



Effect of landscape composition on the invasive pest *Halyomorpha halys* in fruit orchards

Giovanni Tamburini^{a, *}, Ilaria Laterza^a, Davide Nardi^b, Alberto Mele^b, Nicola Mori^c,
Massimiliano Pasini^d, Davide Scaccini^b, Alberto Pozzebon^b, Lorenzo Marini^b

^a University of Bari, Department of Soil, Plant and Food Sciences (DiSSPA – Entomology and Zoology), Bari, Italy

^b University of Padova, Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), Padova, Italy

^c University of Verona, Department of Biotechnology, Verona, Italy

^d AGREA S.r.l. Centro Studi, Verona, Italy

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ABSTRACT

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), native to eastern Asia, has become one of the most serious pests of fruit orchards worldwide. This invasive species is highly polyphagous and capable of moving across the agricultural matrix at long distances. However, comprehensive studies exploring how landscape characteristics influence *H. halys* colonization of orchards are still lacking. Here, we investigated the impact of landscape composition on the trap captures of *H. halys* in 113 orchards of different fruit tree crops (i.e., apple, pear, peach, walnut and kiwi) in northern Italy. We found that landscapes rich in semi-natural habitats and vineyards and poor in annual crops supported a higher abundance of *H. halys* juveniles in traps. This pattern became more evident towards the end of the growing season as the abundance of juveniles increased. Adults were instead not affected by the landscape. The invasive stink bug best responded to landscape processes at large spatial scales (3000 m) confirming its high dispersal ability. Moreover, *H. halys* did not display a strong preference among fruit orchards, although fewer individuals were caught in walnut orchards. Our findings suggest that the habitat composition of agricultural landscapes is a key factor driving the dynamics of this pest in agroecosystems and that semi-natural habitats might be important in supporting *H. halys* populations and crop colonization. These effects are however limited to juveniles while adult density was similar even in landscapes with very contrasting structures.

1. Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), native to eastern Asia, has become one of the most harmful invasive pests in North America and Europe (Leskey and Nielsen, 2018). This stink bug is highly polyphagous and is characterized by a high reproductive rate and dispersal ability (Lee and Leskey, 2015; Wiman et al., 2015; Bergmann et al., 2016)). It feeds on a broad range of wild and cultivated plants, causing extensive damage to orchard crops, vegetables, grapes, small fruits, row crops, ornamentals, and nursery crops (Lee et al., 2013). *Halyomorpha halys* is a multivoltine species (1–4 generations per year in southern China, 1–2 in Europe; Lee et al., 2013), with contemporary presence of different stages of development throughout late spring and summer (Costi et al., 2017). Non-reproductive adults overwinter in natural shelters (i.e., under tree bark) (Lee et al., 2013) or in anthropogenic structures (i.e., human residential

building), often becoming a serious nuisance pest (Inkley, 2012). During early spring adults gradually emerge from their overwintering sites, looking for host plants and colonizing cultivated crops. Adults can disperse several kilometers (potential flight distance of c. 2000–2500 m day⁻¹; Lee and Leskey, 2015; Kirkpatrick et al., 2020), while juveniles have sufficient crawling capacity to move between plots at farm scale (Lee et al., 2014). Current control strategies heavily rely on frequent applications of broad-spectrum insecticides, with potential detrimental impacts on non-target organisms and the environment (Kuhar and Kamminga, 2017). A better understanding of the main factors driving the dynamics of *H. halys* in agroecosystems is fundamental to support innovative and more sustainable control management strategies (Mazzi and Dorn, 2012; Rusch et al., 2013; Mele et al., 2022).

Research on control strategies for *H. halys* have mainly focused on the local field scale (Mathews et al., 2017; Kuhar and Kamminga, 2017; Morrison et al., 2019). However, pest occurrence in the field can be in-

* Correspondence to: University of Bari, Department of Soil, Plant and Food Sciences (DiSSPA - Entomology), Bari, Italy.

E-mail address: giovanni.tamburini@uniba.it (G. Tamburini).

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fluenced by the characteristics of field's surroundings: insect pests, and especially mobile ones that exploit resources from different habitats, can in fact move across the agricultural matrix during their life cycle (Kennedy and Storer, 2000). Moreover, the biological control of crop pests often relies on the spillover of natural enemies from nearby habitat patches into the fields (Thies et al., 2003; Tschamtko et al., 2005). Although pest response to landscape composition is often inconsistent (Karp et al., 2018; Tamburini et al., 2020; Delaune et al., 2021), studies that consider the characteristics of the agroecosystem at the landscape scale are pivotal to better describe and forecast pest population occurrence in the field (Dainese et al., 2019; Martin et al., 2019).

Stink bug pests have been shown to benefit from the presence of semi-natural habitats in the landscape such as grasslands and forests, that provide alternative feeding, reproduction, and overwintering sites (Taki et al., 2014; Rice et al., 2016; Laterza et al., 2022; Laterza et al., 2023). In some cases, semi-natural habitats also support higher control by parasitoids (González et al., 2017, 2020). Studies focusing on *H. halys* response to landscape composition are, however, still scarce. Wallner et al. (Wallner et al., 2014) found that *H. halys* density in New Jersey, USA, was higher in landscapes rich in urban areas (2 km radius around traps) during the initial invasion and establishment phase. During a later phase of population growth and range expansion, the pest abundance was positively correlated to urban areas, semi-natural habitats and agricultural fields. In the mid-Atlantic USA, damages caused by stink bugs (most probably by *H. halys*) in tomato fields were higher in landscapes with larger forest edge (250 m buffer zone) (Rice et al., 2016). Finally, in northern Italy, higher abundance of *H. halys* adults and also higher egg parasitism rates were recently found in kiwifruit orchards located close to riparian areas (distance range 0.3 – 4.5 km) (Mele et al., 2022). These findings show that *H. halys* is capable of dispersing across the agricultural matrix (Wiman et al., 2015; Lee and Leskey, 2015) and indicate that landscape structure is likely to influence its occurrence in the field. Non-crop habitats in agricultural landscapes such as forests, grasslands and urban sprawls, might provide alternative hosts, overwintering sites or support communities of natural enemies. Comprehensive studies on the impact of landscape composition on the population dynamics of *H. halys* in different agricultural settings and crops are urgently needed.

Here, we investigated the impact of landscape composition on the abundance of *H. halys* in Veneto region, northern Italy. *Halyomorpha halys* was first reported in Italy in 2012 (Maistrello et al., 2016) and is now present all over the country and considered as a key pest of fruit orchards (Maistrello et al., 2017, 2018; Moore et al., 2019; Francati et al., 2021; Zapponi et al., 2021;). We sampled 113 orchards of different fruit tree crops (i.e., apple, pear, peach, walnut and kiwi). We hypothesized that a high proportion of semi-natural habitats and urban areas in the landscape would favour *H. halys* compared to crop fields and orchards, especially at the beginning and at the end of the season, when the adults disperse from and to overwintering sites, respectively. We also tested *H. halys* preference for fruit tree crop and whether adults and juveniles responded differently to landscape characteristics.

2. Material and methods

2.1. Sampling sites and landscape analyses

The study was conducted in Veneto region, northeast Italy (centered on latitude 45°22'27" N, longitude 11°45'43" E). This region presents an extensive lowland area characterized by temperate climate with a mean annual precipitation of c. 700 mm and a mean annual temperature of c. 14 °C. The agricultural landscapes in the study area are dominated by annual crops (55%; mainly wheat, corn and soybean), perennial crops (18%; mainly fruit orchards and vineyards), and urban sprawls (18%). Semi-natural habitats (4%) generally include pastures and small patches of mixed broadleaf forests. *Halyomorpha halys* is multivoltine in

the study region (2 generations per year) where it was first reported in 2014, rapidly expanding its distribution area in the subsequent years (Cesari et al., 2018).

The sampling took place in 113 fruit orchards mainly located in the southwestern part of the region (Fig. 1; elevation range: from 6 to 98 m a.s.l.). The survey was carried out in 2020 and included 34 apple, 33 pear, 19 peach, 18 walnut and 9 kiwifruit orchards. Most of the monitored orchards were conventionally managed (85%), whereas only 17 were organic (10 apple, 4 pear, 2 kiwifruit, and 1 peach orchards, while walnut orchards were all conventionally managed). Because of the imbalance between conventional and organic sites, local management was not further considered in this study (for further information see Fig. S1). We quantified the landscape composition around each orchard within a 250, 500, 1000, 1500, 2000 and 3000-m radius buffer as, to our knowledge, scale dependency has never been tested for *H. halys* before. Within each buffer, we measured the cover of annual crops, orchards, vineyards, semi-natural habitats (i.e., grasslands and forests), and urban areas (see Table S1 for range values) by analyzing regional land use maps updated to 2020 (<https://idt2.regione.veneto.it>) in GIS (QGIS, 2022). Despite the high mapping resolution (5 m), field margins, grassy strips or small hedgerows were not mapped and hence not considered in our analysis. Since we found considerable correlation among landscape factors (Table S2), we used principal component analysis to extrapolate two independent variables (i.e., principal components) that described landscape characteristics surrounding the monitored sites at each spatial scale (250 – 3000 m radii) (Gardiner et al., 2009). PC1 (numeric; principal component 1) and PC2 (numeric; principal component 2) explained 70.7% of the total variance of the dataset, contributing 49.0% and 21.6%, respectively (Fig. 3A). Sites characterized by positive values on PC1 were correlated with the variables semi-natural habitats and vineyards, while PC1 negative values were correlated with annual crops. Sites with positive values on PC2 were correlated with urban areas, while PC2 negative values were correlated with fruit orchards.

The insect monitoring was performed from the 6th of April to the 2nd of November 2020 by the personnel of the University of Padova, AGREA S.r.l. Centro Studi, phytosanitary services of the Veneto region and by field technicians belonging to different fruit grower associations, following a common protocol defined by the personnel of the University of Padova. *Halyomorpha halys* populations were monitored using one clear sticky trap per site baited with the commercial aggregation pheromone lure Trécé (Trécé Inc., Adair, OK, USA) containing both the specific two-component aggregation pheromone ((3 S,6 S,7 R,10 S) – 10,11-epoxy-1-bisabolene-3-ol and (3 R,6 S,7 R,10 S) – 10,11-epoxy-1-bisabolene-3-ol; Khramian et al., 2014) and pheromone synergist

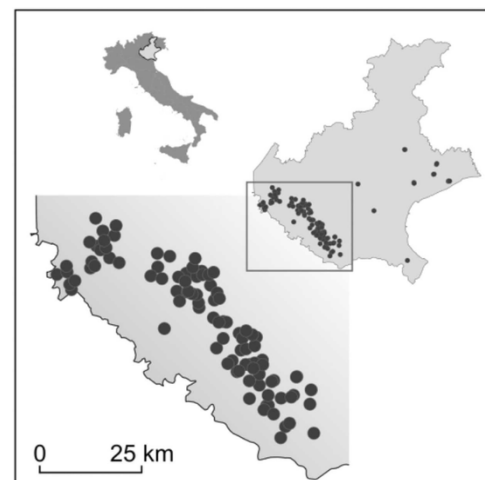


Fig. 1. Location of monitored orchards.

(methyl (2*E*,4*E*,6*Z*)-decatrienioate; Weber et al., 2014). This type of trap and lure has been proven to effectively attract both adults and juveniles of *H. halys* and to reliably monitor the relative population abundance of the stink bug (Acebes-Doria et al., 2018, 2019). Traps were placed at the outer margins of the orchards to avoid increasing stink bug infestation into the orchards, and they were attached to non-crop vegetation, wooden stakes or to fruit tree branches, at c. 1.5 m above the ground. Pheromone-baited clear sticky card traps deployed in similar conditions (i.e., at the outer orchard margins, in association with host plants) can capture *H. halys* present in a 73 m radius buffer, with a resulting trapping area of 1.67 ha (Kirkpatrick et al., 2019). Traps were exposed on average 173.5 ± 35.0 consecutive days per site and checked weekly, where adults and juveniles were counted separately. The lure was replaced every two months.

2.2. Statistical analyses

Abundance of adults and juveniles was averaged at the site level for each month and log-transformed to improve model residuals. Because of the large number of zeros in our dataset (34.1% of the observations, 11.6% for adults and 56.6% for juveniles), we tested the response of *H. halys* to landscape composition with zero-inflated GLMMs. We run six models to test the effect of landscape factors at different spatial scale (250, 500, 1000, 1500, 2000 and 3000-m radius). Each model included PC1 and PC2, sampling month (numeric; from April to October), development stage (categorical; juveniles, adults), their interactions, and fruit tree crop (categorical; pear, kiwi, peach, apple, walnut) as fixed effects. We also included the quadratic and cubic terms of sampling month to better fit the temporal dynamics of *H. halys* populations. We did not consider four-ways interactions to limit model complexity. Site ID was included as random factor. The best landscape scale was then identified based on model AIC (Akaike, 2011). Tukey multiple comparison test was applied to determine significant differences among fruit tree crops. To assess potential multicollinearity among the explanatory variables, we calculated the variance inflation factor (VIF) for all models without interactions and quadratic or cubic terms. VIF scores were always below 1.5, indicating low collinearity in our dataset (Dormann et al., 2013). We also tested for potential spatial autocorrelation of model residuals using Moran's I-statistic. We did not find significant spatial autocorrelation in the residuals for any of the six models examined (Table S3).

We performed sensitivity analyses to explore the robustness of our results. We first performed the analysis excluding 16 orchards located in the central and eastern part of the region, distant more than 40 km from the majority of the sites situated instead in the southwestern part of the region (Fig. 1). Second, we tested the potential influence of local management excluding the 17 organically managed sites. Third, we analyzed abundance data for adults and juveniles separately. Finally, to test whether the large number of zeros in our dataset influenced our results, we averaged the abundance of adults and juveniles at the site level for the whole sampling period (i.e., time was not considered in the analysis, zeros represented 9.7% of the observations, 2.6% for adults and 16.8% for juveniles), and run linear mixed effect models (i.e., no zero inflation). In all cases results were qualitatively similar to those produced by the main analysis (see "Sensitivity analysis" in Supplementary Information).

We checked all the models for overdispersion and residual distribution using the "DHARMA" package (Hartig, 2021). We performed the analyses using the 'glmmTMB' package (Magnusson et al., 2017) implemented in R version 4.0.2 (R Core Team, 2021).

3. Results

We collected a total of 14,354 adults and 8,960 juveniles of *H. halys* (mean individuals trap⁻¹ week⁻¹ = 6.2 ± 6.4 and 3.9 ± 5.6 , respec-

tively). The model at 3000-m scale yielded the lowest AIC and explained 55% of the variance (conditional pseudo-R²; Table S4). Despite the worse fit of the models at smaller scales, results were qualitatively similar to those at the 3000-m scale. The abundance of *H. halys* peaked in August and September with an increase since the beginning of the season (Fig. 2). The effect of landscape composition on *H. halys* depended on both development stage and time (PC1 x Month x Stage interaction): abundance of juveniles was positively correlated to PC1 (i.e., more juveniles in landscapes rich in semi-natural habitats and vineyards) and this relationship was stronger at the end of the season (Table 1 and S5; Fig. 3B). Adults instead were not affected by landscape composition. Moreover, fruit tree crop influenced *H. halys* abundance, since we found more individuals on traps placed in pear, kiwifruit, peach, and apple orchards than in walnut orchards (Table S6, Fig. 4). We found no significant effects of PC2 (i.e., urban areas and fruit orchards).

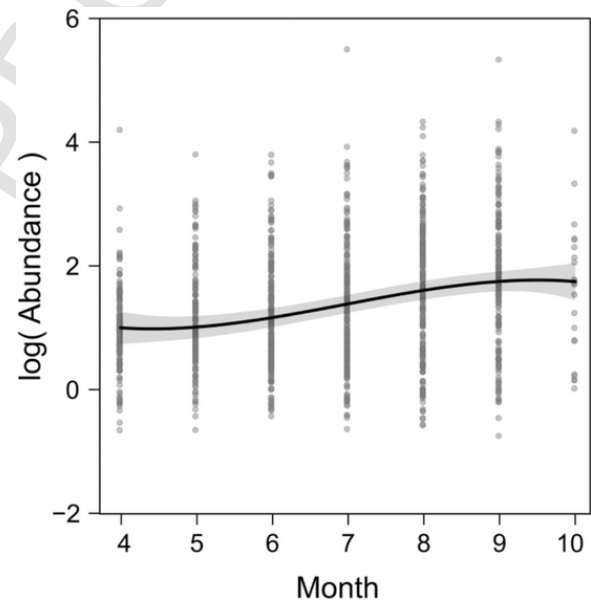


Fig. 2. Abundance of *Halyomorpha halys* (both adults and juveniles) across the sampling season (from April to October). Plots display prediction lines, partial residuals and confidence bands (95%).

Table 1

Results of the zero-inflated GLMM testing the response of *Halyomorpha halys*'s abundance to landscape composition (PC1 and PC2 at 3000 m scale), sampling month (Month; from April to October), development stage (Stage; juveniles, adults) and fruit tree crop (Fruit tree; pear, kiwi, peach, apple, walnut).

Variable	χ^2	P-value
PC1	0.68	0.408
PC2	1.38	0.241
Month	7.48	0.006
Stage	53.49	< 0.001
Fruit tree	21.89	< 0.001
Month²	4.55	0.033
Month³	4.34	0.037
PC1 x PC2	0.28	0.599
PC1 x Month	11.84	0.001
PC2 x Month	3.03	0.082
PC1 x Stage	41.61	< 0.001
PC2 x Stage	0.41	0.520
Month x Stage	2.21	0.137
PC1 x PC2 x Month	0.00	0.967
PC1 x PC2 x Stage	1.38	0.240
PC1 x Month x Stage	14.27	< 0.001
PC2 x Month x Stage	0.03	0.870

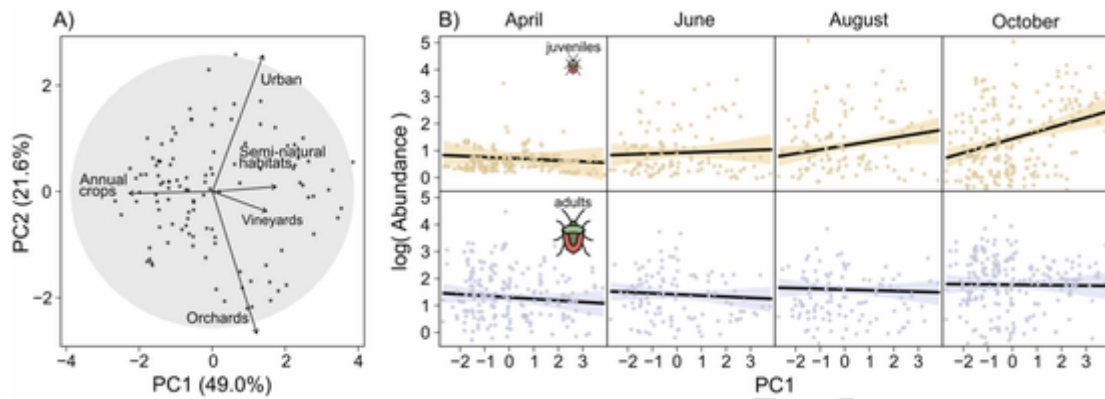


Fig. 3. (A) Landscape characteristics surrounding sampled orchards at a radius of 3000 m using principal component analysis. Sites characterized by positive values on PC1 were correlated with the variables semi-natural habitats and vineyards, while PC1 negative values were correlated with annual crops. Sites with positive values on PC2 were correlated with urban areas, while PC2 negative values were correlated with fruit orchards. (B) Juvenile and adult abundance of *Halyomorpha halys* in response to landscape composition (PC1 at 3000 m scale) across the sampling season (from April to October). Plots display prediction lines, partial residuals and confidence bands (95%). For the monthly change in abundance see Fig. S2. Stink bug icons: Flaticon.com.

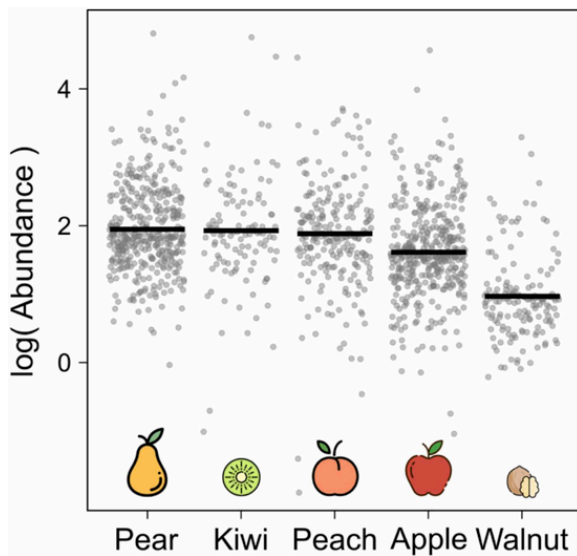


Fig. 4. Abundance of *Halyomorpha halys* (both adults and juveniles) in different fruit orchards. *H. halys* abundance is higher in pear, kiwifruit, peach, and apple orchards than in walnut orchards (Table S5). Plots display prediction lines and partial residuals. Fruit icons: Flaticon.com.

4. Discussion

We found landscape composition to influence the abundance of trapped *H. halys* in fruit orchards. Landscapes rich in semi-natural habitats and vineyards and poor in annual crops, generally supported a higher abundance of *H. halys* juveniles, especially at the end of the season. Adults were not instead affected by landscape composition. *Halyomorpha halys* did not display a strong preference between fruit tree crops, although fewer individuals were caught in walnut orchards. *Halyomorpha halys* best responded to landscape processes at large spatial scale (3000 m) confirming its high dispersal ability. Our findings suggest that the composition of agricultural landscapes is an important factor driving the dynamics of *H. halys* populations.

The populations of *H. halys* in our study peaked in August and September, with the number of both juveniles and adults steadily increasing since the beginning of spring. It is hence difficult to discern distinct generations in the dynamics of trap captures. Most probably, the pest completed two generations, as previously reported in northern Italy, with the simultaneous presence of all development stages and more

than one generation, during summer (Bariselli et al., 2016; Costi et al., 2017). Finally, our study indicates that in autumn, when the temperature dropped and food resources were no longer available in the field, *H. halys* left the orchards probably to reach overwintering sites (Bakken et al., 2015).

We found a higher number of juveniles in orchards located in agricultural landscapes characterized by high cover of semi-natural habitats and vineyards and low cover annual of crops (i.e., high values of PC1). This pattern became evident towards the end of the season as the abundance of juveniles increased (i.e., from June to September, Fig. 3 and S2). Semi-natural habitats probably provide a more suitable environment for oviposition and development of juveniles compared to annual crops, with more diverse and temporarily stable host plants and refuges. The availability of multiple hosts has been shown to positively affect the growth of *H. halys* populations. Funayama (2004) found lower nutritional status and fecundity when *H. halys* fed apple compared to peanuts and soybeans. Acebes-Doria et al. (2016) reported that juveniles reared on mixed-host diets displayed increased survivorship, decreased developmental duration and greater size and weight as adults, compared to individuals that had access to single hosts. Similarly, Stahl et al. (2021) reported that a mixed diet on tree crops in field can increase adult female size. Moreover, semi-natural habitats are probably more suitable reproduction and oviposition sites for *H. halys* compared to crop habitats, that are regularly disturbed by pesticide applications and harvest operations. As previously suggested (Venugopal et al., 2014; Bergh et al., 2021), our study indicates that semi-natural habitats are important in supporting *H. halys* populations, potentially increasing pest colonization and crop damage to neighboring orchards. Whether the presence of vineyards in the landscape played a role in sustaining *H. halys* juveniles in the monitored sites is uncertain, mainly for the lack of potential explanations or evidence from previous studies supporting this hypothesis. Vineyards in fact, although more stable than annual crops, are in terms of plant diversity and level of disturbance similar to fruit orchards, which cover in the landscape was not found to influence *H. halys* captures (Fig. 3). Our analysis does not allow to clearly identify the role of these three habitats (i.e., semi-natural habitats, vineyards and annual crops) in affecting stink bug populations. It is possible for example that the harvest operations in annual crops during summer contributed to lower the abundance of juveniles in landscapes characterized by a high proportion of this type of habitat. Experiments conducted in multiple habitats and designed to control for correlations among landscape variables will help understanding the habitat preference and use of *H. halys* (Tamburini et al., 2022; Laterza et al., 2023).

Contrary to our hypothesis, we did not find any response of *H. halys* adults to landscape composition. In particular, semi-natural habitats and urban areas did not affect its abundance in early spring and autumn, when these habitats were expected to influence the dynamics of *H. halys* being important overwintering sites. Also, the abundance of potential hosts in the landscape (annual crops or orchards) did not affect adult abundance. A possible explanation is that, having become well established and overwhelmingly present in the study region (Cesari et al., 2018), being able to disperse quickly and at great distance (Wallner et al., 2014; Wiman et al., 2015; Kirkpatrick et al., 2020) and being able to exploit multiple habitat types and hosts (Bakken et al., 2015), *H. halys* response to landscape remained hidden (i.e., complex landscapes are source of individuals that quickly spread across the agroecosystem as adults). Moreover, the monitored agricultural landscapes are generally characterized by urban sprawls interspersed within the agricultural matrix, probably representing an optimal balance between presence of overwintering sites and abundant food resources, and hence further promoting a spatially homogeneous distribution of the adults. Differences in local management might have further masked the impact of landscape on adults (Tamburini et al., 2016). Finally, as observed by Wallner et al. (2014) in USA, the importance of different landscape factors can change at different phases of the invasion process: *H. halys* response to landscape composition might become more evident in the future. Long-term studies exploring the impact of landscape composition on the population dynamics of this invasive stink bug over time and at larger scale are need for Europe as well.

The effect of landscape composition on the abundance of *H. halys* in fruit orchards was consistent across different spatial scales but stronger at 3000 m radius, confirming the available information on the great dispersal ability of this stink bug and its capacity to move across the agricultural matrix (Wallner et al., 2014; Wiman et al., 2015; Lee and Leskey, 2015). Interestingly, the models for adults and juveniles both presented the best fit at 3000-m scale (see [Supplementary Information](#)). Although *H. halys* nymphs have high dispersal capacity compared to other species (5th instars can walk 8 m in 30 min in a mowed plot; Lee et al., 2014), their movements are expected to be limited to the farm-scale level. The strong response of juveniles to landscape composition at large scales does not hence reflect the dispersal potential of the juveniles, but probably landscape processes also involving *H. halys* adults (e.g., mating, oviposition) that, however, did not appear in our analyses (i.e., no significant effect of landscape on adults). As mentioned before, the response of *H. halys* adults to landscape composition might have remained hidden. We found comparable levels of *H. halys* abundance in pear, kiwi, peach and apple orchards, confirming previous findings regarding its polyphagy and potential to damage these fruit tree crops (Lee et al., 2013; Bergmann et al., 2016; Stahl et al., 2021). Walnut, although recently recognized as a potential host (Bosco et al., 2020; Mityushev, 2021), is probably less preferred by the stink bug if compared to other available plants (Scaccini and Pozzebon, 2021). However, differences in pest management strategies among fruit tree species might have influenced these results. Moreover, it should be noted that data used here refer to insects attracted by pheromone-baited traps located near the orchards, and thus the real extent of *H. halys* infestation inside orchards – and reasonably the related damage – may vary at both spatial and temporal scales. Indeed, in a previous study performed in the same region where *H. halys* abundance was measured directly sampling individuals on fruit trees within the orchards (Mele et al., 2022), both adults and juveniles resulted influenced by landscape composition, being higher in orchards closer to semi-natural areas than those situated far away.

In our study we observed an ample variability in pest abundance across the monitored orchards. This suggests that other factors influenced *H. halys* populations besides those explored here. For example, although the great majority of fruit orchards were conventionally man-

aged, we did not consider detailed differences in local management (e.g., number and type of insecticide applications) that can substantially influence local pest abundance (Rusch et al., 2010). Moreover, the trapping strategy adopted in this monitoring study (i.e., one trap per site baited with a relatively short-range lure, trap placement at the outer margins of the orchards on heterogeneous supports) probably also contributed to increase variability in the collected data.

Identifying the main factors driving the dynamics of *H. halys* populations is crucial to support effective and more eco-friendly pest control. Our study shows that landscapes rich in semi-natural habitats and vineyards and poor in annual crops are more likely to harbour abundant populations of *H. halys*. Semi-natural habitats might hence be important for this pest, supporting population build-up in agroecosystems and acting as a season-long source for crop infestation. Nevertheless, semi-natural habitats have been also shown to support natural enemies of several stink bug pests (Abram et al., 2017; Conti et al., 2021) and to contribute to their control without however reducing their abundance in the field (González et al., 2017, 2020; Mele et al., 2022). Moreover, semi-natural habitats promoted higher parasitism in fruit orchards by the adventive egg parasitoid *Trissolcus mitsukurii* (Ashmead) (Hymenoptera: Scelionidae) (Mele et al., 2022) and can potentially play a fundamental role in the success of classical biological control programs against the stink bug (Ogburn et al., 2021). More studies are urgently needed to better understand the role of semi-natural habitats in regulating the populations of *H. halys*.

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CRediT authorship contribution statement

AM, DS, MP, AP and NM designed and supervised data collection. AM, DS, AP defined the sampling protocol. GT, and LM conceived the research. DN elaborated GIS data. GT and LM performed data analysis. GT and IL wrote the first draft of the manuscript. All authors participated to results' interpretation and in reviewing 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

Data will be made available on request.

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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.2023.108530](https://doi.org/10.1016/j.agee.2023.108530).

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