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Occupancy and detection of agricultural threats: The case of *Philaenus spumarius*, European vector of *Xylella fastidiosa*

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ABSTRACT

Occupancy models estimate presence and detection probability of species of interest of which they provide useful information and also contribute to decision making. In this proof-of-concept, we propose an approach to demonstrate the applicability of occupancy models in insect monitoring having as targets the spittlebug *Philaenus spumarius*, the main European vector of *Xylella fastidiosa*, and other spittlebugs. Surveys were performed in two different agricultural settings (olive orchards and vineyards) in Trentino (northern Italy). *Philaenus spumarius* was present in all surveyed sites and its detectability was significantly influenced by site covariates (i.e., forest and vineyard coverage, hours of sunlight) and plot covariates (i.e., weed height). Site covariates influenced the detection probability of other spittlebugs as well, while the co-occurrence of different species did not affect the *P. spumarius* occupancy. Our outcomes suggest that occupancy models are valuable tools that should support future studies aimed at estimating the presence and abundance of pest insects, especially when site covariates and/or sampling methods affect the detectability of a species.

1. Introduction

Understanding environmental drivers that explain presence and absence of a given species in a site is the basis of conservation and management of populations of a certain organism (Kellner and Swihart, 2014). Species distribution models can predict the occurrence of species in a site and support studies dealing with biogeography, species conservation, invasive species ecology, and natural resource management (Duarte et al., 2018; Malek et al., 2018; Piyapong et al., 2020). These models enable researchers to disentangle the effects of ecological and abiotic variables on species distribution (Duarte et al., 2018; Kellner and Swihart, 2014). Nonetheless, species distribution models may be affected by imperfect species detection, mainly associated by unproper sampling scheme and methods and/or biotic and abiotic factors (Kellner and Swihart, 2014). As a result, the target species is missed at certain locations, even if sites are occupied.

Occupancy models have been designed to solve this issue and produce estimations on detection and occupancy probability of a species (MacKenzie et al., 2003, 2009; MacKenzie et al., 2017). Ignoring imperfect detection in a survey can lead to unreliable outcomes and consequent wrong decisions for conservation and management (Guillera-Arroita et al., 2014). Moreover, current models allow to run site-occupancy models for either one or several species (Bailey et al., 2014; Dorazio et al., 2006). Although the number of studies applying occupancy models showed an increasing trend in the last decades, there is a taxonomic bias towards terrestrial organisms, especially vertebrates, which are the main targets of most studies while invertebrates, such as insects, have been neglected (Devarajan et al., 2020; Mourguiart et al., 2021). For instance, to our best knowledge, a similar method was never applied to study species of Auchenorrhyncha (Hemiptera: Cicadomorpha), a taxon embracing important agricultural pests (Raven, 1983; Katis et al., 2007). Indeed, pest management strategies could benefit from applying occupancy models to monitor insects of agricultural interest, as occupancy model could represent a particularly suitable tool in the field of entomology, given that insects pose detection issues due to ecological traits as phenology (Mourguiart et al., 2021). Single and multi-species occupancy models have been used to study insect species of different orders using either field collected data (Orthoptera: Mourguiart et al., 2021; Odonata, Orthoptera, Lepidoptera: Malinowska et al., 2014; Lepidoptera: Cabeza et al., 2010; Hymenoptera and Homoptera:

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Sileshi, 2007; Coleoptera: Brodie et al., 2019) or museum data (Zeilinger et al., 2017). In the case of pest insects, occupancy models could support monitoring or pest management programs, assess the efficacy of management actions, evaluate the potential reduction of a species or of its range, and model its habitat (Tyre et al., 2003; Sileshi, 2007). The sampling aimed at assessing presence/absence of the target species allows saving time when the species itself is a small insect occurring at high densities, in particular in surveys requiring multiple visits during the same season (Sileshi, 2007; Wilson and Room, 1983). It follows that the development of models of presence and/or distribution in a certain territory can support the development of effective prophylaxis or protection strategies.

Notwithstanding the potential advantages, occupancy models have never been applied to assess the presence of the meadow spittlebug *Philaenus spumarius* (Hemiptera: Aphrophoridae). Studies aimed at understanding the ecology of this species exponentially increased after it was recognized as main vector of the plant pathogen *Xylella fastidiosa* (Cornara et al., 2018; Saponari et al., 2014, 2017). This bacterium was recently introduced in Europe and is associated with important plant diseases such as Pierce's disease of grapevine and the Olive Quick Decline Syndrome but can infect numerous other plant species (Almeida, 2016; Saponari et al., 2017, 2019; Desprez-Loustau et al., 2020). To collect data regarding *P. spumarius* ecology and estimate disease dynamics, large-scale surveys were conducted to characterize its phenology, abundance, and plant preference in different European location (Antonatos et al., 2019; Bodino et al., 2019, 2020; Dongiovanni et al., 2019; Morente et al., 2018). These studies provided fundamental information on the meadow spittlebug bionomic and highlighted that current sampling methods are not completely effective in collecting *P. spumarius*, especially from tree canopies (Morente et al., 2018).

We therefore propose a simple approach to demonstrate the applicability of occupancy models in pest insect monitoring by studying *P. spumarius* presence while accounting for detectability.

2. Materials and methods

2.1. Field surveys

Field surveys were conducted from March to September 2018 in two agricultural areas of the Trentino region (northern Italy), which is a *X. fastidiosa*-free area, to study the presence of *P. spumarius* by using occupancy models. The first area was in Riva del Garda, where five olive orchards were selected (sites rdg1, rdg2, rdg3, rdg4, rdg5; Fig. 1). The second area was in San Michele all'Adige, where five sites were selected and consisted of vineyards (sma1, sma2, sma3) or riparian habitat comprising vineyards (sma4, sma5) (Fig. 1). Each site was subjected to a low-input management (organic). In total, each site was visited 17 times, i.e., at least twice a month for the duration of the survey. The location of each sample site of 0.25 m^2 are available in the form of KML at the online data repository for this article. The presence of other spittlebugs (superfamily Cercopoidea) such as *Neophilaenus* spp., *Lepyronia coleoptrata* (i.e., there are no other Lepyronia species, at our knowledge, in northern Italy), *Cercopis* spp. and *Aphrophora* spp. was recorded to assess whether the co-occurrence of different species could influence the presence of *P. spumarius*. Moreover, these spittlebugs, being xylem-feeders, could be potential vectors of *X. fastidiosa* (Bodino et al., 2019, 2020; Morente et al., 2018).

The quadrat sampling method was used to monitor the nymphal

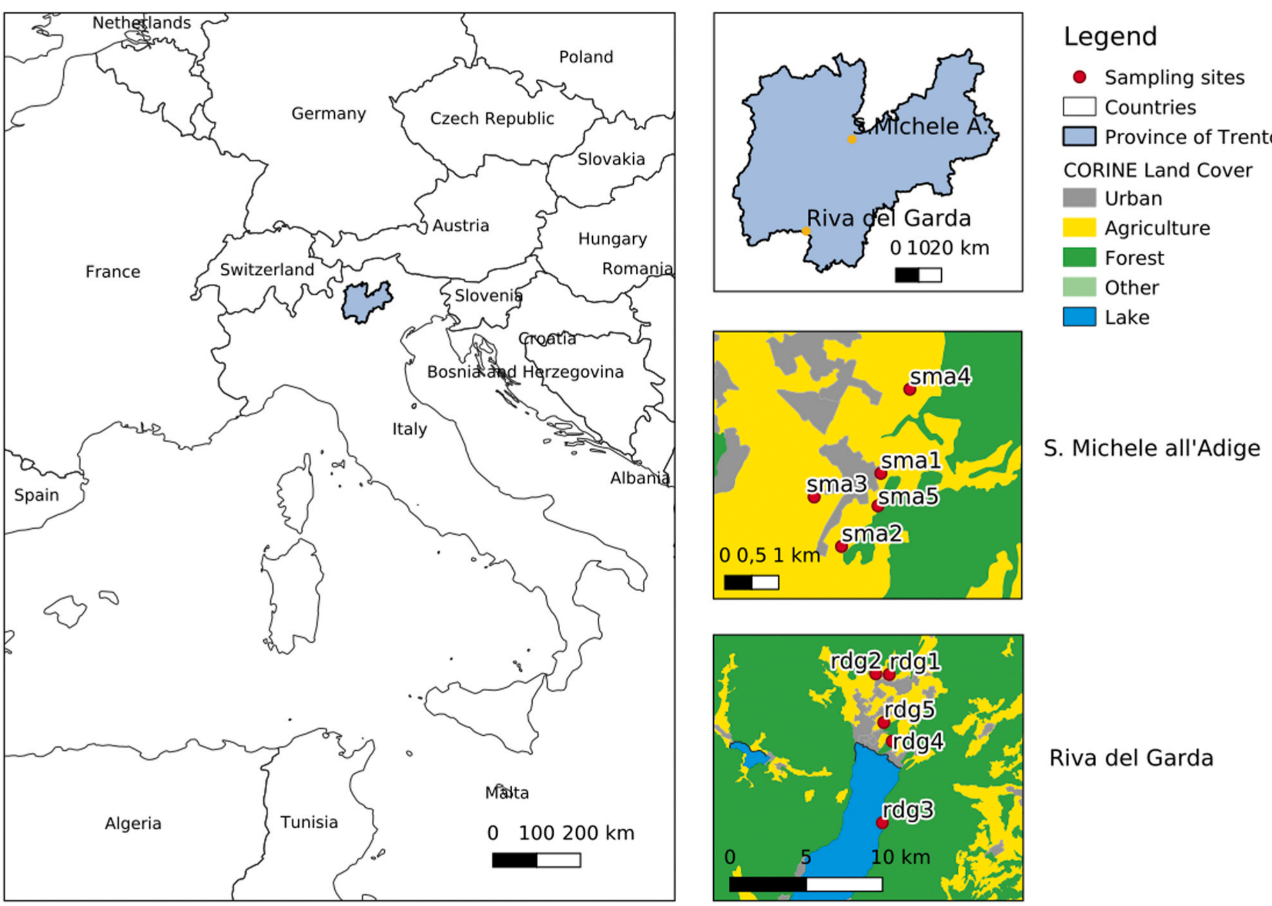

Fig. 1. Study areas in Trentino, which were visited to investigate occupancy and detectability of *Philaenus spumarius* and other Auchenorrhyncha species. Five olive orchards (rdg1, rdg2, rdg3, rdg4, rdg5) and five habitats comprising vineyards (sma1, sma2, sma3, sma4, sma5) were sampled. Detailed information regarding the sites and distances between sites are provided in the Supplementary Material.

populations, since it is an effective method for detecting and counting spittlebug juveniles (Bodino et al., 2020; Dongiovanni et al., 2019; Morente et al., 2018; Whittaker, 1973). In particular, the sampling unit (SU) was a rectangle of 0.25 m^2 (100 × 25 cm), which was randomly positioned on the ground (for each visit: 20 SU per site). The soil and vegetation inside the SU were inspected for the presence of spittlebug nymphs, which were removed from the host plant with a thin paint brush and counted. Surveys were conservative; thus species identity and larval instar were determined directly in the field using the identification keys from Vilbaste (1982), and after counting, nymphs were placed on their hosts. Beside *P. spumarius*, number and stage of other spittlebug nymphs were recorded and identified, when possible. Nymph surveys were carried out biweekly from the end of March until the mid of June 2018, when only adults were found.

Surveys aimed at detecting adults were carried out weekly from May (when first emerging adults could be found on the herbaceous cover) to the end of September 2018. A sweeping net (diameter 30 cm, length 60 cm) was used to sample herbaceous plants and tree canopies at 20 randomly selected points (for each visit: 20 points per site). The sweeping net was chosen due to its reliability as sampling method for spittlebug adults in the herbaceous cover (Bodino et al., 2019; Morente et al., 2018). For each point, five sweeps were performed on the ground cover and five on the tree canopy (either olive or grapevine, depending on whether the site was a olive orchard or a vineyard). Given that the sampling points happened at random locations within a site, olive trees/grapevines could not occur at the selected location. If other woody plants were present, insects were sampled with the sweeping net from their canopies, and plants were identified at genus level. *Philaenus spumarius* and other sampled spittlebug species were counted, identified, and sexed (when possible) directly in the field. The dataset with the information collected during each visit may be found in the Mendeley online data repository for this article, together with geographic coordinates and data of the studied sites.

2.2. Occupancy models

Occupancy models were chosen because they account for imperfect detection of organisms in surveys and determine the probability of true presence or absence of a species in a site. Within a survey, each site is visited several times and the identities of the target species detected during each visit is noted (Dorazio et al., 2006). Occupancy models are defined as an extension of Generalized Linear Mixed Effects models (GLMMs) using a Bernoulli distribution where variables (or covariates) model the true state of occurrence (Duarte et al., 2018; MacKenzie et al., 2003, 2002). Two different probabilities are modeled, namely ψ (occupancy: probability that a site is occupied by the target species) and p_j (detectability: probability of detecting the species during the j^{th} survey, given it is present) (Devarajan et al., 2020; Kéry, 2011).

Our single season occupancy model contained two assumptions, according to Devarajan et al. (2020). The first assumes that the occupancy state is "closed", thus species are present at occupied sites for the duration of the sampling season and occupancy does not change at a site within the sampling season. In warm Mediterranean areas such as Apulia (southern Italy), Greece, and Spain, *P. spumarius* adults almost disappear in summer from the olive agroecosystem (Antonatos et al., 2019; Morente et al., 2018; Bodino et al., 2019, 2020). We assumed that in Trentino (northern Italy) the presence of spittlebugs would not change during the survey because its host plants are not subjected to a severe water stress, as reported in an Italian coastal region (Liguria) (Bodino et al., 2020). The second assumption states that sites are independent, hence detection of a species at one site is independent of detecting it at other sites. Our sites were sufficiently far from each other to assume independence, as the average distance between sites in Riva del Garda was 4.9 km (min = 0.9 km, max = 9.7 km, standard deviation = 2.9 km), while the average distance between the sites in San Michele all'Adige was 1.6 km (min = 0.6, max = 3.1, standard deviation = 0.7 km). The distance between Riva del Garda and San Michele all'Adige is about 40 km (Fig. 1, coordinates available at the online repository for this article.

Single- and multi-species occupancy models were run to estimate occupancy and detection probabilities for *P. spumarius* and co-occurring spittlebug species, respectively.

2.2.1. Single-species occupancy models

Occupancy and detection probability of *P. spumarius* were estimated by using occupancy models to determine true presence or absence of the insect in surveyed sites. Due to the sampling design used, two occupancy models were run at two different scales for *P. spumarius*.

The first was a site-level scale model, which was fed with "pooled" data collected during 17 visits to assess a general trend for species occurrence. Data collected from each sampling unit (i.e., the quadrat and the sweeping net) were pooled for each surveyed site, to obtain single presence/absence values for the n visit at the given site.

The second model (plot-level model) was run at sampling unit-level, to assess the effects of plot-level covariates on the detection of *P. spumarius*. The model was fed with a 200 × 17 data matrix, where 200 was the total number of sampled units (20 per site) and 17 was the number of visits.

2.2.2. Multi-species occupancy models

A multi-species occupancy model was run with site-level data and included second order interactions to evaluate the occupancy conditioned by other spittlebug species, given the presence of *P. spumarius* and the effect of covariates on detectability of co-occurring species.

2.3. Model selection and statistical analyses

Single- and multi-species occupancy models were run using different linear combination of the covariates, and the best models were later selected using Akaike's information criterion (AIC). The best models were selected when Delta AIC < 2 in comparison to the first best model and were averaged to create a single best model (Burnham and Anderson, 2004). Statistical analysis and plots were carried out in the framework of Rstudio (RStudio Team, 2020) using R (R Development Core Team, 2017) and the packages *Unmarked* (Fiske and Chandler, 2011), *ggplot2* (Wickham, 2016), *reshape2* (Wickham, 2007) and *MuMIn* (Barton, 2009).

2.4. Environmental Covariates

In occupancy models, it is possible to define site-level covariates and plot-level covariates. While the first describe the environment using site-specific data that do not change with repeated visits (i.e., land use, elevation), plot-level covariates are collected at each visits and can change across sampling occasion and site (i.e., air temperature, humidity) (MacKenzie and Bailey, 2004).

In our study, site-level covariates were the following: olive tree coverage (from 0 to 1), vineyard coverage (from 0 to 1), anthropic coverage (from 0 to 1), forest coverage (from 0 to 1), agricultural coverage (crops other than olive and grapevine, from 0 to 1), average elevation (m.a.s.l.), average slope (degrees), average sun hours during the vegetative period (1st April – 31st October), and aspect of the slope (i.e., the direction that it faces) (N, S, E, W, NW, NE, SW, SE). After creation of a buffer zone of 200 m for each site, covariates data were collected from real land use dataset PAT 2003/08 provided by "Servizio Urbanistica e Tutela del Paesaggio" of the province of Trento (https://www.sciamlab.com/opendatahub/it/dataset/p_tn_uso-del-suolo-reale-urbanistica-ed-08–2003–200509/resource/9d522d8f-68ae-46b1-a0b3-4067751873f). The covariate dataset is available at the online repository for this article.

Plot-level covariates were collected from the sampling units (quadrat or sweeping net) at each visit and were the following: coverage of herbaceous cover (from 0 to 1), height of herbaceous cover (cm), composition of herbaceous cover (i.e., which plant families are mainly found within the quadrat), composition of swept canopies (i.e., composed of olive, grapevine, other tree hosts), and period of sampling.

3. Results

3.1. Single-species occupancy models

3.1.1. Site-level occupancy model

The presence of *P. spumarius* was detected 107 times and its absence 63 times during our survey (Fig. 2). Number of visits in which the species was detected ranges from a minimum of 4 (site sma1) to a maximum of 17 (recorded at all visits in site rdg3) with an average of 11 ± 4.37 detections per site (Table S2). The total number of nymphs and adults collected during the survey is reported in Fig. S1. The proportion of sites where *P. spumarius* presence was recorded at least once (namely, the naïve occupancy) was equal to one. During some visits the spittlebug was not recorded, thus the value of the naïve occupancy suggests that even if the species was present, it was not always detected. The model without any covariate (occupancy null model) yielded a baseline of $\psi = 0.999$, SE = 0.003 (occupancy); and p = 0.65, SE = 0.037 (detectability), suggesting that *P. spumarius* can be under detected even if it is present. According to this outcome, variables that affected the detectability (p) of the species were estimated.

In total, 1022 occupancy models were run by varying the combination of 10 site covariates in the detection part of the model. In the best models, significant covariates that explained detectability (p) were vineyard coverage (p-value < 0.001), forest coverage (p-value = 0.002), and average hours of sunlight (p-value = 0.002).

Detection probability of *P. spumarius* resulted high in vineyards regardless of the amount of coverage within the 200 m buffer (Fig. 3A). The detectability of this species was significantly affected by the presence of forests, since it steadily decreased when the forest coverage was higher than 0.4 within the 200 m buffer at the sampled sites (Fig. 3B). In sites with an average number of sunlight hours greater than 10, the detectability of *P. spumarius* decreased as well (Fig. 3C).

3.1.2. Plot-level occupancy model

The presence of *P. spumarius* was recorded 436 times, with 162 plots (out of 170 in total) in which it was detected at least one time. The average number of presences recorded per sampling unit was 2 ± 2.09. Although *P. spumarius* presence at plot-level was more scattered than at site-level, the occupancy null model yielded a high occupancy probability ($\psi = 0.867$, SE = 0.031) and a detection probability of p = 0.148, SE = 0.007. According to this, the effect of plot-level variables on *P. spumarius* detectability (p) was evaluated. In total, 169 occupancy models were run with varying combinations of five covariates in the detection part of the model. The best models retained weed height and weed coverage, but only weed height was significant in explaining the detection probability (p-value = 0.0259) (Fig. 4). The possibility to detect the spittlebug in our study area increased when weeds were taller, while weed coverage had apparently no effect.

3.2. Multi-species occupancy model

Beside *P. spumarius*, other spittlebug species belonging to the genus *Neophilaenus, Aphrophora, Lepyronia* and *Cercopis* were recorded. Number of sites with at least one detection, number of presences, absences, and total individuals per each species in the sites is shown in Table 1. The percentage of sites occupied by each species per visit is reported in Fig. S2. Similar to Dorazio et al. (2006), a heatmap was used to display the number of individuals across the surveyed sites (Fig. 5). Number of individuals found in each site was generally lower than 30, whilst more than 50 specimens of either *P. spumarius, Neophilaenus* spp., or *Lepyronia coleoptrata* were occasionally counted in the same site.

A null model was run to compute naive probabilities of occupancy and detection for each species (Table 2): most of the species showed a very high occupancy rate of study sites, except *Aphrophora* spp. ($\psi = 0.45$). Naïve detection probabilities for all co-occurring species were much lower than that of *P. spumarius* (Table 2).

A multi-species occupancy model was run with the same set of covariates as the single-species model, and effects of environmental variables on detectability of the species were estimated. The variable that better explained the detectability of the species co-occurring with

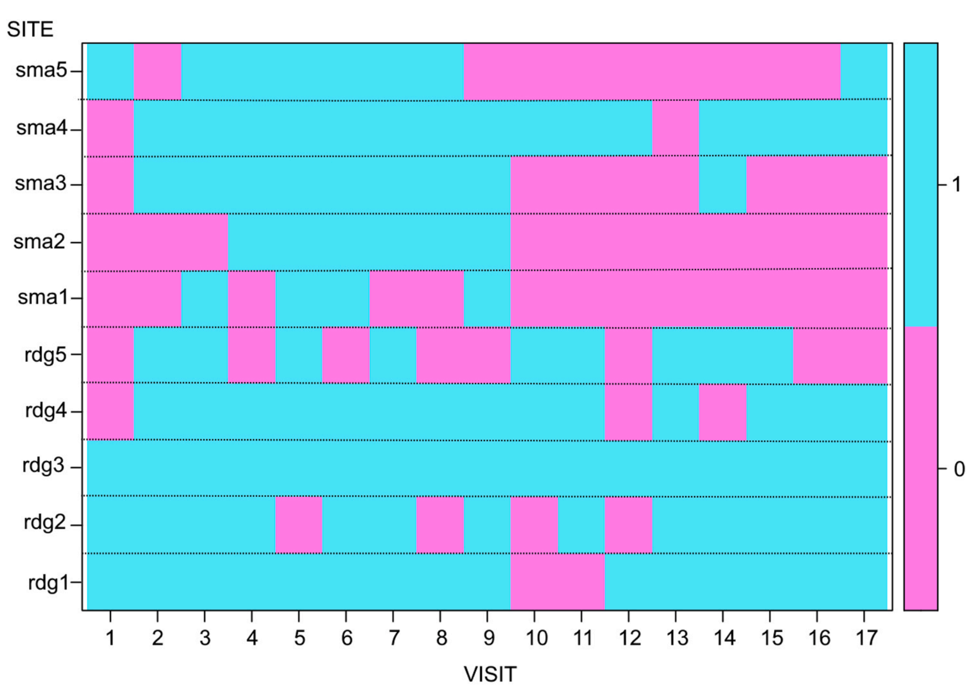

Fig. 2. Presence (light blue squares) and absence (pink squares) of *Philaenus spumarius* per visit (x axis) across surveyed sites (y axis) from March to September 2018 in Trentino. Riva del Garda sites: rdg1, rdg2, rdg3, rdg4 and rdg5. San Michele all'Adige sites: sma1, sma2, sma3, sma4 and sma5. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

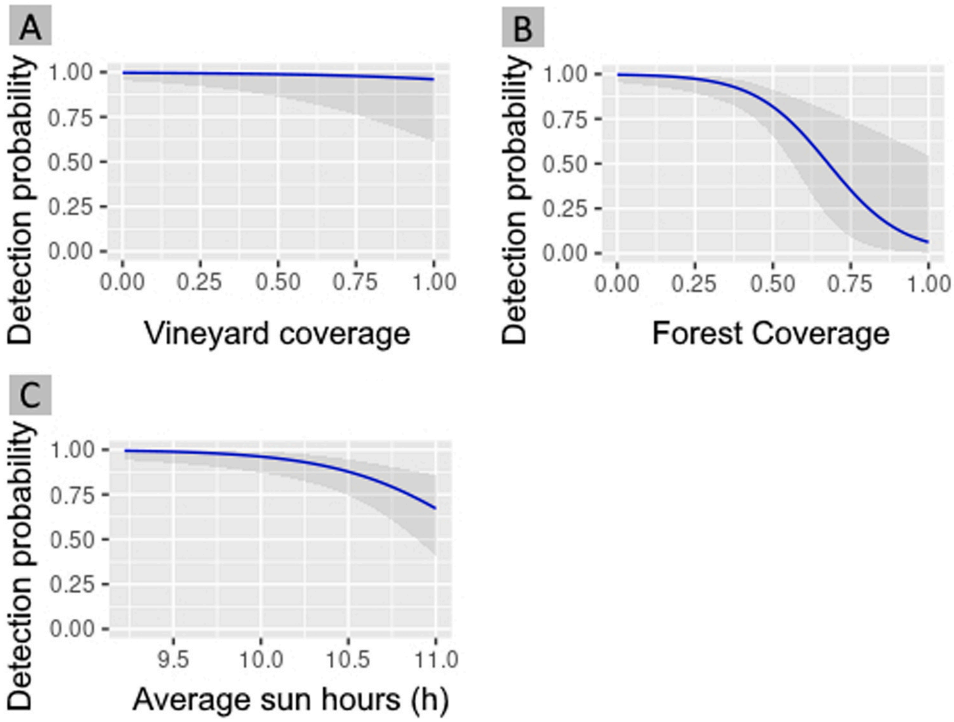

Fig. 3. Detection probability of *Philaenus spumarius* according to different site covariates (A, B, C) in olive groves and vineyards located in Trentino. Shaded areas represent 95% confidence interval.

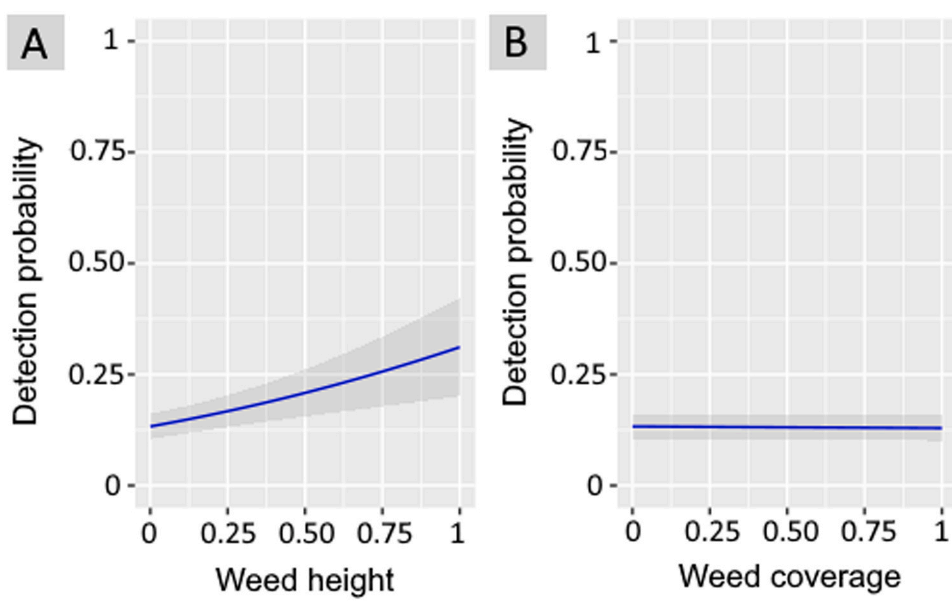

Fig. 4. Detection probability of *Philaenus spumarius* according to two plot-level covariates in olive groves and vineyards located in Trentino. Shaded areas represent 95% confidence interval. Shaded areas represent 95% confidence interval.

P. spumarius were the vineyard and olive tree coverages. These variables had a species-specific effect on species detectability (Fig. S3A and B). The coverage of olive trees steadily increased the probability of detecting *Aphrophora* spp., *Lepyronia coleoptrata,* or *Neophilaenus* spp., while for *Cercopis* spp. this effect was very limited (Fig. S2B). A growing coverage of vineyards within the buffer increased the detectability of *Cercopsis* spp. but had a negative effect on that of *Aphrophora* spp., *Neophilaenus* spp. and no effect on *Lepyronia coleoptrata*'s (Fig. S2B). The models suggested that *P. spumarius* occupancy was not statistically influenced by presence of other species ($\psi = 0.99$).

4. Discussion

In this study, occupancy models were used for the first time to estimate occupancy and detection probabilities of *P. spumarius* and other Auchenorrhyncha field collected in Trentino.

Philaenus spumarius is the main vector of *X. fastidiosa* in Europe and colonizes several habitats (Cornara et al., 2018; Saponari et al., 2017; Weaver and King, 1954). In our research, although the *P. spumarius* occupancy was high in all the visited sites, its detectability was influenced by characteristics of the area such as presence of forests, vineyard

Table 1
Summary of the multi-species survey. For each species, number of sites with at least one detection, number of times a species was recorded as present or absent, and the total number of individuals recorded during the whole survey are reported.

Species or Genus	Sites with at least one detection	Present	Absent	Total Individuals
Philaenus spumarius	10	107	63	788
Neophilaenus spp.	6	18	152	118
Aphrophora spp.	5	19	151	40
Lepyronia coleoptrata	9	40	130	274
Cercopis spp.	7	16	154	71

coverage, sunlight hours and plant height.

Several authors stated that "almost any species may be overlooked" (Kéry, 2011; Mata et al., 2014) and our results accordingly suggest that *P. spumarius*, the most abundant spittlebug in Europe (Cornara et al., 2018, 2019), may be missed during a survey. Even if we identified some environmental covariates influencing the detectability of the spittlebug in Trentino, a main factor affecting the detection and the presence/absence inference is indeed the lack of an effective sampling method (Morente et al., 2018). In their work, Morente et al. (2018) discussed the almost complete inefficiency of methods such as stem tapping, interception sticky traps, sticky-shoot, and yellow sticky traps for the sampling of spittlebugs. They also showed that the sweep net easily collects adults from the ground vegetation but captures only few individuals from olive canopies. Therefore, even if the sweep net currently represents the most efficient method in terms of sampling time and trapping efficacy (Morente et al., 2018), it is possible that *P. spumarius* may be under detected at certain sites. At any rate, as sticky traps are economic tools to monitor the presence of insect pests, future occupancy studies should assess the detectability of spittlebugs using this method. For example, similar information could allow the use of sticky traps in cases when a more efficient sampling is unfeasible.

Inefficient sampling can have important repercussions on decision making (i.e., pest management), since biased information regarding the presence of a species can introduce errors in the choice of when and where pest management strategies should be applied. In such a context, investigations in agroecosystems (i.e., Bodino et al., 2019, 2020; Cornara et al., 2017; Dongiovanni et al., 2019; Morente et al., 2018; Santoiemma et al., 2019), as much as they are accurate and provide valuable knowledge, can suffer from the omission of the detection estimation. In our study, we assumed that the occupancy state of *P. spumarius* was "closed", hence that the occupancy did not change within the sampling season. In fact, the vegetation in our sites is not subjected to a severe water stress in the summer, while in warmer and drier areas, the spittlebug adults are forced by the drought to find new hosts (i.e., Bodino et al., 2020). Even if *P. spumarius* migrates due to unsuitable climatic conditions, occupancy models can still be used to estimate the spittlebug presence and detectability. In this regard, Kéry et al. (2009) developed a multispecies extension of occupancy models that deals with several forms of temporary emigration and estimates the species richness of the site. Moreover, occupancy models allow reliable comparisons between sites and can be used to determine peaks of presence (i.e., by indicating when and where the target species was recorded) and detection probabilities in association with the characteristics of the study sites. For these reasons, they are valuable tools that should be used when estimating the presence and abundance of a pest insect such as *P. spumarius*.

Human disturbances related to the cropping system should be added as variable as well. In our study, as example, the presence of *P. spumarius* was not detected from the 10th to the 17th visit in two sites consisting of vineyards (sma1 and sma2). Given that this period (September) is associated with grape harvest in Trentino, the anthropic disturbance could have influenced the probability of detecting the spittlebug. Even so, high vineyard coverage was associated with an increase in the *P. spumarius* detectability. Vineyards in Trentino are trained as pergola, which protects a relative high portion of surface from direct sunlight, while plants are irrigated. These conditions seem guarantee a humid microclimate that supports populations of *P. spumarius*, favoring a widespread presence and high detectability in this agroecosystem (Cornara et al., 2018). However, this species was found abundant on herbaceous vegetation within and surrounding vineyards also in other Italian regions that use different trellis systems, like Guyot or cordons (Aldini et al., 1998; Braccini and Pavan, 2000; Pavan, 2006). Again, farming practices can influence the spittlebug presence, but rather than the trellis system, the management and the landscape seem to make the difference. In fact, rich populations of *P. spumarius* were found in low-input management plantations (Kunz et al., 2010; Mazzoni, 2006; our study), whereas the spittlebug was absent in vineyards subjected to conventional management (Santoiemma et al., 2019). In our study,

Table 2
Naïve occupancy and detection probabilities of auchenorrhynchan species in different sites, surveyed from March to September 2018 in Trentino.

Species or genus	Naïve occupancy	Naïve occupancy SE	Naïve detection	Naïve detection SE
Philaenus spumarius	1.000	0.003	0.629	0.037
Neophilaenus spp.	0.627	0.163	0.169	0.039
Aphrophora spp.	0.452	0.150	0.025	0.009
Lepyronia coleoptrata	0.905	0.096	0.260	0.036
Cercopis spp.	0.792	0.177	0.119	0.033

Fig. 5. Heatmap showing the number of Auchenorrhyncha individuals detected at different sites, surveyed from March to September 2018 in Trentino. Riva del Garda sites: rdg1, rdg2, rdg3, rdg4 and rdg5. San Michele all'Adige sites: sma1, sma2, sma3, sma4 and sma5.

higher percentages of vineyards were also associated with an increased probability of detecting *Cercopis* spp., a species frequently observed in humid habitats and on woody plants (Alma, 2002; Mazzoni et al., 2008). On the other hand, high vineyard coverages had a negative effect on the detectability of *Aphrophora* spp. and *Neophilaenus* spp. The scattered presence of these species and the scarce probability of detecting them is consistent with the literature, considering that they are only occasionally found within Italian vineyards (Mazzoni et al., 2008).

The olive coverage had a positive effect on the detectability of spittlebugs, more pronounced for *Aphrophora* spp., L. *coleoptrata*, or *Neophilaenus* spp., and less for *Cercopis* spp. The herbaceous cover of olive groves in Trentino remains flourishing during summer, providing a shady environment and a humid microclimate and fostering the presence of spittlebugs, which can be easily detected. However, presumably due to the low number of occupied sited, the confidence intervals of the effect of vineyard and olive coverage on the detectability of spittlebug species were rather large, affecting the model sensitivity (Fig. S3).

Besides the coverage of crops, there was an important factor significantly affecting the probability of detecting *P. spumarius*: the presence of forests. In fact, relatively high forest coverage in the 200 m buffer surrounding the site was associated to a lower probability of detecting the spittlebug. This habitat likely provides a shelter for *P. spumarius*, especially adults, which may move into woodland areas when the conditions in olive orchards or vineyards are less favorable (i.e., during hot days or crop management practices). Moreover, forests can provide nutritious hosts such as actinorhizal plants, which are characterized by a reliable supply of xylem-borne organic nitrogen compounds and are exploitable by spittlebugs when plants within crops are under stress (Thompson, 1999). Nevertheless, the effect of forest covers on the *P. spumarius* presence was considered of scarce relevance and thereby discarded from previous distribution models (see Santoiemma et al., 2019). The role of forest coverage in our study could also suggest that the occupancy state of *P. spumarius* was not closed and that some adults could move to wild woody plants during some periods. As consequence, their absence from the crop field would not be only the result of an imperfect detection but could be influenced by the surrounding environment as well. Indeed, the information that spittlebugs could be outside the orchard due to the presence of forests in certain periods is very important to support risk-assessment and suggests that forests should be included into future models. Even though the assumption of a closed occupancy state could have been violated, our proof-of-concept study indicates that occupancy models provide useful information regarding the presence of *P. spumarius*, especially considering that it is possible to use extensions that account for temporary emigrations (Kéry et al., 2009).

The increasing number of sunlight hours is another factor associated with a lower probability of detecting *P. spumarius*. The quantity of sun reaching a site is generally dependent on topographic factors (i.e., elevation and slope angle) and has repercussions on growing and quality of plants, as well as on crop management (Zorer et al., 2017). This factor can indeed impact the life of *P. spumarius*, whose biology strictly depends on temperature and humidity (Cornara et al., 2018). A rise in temperatures could, for instance, elicit a lower detectability due to behavioral adjustments. In fact, spittlebug nymphs find shelter in hidden parts of plants to escape direct sunlight, while adults migrate during the summer period and delay oviposition until weather cools (Cornara et al., 2018; Weaver and King, 1954). Tall plants (up to 100 cm), on the other hand, increased the detectability of *P. spumarius*, potentially because the sweeping net is scarcely efficient in collecting insects located too close to the soil level, thus from short grasses.

In our study, *P. spumarius* was the predominant spittlebug in the surveyed olive groves and vineyards, in accordance with other Italian surveys (Bodino et al., 2020, 2019; Cornara et al., 2017) and thrived in the same habitat with other spittlebugs. As a fact, the presence of other species did not affect the occupancy of *P. spumarius*, likely due to a trade-off between costs and benefits of gregarious feeding. In fact, although nymphs can share the same host to overcome plant barriers and allocate less resources to spittle production, this strategy implies a reduced food quality, to the detriment of some individuals (Mangan and Wutz, 1983; McEvoy, 2013; Wise et al., 2006). Considering that the percentages of sites occupied by *P. spumarius* were constantly high during our survey, serious consequences are expected if *X. fastidiosa* is introduced in Trentino, where a renowned niche extra virgin olive oil is made and where wine production is a key economic input (Asero and Patti, 2009; Moreno-Sanz et al., 2020; Mucci et al., 2019). In this context, a precise knowledge of the *P. spumarius* distribution and abundance all over a territory is a key element (Godefroid et al., 2021). Although occupancy models allow estimation of species abundance (Fiske and Chandler, 2011; MacKenzie et al., 2009), we did not estimate *P. spumarius* abundance within the sites, as ours was a preliminary work assessing the applicability of these models for pest monitoring. However, future studies should consider this aspect, given that *X. fastidiosa* outbreaks depends on the abundance of vectors, together with the time they spend feeding on the host plant and their transmission efficiency (Purcell, 1981). In addition, a recent study showed that northern Italy will remain a suitable region for *P. spumarius* even by the period 2040–2060, during which several Mediterranean regions (Iberian Peninsula, eastern Greece, northern parts of the Apulia region, some regions of Turkey) will presumably be less suitable for the spittlebug (Godefroid et al., 2021). According to this information, occupancy models could be applied to estimate the probability and severity of future *X. fastidiosa* outbreaks related to *P. spumarius'* presence and abundance in northern Italy.

To conclude, we demonstrated that the presence of *P. spumarius* and other spittlebugs can be underestimated even when using the most efficient sampling methods for these species (i.e., the sweeping net on the herbaceous cover). Although a reliable and convenient sampling tool should be developed for sampling the spittlebugs from tree canopies, we recommend including occupancy models when studying the presence of pest species such as *P. spumarius*, given that these models can accurately estimate species distribution and abundance by considering imperfect detection. Our study is a proof-of-concept that should be implemented with extensions considering the complex behavior of *P. spumarius*, but we warmly suggest including occupancy models to future field surveys, in particular those that consider the migration and the phenology of this species.

Author contribution

SA, CT, VM and MC conceived research. SA conducted the surveys. SA and CT analyzed data and conducted statistical analyses. SA, CT, VM and MC wrote the manuscript. VM and MC secured funding. All authors read and approved the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data supporting the findings of this study are available within the article, on the Mendeley data repository and within the supporting information.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107707.

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