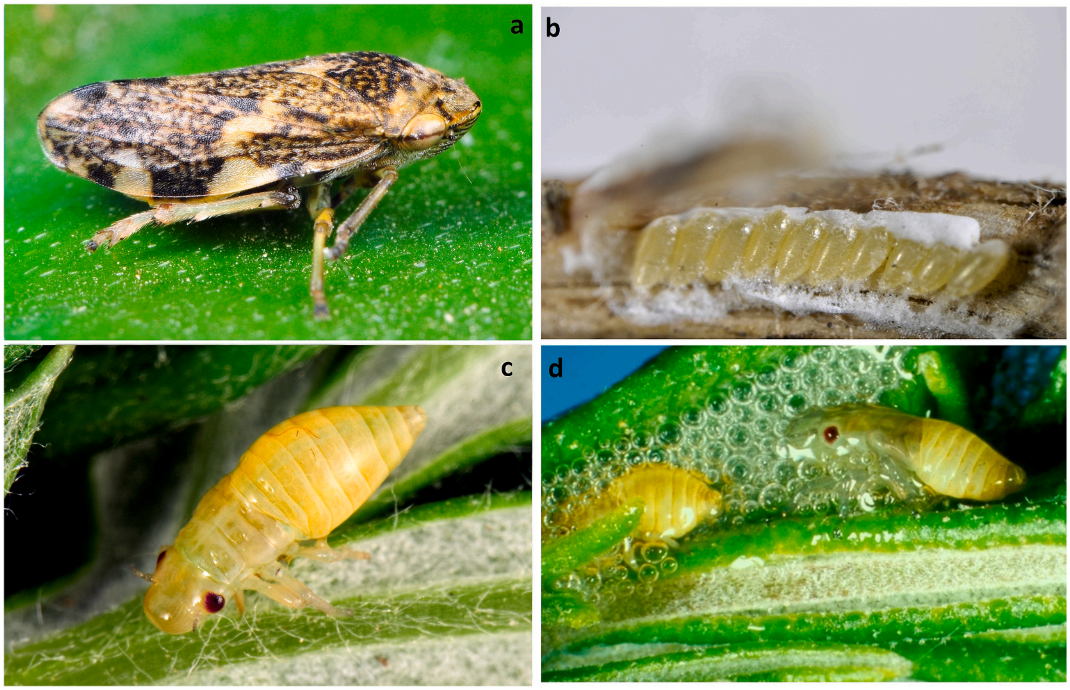

Fig. 1. *Philaenus spumarius* a) adult; b) eggs (photo by Alberto Fereres); c) neanid newly emerged from the egg; d) mature nymphs in their foam.

Table 1
Observations on *Philaenus spumarius* development in the open field in Central Italy.

Date	Development of instars sampled	Temperature (min-max °C) [a]
20 March	Newly emerged neanids	10.6–16.6
12 April - 3 May	Presence of neanids and nymphs in the frothy nests	8.2–16.6
26 April	Presence of new adults	7.5–22.5
7 May	Beginning of adult mating	11.8–23.9
May - 15 September	Pre-reproductive adults	12.0–30.3
October	Presence of eggs and adults	15.8–23.0
3 November	Sporadic adults	12.5–17.3
November - March	Overwintering eggs	7.5–18.4

[a] Data from the Regional Hydrological Service of Tuscany database (SIR).

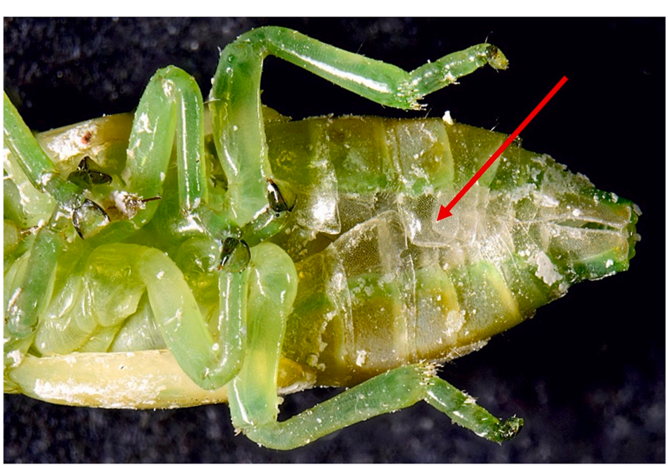

Fig. 2. *Philaenus spumarius*: ventral view of the thorax and abdomen of the last instar nymph with evidence of the paratergal lobes of the urites (red arrow).

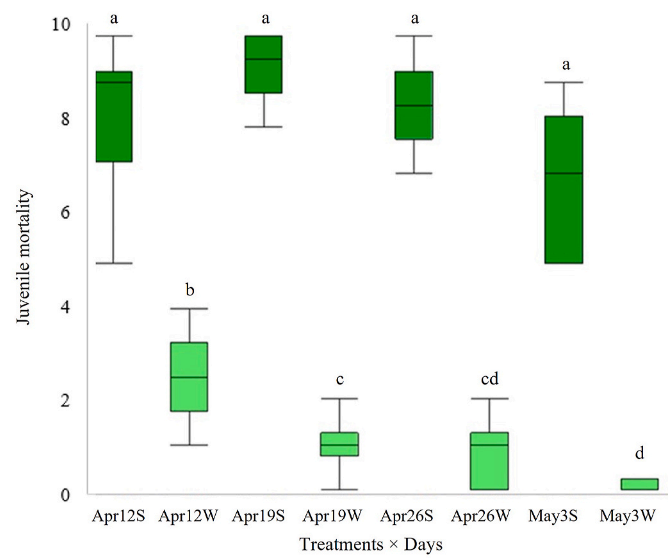

Fig. 3. Box plots of mortality rates for *Philaenus spumarius* neanids/nymphs across treatments (W = water; S = soft soap) over time. Lines within boxes represent the median, and the box bounds the 25th (lower) and 75th (upper) percentiles. Different letters indicate statistically significant differences ($p < 0.05$).

4. Discussion

Biological observations on *P. spumarius* in Central Italy provided insights into the species' life cycle in this region. Comparing our data with those recorded in other environments, including Southern Italy (Apulia region) (Cornara et al., 2018; Picciotti et al., 2021), we detected no differences in the biological cycle of the species, despite diverse climatic conditions and average temperatures. These findings suggest a remarkable consistency in the developmental stages across different areas, highlighting the species' adaptability. In addition, they may allow better organisation and management of the planned treatments, both for

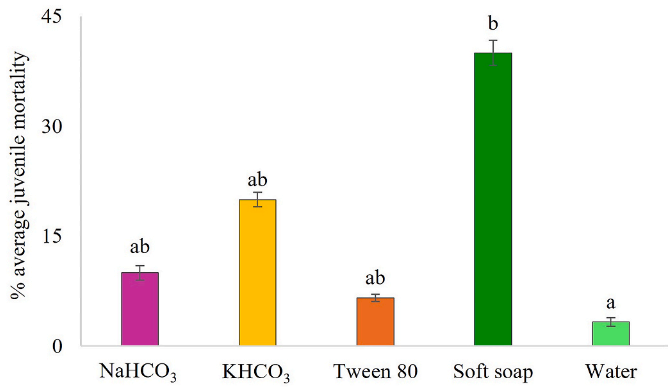

Fig. 4. Average mortality (%) of *Philaenus spumarius* neanids/nymphs 24 h after the treatment with $NaHCO_3$, $KHCO_3$, Tween 80, soft soap, and water. Histograms represent the mean ± standard deviation (SD) across the replicates ($n = 3$).

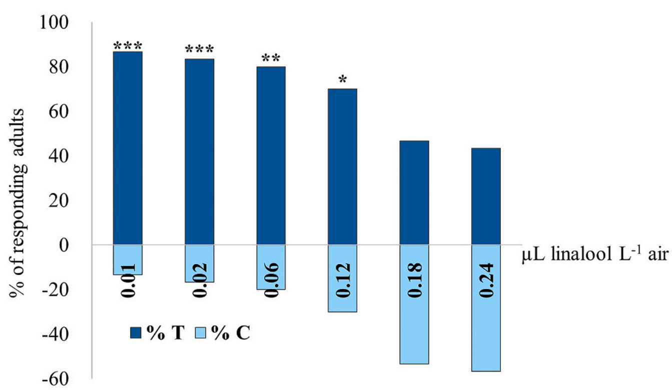

Fig. 5. Percentage of *Philaenus spumarius* adults choosing between the control (C – negative y-axis values) or linalool-treated (T – positive y-axis values) chamber of a planar olfactometer. Asterisks indicate the significant effect of linalool on the ratio of insects choosing between the two chambers (χ^2 test; significance level ***$p < 0.001$, **$p < 0.01$; *$p < 0.05$).

the juvenile and adult stages, aimed at reducing the population.

Several commercial soft soap formulations were successfully applied against eggs, juvenile instars, and adult arthropods under laboratory conditions and/or in the field. In our study, the average *P. spumarius* neanids/nymphs' mortality was 82.2 ± 10.4% after 24 h when using a concentration of soft soap of 0.7%. Our data are in agreement with Hall and Richardson's (2012) findings that, using a direct spray at 0.8, 1.6, and 2.0% of a soft soap solution, recorded 90, 96, and 100% adult mortality, respectively of the Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae), and complete mortality of its nymphs. The same treatments, however, induced over 80% mortality in the Asian citrus psyllid parasitoid *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae) (Hall and Richardson 2012).

There are pieces of evidence of the soft soap's effectiveness at concentrations not comparable to the one we used. For example, the application, under laboratory conditions, of 4.0 mL of a 1.0% solution of a soft soap directly on eggs, nymphs, and adults of the brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), gave from 80 to 100% mortality (Bergmann and Raupp, 2014). In a field experiment on snap beans, a soft soap at 1.5% reduced by 54% adult whiteflies (Hemiptera: Aleyrodidae) on sticky cards, 83% their nymphs on leaves, and up to 68% thrips (Thysanoptera: Thripidae) on flowers, thus resulting in an increase in beans' yield by up to 151% (Wafula et al., 2017). Furthermore, a 2.0% soft soap application on the soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), gave more than 80% mortality after 72 h on nymphs and adults (Kraiss and Cullen 2008). On apple trees treated with a soft soap solution (20 L ha^{-1}), the mortality of the green apple aphid, *Aphis pomi* De Geer, after 14 days was almost 85% (Raudonis et al., 2009), similarly to the effect on *Aphis gossypii* Glover on greenhouse-grown cucumber (Emami 2016).

Conversely, a pest species closer to *P. spumarius*, namely the grapevine leafhopper *Scaphoideus titanus* Ball (Hemiptera: Cicadellidae), was not significantly affected by soft soap applications in the field (Tacoli et al., 2017).

When talking about non-target toxicity, predators are usually unharmed, while some parasitoids are susceptible (as seen for *T. radiata*) to direct spray applications of soft soap and its residues in terms of lethal and sub-lethal effects. About the Coleoptera Coccinellidae predators, a soft soap at 10 mL L^{-1} was harmless to the last instar larvae of *Coccinella septempunctata* and *Hippodamia variegata* (Goeze) (Skouras et al., 2019), and *Cycloneda sanguinea* (L.) adults were only weakly susceptible to a 2.0% soft soap solution (Hall and Richardson 2012). Furthermore, the application of a 2.0% soft soap was moderately lethal to *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae) larvae (about 40% of mortality) but was not toxic to its pupae and adults (Kraiss and Cullen 2008). For the Neuroptera Chrysopidae predators, a 1.0% soft soap was not toxic to the lacewing *Chrisoperla rufilabris* (Burmeister) and *Ceraeochrysa cubana* (Hagen) eggs, larvae, and adults by topical application nor by residual exposure (Schuster and Stansly, 2000).

The most accredited modes of action reported for soft soap involve the obstruction of insects' spiracles, thus causing death by asphyxiation, and disruption of cuticle's waxes and lipoprotein matrix of insects' cellular membranes, leading to leaking of the cell contents and dehydration of the treated soft-bodied pests (Puritch 1981; Osborne and Henley 1982; Isman 2006). This is why soft soap has scarce activity on hard-bodied insects due to their thickened and penetration-resistant cuticle, as seen for adult coccinellids (Hall and Richardson 2012; Kraiss and Cullen 2008; Skouras et al., 2019).

Other Authors reported that soaps can chemically interact with the proteinaceous content of the froth, by stabilising, destabilising, unfolding, or avoiding the bindings of the different proteins (Pedersen et al., 2019). In fact, according to our observations, after applying the soft soap on *P. spumarius*' frothy nests, the foam quickly dried. Besides any surface tension effect, possibly implied by the protein interaction noted above, these findings could be due to additional mechanisms of action. One is the unbalancing of the hydrophilic/hydrophobic properties of the treated foam, resulting in a faster water evaporation rate (Pasquet et al., 2022) and, hence, a more pronounced vulnerability of the juveniles to drying out. Alternatively, the strongly alkaline nature of the soft soap (pH = 8.6 in the diluted solution) might reduce the capacity of the foam to adsorb and neutralise ammonia, a toxic metabolic by-product in ammonotelic insects, thus impairing one of the physiological roles proposed for the spittlebug' nest (Rakitov 2002). However, control experiments revealed that neither 1.28 wt% Tween 80 (polyoxyethylenesorbitan monooleate, a non-ionic surfactant used for, *e.g.*, solubilising membrane proteins), nor solutions of the basic salts $NaHCO_3$ or $KHCO_3$ (9.8 mM, pH = 8.4), are appreciably effective in killing the *P. spumarius* neanids/nymphs. Overall, these findings indicate that the biocide action of soft soap is not allied to its surface tension or pH-modulation effects, taken separately, but it is likely to be rooted in the specific molecular structure, and associated physical-chemical properties (*e.g.*, propensity to precipitate), of the salts of long-chain carboxylic acids.

In a recent paper, an electroantennographic screening on 50 plant volatile organic compounds (VOCs) revealed that *P. spumarius* adults have a strong response to (±)-linalool, with a significant difference in the EAG magnitude between the more stimulated females (0.48 ± 0.05 mV) and males (0.33 ± 0.03 mV) (Germinara et al., 2017). Having the certainty that *P. spumarius* can perceive VOCs, and particularly this terpene alcohol, we verified the behavioural impact of its stimulus on the species. We observed that linalool is significantly attractive to individuals in a concentrations range between 0.01 and 0.12 μL linalool L^{-1} air. Contrarily, at higher concentrations, linalool does not influence insect behaviour. Bedini et al. (2024) reported that some essential oils and their compounds exhibit hormetic behaviour against the same insect species, changing from repellent to attractive and *vice versa* as the dose administered decreases or increases. In fact, according to Bedini et al. (2024), linalool is one of the attractive substances at the lowest concentrations, while, at the highest concentrations tested, it does not become significantly repellent.

In a flow-olfactometer, Rodrigues et al. (2022) tested the attractiveness of cis-3-hexen-1-ol and cis-3-hexenyl acetate, the main VOCs emitted by almonds, olives, and vines' leaves to *P. spumarius.* The Authors observed that, at the concentration of 5 μg μl^{-1}, females were significantly attracted by both compounds while males, at the same concentration, preferred the alcohol. In a Y-tube olfactometer, females were also attracted to camphor at 100 μg mL^{-1} (Anastasaki et al., 2021) and males to *Pelargonium graveolens* (Thunb.) L'Hér. plants (Ganassi et al., 2020).

Besides linalool, the electroantennographic bioassays conducted by Germinara et al. (2017) demonstrated that other compounds such as octanal, 2-octanol, 2-decanone, (*E*)-2-hexenyl acetate, and vanillin were able to elicit high responses from both sexes of *P. spumarius*, as well as the VOC blends emitted from host plants (*e.g.*, *Olea europaea* L., *Polygala myrtifolia* L., *Cistus creticus* L.) (Anastasaki et al., 2021) and some essential oils (Ganassi et al., 2020).

As also suggested by Germinara et al. (2017) and Anastasaki et al. (2021), the identification of bioactive compounds attractive to *P. spumarius*, including the linalool here tested, could be useful to implement semiochemical-based management strategies to manipulate the pest's behaviour. The identified attractants could also be used in attract-and-kill traps or for the second phase of a push-pull strategy, as already proposed by Ganassi et al. (2020) and Morente et al. (2022) for *P. spumarius*.

5. Conclusions

In our study, we aimed to develop a potential protocol for controlling *P. spumarius* in Central Italy by integrating two products: soft soap, which targets the juvenile stages, and linalool, which is effective in attracting adults.

Our trials confirmed the toxicity of soft soap, under laboratory conditions, on a pest species usually not reported as a target on the manufacturers' labels, namely the soft-bodied neanids and nymphs of *P. spumarius*. The application of this biopesticide, authorised in organic farming, on the herbaceous vegetation surrounding the orchards of olive and other trees of agricultural interest could reduce the juvenile density with almost no adverse ecological effects.

Regarding the adults, the implementation of linalool-activated traps is suggested to manipulate the pest's behaviour and play a substantial role in its limitation once it has reached trees and bushes canopies. Linalool, being attractive at low concentrations, according to our data, could represent an inexpensive lure. Additionally, as its attractive effect increases as the concentration decreases, its volatility should not negatively affect its efficacy. However, we hope and expect that the industry will embrace the challenge of producing long-release, stabilised linalool attractive traps.

Overall, by closely monitoring the biological cycle of *P. spumarius*, we recommend the application of soft soap from the beginning of April to mid-May for juvenile stages control and the usage of attract-and-kill traps with linalool from the end of April for the mass trapping of adults. Notwithstanding that a successful strategy should involve all the actors of the complex interaction plant-pathogen-vector, the dual, integrated control approach on *P. spumarius* here proposed is suggested as part of a broader management system. Ensuring the applicability and effectiveness of these two control methods with further trials is crucial for developing a comprehensive and effective system for managing *P. spumarius*.

Funding

Research not funded

CRediT authorship contribution statement

Linda Abenaim: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Priscilla Farina:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Alessandro Mandoli:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Giuseppe Conte:** Writing – review & editing, Software, Formal analysis, Data curation. **Barbara Conti:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

We are deeply grateful to Professor Alberto Fereres and Mr Paolo Giannotti for the pictures.

References

Abbott, W.J., 1925. A method of computing the effectiveness of an insecticide. J. Econ. Entomol. 18, 265–267. https://doi.org/10.1093/jee/18.2.265a.

Abenaim, L., Mandoli, A., Venturi, F., Bedini, S., Conti, B., 2022. Evaluation of a quasi-dimeric eugenol derivative as repellent against the stored grain insect pest *Sitophilus oryzae* (Coleoptera Curculionidae). Pest Manag. Sci. 78, 2588–2595, 10.1002%2Fps.6890.

Almeida, R.P.P., Purcell, A.H., 2006. Patterns of *Xylella fastidiosa* colonization on the precibarium of leafhopper vectors relative to transmission to plants. Ann. Entomol. Soc. Am. 99, 884–890. https://doi.org/10.1603/0013-8746(2006)99[884:POXFCO]2.0.CO;2.

Anastasaki, E., Psoma, A., Partsinevelos, G., Papachristos, D., Milonas, P., 2021. Electrophysiological responses of *Philaenus spumarius* and *Neophilaenus campestris* females to plant volatiles. Phytochemistry 189, 112848. https://doi.org/10.1016/j.phytochem.2021.112848.

Aprotosoaie, A.C., Hăncianu, M., Costache, I.I., Miron, A., 2014. Linalool: a review on a key odorant molecule with valuable biological properties. Flavour Fragrance J. 29, 193–219. https://doi.org/10.1002/ffj.3197.

Batista, P.A., Werner, M.F., Oliveira, E.C., Burgos, L., Pereira, P., Brum, L.F., Santos, A.R., 2008. Evidence for the involvement of ionotropic glutamatergic receptors on the antinociceptive effect of (-)-linalool in mice. Neurosci. Lett. 440, 299–303. https://doi.org/10.1016/j.neulet.2008.05.092.

Bedini, S., Djebbi, T., Ascrizzi, R., Farina, P., Pieracci, Y., Echeverría, M.C., Flamini, G., Trusendi, F., Ortega, Chiliquinga, A., Conti, B., 2024. Repellence and attractiveness: the hormetic effect of aromatic plant essential oils on insect behavior. Ind. Crop. Prod. 210, 118122. https://doi.org/10.1016/j.indcrop.2024.118122.

Bergmann, E.J., Raupp, M.J., 2014. Efficacies of common ready to use insecticides against *Halyomorpha halys* (Hemiptera: Pentatomidae). Fla. Entomol. 97, 791–800.

Betsy, K.J., Jilu, M., Fathima, R., Varkey, J.T., 2013. Determination of alkali content & total fatty matter in cleansing agents. AJSAT 2, 8–12.

CFR - Code of Federal Regulations, 2023. Title 21, volume 3, 21CFR172.863. Part 172-food additives permitted for direct addition to food for human consumption. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=172.863. (Accessed 6 January 2024).

CFR - Code of Federal Regulations, 2023. Title 21, Volume 3, 21CFR182.60. Part 182-synthetic flavoring substances and adjuvants. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm?fr=182.60. (Accessed 6 January 2024).

Chang, S.C., Shih, H.T., Lu, K.H., 2019. Antifungal effect and chitinase activities of the froth of spittlebug *Poophilus costalis* (Walker) (Hemiptera: cercopoidea: Aphrophoridae). J. Asia Pac. Entomol. 22, 269–273. https://doi.org/10.1016/j.aspen.2019.01.006.

Chen, X., Meyer-Rochow, V.B., Fereres, A., Morente, M., Liang, A.P., 2018. The role of biofoam in shielding spittlebug nymphs (Insecta, Hemiptera, Cercopidae) against bright light. Ecol. Entomol. 43, 273–281. https://doi.org/10.1111/een.12496.

Cline, M., Taylor, J.E., Flores, J., Bracken, S., McCall, S., Ceremuga, T.E., 2008. Investigation of the anxiolytic effects of linalool, a lavender extract, in the male Sprague-Dawley rat. AANA J. (Am. Assoc. Nurse Anesth.) 76, 47–52.

Coldiretti, 2023. Xyella: infettato il 40% della Puglia, addio a 21 mln di ulivi. https://www.coldiretti.it/economia/xyella-infettato-il-40-della-puglia-addio-a-21-mln-di-ulivi. (Accessed 6 January 2024).

Cornara, D., Bosco, D., Fereres, A., 2018. *Philaenus spumarius*: when an old acquaintance becomes a new threat to European agriculture. J. Pest. Sci. 91, 957–972. https://doi.org/10.1007/s10340-018-0966-0.

Council Regulation (EC). No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32007R0834. (Accessed 6 January 2024).

Council Regulation (EEC. No 2092/91 of 24 June 1991 on organic production of agricultural products and indications referring thereto on agricultural products and foodstuffs. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:31991R2092. (Accessed 6 January 2024).

Dongiovanni, C., Altamura, G., Di Carolo, M., Fumarola, G., Saponari, M., Cavalieri, V., 2018. Evaluation of efficacy of different insecticides against *Philaenus spumarius* L., vector of *Xylella fastidiosa* in olive orchards in southern Italy, 2015–17. Arthropod Manag. Tests 43, 1–4. https://doi.org/10.1093/amt/tsy034.

Emami, M.S., 2016. Bioefficacy of some biorational insecticides for the control of *Aphis gossypii* Glover, 1877, (Hemiptera: Aphididae) on greenhouse grown cucumber. Acta Agric. Slov. 107, 419–427. https://doi.org/10.14720/aas.2016.107.2.14.

EPA - Environmental Protection Agency, 2018. Linalool biopesticides registration action document. U.S. decision_PC-128838_10-Jun-08. https://www3.epa.gov/pesticides/chem_search/reg_actions/registration/decision_PC-128838_10-Jun-08.pdf. (Accessed 6 January 2024).

EPPO, 2020. - European and Mediterranean Plant Protection Organization 2020. DiagnosticsPM 7/141 (1) *Philaenus spumarius*, *Philaenus italosignus* and *Neophilaenus campestris*. Bulletin OEPP/EPPO Bulletin 50 (1), 32–40.

Evans, J.W., 1940. Tube-building cercopids (Homoptera: machaerotidae). Trans. Roy. Soc. S. Aust. 64, 70–75.

Farina, P., Bedini, S., Conti, B., 2022. Multiple functions of Malpighian Tubules in insects: a review. Insects 13, 1001. https://doi.org/10.3390/insects13111001.

Ganassi, S., Cascone, P., Di Domenico, C., Pistillo, M., Formisano, G., Giorgini, M., Grazioso, P., Germinara, G.S., De Cristofaro, A., Guerrieri, E., 2020. Electrophysiological and behavioural response of *Philaenus spumarius* to essential oils and aromatic plants. Sci. Rep. 10, 3114. https://doi.org/10.1038/s41598-020-59835-1.

Germain, J.F., Lester, K., Cornara, D., Eppo, P., 2020. 7/141 (1) *Philaenus spumarius, Philaenus italosignus* and *Neophilaenus campestris*. EPPO Bull. 50, 32–40. https://doi.org/10.1111/epp.12610.

Germinara, G.S., Ganassi, S., Pistillo, M.O., Di Domenico, C., De Cristofaro, A., Di Palma, A.M., 2017. Antennal olfactory responses of adult meadow spittlebug, *Philaenus spumarius*, to volatile organic compounds (VOCs). PLoS One 12, e0190454. https://doi.org/10.1371/journal.pone.0190454.

Hall, D.G., Richardson, M.L., 2012. Toxicity of insecticidal soaps to the Asian citrus psyllid and two of its natural enemies. J. Appl. Entomol. 137, 347–354.

Hill, B.L., Purcell, A.H., 1995. Acquisition and retention of *Xylella fastidiosa* by an efficient vector, *Graphocephala atropunctata*. Phytopathology 85, 209–212.

Isman, M.B., 2006. Botanical insecticides, deterrents, and repellents in modern agriculture and increasingly regulated world. Annu. Rev. Entomol. 51, 45–66. https://doi.org/10.1146/annurev.ento.51.110104.151146.

Kamatou, G.P.P., Viljoen, A.M., 2008. Linalool – a review of a biologically active compound of commercial importance. Nat. Prod. Commun. 3, 1183–1192. https://doi.org/10.1177/1934578X0800300727.

Knudsen, J.T., Eriksson, R., Gershenzon, J., Ståhl, B., 2006. Diversity and distribution of floral scent. Bot. Rev. 72, 1. https://doi.org/10.1663/0006-8101(2006)72[1:DADOFS]2.0.CO;2.

Kraiss, H., Cullen, E.M., 2008. Efficacy and nontarget effects of reduced-risk insecticides on *Aphis glycines* (Hemiptera: Aphididae) and its biological control agent *Harmonia axyridis* (Coleoptera: Coccinellidae). J. Econ. Entomol. 101, 391–398. https://doi.org/10.1603/0022-0493(2008)101[391:eaneor]2.0.co, 2.

Linck, V.M., da Silva, A.L., Figueiró, M., Caramão, E.B., Moreno, P.R.H., Elisabetsky, E., 2010. Effects of inhaled Linalool in anxiety, social interaction and aggressive behavior in mice. Phytomedicine 17, 679–683. https://doi.org/10.1016/j.phymed.2009.10.002.

Marshall, A.T., 1964. Spittle-production and tube-building by cercopoid nymphs (Homoptera). 1. The cytology of the Malpighian tubules of spittle-bug nymphs. Q. J. Microsc. Sci. 105, 257–262. https://doi.org/10.1242/jcs.s3-106.73.37.

Marshall, A.T., 1973. Protein synthesis and secretion by the Malpighian tubules of cercopoid larvae (Homoptera). J. Insect Physiol. 19 (12), 2317–2326. https://doi.org/10.1016/0022-1910(73)90238-2.

Morente, M., Ramírez, M., Lago, C., de Las Heras-Bravo, D., Benito, A., Moreno, A., Fereres, A., 2022. Habitat manipulation for sustainable management of *Philaenus spumarius*, the main vector of *Xylella fastidiosa* in Europe. Pest Manag. Sci. 78 (10), 4183–4194. https://doi.org/10.1002/ps.7036.

Osborne, L.S., Henley, R.W., 1982. Evaluation of Safer agro-chems insecticidal soap for the control of mites in the interior environment. Foliage Digest 5, 10–11.

Pasquet, M., Wallon, L., Fusier, P.Y., Restagno, F., Rio, E., 2022. An optimized recipe for making giant bubbles. EPJE 45 (12), 101.

Peana, A.T., D'Aquila, P.S., Panin, F., Serra, G., Pippia, P., Moretti, M.D., 2002. Anti-inflammatory activity of linalool and linalyl acetate constituents of essential oils. Phytomedicine 9, 721–726. https://doi.org/10.1078/094471102321621322.

Pedersen, J.N., Lyngsø, J., Zinn, T., Otzen, D.E., Pedersen, J.S., 2019. A complete picture of protein unfolding and refolding in surfactants. Chem. Sci. 11, 699–712. https://doi.org/10.1039/C9SC04831F.

Picciotti, U., Lahbib, N., Sefa, V., Porcelli, F., Garganese, F., 2021. Aphrophoridae role in *Xylella fastidiosa* subsp. pauca ST53 invasion in southern Italy. Pathogens 10 (8), 1035. https://doi.org/10.3390/pathogens10081035.

Puritch, G.S., 1981. Pesticidal soaps and adjuvants-what are they and how do they work? Proceedings of the 23rd annual lower mainland horticultural improvement association growers. Short Course, Abbotsford, British Columbia.

Raguso, R.C., Pichersky, E., 1999. New perspectives in pollination biology: floral fragrances. A day in the life of a linalool molecule: chemical communication in a plant-pollinator system. Part 1: linalool biosynthesis in flowering plants. Plant Species Biol. 14, 95–120. https://doi.org/10.1046/j.1442-1984.1999.00014.x.

Rakitov, R.A., 2002. Structure and function of the Malpighian tubules, and related behaviors in juvenile cicadas: evidence of homology with spittlebugs (Hemiptera: cicadoidea & Cercopoidea). Zool. Anz. 241 (2), 117–130. https://doi.org/10.1078/0044-5231-00025.

Raudonis, L., Valiuškaitė, A., Duchovskienė, L., Survilienė, E., 2009. Toxicity of biopesticides to green apple aphid in apple-tree. Scientific Works of the Lithuanian Institute of Horticulture and Lithuanian University of Agriculture. Sodininkystė ir daržininkystė 28 (3).

Rodrigues, I., Benhadi-Marín, J., Rodrigues, N., Baptista, P., Pereira, J.A., 2022. Olfactory responses to volatile organic compounds and movement parameters of *Philaenus spumarius* and *Cicadella viridis*. J. Appl. Entomol. 146, 486–497. https://doi.org/10.1111/jen.12992.

Sanna, F., Mori, N., Santoiemma, G., D'Ascenzo, D., Scotillo, M.A., Marini, L., 2021. Ground cover management in olive groves reduces populations of *Philaenus spumarius* (Hemiptera: Aphrophoridae), vector of *Xylella fastidiosa*. J. Econ. Entomol. 114, 1716–1721. https://doi.org/10.1093/jee/toab116.

Saponari, M., Loconsole, G., Cornara, D., Yokomi, R.K., De Stradis, A., Boscia, D., Bosco, D., Martelli, G.P., Krugner, R., Porcelli, F., 2014. Infectivity and transmission of *Xylella fastidiosa* by *Philaenus spumarius* (Hemiptera: Aphrophoridae) in Apulia, Italy. J. Econ. Entomol. 107, 1316–1319. https://doi.org/10.1603/EC14142.

Schuster, D.J., Stansly, P.A., 2000. Response of two lacewing species to biorational and broad-spectrum insecticides. Phytoparasitica 28, 297–304.

Sevarika, M., Rondoni, G., Ganassi, S., Pistillo, O.M., Germinara, G.S., De Cristofaro, A., Romani, R., Conti, E., 2022. Behavioural and electrophysiological responses of *Philaenus spumarius* to odours from conspecifics. Sci. Rep. 12 (1), 8402. https://doi.org/10.1038/s41598-022-11885-3.

RED - Registration Eligibility Decision Document, 1992. Soap Salts. U. S. Government Printing Office, Washington, DC EPA-738-R-92–015. U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances. https://archive.epa.gov/pesticides/reregistration/web/pdf/4083fact.pdf. (Accessed 29 March 2024).

SIR (Servizio Idrologico della Regione Toscana). (n.d.) ID TOS01000544, Pisa (Fac. Agraria). http://www.sir.toscana.it/consistenza-rete (accessed 4 June 2024).

Skouras, P.J., Stathas, G.J., Demopoulos, V., Louloudakis, G., Margaritopoulos, J.T., 2019. The effect of five insecticides on the predators *Coccinella septempunctata* and *Hippodamia variegata*. Phytoparasitica 47, 197–205. https://link.springer.com/article/10.1007/s12600-019-00731-4.

Tacoli, F., Mori, N., Pozzebon, A., Cargnus, E., Da Vià, S., Zandigiacomo, P., Duso, C., Pavan, F., 2017. Control of *Scaphoideus titanus* with natural products in organic vineyards. Insects 8, 129, 10.3390%2Finsects8040129.

Thompson, V., Harkin, C., Stewart, A.J.A., 2023. The most polyphagous insect herbivore? Host plant associations of the Meadow spittlebug, *Philaenus spumarius* (L.). PLoS One 18, e0291734. https://doi.org/10.1371/journal.pone.0291734.

Wafula, G.O., Muthomi, J.W., Nderitu, J.H., Chemining'wa, G.N., 2017. Efficacy of potassium salts of fatty acids in the management of thrips and whitefly on snap beans. Sustain. Agric. Res. 6, 4. https://doi.org/10.5539/sar.v6n4p45.

Whittaker, J.B., 1973. Density regulation in a population of *Philaenus spumarius* (L.) (Homoptera: cercopidae). J. Anim. Ecol. 42, 163–172. https://doi.org/10.2307/3410.