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

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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 seminatural 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 *H. halys* in agroecosystems and that seminatural 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.

Keywords: alien species, brown marmorated stink bug, crop pest, insect monitoring, seminatural habitats.

1. Introduction

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), native to eastern Asia, has become one of the most harmful invasive pest 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 (Wiman et al. 2015; Lee and Leskey 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, Leskey and Nielsen 2018). Moreover, this species represents a serious household pest, as it can use man-made structures as overwintering sites (Inkley 2012). 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 on 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 influenced 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; Tscharntke 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, that provide alternative feeding, reproduction, and overwintering sites (Taki et al. 2014; Rice et al. 2016). 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. (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. Nevertheless, 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; Zapponi et al. 2021; Francati et al. 2021). We sampled 113 orchards of different fruit tree crops (i.e., apple, pear, peach, walnut and kiwi). We hypothesized that i) landscapes characterized by a high proportion of semi-natural habitats and urban areas would favour *H. halys*, especially at the beginning and at the end of the season, when the adults disperse from and to overwintering sites, respectively; ii) landscapes characterized by a high proportion of arable land (i.e., annual and/or perennial crops) would generally favour *H. halys*. 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* was reported for the first time in the study region 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 15 were organic. Walnut orchards were all conventionally managed. Because of the imbalance between conventional and organic sites, local management was not further considered in this study. 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, grasslands, forests, and urban areas by analyzing regional land use maps (https://idt2.regione.veneto.it) in GIS (QGIS 2022). Since we found considerable correlation among landscape factors (Table S1), 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 seminatural 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). 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. 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

We used linear mixed-effects models to explore the effects of landscape composition on *H. halys*. Abundance of adults and juveniles was averaged at the site level for each month and log-transformed to improve model residuals. 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. Sixteen orchards were located in the central and eastern part of the region and were distant more than 40 km from the majority of the sites, situated instead in the southwestern part of the region (Fig. 1). Nevertheless, excluding those sites did not qualitatively affect the results of the analyses (see Table S2). Finally, analyzing abundance data for adults and juveniles separately, produced qualitatively similar results for all the models (see Table S3). Normality and homoscedasticity of the model residuals were validated graphically. We performed the analyses using the 'lme4' package (Bates et al. 2017) implemented in R (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, respectively). The model at 3000-m scale yielded the lowest AIC and explained 55% of the variance (conditional pseudo-R^2; 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 that was stronger for juveniles than for adults (Month x Stage interaction; 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 seminatural habitats and vineyards) and this relationship was stronger at the end of the season (Table 1; Fig. 3). 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 S5, Fig. 4). We found no significant effects of PC2 (i.e., urban areas and fruit orchards).

4. Discussion

We found landscape composition to influence the abundance of trapped *H. halys* in fruit orchards. Landscapes rich in seminatural 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). Interestingly, the abundance of adults was already quite high at the beginning of April, suggesting that, when the monitoring started, the overwintered individuals already moved to the fields. 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 seminatural habitats and vineyards and low cover annual 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 S1). Seminatural 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, seminatural habitats are probably more suitable reproduction and oviposition sites for *H. halys* compared to annual crops, that are regularly disturbed by pesticide applications and harvest operations. As previously suggested (Venugopal et al. 2014; Bergh et al. 2021; Mele et al. 2022), our study indicates that seminatural 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., seminatural habitats, vineyards and annual crops) in affecting stink bug populations. Experiments designed to control for correlations among landscape variables will help understanding the habitat preference and use of *H. halys*.

Contrary to our hypothesis, we did not find any response of *H. halys* adults to landscape composition. In particular, seminatural 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 establish and overwhelmingly present in the study region (Cesari et al. 2018), being able to disperse quickly and at great distance (Lee and Leskey 2015; Wiman et al. 2015) 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. In our study we did not consider differences in local management (although the great majority of fruit orchards were conventionally managed) that might have further masked the impact of landscape on adults (Tamburini et al. 2016). Interestingly, as observed by Wallner et al. (2014) in USA, the importance of different landscape factors can change at different phases of the invasion process of *H. halys*. 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 (Table S4). Although *H. halys* nymphs have high dispersal capacity compared to other species (5th instars can walk 8 meters in 30 min in a mowed plot; Lee et al. 2014), their movements are expected to be limited to the farmscape 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 species (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), it is probably less preferred by the stink bug (Scaccini and Pozzebon, 2021). However, 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 closed to semi-natural areas than those situated far away.

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 seminatural habitats and vineyards and poor in annual crops are more likely to harbor abundant populations of *H. halys*. Seminatural habitats might hence be important for *H. halys*, 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). Moreover, seminatural habitats promoted higher parasitism in fruit orchards by the adventive egg parasitoid *Trissolcus mitsukurii* (Ashmead) (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.*

TABLES

Table 1. Results of the 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	**$\chi 2$**	***P*-value**
PC1	1.99	0.158
PC2	1.73	0.189
Month	**6.83**	**0.009**
Stage	**310.42**	**<0.001**
Fruit tree	**25.27**	**<0.001**
Month^2	**7.62**	**0.006**
Month^3	**7.91**	**0.005**
PC1 x PC2	0.27	0.604
PC1 x Month	**33.60**	**<0.001**
PC2 x Month	**2.74**	**0.098**
PC1 x Stage	**35.50**	**<0.001**
PC2 x Stage	2.01	0.156
Month x Stage	**64.90**	**<0.001**
PC1 x PC2 x Month	0.06	0.805
PC1 x PC2 x Stage	1.46	0.227
PC1 x Month x Stage	**16.03**	**<0.001**
PC2 x Month x Stage	0.10	0.757

FIGURES

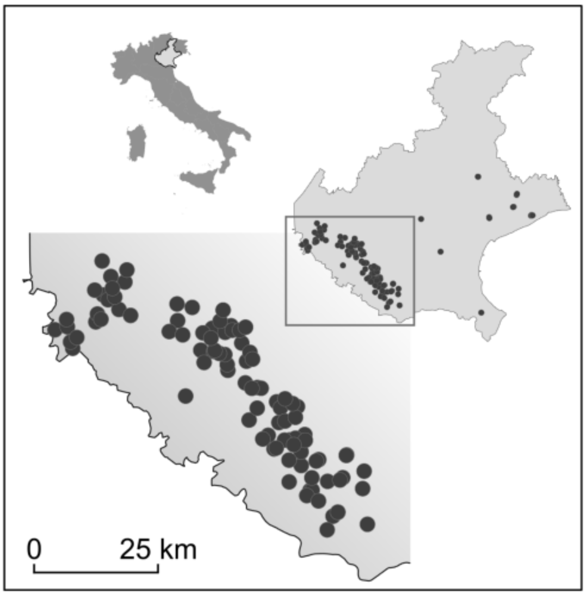

Fig. 1 Location of monitored orchards.

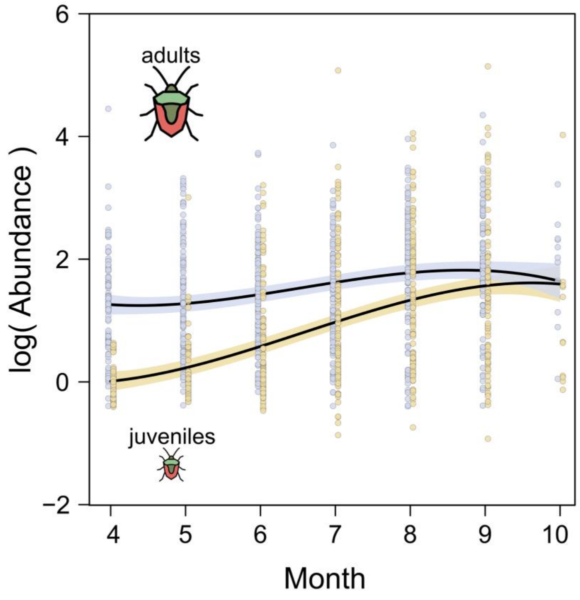

Fig. 2 Juvenile (in yellow) and adult (in light blue) abundance of *Halyomorpha halys* across the sampling season (from April to October). Plots display prediction lines, partial residuals and confidence bands (95%). Stink bug icons: Flaticon.com.

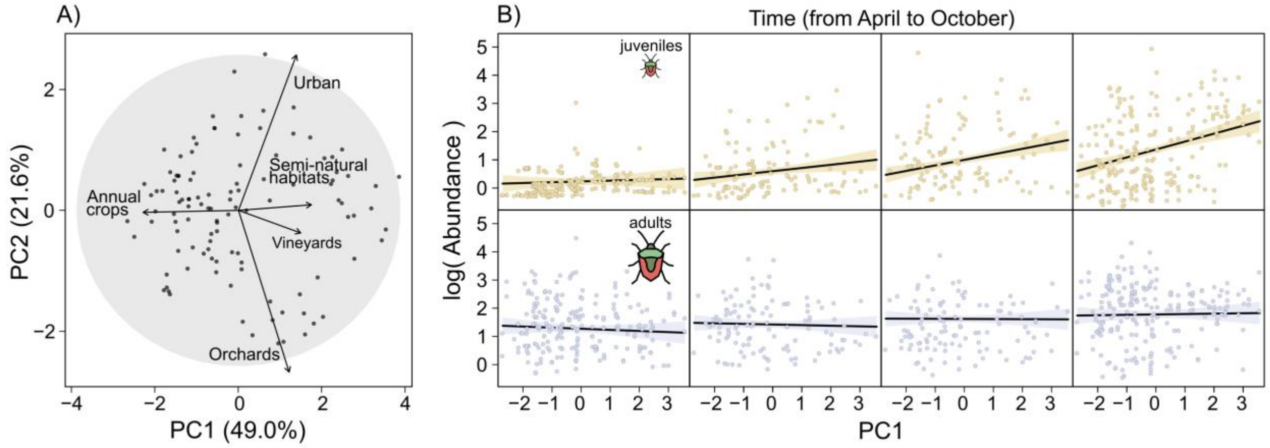

Fig. 3 (A) Landscape characteristics surrounding sampled orchards at a radius of 3000 m using principal component analysis**.** Sites characterized by positive values on PC1 were correlated with the variables seminatural habitats and vineyards, while PC1 negative values were correlated with annual crops. 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%). Stink bug icons: Flaticon.com.

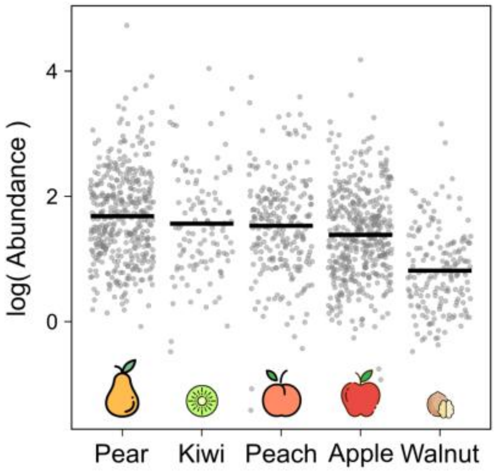

Fig. 4 Abundance of *Halyomorpha halys* (both adults and juveniles) in different fruit orchards. *H. halys* abundance is higher in pear, kiwifruit, peach, and apple orchards than in walnut orchards (Table S5). Plots display prediction lines and partial residuals. Fruit icons: Flaticon.com.

Author contribution: 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.

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