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Halyomorpha halys, a serious threat for hazelnut in newly invaded areas

Lara Bosco, Silvia T. Moraglio, Luciana Tavella

Dipartimento di Scienze Agrarie, Forestali e Alimentari (DISAFA), ULF Entomologia Generale e Applicata, University of Torino, Largo P. Braccini 2, 10095 Grugliasco (TO), Italy

Corresponding author: Luciana Tavella

Phone +39 011 6708533, fax +39 011 6708535, email luciana.tavella@unito.it

Abstract

Following its first detection, *Halyomorpha halys* has become a key pest in many crops in NW Italy. In this area, one of the most important crops is hazelnut, in which the species can cause severe damage through feeding on nuts. Therefore, semi-field trials were carried out in NW Italy to compare the harmfulness of *H. halys* with that of the local hazelnut bug species, such as *Gonocerus acuteangulatus*, *Nezara viridula*, and *Palomena prasina*. Additionally, a 2-year field survey was conducted in hazel groves in NW Italy and W Georgia, another important hazelnut cropping area, to assess the presence and abundance of the new invasive species and to evaluate the damage at harvest. Monitoring was carried out by plant beating and by commercial traps throughout the growing season. In semi-field trials, *H. halys* was the most harmful species, causing the highest damage in kernels, and was able to survive and reproduce at higher rates. During field surveys in NW Italy, *H. halys* was sampled in groves late in the season in 2015 and, with higher populations, throughout the season in 2016. In W Georgia, bug population levels consistently increased in the 2-year period, resulting in a significant increase of damage at harvest in 2016. A similar trend is hence expected also in NW Italy in the following years. Moreover, data on individuals collected in different points of the hazelnut groves confirmed the border-driven behavior of this pest, leading to consideration of potential integrated pest management solutions.

Key words: Brown marmorated stink bug, Semi-field trials, Field surveys, Damage evaluation, NW Italy, W Georgia

Key message:

- *Halyomorpha halys* has become a serious pest in NW Italy.

- In semi-field trials, *H. halys* was more harmful than common hazelnut pest bug species because of greater damage on kernels and maximum survival and reproductive rates.
- In field surveys, in NW Italy *H. halys* was scarcely found in 2015-2016, whereas in W Georgia its population consistently increased in 2016, resulting in significantly higher damage.
- A similar trend is hence expected on hazelnut in NW Italy in the following years.

Introduction

Different bug species belonging to the families Coreidae and Pentatomidae (Hemiptera: Heteroptera) are responsible for economic damage to hazelnut in the main producing areas of Europe and Turkey (Moraglio et al. 2014; Tuncer et al. 2014; Erper et al. 2016). Adults and nymphs can cause different types of damage in relation to the period when they feed on the nuts: early attacks during nut development, i.e., in May-early June, lead to an increase of seed abortion and early nut drop, while later attacks during kernel growth, i.e., in mid-June-August, determine symptoms on kernels, such as whitish or brownish spots, spongy tissue, and surface depression (Boselli 1932; Tavella et al. 2001a, 2003). Damage on kernels result from an injection of saliva rich of enzymes during feeding, which changes kernel composition (Vaccino et al. 2008; Memoli et al. 2017). Currently, *Gonocerus acuteangulatus* (Goeze) (Hemiptera: Coreidae), *Nezara viridula* (L.), and *Palomena prasina* (L.) (Hemiptera: Pentatomidae) are the primary insect pests of hazelnut in Europe and Turkey (Tuncer et al. 2005; Romero et al. 2009; Moraglio et al. 2014).

Besides the well-known hazelnut bugs, the recent invasion of the exotic brown marmorated stink bug *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) represents a serious threat to hazelnut in Europe and Turkey, as already observed in North America, where this species has also been producing economic losses in hazelnut crops. In semi-field trials carried out in Oregon, *H. halys* caused damage on different hazelnut cultivars throughout the entire period of nut and kernel development (Hedstrom et al. 2014). Therefore, one purpose of our study was to investigate the potential of *H. halys* to damage the local hazelnut cultivar in Piedmont (NW Italy), in comparison with the main indigenous bug species, such as the most widespread *G. acuteangulatus* and *P. prasina* (Sonnati et al. 2009) and the occasionally found *N. viridula* (authors' personal observation).

Since the first report of *H. halys* in Europe more than 10 years ago, the species has recently become an important fruit pest in many agroecosystems (Haye et al. 2015b). In Italy, the second hazelnut-producing country worldwide (data of 2014, FAOSTAT 2017), the exotic pest was first recorded in the Emilia Romagna in 2012 (Maistrello et al. 2013) and in the Piedmont in 2013 (Pansa et al. 2013). In this latter region of NW Italy, where hazelnut is widely cultivated and still increasing, *H. halys* has been causing severe damage and high economic losses in apple, nectarine, pear, and nashi pear (Pansa et al. 2015; Candian et al. unpublished data) as well as in corn (Rancati et al. 2017). By contrast, only a few data are available about the presence and abundance of *H. halys* in Georgia (Gapon 2016), the third hazelnut-producing country worldwide after Turkey and Italy (data of 2014, FAOSTAT

2017). Hazelnut is an important traditional nut crop in different Georgian zones, such as the regions Abkhazia, Adjara, Samegrelo, Guria, Imereti, and Kakheti (Mirotadze et al. 2009). Therefore, another purpose of this study was to assess the presence, abundance, and harmfulness of *H. halys* by plant beating, use of traps, and damage evaluation in commercial hazel groves in NW Italy, in the Piedmont region, and in W Georgia, in the Samegrelo region, during 2015-2016.

The overall objectives of this study are: (1) comparing the damage caused by different hazelnut bugs, (2) comparing their survival and reproduction on hazelnut under semi-field conditions, (3) assessing the presence and abundance of *H. halys*, and (4) evaluating the damage to hazelnut production due to bug feeding in two important growing regions in Italy and Georgia.

Material and method

Harmfulness of H. halys *in comparison with other hazelnut bug species*

In 2015, semi-field trials were carried out in a commercial hazel grove untreated with insecticides, located in Magliano Alfieri (province of Cuneo, 44°45'46.50"N, 8° 3'13.56"E, 205 m a.s.l.), planted with the local cultivar Tonda Gentile delle Langhe. In the trials, the following four species were tested: the newly introduced *H. halys* and the commonly present *G. acuteangulatus*, *N. viridula*, and *P. prasina*.

Insect collection and rearing

Starting from April, adults and nymphs of the tested bug species were collected from different wild or cultivated host plants [*Rhamnus cathartica* (L.) (Rhamnaceae), *Cornus sanguinea* L. (Cornaceae), *Crataegus monogyna* Jacq., *Prunus* spp., and *Rosa* spp. (Rosaceae) for *G. acuteangulatus* and *P. prasina*, *Sambucus nigra* L. (Caprifoliaceae) for *N. viridula*; peach and pear for *H. halys*]. Field-collected adults and nymphs were then transferred to the laboratory where they were reared in net cages (930 × 475 × 475 mm) (MegaView Science Co., Ltd, Taichung City, Taiwan) containing broad bean seedlings [*Vicia faba* L. (Fabaceae)], fresh fruits, and shelled hazelnuts. Mass rearing was performed in climatic chambers at 24 ± 1°C and RH 65 ± 5%, with an L/D of 16:8 h.

Hazel branch caging and insect insertion

To prevent insect damage to nuts in early June, 300 hazel branches with at least four clusters of fruits were caged inside sleeve cages of polythene net (730 mm in length, 170 mm in diameter, and 60-mesh grid) [Artes Politecnica, Schio (VI), Italy], supported by an inner cylinder of a plastic net (310 mm in length, 165 mm in diameter). On the tree, each cage was closed with a twist tie proximally at one end around the branch and distally at the other end over the top of the branch.

Single specimens of the tested bug species were inserted in the cages on July 3, i.e., when nuts of the cultivar Tonda Gentile delle Langhe have reached the final volume and kernels are in an advanced stage of development (Guidone et al. 2007), enabling the bugs to cause greater damage (Tavella et al. 2001b, 2003). Specifically, 30 males and 30 females of *H. halys*, *G. acuteangulatus*, and *N. viridula* and 60 nymphs (fourth- and fifth-instar nymphs) of *P. prasina* were individually encaged in 240 cages and left until harvest time, i.e., mid-August. For *P. prasina*, late instars nymphs were used, since adults were not available in the required numbers. Out of 60 remaining cages, 30 cages were discarded since the isolated branches were found dried out or had only few hazelnuts due to the physiological fruit drop, while in the other 30 cages, no insects were inserted to obtain data for undamaged hazelnuts.

<u>Damage evaluation at harvest</u>

On August 4, just before the harvest time, all the cages were removed and brought to the laboratory, where the nuts contained in each cage were collected separately and stored at 5°C until they were shelled. The kernels were examined to detect any bug damage symptoms (i.e., alterations evident only on the seed, consisting of whitish or brownish spots, spongy tissue, surface depressions). Damage assessment was done following the procedure generally used by nut processing industries. First, the kernels were separated into two categories: with evident symptoms of bug damage on the surface (external damage) and without any symptoms on the surface. The nuts with the external damage are usually immediately discarded by processing industry. Subsequently, the latter kernels were cut into four parts to detect the presence of possible internal symptoms, not evident on the surface, and separated into two further categories: with internal symptoms of bug damage (internal damage) and healthy. All damaged kernels were further divided into two categories: with spongy and only white tissue (white) or with brown tissue or both white and brown tissues (brown). The brown category in particular affects the commercial quality of kernels in industrial chain processes. Additionally, shriveled and rotten or moldy kernels were also recorded, as well as blank nuts. The cages containing dried-out branches or only blank nuts were discarded.

Proportions of damaged kernels in total kernels and of kernel showing external and brown symptoms within damaged kernels in each cage were compared among species via a binomial distribution model with a logit link function, using the general linear model (GLM) procedure of the software IBM SPSS® Statistics 22 (IBM Corp., NY, USA). The two outcomes of each of the three binomial analysis were: (1) damaged versus non-damaged kernels, (2) kernels showing external versus internal damage within all damaged kernels, and (3) kernels showing brown versus white damage within all damaged kernels. Means were then separated at $P < 0.05$ using the Bonferroni test under the GLM procedure.

Insect survival in the cages

During the trials, the insects were checked weekly for survival. All dead specimens were recorded and replaced with new ones of the same species and sex. After their removal and transfer to the laboratory on August 4, the cages were inspected to check for insect survival and the presence of eggs and nymphs. Percentages of replacement (i.e., the insects introduced to replace the dead ones) were arcsine square-root-transformed and analyzed with one-way ANOVA, using the sex/stage (i.e., male, female, or female with offspring) within the same species as the main factor. Subsequently, when any difference in mortality was found between sex/stage within the species, species was used as the main factor. Means were separated at $P < 0.05$ using Tukey´s test. Total numbers of nymphs per each cage containing offspring were analyzed with one-way ANOVA, using species as the main factor. Means were then separated at $P < 0.05$ using Tukey´s test. The software IBM SPSS® Statistics 22 (IBM Corp., NY, USA) was used for all analyses.

Field monitoring of bugs and damage evaluation

To assess the presence and abundance of bug species, a 2-year (2015–2016) field survey was carried out in five commercial hazel groves, of which three were located in NW Italy (Piedmont region) and two in W Georgia (Samegrelo region). In these two regions, both grove size and the agroecosystem were different. In NW Italy, the three groves were integrated in a heterogeneous landscape, composed of various cultivations, such as cherry, peach, and pear orchards, vineyards, vegetable crops. On the borders of these groves, there were wild plants well known as host plants for hazel bugs, such as *C. sanguinea*, *Prunus* spp., and *Pyrus* spp. In addition, favorite hosts of the bugs, in particular of *G. acuteangulatus* (i.e., *C. sanguinea*, *R. cathartica*, and *Rosa canina* L.) (Schaefer and Mitchell 1983, Werner 2007, Moraglio et al. 2014), had been planted in four groups in the corners of each orchard in 2014. In W Georgia, the two groves were integrated in a simplified landscape (i.e., a large hazelnut cropping area of about 300 ha), surrounded by other hazelnut groves, and characterized by the presence of wild *Cornus* sp., *Rubus* sp., and *Cryptomeria japonica* (Thunb. ex L.f.) D. Don on some borders. Sites, hazelnut cultivars, pest management, and wild plants grown in the surroundings of the groves are reported in Table 1.

Monitoring of bugs by plant beating and traps

In the surveyed groves, the presence and abundance of *H. halys* and other bug species were assessed on groups of hazel trees in different positions of the grove, by plant beating, and by using traps.

Plant beating consisted of scouting the branches of the selected plants over a white nylon tarpaulin (2.5 × 2.2 m) placed on the ground, collecting and counting all the fallen bugs. It was performed early in the morning (5:00-7:00 am) to prevent adults from flying away. In NW Italy, monitoring by plant beating was carried out on July 10 and 27 in 2015 and on July 1, 15, and 29 in 2016. In each grove, the sampling was performed on groups of hazel trees located in the center (one and two groups in 2015 and 2016, respectively) and along the borders (four groups, i.e., one per border). In 2015 and in 2016, each group consisted of three plants (total of 15 plants) and four plants (total of 24 plants), respectively. In W Georgia, monitoring by plant beating was carried out on June 10, July 9, and August 5 in 2015 and on June 15 and 28, July 13 and 27, and August 9 in 2016. Due to the large size of the groves (see Table 1), the sampling was performed on groups of trees located at the following three distances from the border with attractive plants: 5 m (i.e., border area), 100 m, 200 m (i.e., central area). At each distance, three groups of plants were selected, each consisting of two plants (total of 18 plants) and of four plants (total of 36 plants) in 2015 and 2016, respectively.

The presence of *H. halys* was also assessed by using commercially available traps, i.e. Rescue® (Sterling International, Inc., Spokane, WA, USA) traps in 2015, and Alpha Scents® (Alpha Scents, Inc., West Linn, OR, USA) in 2016. The traps were always baited with Alpha Scents® lures [methyl (*E,E,Z*)-2,4,6-decatrienoate, *EEZ*-MDT) and used in both years in NW Italy and only in 2016 in W Georgia. In particular, one trap in NW Italy and two traps in W Georgia were placed along the border of each surveyed grove in mid-June and checked every 2 weeks until mid-November.

Mean numbers of bugs collected per plant and per survey were compared in each grove between the 2 years; in each region across all groves, the same data were compared on the basis of the position of plants (i.e., on the border or in the center in NW Italy, at different distance from the border in W Georgia). Data were analyzed with a Poisson distribution model with a log link function using the GLM procedure of the software IBM SPSS® Statistics 22 (IBM Corp., NY, USA). Means were then separated at $P < 0.05$ using the Bonferroni test under the GLM procedure.

<u>Damage evaluation at harvest</u>

At harvest time, a sample of 1 kg of hazelnuts was manually collected beneath each surveyed tree at each position in the five groves. In 2015, additional nut samples were collected from a further central group of hazel trees in groves 1 and 2 in NW Italy. In the laboratory, hazelnuts were shelled and 300 intact kernels were randomly chosen from each plant and checked for bug damage as described above. As with numbers of bugs collected per plant, also mean proportions of damaged kernels per plant were compared in each grove between the 2 years and in each region overall the groves on the basis of the position of plants with a binomial distribution model (outcomes: damaged versus non-damaged kernels) with a logit link function using the general linear model (GLM) procedure of the software IBM SPSS® Statistics 22 (IBM Corp., NY, USA). Means were then separated at $P < 0.05$ using the Bonferroni test under the GLM procedure.

Results

Harmfulness of **H. halys** *in comparison with other hazelnut bug species*

The mean percentages of kernels exhibiting symptoms due to bug feeding were significantly higher in the cages with all the tested species than in the control; in particular, the values were significantly higher for *H. halys* (75% of analyzed kernels) in comparison with *N. viridula* (57%), *P. prasina* (39%), and *G. acuteangulatus* (39%) (Table 2). For all the tested species, no significant differences were found by comparing the percentages of kernels damaged by males and females within the species (data not shown). Among damaged kernels, *H. halys* and *G. acuteangulatus* showed significantly higher percentages of external symptoms (81 and 78%, respectively) in comparison with the other two species, and *G. acuteangulatus* showed significantly higher percentages of brown tissue (93%) in comparison with the other species. The mean percentages of shriveled kernels were significantly higher for *H. halys* and *N. viridula* (20% of analyzed kernels), followed by *P. prasina* (10%) and *G. acuteangulatus* (5%), which did not differ significantly from the control (6%). The highest mean percentages of rotten and/or moldy kernels were observed in the cages with *H. halys* (10% of analyzed kernels); *G. acuteangulatus* (5%) and *N. viridula* (6%) showed values not significantly different, while *P. prasina* (1%) did not differ significantly from the control (2%) (Table 2). Some females of *H. halys* ($n = 24$), *G. acuteangulatus* ($n = 8$), and *N. viridula* ($n = 11$) laid eggs inside the cages, and the offspring could survive and develop (Table 3). Such ovipositing females were mostly alive throughout the trials ($n = 23, 4, 10$ for *H. halys*, *G. acuteangulatus* and *N. viridula*, respectively) or replaced only once in the first survey ($n = 1, 4, 1$ for *H. halys*, *G. acuteangulatus* and *N. viridula*, respectively). For *P. prasina*, since the individuals were caged as late instar nymphs, adults emerging into the cages could not mate, and consequently females could not oviposit. The mean number of nymphs per female was significantly higher for *N. viridula* (32.2) compared to *H. halys* (19.6) and *G. acuteangulatus* (12.3) (Table 3). The mean percentages of replacement were not significantly different in the cages with males, females, and females plus nymphs of the same species for *H. halys* (ANOVA: P = 0.126; $F_{2;9}$ = 2.636), *G. acuteangulatus* (ANOVA: P = 0.393; $F_{2;9}$ = 1.039), and *N. viridula* (ANOVA: P = 0.70; $F_{2;9}$ = 3.624) or with nymphs, females, and males for *P. prasina* (ANOVA: P = 0.564; $F_{2;9}$ = 0.610) (Table 3). Nevertheless, significant differences were found between the mean replacement percentages of the four species. In particular, the lowest and highest rates of insects replaced during surveys were observed for *H. halys* and for *G. acuteangulatus*, respectively (Table 3).

Field monitoring of bugs and damage evaluation

<u>Monitoring of bugs by plant beating and traps</u>

In NW Italy, *H. halys* was not found in the samples taken by plant beating in 2015 (0%; *n* = 134), while it represented 3% of total collected bugs in 2016 (*n* = 272). In particular, adults and nymphs of this species were collected in mid- and late July in a group of plants on the border near the attractive plants planted in 2014, in both groves 1 and 3. The other bug species were *G. acuteangulatus*, *N. viridula*, and *P. prasina*, which were sampled by plant beating in variable amounts in the surveyed groves. For all Italian sites, average numbers of bugs per plant were 1.48 ± 0.65 in 2015 and 2.01 ± 1.22 in 2016 (Table 4). By using traps, in 2015, specimens of *H. halys* were captured only in grove 3, namely, eight nymphs on September 15 and one adult plus 59 nymphs on October 8. In 2016, higher numbers of specimens were collected in groves 1 and 3 from late August or early September, respectively (Fig. 1). High numbers of insects were trapped during October; the numbers then decreased during early (grove 1) or late November (grove 3) (Fig. 1).

In W Georgia, *H. halys* represented 67 and 84% of total sampled bugs in 2015 (*n* = 45) and in 2016 (*n* = 829), respectively. Specimens of this species were collected on hazel starting from July 9 in 2015 and from June 15 in 2016. Overall, the 45% of total collected specimens were nymphs (*n* = 735). Average numbers of bugs per plant were 0.46 ± 0.06 in 2015 and 2.83 ± 1.43 in 2016 (Table 5). Therefore, there was an evident increase of bugs between the 2 years, essentially corresponding to the increase of *H. halys* compared to the other bug species (Table 5). In particular, the following three species were also collected on hazelnut in W Georgia: *G. acuteangulatus* (17 and 2% of total bugs in 2015 and 2016, respectively), *N.*

viridula (7 and 12% of total bugs in 2015 and 2016, respectively), and *P. prasina* (7 and 1% of total bugs in 2015 and 2016, respectively). By traps (placed only in 2016), the first specimens of *H. halys* were captured in late June (grove 4) and in mid-July (grove 5) (Fig. 1). Then, in grove 4, the captures suddenly increased between late July and early September; afterward, they started to decrease. In grove 5, the highest mean values of insects were recorded in early September, while in the previous dates, on average 11.5 bugs per trap were captured (Fig. 1).

Population levels were variable in relation to the plant position in the orchards. In NW Italy, the mean numbers of bugs per plant were significantly higher in the groups of plants on the borders than in the center of the surveyed hazel groves, in both 2015 and 2016 (Table 4). In W Georgia, a marked gradient of population levels was observed, starting from the border towards the center of the orchards, especially in 2016, when the mean values were significantly higher than in 2015 (Table 5).

Damage evaluation at harvest

In NW Italy, the percentages of kernels exhibiting symptoms due to bug feeding in the three hazel groves surveyed in both years ranged, on average, between 7.8 and 19.4% (Table 4). Consistent with the results of bugs sampled by plant beating, the kernels collected from the groups of plants located in the center of the orchard were significantly less damaged than those collected along the borders (Table 4).

In W Georgia, the mean percentages of kernels showing symptoms of damage caused by bugs increased strongly from 2015 to 2016, from 4.3 to 51.3% in grove 4 and from 1.4 to 26.6% in grove 5 (Table 5). In 2016, the highest percentages of damage were recorded in kernels collected from the groups of plants along the border, and a marked gradient from the border toward the center of the orchard was evident (Table 5).

Discussion and Conclusions

In the semi-field trials, the symptoms on kernels resulting from *H. halys* feeding were similar to those caused by the other tested species as well as to those observed in similar trials performed on local cultivars in Oregon (Hedstrom et al. 2014). Nevertheless, in our trials, the newly introduced species was the most harmful one in comparison with the common hazelnut bugs. Among the categories of symptoms (i.e., external or internal damage, white or brown tissues), we defined within damaged kernels, *H. halys* caused mainly external damage, together with *G. acuteangulatus*, and brown tissue symptoms, and such categories particularly affect the commercial quality of kernels, especially in nuts used in processed foods. In the cages with *H. halys* and with *N. viridula*, the highest percentages of shriveled hazelnuts were also found, probably due to feeding during kernel expansion (Hedstrom et al. 2014). Additionally, in the cages with *H. halys*, the highest percentages of moldy and/or rotten hazelnuts were recorded; hence, an indirect damage due to secondary pathogenic infections through the punctures on kernels and/or to transmission with the feeding stylets cannot be excluded (Rice et al. 2014). The role played by *H. halys* on this indirect damage needs to be further investigated, as well as its contribution to the increase of blank nuts when it feeds on hazelnuts before shell and kernel expansion (Hedstrom et al. 2014). In our trials, blank nuts were not considered, since bugs fed on hazelnuts from kernel expansion to the harvest, therefore resulting in kernel malformations and/or spongy or corky symptoms.

In NW Italy, from its first report in 2013, *H. halys* has significantly spread, becoming worrisome, and caused economic losses in stone and pome fruits as well as cereals (Pansa et al. 2013, 2015; Rancati et al. 2017), whereas it was rarely observed on hazelnut until 2015. During field surveys in 2015, few adults and nymphs were sampled in the groves, while their numbers increased in 2016; however, the damage at harvest was similar in the 2 years and probably caused by the other bug species. The augmentation of infestations on hazelnut in the following growing seasons is expected, as suggested by the outbreaks of *H. halys* already observed in the early 2017 growing season (personal observation).

In W Georgia, *H. halys* was first observed in the hazelnut groves in 2015, and the proportion of the field-collected specimens (69% of total sampled hazel bugs) was by far greater than that observed in NW Italy. However, during the 2016 season, populations were significantly higher than in the previous season, which is consistent with the first outbreaks of the exotic species recorded in Georgia in the same year (Gapon 2016). In fact, in our study, the first serious damage on hazelnut was reported in 2016, with mean percentages of damaged kernels of 51 and 27% in 2016 versus 4 and 1% in 2015, in groves 4 and 5, respectively.

The high percentages of nymphs found through plant beating indicate that hazelnut can serve both as feeding and reproductive host for *H. halys*, while on other host plants, only or mostly adults are observed (Acebes-Doria et al. 2016; Zobel et al. 2016). In addition, *H. halys* showed the highest percentages of survivors as well as of females laying eggs in the cages, further suggesting the suitability of hazelnut as a host plant.

Across all field surveys, irrespective of the grove, region, and year, the highest numbers of bugs per plant, and also of *H. halys*, were collected in the groups of plants along the borders of the orchards compared to those in the center. Even considering the high heterogeneity of the two areas, this result confirms that the invading population of *H. halys* establishes on wild or cultivated host plants grown in the surroundings and migrates into the hazel crop area throughout the season, as already reported for other crops (Leskey et al. 2012; Rice et al. 2014). This perimeter-driven behavior could be exploited by using perimeter applications of insecticides to control *H. halys* in the borders, as suggested for other fruit crops (Blaauw et al. 2015). To increase efficiency, the perimeter treatment could be coupled with the use of attractive plants (e.g., grown on the borders of the grove not used for vehicle movement) to manage the pest populations outside the crop (Mathews et al. 2017; Nielsen et al. 2016; Soergel et al. 2015).

Commercially available traps and lures can be useful tools for monitoring and detection, decision making, and management strategies. In our study captures varied substantially among sites during the sampling period, but generally peaked in the late season (mid-August to early October), consistently with other studies carried out using commercially available lures (combination of aggregation pheromone *EEZ*-MDT) (Weber et al. 2017). Only in one orchard in W Georgia, earlier captures we recorded from mid-June come from overwintering populations. Differences in the captures may reflect the size of the overwintering population in the general vicinity of the traps (Bergh et al. 2017), but earlier peaks are also typical of higher population years (Weber et al. 2017), as well as affected by lure composition. Both these factors can be at the base of the significant increase in 2017 of early captures by traps on hazelnut in both NW Italy and W Georgia (personal observation). Therefore, the traps can also be used in hazelnut crops to develop and apply thresholds to trigger management decisions which ultimately reduce insecticide usage.

Broad-spectrum insecticides can provide an effective control of *H. halys*, but only if they are applied directly on the insects (Kuhar and Kamminga 2017; Leskey et al. 2012; Rice et al. 2014). Therefore, multiple applications are needed for bug control throughout the season, nullifying the integrated pest management programs largely adopted in NW Italy. Moreover, due to the scarcity of active ingredients authorized on hazelnut crops in Italy, the repeated application of insecticides such as pyrethroids would be particularly detrimental for secondary pest outbreaks (e.g., spider mites, aphids, mealybugs) and for the community of beneficial species (AliNiazee, 1998). Additionally, in some areas (e.g., in Georgia and Turkey), few local farms are equipped for the application of pesticides at the level required for a successful management of *H. halys*. Moreover, chemical treatments are not always feasible due to several factors such as strongly sloping land, non-rational management of plantations (e.g. irregular tree spacing, high number of branches per plant, uncontrolled growth of suckers), and excessive tree height and canopy density.

In a perspective of reduction or avoidance of chemicals and preservation of a relatively stable agroecosystem, such as the hazelnut orchard, alternative pest management strategies should be further developed and tailored for the peculiar characteristics of the considered hazel groves (geographical area, size of the orchards, surroundings, agroecosystem traits, etc.). As observed in apple orchards (Morrison et al. 2016), the attract-and-kill strategy, using a few trees intensively baited with pheromone and sprayed on a weekly basis with insecticides efficacious against *H. halys*, could reduce the area treated with an insecticide. This strategy should be evaluated also for hazelnut, even if it is currently not cost effective due to the high costs of the intensive usage of lures (Weber et al. 2017). Moreover, as a long-term solution, biological control with the natural enemy complex of *H. halys*, native or introduced, could play a role in managing this pest, especially in organic farming systems. In particular, hymenopteran egg parasitoids within the genera *Anastatus* (Eupelmidae), *Ooencyrtus* (Encyrtidae), *Trissolcus*, and *Telenomus* (Scelionidae) are under evaluation for *H. halys* control (Dieckhoff et al. 2017; Haye et al. 2015a; Herlihy et al. 2016; Ogburn et al. 2016).

Author Contribution

LT conceived and designed the research. LB and STM conducted the experiments, analyzed the data, and wrote the manuscript. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

Tables and Figures

Table 1 Localization and characteristics of the five hazel groves surveyed in NW Italy (Piedmont) and W Georgia (Samegrelo) during 2015 and 2016

Hazel grove	Location	Cultivar/ pest management	Size (m^2)	Bordering host plants
1	Italy, Piedmont, Asti (44°54'35.59"N, 8°15'43.26"E; 129 m a.s.l.)	TGdL[a]/ organic	4950	*Cornus sanguinea*
2	Italy, Piedmont, Cossano Belbo (CN) (44°38'27.53"N, 8°11'54.06"E; 460 m a.s.l.)	TGdL/ conventional	5527	*Prunus avium* *Prunus persica* *Pyrus malus*
3	Italy, Piedmont, Magliano Alfieri (AT) (44°45'46.50"N, 8° 3'13.56"E; 205 m a.s.l.)	TGdL/ no insecticide treatments	3200	*Cornus sanguinea*
4	Georgia, Samegrelo, Chitatskari (42°27'18.21"N, 41°52'18.68"E; 60 m a.s.l.)	Tonda di Giffoni/ conventional	71200	*Cornus* sp. *Rubus* sp. *Cryptomeria japonica*
5	Georgia, Samegrelo, Chitatskari (42°26'50.0"N, 41°51'52.41"E; 60 m a.s.l.)	Anakliuri/ conventional	183200	*Cornus* sp. *Rubus* sp. *Cryptomeria japonica*

[a]: Tonda Gentile delle Langhe cultivar

Table 2 Mean percentages (± SE) of kernels damaged by bugs, shriveled, and moldy per cage in the presence of the tested bug species and in the absence of insects (control)

Species	No. of cages[a]	No. of nuts[b]	% Of total damaged kernels[c]	% On total damaged kernels[d]		% Of other defects	
				External	Brown	Shriveled	Moldy/rotten
Halyomorpha halys	54	532	74.82±4.14 **a**	80.53±3.24 **a**	87.69±2.24 **b**	19.60±3.06 **a**	10.22±2.44 **a**
Gonocerus acuteangulatus	53	580	39.07±4.49 **c**	78.02±4.28 **a**	92.59±3.42 **a**	5.08±1.80 **c**	5.50±1.39 **ab**
Nezara viridula	58	579	57.03±4.31 **b**	61.67±4.21 **b**	80.39±3.43 **b**	19.73±3.96 **a**	6.03±1.71 **b**
Palomena prasina	59	568	39.49±3.94 **c**	56.79±5.01 **b**	84.72±3.91 **b**	10.26±2.75 **b**	0.75±0.33 **c**
Control	30	295	0.00±0.00 **d**	-	-	5.91±3.68 **c**	1.56±1.23 **c**
GLM	Wald χ^2		81708.480	72.323	18.988	69.459	38.313
	df		3	3	3	4	4
	P		<0.001	<0.001	<0.001	<0.001	<0.001

In each column, values followed by the same letter are not significantly different (Bonferroni test, $P < 0.05$, under GLM procedure with binomial distribution and logit link)

[a]Total number of cages (excluding cages containing only blank nuts)

[b]Total number of analyzed kernels

[c]% Of total damaged kernels on total number of analyzed kernels.

[d]% Of kernels showing external (versus internal) and brown (versus white) symptoms on total damaged kernels

Table 3 Numbers of cages with females, females plus nymphs (i.e., females laying eggs in the cages), males, and nymphs of the tested bug species: mean numbers (± SE) per female of nymphs developed in the cages (offspring): percentages of the specimens replaced during weekly surveys (% of replacement, mean ± SE per survey) and of the specimens alive throughout the trials, therefore never replaced (% of survival), in 2015

Species	Stage/sex	No.	Offspring (mean per cage)	% Of replacement	% Of survival
Halyomorpha halys	females + nymphs	24	**19.58±1.62 b**	1.04±0.01	95.83
	females	7		14.29±0.06	42.86
	males	29		5.17±0.03	75.86
	total	60		**4.58±0.02 a**	80.00
Gonocerus acuteangulatus	females + nymphs	8	**12.25±3.73 b**	15.63±0.06	50.00
	females	24		26.04±0.06	41.67
	males	26		17.31±0.03	65.38
	total	58		**20.69±0.04 b**	53.45
Nezara viridula	females + nymphs	11	**32.18±5.20 a**	4.55±0.03	81.82
	females	19		10.27±0.03	62.50
	males	29		15.52±0.04	55.17
	total	59		**11.83±0.03 ab**	62.50
Palomena prasina	nymphs	5		12.50±0.13	50.00
	nymphs (emerg. female)	29		6.29±0.04	77.78
	nymphs (emerg. male)	27		13.89±0.04	55.56
	total	61		**10.06±0.03 ab**	65.52
ANOVA	*F*		7.797	4.199	
	df		2; 40	3; 12	
	P		0.001	0.030	

In each column, values in bold followed by the same letter are not significantly different (Tukey´s test, $P < 0.05$)

Table 4 Mean numbers (± SE) of hazel bugs total collected per plant and per date and mean percentages (± SE) of damaged kernels per plant (n = 300) in each grove, on the borders, and in the center across all three hazel groves surveyed in NW Italy (Piedmont) during 2015 and 2016

Grove/ position	Mean n. of bugs per plant per date (% of *H. halys*)		GLM			Mean % of damaged kernels per plant		GLM		
	2015	2016	Wald χ^2	*df*	*P*	2015	2016	Wald χ^2	*df*	*P*
Grove										
1	2.77±0.96	1.04±0.23 (5.33%)	37.596	1	<0.001	19.42±2.76	19.44±2.55	0.002	1	0.966
2	0.70±0.24	0.47±0.11	2.011	1	0.156	7.82±1.13	16.47±2.60	242.383	1	<0.001
3	0.97±0.26	4.53±0.98	58.702	1	<0.001	13.98±1.18	14.58±1.58	0.664	1	0.415
Position										
Border	1.78±0.43	2.03±0.36				6.51±0.74	5.66±0.61			
Centre	0.28±0.14	0.47±0.11				2.60±0.30	3.07±0.58			
GLM										
Wald χ^2	16.581	54.411				368.105	314.177			
df	1	1				1	1			
P	<0.001	<0.001				<0.001	<0.001			

GLM procedure was performed with Poisson distribution and log link for number of bugs, with binomial distribution and logit link for percentage of damaged kernels

Table 5 Mean numbers (± SE) of hazel bugs total collected per plant and per date and percentages (± SE) of damaged kernels by bugs per plant, in each grove, and overall in the different groups of plants in the two hazel groves surveyed in W Georgia (Samegrelo) during 2015 and 2016

Grove/	No. bugs per plant per date (% of *H. halys*)		GLM			% Of damaged kernels		GLM		
Position[a]	2015	2016	Wald χ^2	*df*	*P*	2015	2016	Wald χ^2	*df*	*P*
Grove										
4	0.46±0.16 (68.42%)	1.44±0.38 (89.27%)	11.963	1	<0.001	1.43±0.17	26.63±2.36	1301.845	1	<0.001
5	0.46±0.19 (65.38%)	4.22±2.10 (82.53%)	50.578	1	0.001	4.25±0.51	51.31±2.84	3338.852	1	<0.001
Position										
5 m	0.89±0.23	6.50±3.06 a				3.58±0.77 a	55.78±3.49 a			
100 m	0.83±0.23	1.63±0.59 b				2.39±0.30 b	33.28±4.10 b			
200 m	0.00±0.00	0.38±0.15 c				3.00±0.82 ab	27.85±1.71 c			
GLM										
Wald χ^2	1.445	117.020				17.070	972.285			
df	1	2				2	2			
P	0.229	<0.001				<0.001	<0.001			

In each column, values per position followed by the same letter are not significantly different (Bonferroni test, $P < 0.05$, under GLM procedure).

GLM procedure was performed with Poisson distribution and log link for number of bugs, with binomial distribution and logit link for percentage of damaged kernels

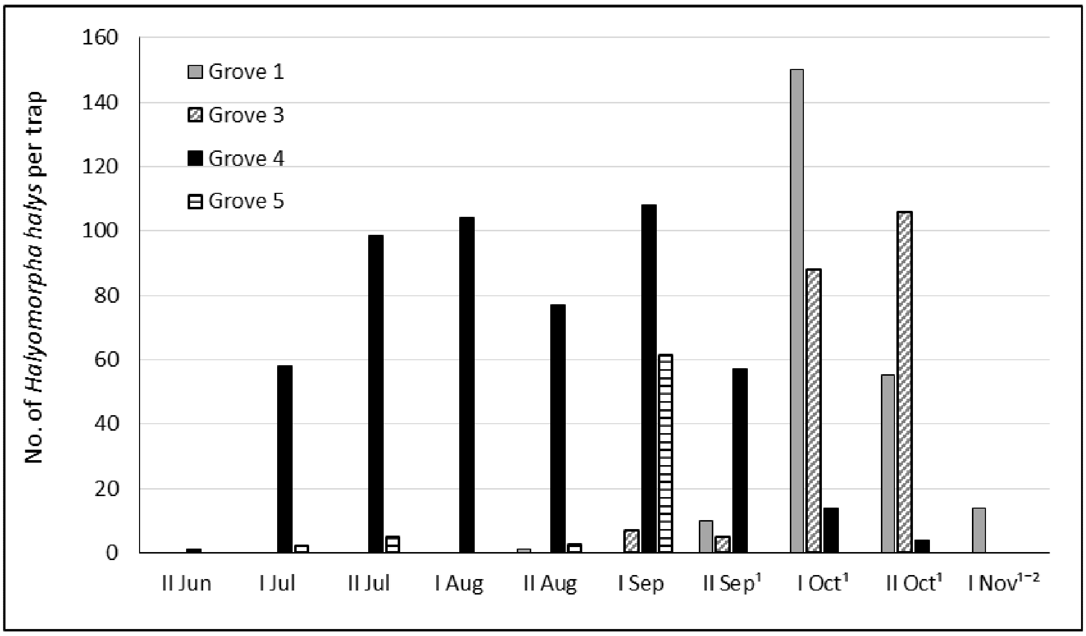

Fig. 1 Numbers of adults of *Halyomorpha halys* captured per pheromone trap in the hazel groves 1 and 3 in NW Italy (Piedmont) and 4 and 5 in W Georgia (Samegrelo) during 2016. In the x-axis, the Roman numerals I and II referred to the first and the second half of the month, respectively. [1]Missing data for grove 5; [2]missing data for grove 4

References

Acebes-Doria AL, Leskey TC, Bergh JC (2016) Host plant effects on *Halyomorpha halys* (Hemiptera: Pentatomidae) nymphal development and survivorship. Environ Enomol 45(3):663-670

AliNiazee MT (1998) Ecology and management of hazelnut pests. Annu Rev Entomol 43(1):395-419

Bergh JC, Morrison WR III, Joseph SV, Leskey TC (2017) Characterizing spring emergence of adult *Halyomorpha halys* using experimental overwintering shelters and commercial pheromone traps. Entomol Exp Appl 162:336–345

Blaauw BR, Polk D, Nielsen AL (2015) IPM-CPR for peaches: incorporating behaviorally-based methods to manage *Halyomorpha halys* and key pests in peach. Pest Manag Sci 71(11):1513-1522

Boselli FB (1932) Studio biologico degli Emitteri che attaccano le nocciuole in Sicilia. Bollettino del Laboratorio di Zoologia Generale e Agraria di Portici 26:1–309

Dieckhoff C, Tatman KM, Hoelmer KA (2017) Natural biological control of *Halyomorpha halys* by native egg parasitoids: a multi-year survey in northern Delaware. J Pest Sci Special Issue: The brown marmorated stink bug *Halyomorpha halys* an emerging pest of global concern. J Pest Sci 90(4):1143-1158

Erper İ, Saruhan İ, Akca İ, Aksoy HM, Tuncer C (2016) Evaluation of some entomopathogenic fungi for controlling the green shield bug, *Palomena prasina* L. (Heteroptera: Pentatomidae). Egypt J Biol Pest Co 26(3):573

FAOSTAT database: http://www.fao.org/faostat/en/#data/QC. Accessed 20 Jan 2017.

Gapon DA (2016) First records of the brown marmorated stink bug *Halyomorpha halys* (Stål, 1855) (Heteroptera, Pentatomidae) in Russia, Abkhazia, and Georgia. Entomol Rev 96:1086–1088

Guidone L, Valentini N, Rolle L, Me G, Tavella L (2007) Early nut development as a resistance factor to the attacks of *Curculio nucum* (Coleoptera: Curculionidae). Ann Appl Biol 150(3):323-329

Haye T, Fischer S, Zhang J, Gariepy T (2015a) Can native egg parasitoids adopt the invasive brown marmorated stink bug, *Halyomorpha halys* (Heteroptera: Pentatomidae), in Europe? J Pest Sci 88(4):693-705

Haye T, Gariepy T, Hoelmer K, Rossi JP, Streito JC, Tassus X, Desneux N (2015b) Range expansion of the invasive brown marmorated stinkbug, *Halyomorpha halys*: an increasing threat to field, fruit and vegetable crops worldwide. J Pest Sci 88(4):665-673

Hedstrom CS, Shearer PW, Miller JC, Walton VM (2014) The effects of kernel feeding by *Halyomorpha halys* (Hemiptera: Pentatomidae) on commercial hazelnuts. J Econ Entomol 107(5):1858-1865

Herlihy MV, Talamas EJ, Weber DC (2016) Attack and success of native and exotic parasitoids on eggs of *Halyomorpha halys* in three Maryland habitats. PLoS ONE 11(3):e0150275. https://doi.org/10.1371/journal.pone.0150275

Kuhar TP, Kamminga K (2017) Review of the chemical control research on *Halyomorpha halys* in the USA. J Pest Sci Special Issue: The brown marmorated stink bug *Halyomorpha halys* an emerging pest of global concern. J Pest Sci 90(4):1021-1031

Leskey TC, Short BD, Butler BR, Wright SE (2012) Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in mid-Atlantic tree fruit orchards in the United States: case studies of commercial management. Psyche 2012:1-14. https://doi.org/10.1155/2012/535062

Maistrello L, Dioli P, Bariselli M (2013) Trovata una cimice esotica dannosa per i frutteti Agricoltura, 67-68 http://agricoltura.regione.emilia-romagna.it/fitosanitario/doc/pubblicazioni/articoli/trovata-una-cimice-esotica-dannosa-per-i-frutteti/at_download/file/Agricoltura_6_2013-067-068.pdf. Accessed 25 Jan 2017

Mathews CR, Blaauw B, Dively G, Kotcon J, Moore J, Ogburn E, Pfeiffer DG, Trope T, Walgenbach JF, Welty C, Zinati G, Nielsen AL (2017) Evaluating a polyculture trap crop for organic management of *Halyomorpha halys* and native stink bugs in pepper. J Pest Sci Special Issue: The brown marmorated stink bug *Halyomorpha halys* an emerging pest of global concern. J Pest Sci 90(4):1245-1255

Memoli A, Albanese D, Esti M, Lombardelli C, Crescitelli A, Di Matteo M, Benucci I (2017) Effect of bug damage and mold contamination on fatty acids and sterols of hazelnut oil. Eur Foor Res Technol 243(4):651-658

Mirotadze N, Gogitidze V, Mikadze N, Goginava L, Mirotadze M (2009) Agro-ecological zones of hazelnut in Georgia. Acta Hortic 845:291-294

Moraglio ST, Ingegno BL Tavella L (2014) Studies on semiochemicals produced by *Gonocerus acteangulatus* for their use as control methods in hazelnut orchards. Acta Hortic 1052:281-287

Morrison III WR, Lee DH, Short BD, Khrimian A, Leskey TC (2016) Establishing the behavioral basis for an attract-and-kill strategy to manage the invasive *Halyomorpha halys* in apple orchards. J Pest Sci 89(1):81-96

Nielsen AL, Dively G, Pote JM, Zinati G, Mathews C (2016) Identifying a potential trap crop for a novel insect pest, *Halyomorpha halys* (Hemiptera: Pentatomidae), in organic farms. Environ Enomol 45(2):472-478

Ogburn EC, Bessin R, Dieckhoff C, Dobson R, Grieshop M, Hoelmer KA, et al. (2016) Natural enemy impact on eggs of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in organic agroecosystems: a regional assessment. Biol Control 101:39-51

Pansa MG, Asteggiano L, Costamagna C, Vittone G, Tavella L (2013) Primo ritrovamento di *Halyomorpha halys* nei pescheti piemontesi. Inftore Agrario 69(37):60-61

Pansa MG, Pizzinat A, Bardella S, Vittone L, Tavella L (2015) *Halyomorpha halys* in Piemonte, prime risposte dal monitoraggio. Inftore Agrario 71(21):48-49

Rancati M, Pansa MG, Ghiglione M, Tavella L (2017) Danni da cimice asiatica su mais di secondo raccolto. Inftore Agrario 73(14):1-3

Rice KB, Bergh CJ, Bergmann EJ, Biddinger DJ, Dieckhoff C, Dively G, Fraser H, Gariepy T, Hamilton G, Haye T Herbert A, Hoelmer K, Hooks CR (2014) Biology, ecology, and management of brown marmorated stink bug (Hemiptera: Pentatomidae). J Integr Pest Manag 5(4):A1-A13

Romero A, Tous J, Martí E (2009) White spots in hazelnut kernel: symptoms, causes and quality loss. Acta Hortic 845:607-612

Schaefer CW, Mitchell PL (1983) Food plants of the Coreoidea (Hemiptera: Heteroptera). Ann Entomol Soc Am 76:591–615

Soergel DC, Ostiguy N, Fleischer SJ, Troyer RR, Rajotte EG, Krawczyk G (2015) Sunflower as a potential trap crop of *Halyomorpha halys* (Hemiptera: Pentatomidae) in pepper fields. Environ Entomol 44(6):1581-1589

Sonnati C, Molinari F, Ughini V (2009) Seven years of observation of the presence of different plant bug species in the hazelnut orchards of cultivar 'Tonda Gentile delle Langhe' in Piedmont. Acta Hortic 845:543-548

Tavella L, Sonnati C, Arzone A, (2001a) Sampling of Coreidae and Pentatomidae (Heteroptera) in hazelnut orchards in Piemonte, northwestern Italy. Informatore Fitopatologico 51(3): 55–59

Tavella L, Arzone A, Miaja ML, Sonnati C (2001b) Influence of bug (Heteroptera, Coreidae and Pentatomidae) feeding activity on hazelnut in northwestern Italy. Acta Hortic 556: 461-468

Tavella L, Migliardi M, Sonnati C, Miaja ML (2003) Effects of the trophic activity of bugs (Heteroptera Coreidae and Pentatomidae) on hazelnuts referring to the feeding period. Informatore Fitopatologico 53(11): 47–51

Tuncer C, Saruhan İ, Akça İ (2005) The insect pest problem affecting hazelnut kernel quality in Turkey. Acta Hortic 686: 367-376

Tuncer C, Saruhan İ, Akça İ (2014) Seasonal occurrence and species composition of true bugs in hazelnut orchards. Acta Hortic 1052:263-268

Vaccino P, Guidone L, Corbellini M, Tavella L (2008) Detection of damage due to bug feeding on hazelnut and wheat by biochemical techniques. Bull Insectology 61(1):189-190

Weber DC, Morrison III WR, Khrimian A, Rice KB, Leskey TC, Rodriguez-Saona C, Nielsen AL, Blaauw BR (2017) Chemical ecology of *Halyomorpha halys*: discoveries and applications. J Pest Sci Special Issue: The brown marmorated stink bug *Halyomorpha halys* an emerging pest of global concern. J Pest Sci 90(4):989-1008

Werner DJ (2007) Die Verbreitung der Braunen Randwanze *Gonocerus acuteangulatus* (Goeze, 1778) (Heteroptera: Coreidae) in Deutschland mit Angaben zu ihrer Biologie. Mainzer Naturwissenschaftliches Archiv/Beiheft 31:153-180

Zobel ES, Hooks CRR, Dively GP (2016) Seasonal abundance, host suitability, and feeding injury of the brown marmorated stink bug, *Halyomorpha halys* (Heteroptera: Pentatomidae), in selected vegetables. J Econ Entomol 109(3):1289-1302