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Short Paper

Starting an invasion: A five-year monitoring program of *Halyomorpha halys* (Hemiptera: Pentatomidae) in South Tyrol (Northern Italy)

Fünf Jahre Monitoring von *Halyomorpha halys* (Hemiptera: Pentatomidae) in Südtirol (Italien)

Storia d'invasione di *Halyomorpha halys* (Hemiptera: Pentatomidae) in Alto Adige (Italia): Cinque anni di monitoraggio

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ABSTRACT

Monitoring is a fundamental step when non-native species are invading new areas. The brown marmorated stink bug *Halyomorpha halys* (Stål) has by now been introduced into several countries worldwide. Its highly polyphagous behavior, paired with a relatively high reproduction rate under favorable conditions, makes it an important pest of several agricultural crops. In South Tyrol (Northern Italy), one of the largest contiguous apple-growing regions in Europe, first adults had been reported in March 2016. Active monitoring techniques combined by a citizen science approach made it possible to follow up the spread and settlement of stable populations of *H. halys* in South Tyrol. Since its first detection, *H. halys* showed a rapid expansion of colonized area and an increase in population densities from year to year. Established populations coincide mostly with the main apple growing area, namely the Etsch Valley from Meran to Salurn, mainly occupying lower altitudes between 200 and 500 m a.s.l. In apple orchards, *H. halys* showed generally a continuous presence throughout the growing season from April to October, with population peaks in the late season. On the other hand, populations dynamics and densities of adults and nymphs differ between years and surveyed sites. The application of pheromone-baited traps is a good tool for an area-wide monitoring approach in order to get information on its spreading and to draw a general picture of the population dynamics at a larger scale. On the other hand, an area-wide approach has to be interpreted cautiously, as real population densities might be underestimated and do not depict the real situation for singular orchards.

KEYWORDS
brown marmorated stink bug, pheromone traps, citizen science, apple orchard, seasonality

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INTRODUCTION

In recent years, the invasive species *Halyomorpha halys* (Stål) (Pentatomidae: Hemiptera) has become a serious nuisance and agriculture pest on a global scale [1][2][3][4][5][6][7]. Native to subtropical and temperate areas in eastern Asia [4][8][9], first observations outside its native range were reported from Pennsylvania, USA in the late 1990s [9].

H. halys features several characteristics, enabling it to invade and rapid colonize new areas: Adults show strong active dispersal abilities with the capacity for long distant flight (e.g., > 5 km in laboratory trials) [10][11]. Moreover, diapausing adults tend to aggregate and overwinter within protected habitats, such as human-made structures, which facilitates its passive dispersal by human-mediated transportation to new areas [4][9][12][13]. *H. halys* is highly polyphagous, and the over 200 reported host plants on which it feeds and reproduces, include wild, as well as ornamental and cultivated plants [3][4][9][14][15][16][17][18]. Its long seasonal activity and its high reproduction rate under suitable environmental conditions [19][20][21][22], together with the lack of efficient natural enemies able to suppress the populations in newly invaded areas, facilitated its establishment in several countries [3][6][23].

In Europe, first individuals of the species have been detected in Switzerland and Liechtenstein in 2004 [20][24]. Subsequently, the pest invaded further European countries, including Germany, Greece, and Hungary [25][26][27], matching the predicted distribution range of *H. halys* by Zhu et al. [28] and Kriticos et al. [29] through niche modelling. The first presence of *H. halys* in Italy dates back to 2007 in Liguria [7]. In 2012, the species was detected in the surrounding of Modena (Emilia-Romagna) and rapidly established in several regions of Northern Italy [23][30][31][32]. In South Tyrol (Northern Italy), first individuals of *H. halys* were detected occasionally in March 2016, during the inspection of a shipment coming from Bergamo [33]. In the same month, first individuals in open field were discovered close to the locality in Pfatten (Unterland). The mountainous region of South Tyrol is one of the largest contiguous apple growing regions in Europe: the area extends over about 18,500 ha and harvest volumes amount to around one million tons of apples per year [34]. Hence, the arrival of

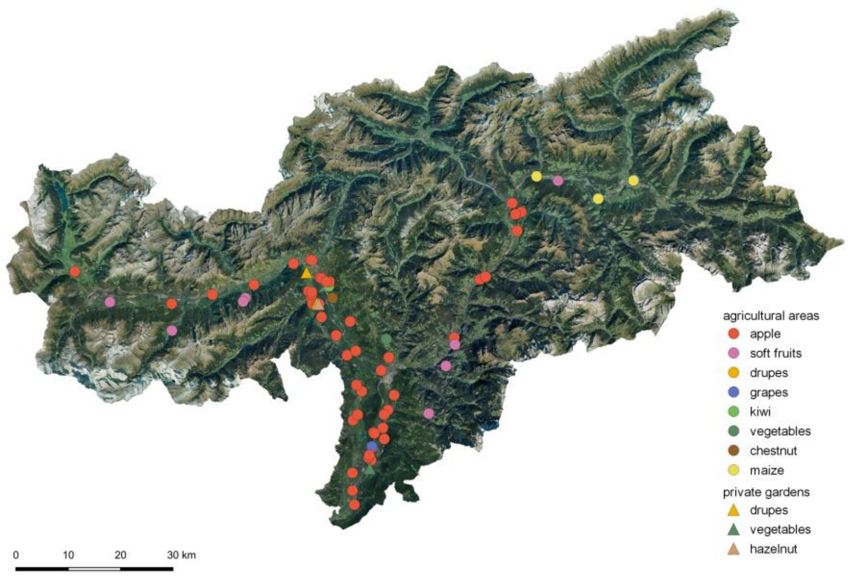

Fig. 1: Active field monitoring sites surveyed from 2016 to 2020.

H. halys, a major pest in apple production [1][3][14][35], represented a potential threat to the local agriculture.

In April 2016, a monitoring program at local scale was launched by the local Plant Protection Service of the Autonomous Province of Bolzano, the Extension Service for Fruit- and Winegrowing, the Extension Service for Mountain Agriculture, and the Laimburg Research Centre with the objectives to:

- gain information on the current distribution range of the newly arrived invasive species,
- monitor its range expansion on the territory at a local scale, and
- understand its population dynamics, with special emphasize on its seasonality in the agricultural context.

Data were obtained using commercially available pheromone-baited traps and observations made by citizens.

MATERIAL AND METHODS

ACTIVE MONITORING

Active field monitoring started in 2016, immediately after the first detection of *H. halys* in the region and was performed in up to 47 selected sample sites per year. In total, data were collected from 87 sample sites during the whole period of monitoring action from 2016 to 2021, whereas 27% of the sites were surveyed at least for four consecutive years. Monitoring sites were situated between 209 and 1,355 m a.s.l. and included various agricultural areas (94%), mainly apple orchards (69%), and a few private gardens in more urbanized areas (6%) (see Fig. 1, Sup. Tab. 1). Sites were selected based on the proximity to potential host plants, hibernation sites, and relevant crops. The program comprised

- the implementation of commercially available traps baited with the male-produced aggregation pheromone of *H. halys* combined with the pheromone of *Plautia stali* (Scott) (reviewed in [36]) and the weekly control and documentation of directly captured nymphal stages and adults from April to the end of October,

followed by

- a visual inspection for five minutes in the 10 m perimeter around the installed trap to assess presence of eggmasses, nymphs, and/or adults.

The trap types used for monitoring included the small hanging pyramid (Rescue®), the sticky panel trap (Trécé Inc.), both installed in the tree canopies, and the ground deployed dead-inn pyramid type (AgBio Inc.), baited with the available standard lures commercially produced by Rescue® or Trécé Inc. (Sup. Tab. 1). In total, the Rescue® trap type was used in 80% of the selected monitored sites, whereas the sticky panels were installed in 16% of the surveyed sites. Since 2019, we used exclusively the Trécé pheromone lure to bait the traps, given the higher attraction of *H. halys* reported in literature

[37]. Results of the active field monitoring are reported as 1) mean number of both adults and nymphs for each month per year and 2) overall mean number of individuals per monitoring site for each month and year.

In order to get more detailed information regarding the seasonal activity of adults and nymphs during the growing seasons in apple orchards, we chose field monitoring data from selected orchards situated in the Etsch Valley. Data of 24 (2017), 22 (2018), 19 (2019) and 11 (2020) orchards situated between 212 and 497 m a.s.l. were used to calculate the mean number of observed adults and nymphs during the calendar weeks (CW) 17 to 42 (end of April until mid to end October).

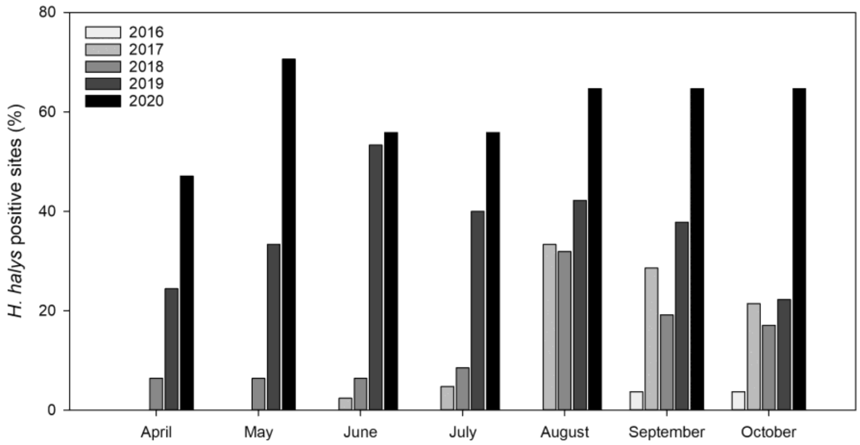

Fig. 2: Positive records of *H. halys* nymphs and adults (indicated as % of all monitoring sites per month) by active field monitoring from 2016 to 2020.

CITIZEN SCIENCE APPROACH

Citizen science surveys were found to be a useful tool to track the spread and establishment of invasive species, especially for *H. halys* [38][39]. From 2016 to 2019, South Tyrolean citizens were asked by local media and internet platforms to report sightings of the invasive species to the Laimburg Research Centre by email. The information should include date of observation and sighting location to support monitoring data. To verify the reports, citizens were asked to provide a photo of the specimen to validate its species identity. Furthermore, reports and sightings made by trained technicians and researchers independently from standard monitoring actions were documented and included in this approach.

DATA ANALYSIS

The data obtained by field monitoring and citizen science were visualized using *QGIS* (version 3.4.13), based on the coordinates of the respective sites, and *SigmaPlot* (version13.0).

RESULTS

ACTIVE MONITORING

Field monitoring using commercially available pheromone-baited traps started in 2016. In this first year of monitoring action, the presence of *H. halys* was confirmed in only two out of 27 sampling sites (7.41%), and the records of the species were restricted to the late season (Fig. 2, Fig. 3). In 2017, the number of sample sites with positive detection of *H. halys* increased up to 20 out of 42 (48%). Incidences were based mainly on single individuals, except for two sites, where a high number of *H. halys* (> 100 individuals) was observed throughout the season (mean = 20.62 individuals per site,). In 2018, positive detections were observed in 19 out of 47surveyed sites (41%, Fig. 2): Population densities substantially increased, with an overall mean of 66.62 individuals per site. Specimens were detected during the whole growing season, even though captures in August and September were highest with a mean of 25.72 and 30.11 individuals per trap, respectively (Fig. 3). In 2019, 29 out of 45 monitoring sites (64%) revealed positive detections of *H. halys* and a further spread of the species towards more eastern sites was documented (Fig. 2, annex Fig. 4). Moreover, in 2019, an increase in the population density was recorded, with an annual mean of 196.33 individuals per trap. Population records peaked in August and September, with means of 46.02 and 69.69 individuals per trap, respectively (Fig. 3). Compared to the previous year, in 2019, the population density slightly decreased, with an annual mean of 153.03 individuals per trap. However, the number of monitoring sites with positive output increased, with the occurrence of *H. halys* in 26 out of 34 monitoring sites (Fig. 2). Similar to previous seasons, the highest incidence of captures was observed in August and September, with means of 35.91 and 62.59 individuals per trap, respectively (Fig. 3).

Generally, elevated numbers *of H. halys* were mainly recorded at monitoring sites situated around 200-400 m a.s.l., i.e., in the bottoms of South Tyrolian valleys (see annex Fig. 5). Since 2019, an increase of *H. halys* on surveyed sites at altitudes between 500 and 600 m a.s.l. was observed. Furthermore, sporadic reports (i.e., 1-30 individuals) were also recorded at monitoring sites located at higher altitudes.

CITIZEN SCIENCE APPROACH

The implementation of a Citizen Science approach helped to evaluate the range expansion of *H. halys* at larger regional scale (see annex Fig. 6): Observations in 2016 occurred only sporadically, with 28 singular reports from 12 municipalities. In 2017, the number of reports increased to more than 100 independent reports from 30 localities and even more in 2018, when the total number of observations was the highest, with 361 singular reports from 45 different municipalities. In 2019, the number of independent reports decreased to 194 singular documentations, though the area of observation remained unchanged. The great majority of sightings arrived from the densely populated area between the cities Meran and Bozen in the Etsch Valley. The total number of reports made from citizens during this 4-year period was 696. Sightings were reported all year round, though more frequently in the late season. Most reports were recorded from the inside or outside of edifices with a percentage of 48.13%, followed by agricultural areas (22.70%), public green areas (13.94%), and private gardens (12.07%). Relatively low numbers of reports were communicated for forest areas or other sites, as well as goods, e.g., cars and packaging material. Observations were made mainly in locations at the bottoms of the valleys between 200 to 400 m a.s.l. (see annex Fig. 5). In 2019, reports frequently arrived from localities up to 600 m a.s.l. Sightings from higher altitudes were less common, but an occasional presence of *H. halys* at sites over 1000 m a.s.l. was confirmed by this approach, too.

SEASONALITY OF *HALYOMORPHA HALYS IN THE* AGRICULTURAL CONTEXT OF THE ETSCH VALLEY

A subset of up to 24 monitoring sites in apple orchards located in the Etsch Valley were used to compare the seasonal performance of *H. halys* from 2017 to 2020 (Fig. 7). In 2017, first single adults were documented at the end of June (CW 26), and regularly from the middle of July onwards (CW 29). Number of adults remained relatively low during the whole vegetation period, with density peaks in August, reaching weekly means of 1.04-1.20 adults per trap (CW 32 and 35). The first nymphs were recorded at the beginning of June (CW 23), with a slight increase from the middle of July (CW 29) onwards, and a further small peak at the beginning of September (CW 36). At the end of the season, an incipient aggregation of adults was observed, and the number of adult captures rose slightly to a weekly mean of 1.76 adults per trap.

In 2018, first adults were already present in the orchards at the end of April (CW 17). In the following weeks, captures comprised only single individuals, while a slight increase in numbers at the end of July (CW 30-31) was reported. After a short period, with relatively small numbers of trap captures, they increased slightly at the beginning of September until mid of October (CW 36-41), with a peak at the end of September and a mean of weekly captures of 2.64 individuals per trap. The total number of reported adults has been higher than in 2017. Progenies emerged at the beginning of June (CW 23); a first small peak at the beginning of August was observed, followed by a second one in the mid of September (CW 37-38), with weekly means of 11.18 and 12.00 nymphs per trap, respectively.

In 2019, the total number of captured individuals in the surveyed apple orchards was higher compared to previous years. Adults were documented during the whole vegetation period, from late April to October 2019. As for 2018, first adults were already present in surveyed apple orchards at the end of April (CW 17), followed by a slight decline and a new rise at the end of May (CW 22). A continuous presence of adults was documented, whereas a small decrease at the end of August (CW 35) was noted. At the end of September an increase of specimens was documented, with a peak in CW 40 (weekly mean of 18.05 adults per trap). First progenies emerged from the middle of June onwards (CW 24) and peaked at the beginning-middle of August (CW 31-33), followed by a continuous decrease until the end of the season.

The vegetation period 2020 started with relatively high numbers of adults till the end of May (CW 21), followed by decreasing numbers until mid of August (CW 33). Captures remained high towards the end of the season and peaked at the beginning of October (CW 41). As in previous years, the first nymphs were captured at the beginning of June (CW 23). A first peak occurred at the end of June (CW 26-27). From CW 33 onwards, a steady increase in the number of captured nymphs was observed, peaking in the middle of September (CW 38), with a calculated weekly mean of 29.18 nymphs per trap.

DISCUSSION

In recent decades, the introduction of non-native pest species to new areas has increased globally [40][41]. A fundamental and first step is the surveillance of spreading and establishment of those invasive organisms in a certain area [42][43]. An area-wide approach, based on active techniques (standardized monitoring) and the implementation of a citizen science program started immediately after the first detection of the invasive phytophagous pest species *Halyomorpha halys* in South Tyrol. Its purpose was

- to survey the spreading of the invasive pest with special emphasis on the apple growing region and
- to understand its population dynamics to gain useful information for the development of a pest management program approach.

In 2016, documented reports and trap captures were only sporadic at various sites (Fig. 2, annex Fig. 4, annex Fig. 6). Despite an increase in individuals detected from 2016 to 2017, the documented numbers in 2017 were still low compared to population densities recorded in neighbouring northern Italian regions [32][44][45], but similar to the situation in the province Trentino [46] In both years, no exceptional bug-feeding injuries on apple or other crops were reported in South Tyrol [47]. Nevertheless, *H. halys* experienced a relatively fast range expansion: From 2018 onwards, we observed a further increase in population densities (Fig. 3) and first incidences of bug-feeding damaged apples attributed to *H. halys* presence were reported in those years [47][48][49]. The rapid spread and increase of population

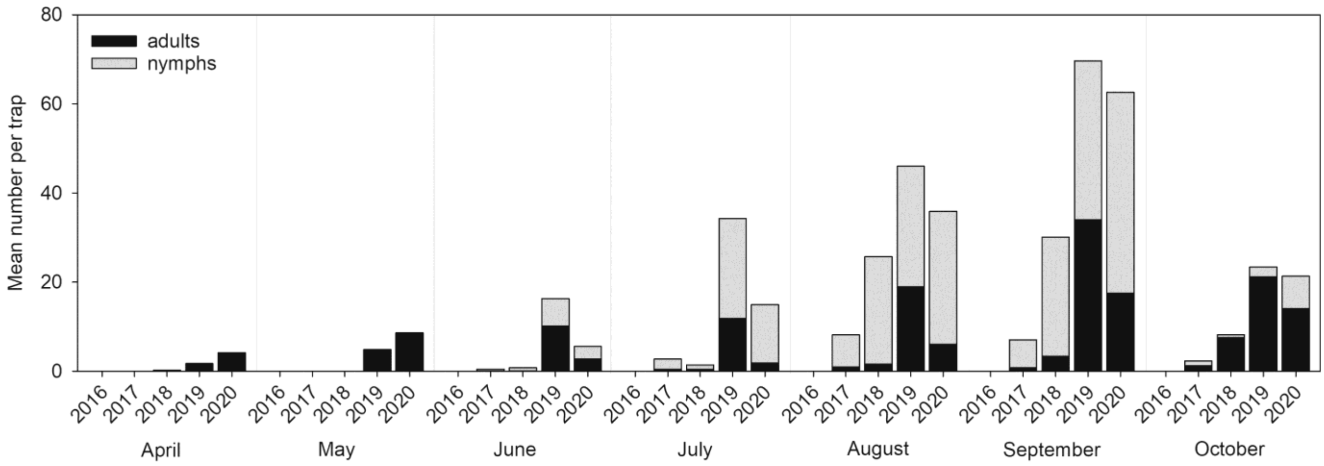

Fig. 3: Calculated mean number of recorded adults and nymphs of *H. halys* during active field monitoring from 2016 to 2020.

densities in South Tyrol are the results of the natural expansion of primary introduced individuals and their establishment, as well as ongoing secondary introduction of individuals from nearby regions and other countries, as demonstrated by Schuler et al. [50], who found a high haplotype diversity in surveyed population of *H. halys* across the region. Furthermore, the study recorded an increasing diversity of haplotypes from 2016 to 2019.

So far, established populations coincide mostly with the main apple growing area, namely the Etsch Valley from Meran to Salurn (see annex Fig. 6). Indeed, first economically important damages on apple were reported from orchards located in that zone [48]. The main distribution area of *H. halys* covers mainly the climatic zone 1, characterized by relatively warm temperatures, with annual means ranging from 8-12 °C [51][52]. First investigations indicated, that in those zones, temperatures are favourable for the development of two full generations per year (Fischnaller, pers. communication), supporting the observation of a rapid increase in population densities in a relatively small-time frame. Our observations showed that, in South Tyrol, the species is currently occupying lower altitudes, as records were mainly limited from 200 to 600 m a.s.l. (see annex Fig. 5). However, over the years, reports from higher altitudes became more frequent. Since 2019, we observed a further spread towards more eastern and western areas, namely the Eisack Valley and lower Vinschgau (see annex Fig. 4, Fig. 6). Considering possible climate change scenarios, as shown by Stoeckli et al. [53] and Streito et al. [54], a further range expansion in higher altitudes may occur in the nearby future.

A major aim of the area-wide monitoring program was to gain information on the performance and annual population dynamics for pest management purposes. The evaluation of mean numbers of individuals recorded during active monitoring action in selected apple orchards located in the Etsch Valley showed a clear increase in abundances from year to year. While in 2017 the activity of *H. halys* was restricted mainly to the late season, in 2019, first individuals were detected already in the early season (CW 17) and were constantly present in the apple orchard during the whole vegetation period (Fig. 7). Favourable weather conditions, with warm summer months and mild temperatures in autumn 2018 [55], may have promoted a further increase in population densities compared to 2017. Indeed, in 2019, population densities increased and caused, for the first time, an elevated economic loss in apple production due to feeding injuries.

During a visual inspection of more than 1 000 randomly chosen apple orchards across the whole region in South Tyrol, 11% exhibited yield losses over 10% attributable to bug feeding damage [48]. In 2020, the observed and documented population densities decreased compared to the previous year: The annual calculated mean number of adults decreased from 119 in 2019 to 60 individuals per monitoring site in 2020, whereby the nymphal captures were only slightly lower (196 nymphs per trap) than in 2019 (Fig. 3). Interestingly, the number of adults in the early season were higher in 2020 than in 2019 but declined rapidly from June onwards. Furthermore, the documented yield losses in apple production attributable to bug feeding were much lower than in 2019: harvest losses exceeding a 10%

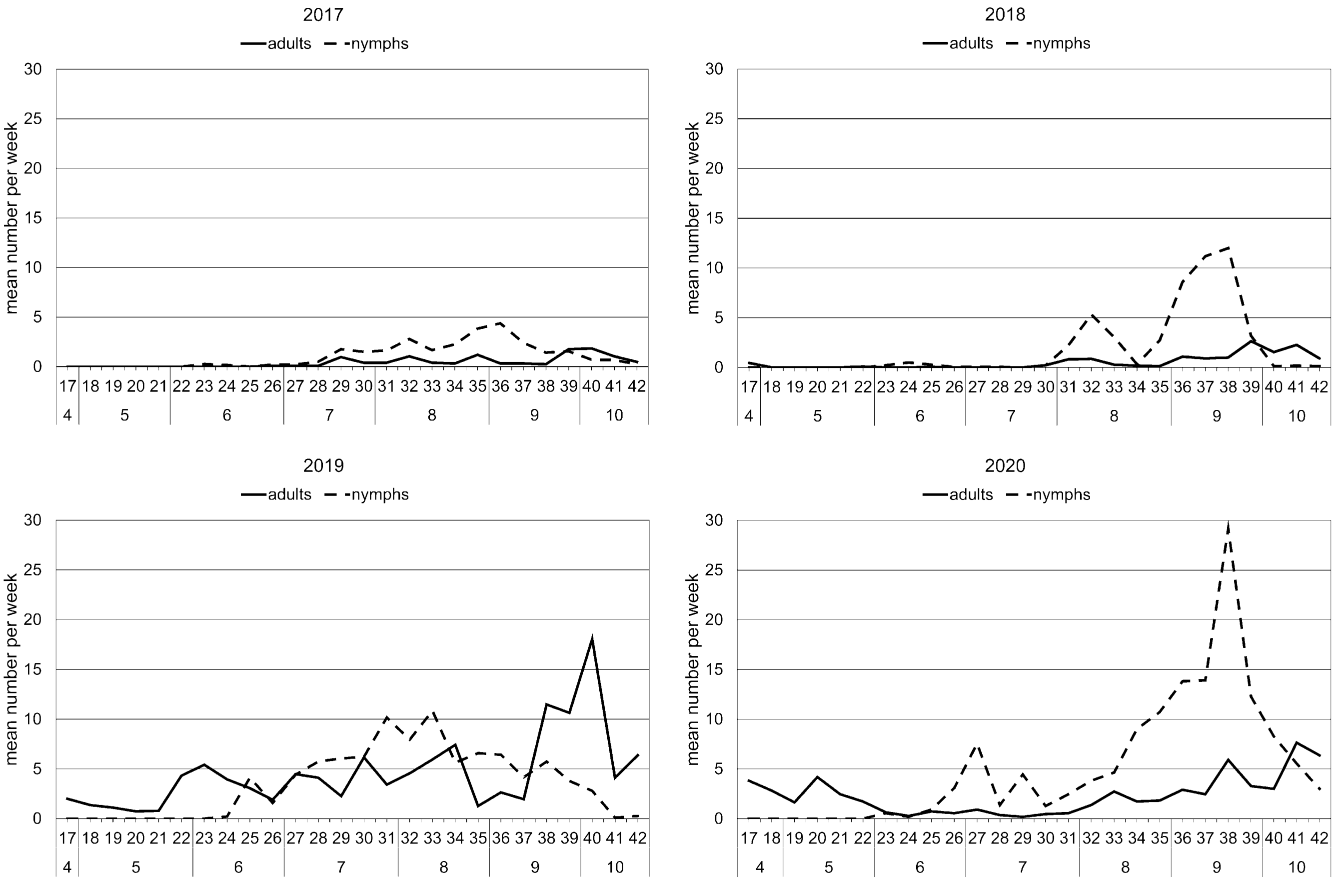

Fig. 7: Population dynamics of *H. halys* nymphs and adults in apple orchards during the growing seasons 2017- 2020. Specified are the calculated mean number of adults and nymphs per calendar week (17 - 42) and month (4 - 10).

threshold were registered in 1% of orchards investigated [49]. Whether the decrease of population densities or other factors positively affected bug feeding damages cannot be addressed properly. The reasons for the decline of absolute numbers of *H. halys* recorded in 2020 by active field monitoring can have various causes: established population could be influenced negatively by abiotic factors during overwintering, the quiescence phase, or during reproduction [56][57][58]. Moreover, biotic factors such as higher predation or parasitism rates may have already impacted the populations densities [59][60]. Additionally, the improved plant protection strategy in 2020 may have led to a certain containment of population build up in apple orchards.

Abundances and densities of adults and nymphs differ significantly between years and surveyed sites. Thus, drawing general conclusion on the timing of colonization and population dynamics and subsequent risk of yield loss due to feeding for apple orchards must be done cautiously when using area-wide monitoring data. Several factors are impacting the results: First, the number of insects in the traps does not always correspond to real population densities at the given site (or orchard). This could lead to false interpretation of the actual situation, as the behavioural response of *H. halys* to the lure may get altered by other key-stimuli [61]. Due to its high mobility and its well pronounced polyphagia, *H. halys* utilizes a broad range of food resources, reproduction, and shelter structures [1][16][62]. Furthermore, attractiveness of host plants changes over the season [62]. Thus, colonization and subsequent feeding damages in apple orchards by adults and nymphs maybe impacted by adjacent ecotones such as hedges, natural habitats, and/or urbanized areas too [63]. At certain seasonal points, pheromone- baited traps may compete with other key stimuli, such as the presence of highly attractive host plants in the ecotone, influencing their trapping area, and subsequently altering the output of the monitoring data [37][61][64]. Furthermore, the aggregation pheromones seem to show different capture efficiency for adults throughout the year: The number of captures of adults seems to rise at the end of the season, when the diapause program is activated [36][65]. On the other hand, the effectiveness of pheromone baited traps was also observed to be high for adults emerging from their overwintering sites in spring, even when a dispersal flight might be necessary before

ZUSAMMENFASSUNG

Überwachung und Monitoring sind grundlegende Schritte, sobald nicht heimische Arten in neue Gebiete vordringen. Die aus Asien stammende Marmorierte Baumwanze, *Halyomorpha halys* (Stål), hat sich mittlerweile in mehreren Ländern weltweit verbreitet. Ihr stark polyphages Verhalten bei gleichzeitiger hoher Reproduktionsrate, macht sie zu einem wichtigen Schädling für eine Vielzahl landwirtschaftlich genutzter Kulturen. In Südtirol (Norditalien), einem der größten zusammenhängenden Apfelanbaugebiete Europas, wurde *H. halys* erstmals im März 2016 nachgewiesen. Aktives Monitoring sowie die Umsetzung eines „Citizen Science“-Ansatzes ermöglichten es, die Ausbreitung dieser invasiven Art in Südtirol zu überwachen. Seit dem Erstnachweis zeigte *H. halys* von Jahr zu Jahr eine rasche Ausdehnung und eine Zunahme der Populationsdichte. Das Hauptverbreitungsgebiet liegt bislang in den tieferen bis mittleren Höhenlagen des Etschtals. Seit 2019 ist eine weitere Ausbreitung in westlichere und östlichere Teile Südtirols zu beobachten. In Apfelanlagen zeigte *H. halys* im Allgemeinen eine kontinuierliche Präsenz während der gesamten Vegetationsperiode von April bis Oktober, mit Populationsspitzen in der späten Saison. Die Ergebnisse deuten darauf hin, dass der Einsatz von Pheromonfallen ein gutes Instrument für einen flächendeckenden Ansatz ist, um Informationen über die Ausbreitung zu erhalten, das Hauptverbreitungsgebiet zu lokalisieren und ein allgemeines Bild der Populationsdynamik in größerem Maßstab zu zeichnen. Auf der anderen Seite sollte ein flächendeckender Ansatz mit Vorsicht interpretiert werden, da die tatsächliche Populationsdichte unterschätzt werden kann und damit die reale Situation in einzelnen Kulturflächen nicht korrekt abgebildet wird.

RIASSUNTO

Le azioni di monitoraggio sono un passaggio fondamentale quando specie alloctone stanno invadendo nuove aree. La cimice asiatica, *Halyomorpha halys* (Stål), originario dell'Asia nord-orientale, è ormai introdotto in diversi paesi del mondo. Il suo comportamento altamente polifago, unito a un tasso di riproduzione relativamente alto, lo rende un importante parassita di diverse colture agricole. In Alto Adige (Nord Italia), una delle regioni melicole contigue più grandi d'Europa, a marzo 2016 erano stati segnalati i primi adulti. Tecniche di monitoraggio attivo, nonché l'implementazione di un approccio di “citizen science”, hanno consentito di seguire la diffusione di *H. halys* in Alto Adige. Fin dalla sua prima individuazione, *H. halys* ha mostrato una rapida espansione dell'area colonizzata e un aumento della densità di popolazione di anno in anno. Popolazioni consolidate coincidono per lo più con la principale area melicoltura, ovvero la Valle dell'Adige da Merano a Salorno. Dal 2019 si può osservare un'ulteriore diffusione nella parte occidentale e orientale dell'Alto Adige. Nei meleti *H. halys* ha mostrato generalmente una presenza continua per tutta la stagione vegetativa da aprile a ottobre, con picchi di popolazione nella tarda stagione. I risultati indicano che l'applicazione di trappole con esca a feromoni è un buon strumento per un approccio a livello di area al fine di ottenere informazioni sulla sua diffusione, individuare l'area di distribuzione principale e tracciare un quadro generale della dinamica della popolazione su scala più ampia. D'altra parte, le densità di popolazione potrebbero essere sottovalutate e non rappresentano la situazione reale per i singoli frutteti.

adults start to respond to the lure [18]. This observation could indicate a change of behavioural response triggered by the aggregation pheromone used in the baited traps and which may be related to the insect's physiology in the mating or feeding state, as already known for other insects [66].

First approaches regarding practical indication for IPM purposes, based on critical population densities, had been evaluated by [67] in Washington State: by setting thresholds based on a cumulative number of trapped individuals in apple orchards, insecticide application was reduced by 40%. Nevertheless, such surveys have to be done at a local scale, as the phenological performances of *H. halys* shaped by abiotic factors and, subsequently, population dynamics, driven by landscape features in the agriculture context, are likely to differ. To get a more detailed picture on the seasonality of *H. halys* in South Tyrol, studies targeting the phenological performance at a local scale (abiotic factors) paired with the identification of risk factors (biotic factors), which promote a subsequent invasion and increase of population densities, are important to gain reliable data for practical indications and sustainable management programs.

Since its first detection in South Tyrol, *H. halys* showed a rapid expansion of colonized area and an increase in population densities from year to year, promoted by primary as well as secondary introductions from other regions and the spreading of founder populations in the area [50]. The main distribution area coincides with the Etsch Valley, characterized by intensive agriculture use, a highly urbanized area, and important traffic routes. Our findings indicate that the application of pheromone baited traps is a good tool for an area-wide approach in order to get information on its spreading, to pinpoint the main distribution area and to draw a general picture of the population dynamics at a larger scale. On the other side, an area wide approach should be interpreted cautiously, as real population densities might be underestimated and do not depict the real situation for singular orchards. Due to the complex behaviour of *H. halys,* promoted by microclimate and surrounding landscape factors [4][22][63], inspection and monitoring had to be done at a local scale to evaluate the actual situation regarding (1) timing of colonization and (2) upbuilding of population in the orchards to take appropriate actions to prevent yield loss.

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ANNEX: FIGURES

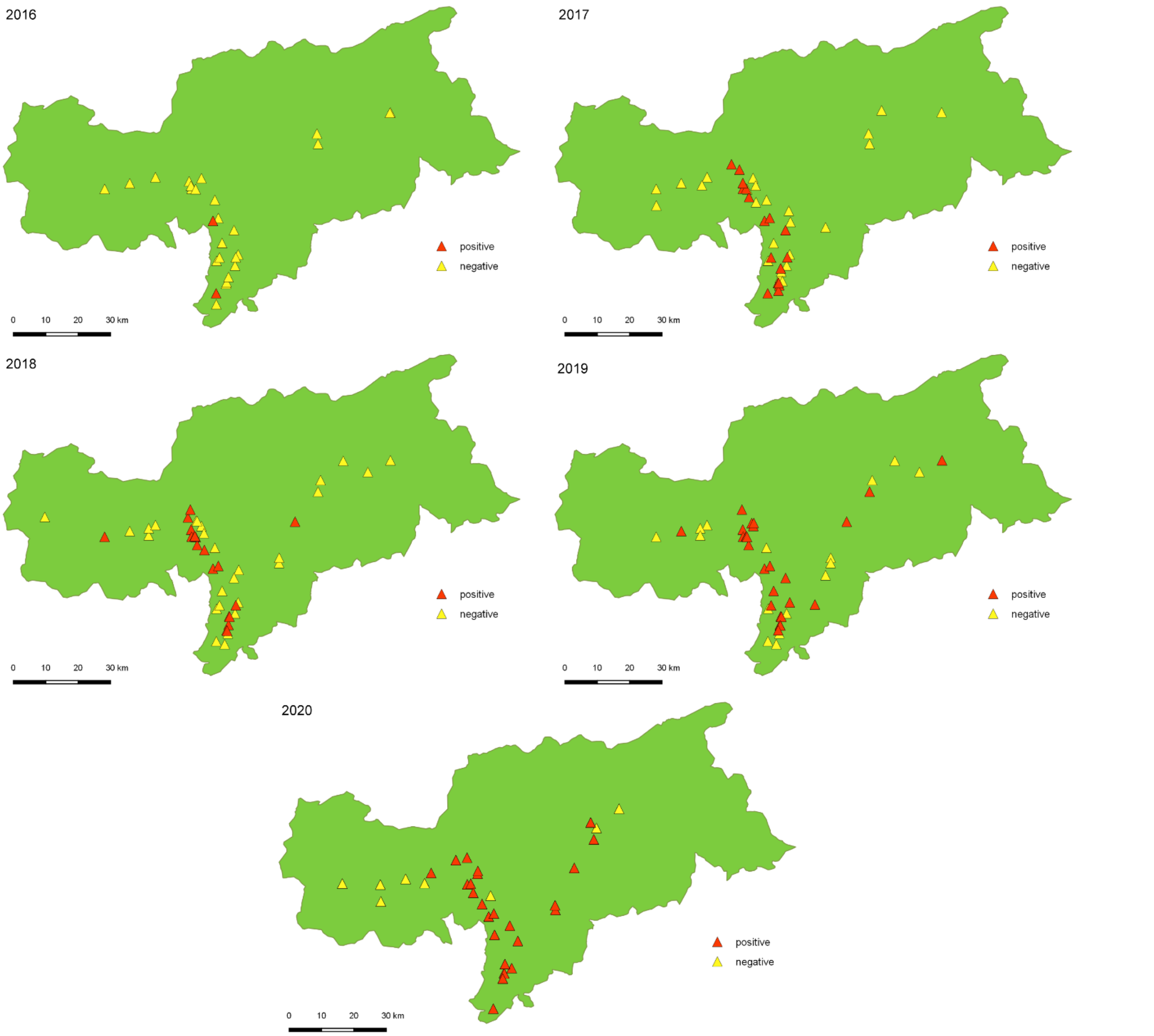

Fig. 4: *H. halys* records during active field monitoring by the implementation of pheromone baited traps from 2016 to 2020. (▲: monitoring sites where no presence of the species was recorded; ▲ monitoring sites with a positive detection of *H. halys*).

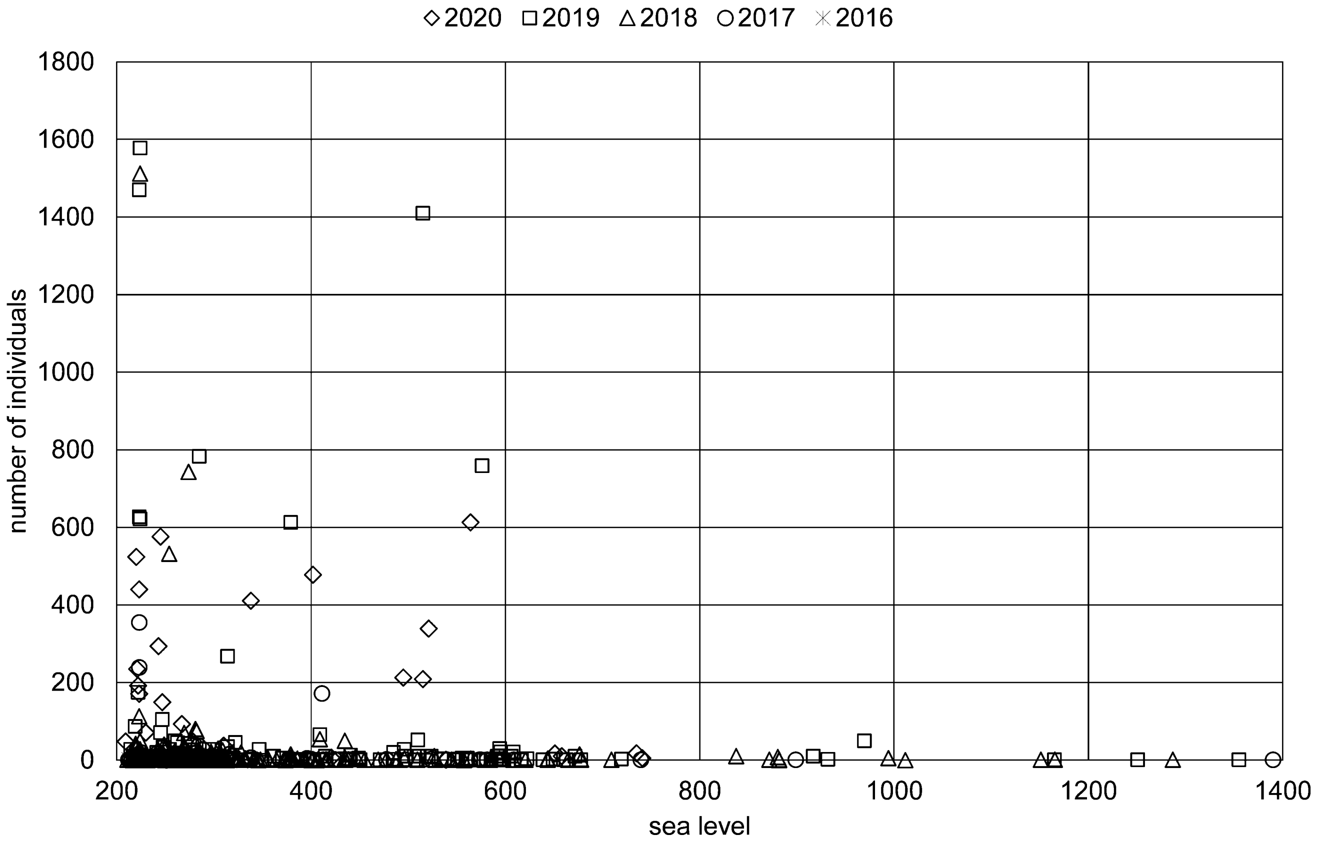

Fig. 5: Absolute numbers of *H. halys* recorded for a given altitude (m a.s.l.) from 2016 till 2020 in South Tyrol. Data were obtained by active field monitoring and a citizen science approach.

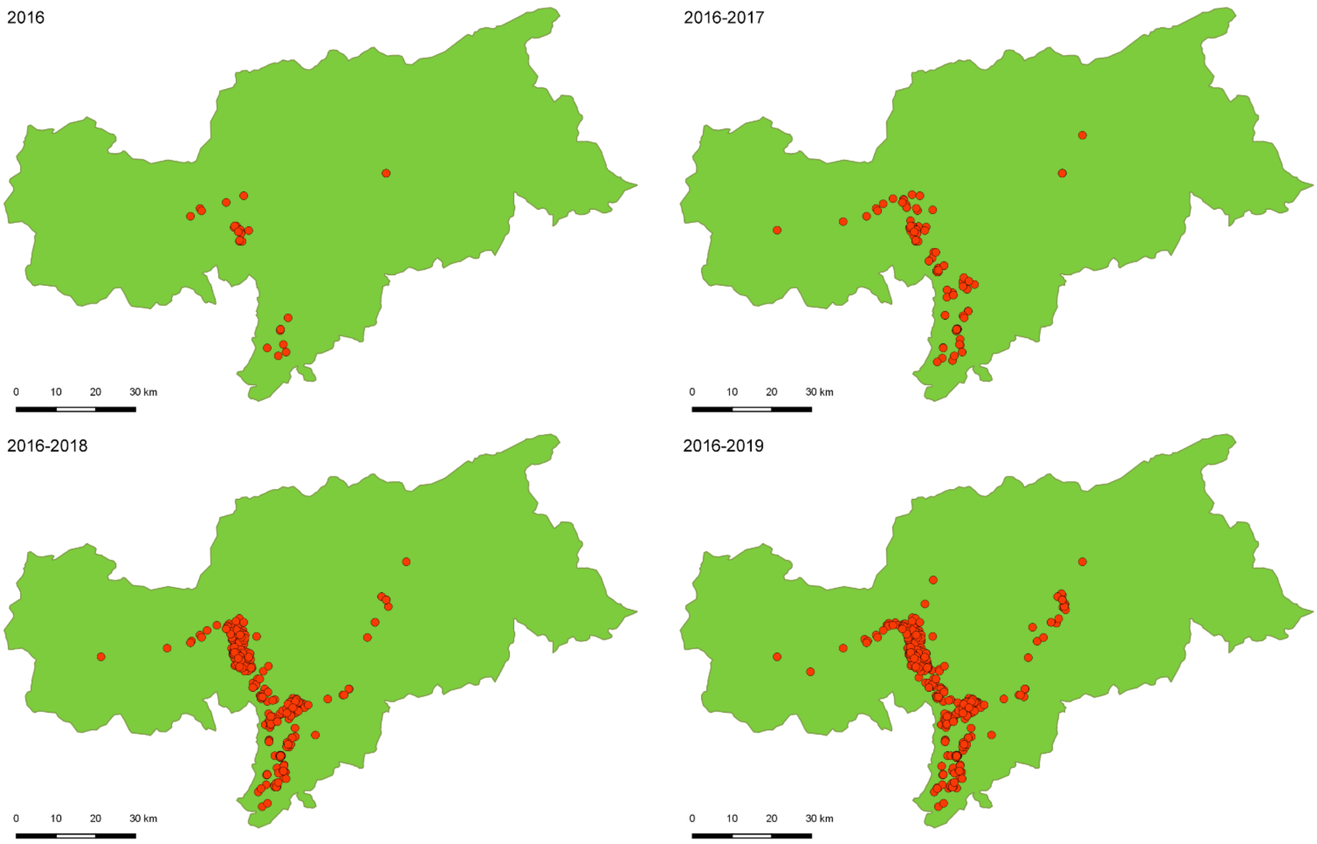

Fig. 6: Accumulated reports of *H. halys* by local citizens in the period from 2016 to 2019.