Tracking the Spread of Sneaking Aliens by Integrating Crowdsourcing and Spatial Modeling: The Italian Invasion of *Halyomorpha halys*

LARA MAISTRELLO, PARIDE DIOLI, MORENO DUTTO, STEFANIA VOLANI, SARA PASQUALI, AND GIANNI GILIOLI

Polyphagous phytophagous organisms that shelter in man-made objects have a higher chance of becoming invasive fast-spreading pests, going undetected during phytosanitary checks and travelling with any type of goods. However, if the same organisms are also a household nuisance, they could be used in crowdsourcing surveys aimed at their early detection and to track their spread in real time. By participating in these surveys, people can be educated on the destructive potential of invasive species and on sustainable management options. However, in order to obtain good-quality data, useful to plant protection stakeholders, a one-to-one approach with people is crucial. The case study is the Italian invasion of Halyomorpha halys, among the most dangerous global crop-threatening pests. A 4-year survey that combined active search and a crowdsourcing approach made the tracking of its spread and investigation of its spatiotemporal dynamics possible, showing the functionality of coordinated multiactor approach in data collection.

Keywords: invasive species, citizen science, crop and nuisance pest, population abundance, brown marmorated stink bug

Invasive organisms are a collateral effect of the growing globalization of trade and travel. They pose great risks to biodiversity and related ecosystem services, with consequences on human health and the economy (Funk et al. 2014, Gilioli et al. 2014). Raising the awareness on the destructive potential of alien species is crucial, both to educate people on the outcome of their voluntary actions (e.g., the transport of living souvenirs) or on noticing occasional minuscule hitchhikers (hidden in clothes and luggage), as well as to indicate appropriate and sustainable management options.

Among phytophagous insects, the ones that shelter in hidden microhabitats other than plants or plant related materials are actually those with a higher chance to threaten plant biosecurity, as they go undetected at phytosanitary checks (thus “sneaking aliens”). Their management at customs goes often beyond the competence of plant protection authorities, but it constitutes a complicated matter that involves the trade of practically any type of goods. The higher the association with man and its structures, the higher the probability of these insects being invasive and the faster their potential diffusion in the invaded areas. Early detection and ability to quickly track the diffusion of an introduced pest are essential to phytosanitary officers and agricultural stakeholders to undertake timely decisions on their management.

Many stink or shield bugs (Hemiptera, Pentatomidae) show a particular aptitude to overwinter in anthropogenic structures, often in large numbers, thus becoming nuisance pests. Indeed, this strict association with humans could be exploited in crowdsourcing surveys to detect and follow the real-time spread of species that threaten economically relevant crops, while at the same time pursuing outreach and the education of the public. Citizen science (crowdsourcing) surveys, the participation of nonprofessionals in the process of creating new scientific knowledge, offer the great advantage of obtaining data sets that would otherwise be infeasible to generate (Bonney et al. 2014). Examples of using crowdsourcing data set to detect new alien species early and to monitor their spread in newly invaded areas are provided by Bodilis and colleagues (2014) and Andow and colleagues (2016).

The present study is the outcome of a 4-year survey on the invasive pest *Halyomorpha halys* Stål (Hemiptera, Pentatomidae), which integrates crowdsourcing data with active search and specific monitoring activities. By using information from the data set, we were able to obtain the map

BioScience 68: 979–989.
doi:10.1093/biosci/biy112
Advance Access publication 17 October 2018

Table 1. Features of the data set used for the study.

Survey	Period	Positive records	Negative records	Total
Former survey (Maistrello et al. 2016)	13 September 2012–17 November 2013	200	177	377
New survey	18 November 2013–31 December 2016	1510	273	1783
Total	13 September 2012–31 December 2016	1710	450	2160

Note: The positive records are validated as *Halyomorpha halys*. The negative records are cases of misidentified species or cases in which *Halyomorpha halys* was actively searched for but never detected in the considered period.

of the current distribution, the contribution over time of the different categories of the survey participants, as well as the contexts (i.e., land use category) and places of occurrence. In addition, by elaborating a subset of data from a restricted area in which records were gathered intensively with constant effort, we derived information on the spatiotemporal patterns of population dynamics in the years immediately following their first introduction in Italy.

The invasive species

Halyomorpha halys, known as the brown marmorated stink bug (BMSB), is a highly polyphagous insect native to eastern Asia, rapidly spreading worldwide as a serious pest of many agricultural crops. It is also a dwelling nuisance, because of the massive overwintering aggregations inside houses and other man-made structures (Inkley 2012). Its global importance is highlighted in the special issue dedicated to it in the *Journal of Pest Science* (Haye and Weber 2017). In about 20 years, it has invaded large areas in North America (USDA-NIFA SCRI 2017), causing millions of dollars losses in fruit orchards and horticultural crops (Leskey et al. 2012). In recent years, increasing occurrences have been reported in many central, eastern and southern European countries (Cesari et al. 2015, Haye et al. 2015, Macavei et al. 2015, Rabitsch and Friebe 2015, Šeat 2015, Dioli et al. 2016, Gapon 2016, Maurel et al. 2016, Mityushev 2016, Simov 2016) and, most recently, in Chile (Faúndez and Rider 2017). Interceptions of BMSB associated with trade materials are increasingly reported at transitional facilities in many countries, and models of its potential global distribution highlight the potential for further spread and establishment, threatening horticultural productions in both Hemispheres (Kriticos et al. 2017).

Data collection

The first Italian records of BMSB in 2012–2013 (Maistrello et al. 2014) elicited great concern, because they occurred in Emilia-Romagna, one of the most important European fruit producing regions (Fanfani and Pieri 2016). The need to quickly acquire data on the spread of this pest was addressed by setting up an investigation combining active search by experts and a citizen science survey (Maistrello et al. 2016). Overall, data were obtained between 13 September 2012 and 31 December 2016 (table 1). The survey methodology was made of a successful combination of the following steps.

Involvement of volunteers via multimedia channels. (Details are in supplemental table S1). Appeals were launched inviting citizens to collect specimens or take high quality photographs of any brown-grey marmorated bug and to email them to the survey coordinators (Lara Maistrello, Paride Dioli, Moreno Dutto), together with details on the collection or sighting. Volunteers were solicited by issuing press releases (once a year, in early autumn) published in many papers or online; publishing alerts for farmers and the general public on the websites of the regional plant protection services and of the local municipalities and sanitary offices; issuing specific extension flyers, distributed in public areas and also published on the websites of regions and municipalities; alerting professional and amateur entomologists, naturalists, photographers, using social networks and specific web forums; organizing public conferences; giving interviews for local broadcasting units and newspapers; and collecting reports by the public health services and the Italian Forestry Corps. Overall, the use of traditional media, websites and social networks, especially web forums for entomologists or naturalists, allowed the study to reach a considerable number of people (more than 1500), particularly from northern Italy.

Active search by the authors, their collaborators and students. BMSB was actively sought by the authors and trained collaborators during occasional sessions performing tree beating, sweep netting, or visual surveys on crops and spontaneous vegetation, as well as by visual surveys in buildings. The approach was *whenever you can and wherever you go, keep an eye on grayish stinkbugs*, and it was also used by the students (both from the University and from high schools) that were purposely motivated by their teachers to look for any brown-grey marmorated bugs.

Monitoring programs by local plant protection organizations (PPOs). The findings obtained in 2013 (Maistrello et al. 2016) induced an alert system in the regions and provinces in northern and central Italy. Therefore, the presence of BMSB was checked by purposely trained PPO personnel from April to September in 2014–2016 during the periodical monitoring programs for other pests, as well as by carrying out specific monitoring in areas with crops susceptible to BMSB damage (mainly fruit orchards but also soybean and maize). In this case, in representative farms (at least 2–3 hectares in size) on which the crop was close (less than 20 meters) to a building and adjacent to a hedge, monitoring was performed weekly (Maistrello et al. 2017). Standardized visual surveys, tree beating, and specific BMSB traps (3 traps per farm) baited with aggregation pheromones lures (Rescue, Sterling International Inc., Spokane, Washington) were used as monitoring techniques.

Data validation

Because BMSB adults can be confused with similar European pentatomids, such as *Rhaphigaster nebulosa* (Poda 1761), *Troilus luridus* (Fabricius 1775), and *Arma custos* (Fabricius 1794), all of the records were validated by the authors. The records were classified as positive if BMSB was recognized when examining dead or alive specimens or digital pictures and as negative when a specimen of another species was misidentified or in cases in which BMSB was actively searched for but never detected in the considered period.

Data organization

All records were stored in a database indicating the date of collection; geographic information (locality and street); the number of specimens observed and collected, categorized using an abundance index ranging from 0 to 4 (0, no individuals; 1, 1–5 individuals; 2, from 6 to 20; 3, dozens; 4, hundreds); the context of detection (*open field* meant crops or uncultivated land, *rural* indicated isolated country farmhouses; *country village* meant a small residential area in the countryside; *urban* represents cities with a population of over 45,000 inhabitants; *wild* was forests, natural parks, and reserves); the place of detection (house or building, terrace, urban green, garden-vegetable garden, crop, park, means of transport); the plant species, if the bug was found on plants; the detector name and category (*researcher* was the investigator at the university or other research institution; *museum* meant a natural history museum's personnel; *ento/nat* refers to an entomologist or a naturalist; *phytosan* is phytosanitary services personnel; *student* refers to a university or high-school student; *farmer* is just what you'd expect; and *citizen* refers to a citizen not belonging to the previous categories); and additional observations if any. For each year, the positive records were used to obtain the percentages of occurrence of BMSB according to the occurrence in different seasons, the presence in different contexts and places, and the category of the survey participants.

Data analysis

The collected data were imported into a geographic information system using QGIS 2.18 software in order to obtain a map of all of the records. To investigate the spatiotemporal pattern of the BMSB invasion in Italy, a 150 × 304 kilometer (km) area was considered and adopted as the study area. The size and the position of this study area were defined to include the area (most of Emilia-Romagna and sections of Veneto and Lombardy) in which the pest was originally reported in Italy and in which most of the findings were reasonably derived from the dispersal of the first established population (figure 1). The hypothesis is that the pest invasion has originated around the first recorded point and that the BMSB population has progressively expanded starting from areas adjacent to that location in the direction of the margin of the study area, joining other populations of different origins. The data falling within the study area and used for the spatiotemporal analysis ranged from 13 September 2012 to 7 December 2016.

To derive information on the BMSB spatial pattern of dispersal and to conduct preliminary analysis of the temporal dynamics of population growth of established populations, the study area was partitioned by a grid of 2 × 2 km cells. The state of the cell was derived from the point-based data and was defined through a series of discrete states (0, 1, 2, 3, 4) representing the classes of abundance defined above. The state of a cell is equal to the mean value of abundance of all of the points belonging to that cell rounded to the nearest integer. A cell with no population (state 0) is considered *empty* (E), whereas cells with any number of individuals is considered *occupied* (O).

To investigate the pattern of BMSB spatial dynamics, a cell occupancy model (Levins 1969) was considered to describe the temporal dynamics of the occupied cells. For simplicity's sake, it was assumed that when a cell changes the status from E to O, the transition is irreversible. The characteristics of the BMSB's population biology and invasion process support this assumption. The analysis of the occupancy was conducted on a yearly basis and on a monthly basis for the within-year dynamics. On the basis of the BMSB activity, the within-year occupancy dynamics is followed between April and September (the favorable season). All of the data reported from September of a year to March of the following year were considered estimates of the population abundance at the end of the favorable season, because the sampled BMSB in autumn and winter are overwintering individuals. Therefore, the occupancy in September of a year is the sum of all of the occupied cells between that moment and March of the following year.

To investigate the temporal evolution of the abundance in an occupied cell the analysis of transition between different states of the cells in discrete times (the time interval is 1 year) has been performed. Denoting by X_n the abundance state of a cell at year n, X_n can take five possible values: 0, 1, 2, 3, and 4. The process $\{X_n, n = 0, 1, 2, \ldots\}$ is a Markov chain (Ross 1996). The transition probabilities can be computed considering the change of state of the cells from a year to the next. Transition matrices were calculated in different years and the stationarity of the Markov chain was evaluated. Through transition matrices the most probable transitions for each year can be derived, and transition matrices can be used to obtain hints on the time required to reach the maximum value of abundance (stage 4 of the Markov chain).

Current distribution of BMSB in Italy

The current distribution map (figure 1) shows that BMSB is widespread all over northern Italian regions (96% of the

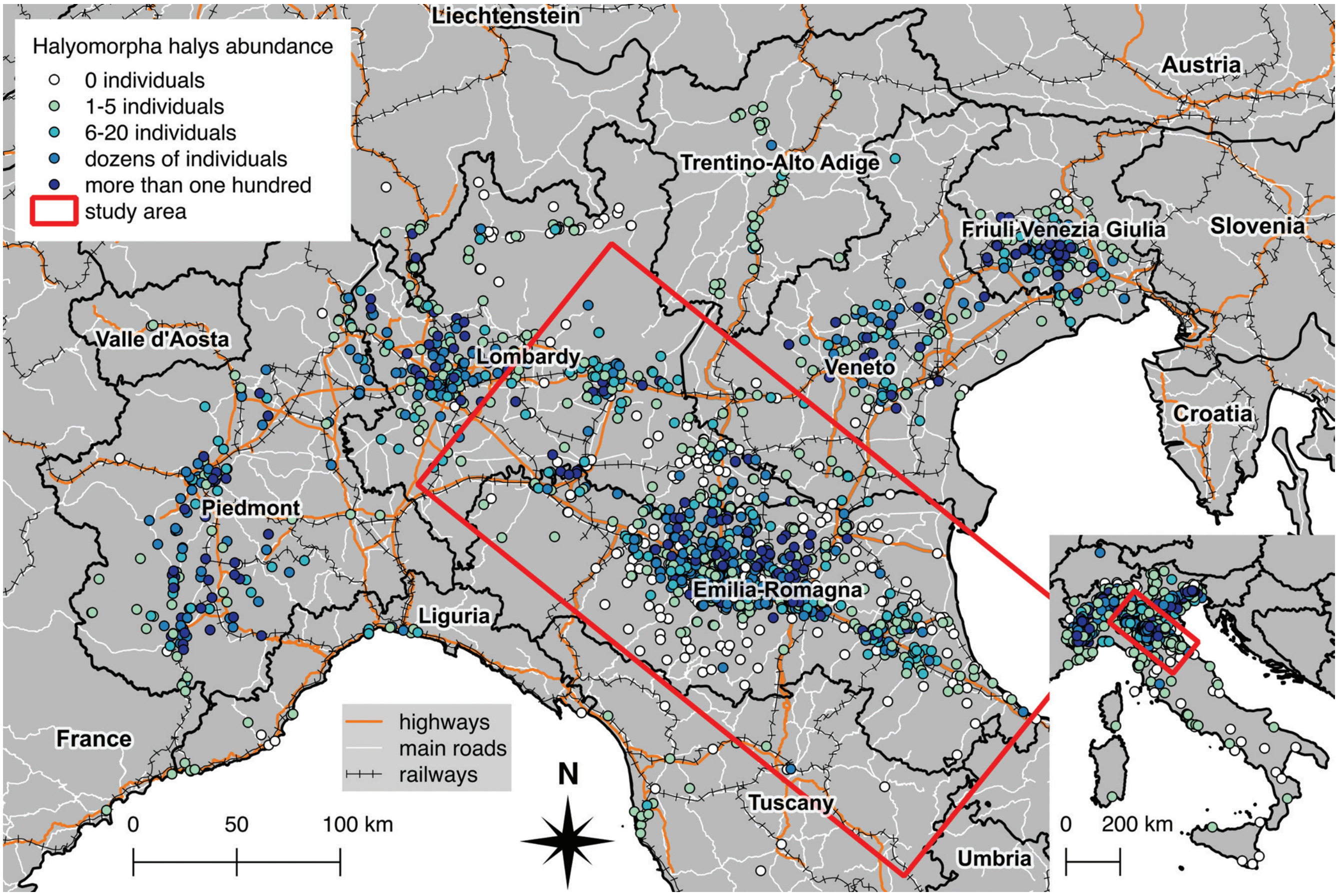

Figure 1. The distribution of Halyomorpha halys in northern Italy, according to the survey (dots). The darker dots indicate positive records with bigger size (the number of specimens detected). The white dots indicate negative records, represented by cases of misidentified species or by cases in which BMSB was actively searched for but never detected in the considered period. The rectangle indicates the study area used for further elaboration.

records) and that central Italy records a few occurrences (1.6% of the survey), whereas only occasional records (0.4%) were reported for southern Italy and in the islands, showing a huge increase compared with the initial investigation, which ended in 2013 (Maistrello et al. 2016). The present survey also included records from Switzerland and France (2%), close to the Italian borders, and one from Corsica, the first ever reported for this island. Descriptive features of the records, including the affected crops, are reported in supplemental material S2. The most abundant populations were concentrated along the main road or railway lines, especially in the area of first detection (Emilia-Romagna region), in some of the main urban centers and their surroundings, and in open field crops. A strong association with railroads and urban development was also observed in the initial establishment and dispersal of BMSB in the United States (Wallner et al. 2014). BMSB was also reported at high altitudes (1100–1830 meters at sea level) in the western Alps. Subsequent accurate inspections in the same locations failed to detect the active presence of the species. These transient populations were likely the outcome of occasional transportation from nearby locations in the plains, where the presence of the species is amply established. As was highlighted by Acebes-Doria and colleagues (2016), a mixed hosts diet improves the survival and development of nymphs and the size and weight of adults, and this could also be an important factor limiting the population persistence at high altitudes.

When and where are BMSB found?

The number of records increased each year (see supplemental figure S3), and in all years, the most detections occurred in autumn, followed by summer. This confirms previous findings (Maistrello et al. 2016) that autumn is the most favorable period to collect data on BMSB presence, because adult bugs are easily noticeable within buildings by all people in any setting. Summer was the second best season for BMSB detection, because the present study also included records from the phytosanitary personnel (see supplemental figures S4), whereas in a crowdsourcing survey by Hahn and colleagues (2016), records were lowest in summer, because the majority of the citizen reports were from homeowners.

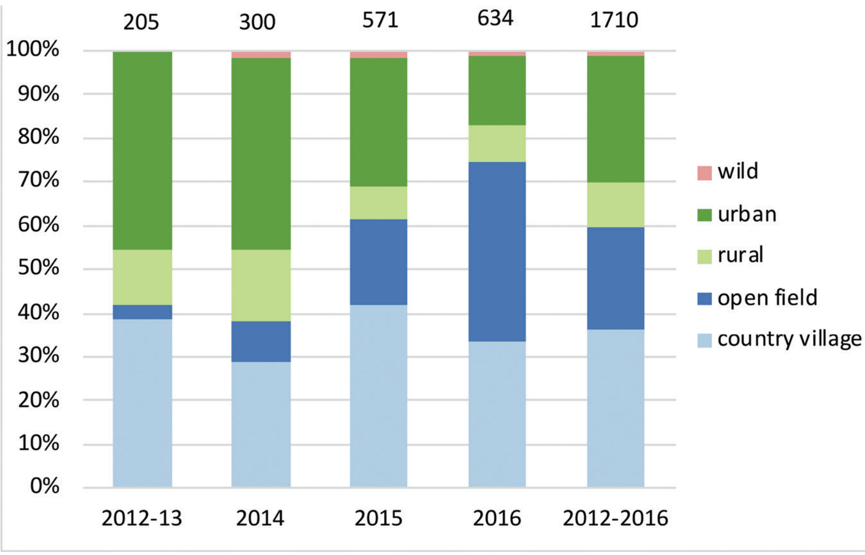

Figure 2. The relative percentage of Halyomorpha halys detected in different landscape contexts for each year of the survey. The numbers on top of the columns indicate the total number of records for each period.

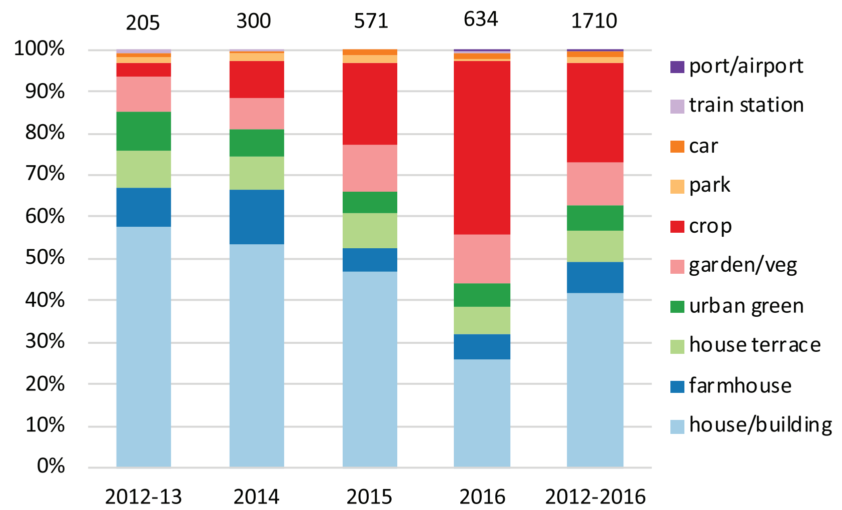

Figure 3. The relative percentage of Halyomorpha halys detected in different places for each year of the survey. The numbers on top of the columns indicate the total number of records for each period.

Regarding the context of detection (figure 2), until 2014, most records occurred in urban areas and countryside villages, whereas in 2016, most cases occurred in open fields. The percentage of records from villages was similar over the years and that from forests always very low. Considering the place of occurrence (figure 3), until 2014, BMSB was detected mainly inside buildings; afterward, the cases involving crops started to increase and peaked in 2016. Occurrences in green areas were similar over all years. Compared with the results of Maistrello and colleagues (2016), the occurrence of the pest and its abundance in the open field on agricultural crops significantly increased. Indeed, in the area of first detection, serious economic damage (over 50% deformed fruits) was reported as early as 2015, with BMSB emerging as a key pest of fruit orchards (Maistrello et al. 2017).

The sneaking hitchhiking aliens

Overall, BMSB was detected 22 times inside cars, 5 times in train stations, once in a port, and once in an airport (figure 3). The detection along main roads or railway lines (figure 1), together with the many occurrences inside means of transport and transit areas strongly support the hypothesis that human assisted spread plays a major role in BMSB invasive potential. The association of this species with any type of transported goods or objects causes high concern for biosecurity authorities at customs, who need to implement special measures to reduce the contamination risks. Warnings of the global dimension of this risk have been reported for example on cargoes from Italy and the United Stats, intercepted both in New Zealand (Ken Glassey, Biosecurity and Environment Group, Ministry for Primary Industries, New Zealand, personal communication, 9 February 2016) and in Australia (Adam Broadley, Department of Agriculture and Water Resources, Australia, personal communication, 19 September 2016), resulting in extra costs and delays and seriously affecting trade between countries. The typical aptitude to hide in dark microhabitats (e.g., in slots of vehicles and other objects, inside packaging of different types of goods, empty boxes and fruit containers, clothes and suitcases) exhibited by BMSB, in particular during the overwintering aggregations (Toyama et al. 2011), is the key factor that facilitates hitchhiking, therefore making the spread of this pest around the world unstoppable. The same trait is shared with other Hemiptera, some of which are emerging as invasive pests—for example, *Megacopta cribraria* Fabricius (Plataspidae), a native Asian stinkbug that threatens legumes and other horticultural crops in the United States (Ruberson et al. 2013).

Spatiotemporal patterns of BMSB

The cell occupancy dynamics allowed us to identify the pattern of both the within-year dispersal and the between years expansion of BMSB. An exponential curve was used

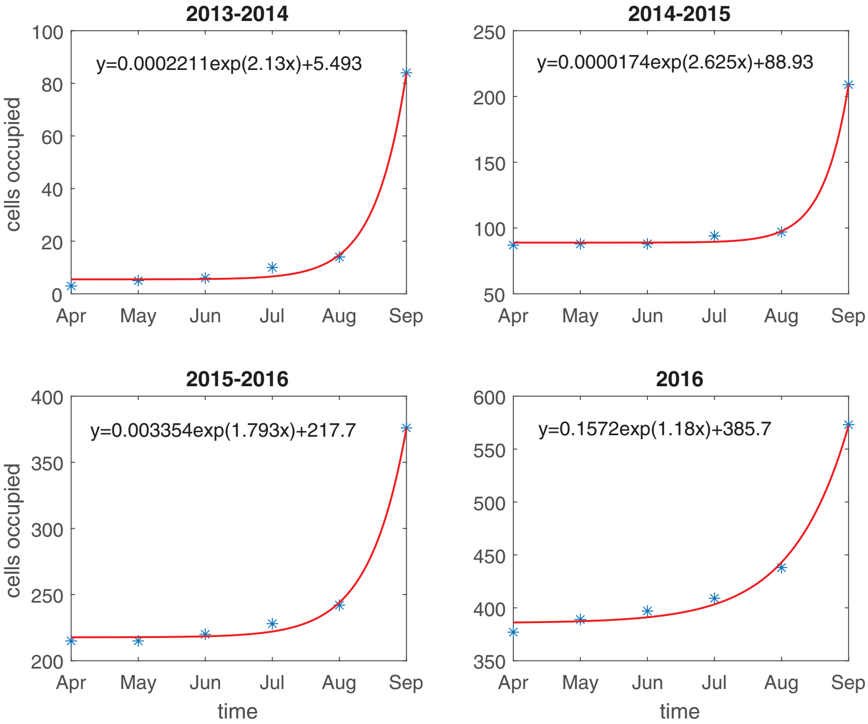

Figure 4. Within-year change in the number of cells occupied by the Halyomorpha halys population in the study area. The occupancy is fitted with an exponential curve. The asterisks represent the occupied cells in each month for the period of April to August, whereas for September, the asterisk represents the sum of the occupied cells in the period from September to March of the next year for the first three graphics and the sum of the occupied cells in the period from September 2016 to December 2016 for the fourth graphic (2016).

in environmental cues (Wiman et al. 2014). This, in turn, may facilitate the spread of BMSB through homes or structures. This pattern clearly indicates the presence of a stratified dispersal in which both short (i.e., continuous spread) and long-distance human-mediated dispersal act in tandem, allowing the species to be widely distributed in the occupied area. The importance of long-distance dispersal and the active population growth rate are at the base of the high spread rate observed in the study area.

A clearer picture of the spread pattern can be obtained through the between-year occupancy dynamics (obtained considering the occupied cells in September of every year, representing the whole occupancy of the year). Presumably, BMSB was present in the area some years before the first detection until the pest reached a level of abundance high enough to be detected. To guess the initial year of the invasion, we assume the species follows a stratified dispersal process (Shigesada et al. 1995, Liebhold and Tobin 2008, Gilioli et al. 2013) leading to an exponential pattern in occupancy. The exponential fit of the number of occupied cells (figure 5) improves as we move backward the beginning of invasion up to 2009. Therefore, we considered this year as the start of the invasion process.

to fit the within-year data (considered in the period April of a year—March of the following year). Because only two cells were occupied in the year 2012–2013, 2013–2014 is the first year with sufficient data to perform the analysis. The coefficient in the exponential term is near 2 for the years 2013–2014, 2014–2015 and 2015–2016, whereas it is near 1 for 2016. This is due to the fact that, in the last case, the data set taken into consideration is limited to 7 December 2016. Therefore, the number of occupied cells in September 2016 is underestimated. The fact that the number of occupied cells toward the end of autumn shows a noticeable increase (figure 4) is due to BMSB behavior, which tends to massively migrate to the urban environment for overwintering, facilitating the detection for the citizen science method. However, part of this increase in the occupancy might be due to the fact that populations of BMSB in the urban environment are also more exposed to the human-assisted spread. It is likely that the availability of host plants during autumn mostly requires short distance dispersal to reach favorable habitats resulting in a lower rate of activity and a lower dispersal rate. As the overwintering period approaches, the search pattern of BMSB may become different together with changes

The exponential curve in figure 5 also allows us to project the number of cells occupied in 2016–2017. We estimated that there is an increase of about two times the number of cells in comparison with the previous year. Using data projected for 2016–2017 we have again estimated the exponential term for the period 2016–2017 for the within-year trend (coefficient in the exponential term near 2; figure 6), which is in line with the ones estimated for the previous years (figure 4).

To describe the evolution of cell abundance over time, we computed the transition probabilities from a cell state to another in a given year. Although few cells have data for consecutive years, from the transition matrices shown in table 2, it is possible to draw some conclusions: (a) Transition probabilities, as expected in an initial phase of invasion, are time dependent, leading to a time inhomogeneous Markov chain. (b) For all of the class values, the highest probabilities are associated with a no change (i.e., the cell remains in the same state) or to a change into an adjacent value. Furthermore, when a cell is in stage 4, the probability that it returns to stages 0 or 1 is zero and, in general, only in a few cases it can

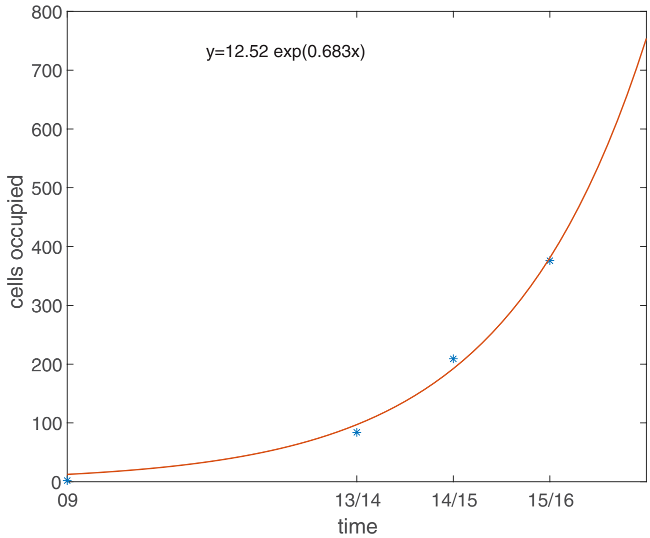

Figure 5. The between-year change in the number of cells occupied by the Halyomorpha halys population in the study area. The occupancy is fitted with an exponential curve. The asterisks represent the total number of the occupied cells in the period of April to March of the next year—that is, the number of cells occupied in September of every year appearing in figure 4.

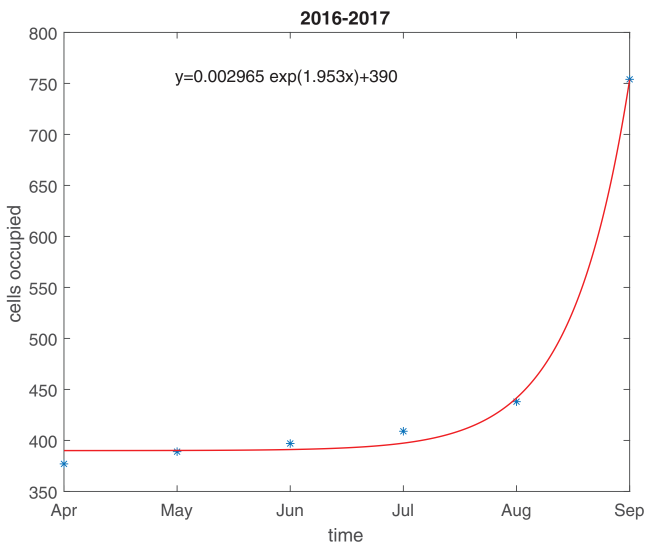

Figure 6. The exponential fit of the number of cells occupied by the Halyomorpha halys population in the study area in the period from 2016 to 2017. The number of cells occupied in September was obtained as a projection of the exponential fit in figure 5.

move to stages 3 or 2. This shows a strong capacity of the species, once established, to persist in a cell (no local extinction). This persistence increases with the level of abundance (high growing potential). (c) In the last two transitions it is more probable that the abundance level moves forward than backward, and the percentage of movement toward state 4 increases over time. This shows how for many cells the relatively short time period considered is enough to reach a high level of abundance (the species only takes a few years to reach state 4). Unfortunately, because the Markov chain is time inhomogeneous and only few transition matrices are available, it is not possible to compute the mean time required to reach stage 4. The capacity to quickly build up abundant populations in an occupied cell is also confirmed by the percentage of cells in each state over time reported in table 3. It can be observed that we move from a 1.2% of cells in stage 4 in 2013 to a 22.2% in 2016. On the contrary, the percentage of cells with value 1 decreases over time.

Transition matrices showed how BMSB can reach population abundance level potentially threatening for crop production in a few years. The growth potential of BMSB populations, as a factor explaining its success as invasive species, was also demonstrated in the life table study performed outdoors (Costi et al. 2017) indicating that in northern Italy it is bivoltine with high reproductive rates for both generations ($R0 = 24.04$ and 5.44 respectively). In addition, the biocontrol potential by native antagonists is presently very limited (Abram et al. 2017), likely contributing to the field outbreak and the economic impact on crops (Maistrello et al. 2017).

The contribution overtime of the different categories of participants to the survey

Considering the category of the participants (figure 7), our survey indicates that the contribution of entomologists or naturalists was always very remarkable, regardless of year. This category of people is more aware of entomological issues, active on web forums and discussions, and generally more attuned to the presence of insects in most contexts. This means that their role is extremely important both in early detection of new species and to obtain data on their spread, and that they should always be involved in programs to spot invasive pests. Students duly motivated by their teachers are important especially during the early phase of the survey; besides curiosity and understanding the importance of the study, they engage in a competition for who first notices the bug. Similarly, the contribution of researchers is conspicuous in the first years, and decreases in the last year, when the percentage of records from the phytosanitary personnel becomes prevalent, because the invasive pest becomes more abundant in agricultural fields and signs of its damage become more prevalent and noticeable. The role of unqualified citizens is strictly seasonal as they report the overwintering insects detected inside the buildings.

Pros and cons of crowdsourcing: The importance of the one-to-one approach

The crowdsourcing approach presents issues related to data reliability, because efficacy in data collection is not exclusively related to pest abundance, but also to people's degree of awareness. The method is expected to have a

Table 2a. Transition matrices of Halyomorpha halys population abundance from year 2013–2014 to 2014–2015.

	j = 0		j = 1		j = 2		j = 3		j = 4	
State	Probability	Number	Probability	Number	Probability	Number	Probability	Number	Probability	Number
i = 0	.5714	4	.4286	3	0	–	0	–	0	–
i = 1	.05	1	.15	3	.4	8	.25	5	.15	3
i = 2	0	–	.6667	4	.1667	1	.1667	1	0	–
i = 3	.1667	1	0	–	.1667	1	.5	3	.1667	1
i = 4	0	0	1	1	0	–	0	–	0	–

Note: Probability is the probability of movement from state *i* to state *j*. *Number* denotes the number of cells that move from state *i* to state *j* that has been used to compute the corresponding transition probability.

Table 2b. Transition matrices of Halyomorpha halys population abundance from year 2014–2015 to 2015–2016.

	j = 0		j = 1		j = 2		j = 3		j = 4	
State	Probability	Number	Probability	Number	Probability	Number	Probability	Number	Probability	Number
i = 0	.875	7	.125	1	0	–	0	–	0	–
i = 1	.05	1	.35	7	.2	4	.3	6	.1	2
i = 2	.05	1	.2	4	.35	7	.3	6	.1	2
i = 3	0	–	0	–	.1429	1	.8571	6	0	–
i = 4	0	–	0	–	0	–	0	–	1	2

Note: Probability is the probability of movement from state *i* to state *j*. *Number* denotes the number of cells that move from state *i* to state *j* that has been used to compute the corresponding transition probability.

Table 2c. Transition matrices of Halyomorpha halys population abundance from year 2015–2016 to 2016.

	j = 0		j = 1		j = 2		j = 3		j = 4	
State	Probability	Number	Probability	Number	Probability	Number	Probability	Number	Probability	Number
i = 0	0	–	0	–	0	–	.5	1	.5	1
i = 1	0	–	.2308	3	.3077	4	.2308	3	.2308	3
i = 2	0	–	.125	1	.375	3	.375	3	.125	1
i = 3	0	–	.2	1	0	–	.4	2	.4	2
i = 4	0	–	0	–	.3333	1	.3333	1	.3334	1

Note: Probability is the probability of movement from state *i* to state *j*. *Number* denotes the number of cells that move from state *i* to state *j* that has been used to compute the corresponding transition probability.

Table 3. The number and percentage of cells in each state in different years.

	State									
	0	1		2		3		4		
Year		Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Sum of cells with no zero value
2012	0	2	–	0	–	0	–	0	–	2
2013	7	53	64.6	17	20.7	11	13.5	1	1.2	82
2014	10	55	35.7	46	29.9	37	24	16	10.4	154
2015	10	90	40.7	49	22.2	52	23.5	30	13.6	221
2016	0	62	25.5	67	27.6	60	24.7	54	22.2	243

Note: The number of the cell in state *i* is given by the number of the cell classified with *i* in the year considered.

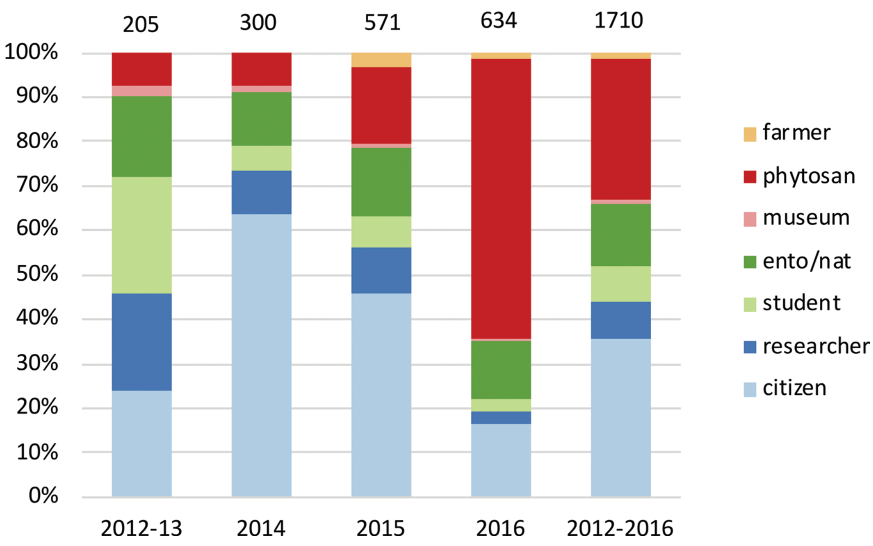

Figure 7. The relative percentage of Halyomorpha halys detected by the different categories of participants for each year of the survey. The numbers on top of the columns indicate the total number of records for each period.

certain delay at the beginning and it may present gaps in the efficacy, depending on the degree of media attention. Geographic variation in the degree of citizens' participation is also expected. Moreover, the method's efficacy depends on the habitat and landscape because the maximum amount of records is reported in autumn–winter, when BMSB takes shelter in buildings. Nevertheless, this approach proved to be extremely useful to get a data set that otherwise would have been impossible to quickly obtain from a large territory. Crowdsourcing surveys are presently burgeoning, also taking advantage of social networking media (Daume 2016) and smartphone technology (Starr et al. 2014). In particular, the use of smartphone applications that allow for geotagging images of insects is impersonal, but fast and easy when compared with an approach based on the exchange of emails, as we did in the present study. However, the approach used in this work, which is time and energy consuming and requires dedicated staff to maintain contact with people, has some important advantages. It has to be remarked that during the survey, all of the participants always received personalized feedback on their records, notifying them of the correct species identification, giving information on the project and suggestions for the management of the bugs in houses and gardens. When the first notification of BMSB lacked some of the requested information, the email exchange allowed for the acquisition of all of the necessary details, guaranteeing the accuracy of the data set, also useful for the analysis of the spread patterns. The participants were also asked to send specimens, thus contributing to a study that shows the genetic diversity of the BMSB populations invading Italy (Cesari et al. 2018). This one-to-one approach made people feel important for their contribution to scientific research, simultaneously increasing their knowledge on the negative effects of invasive species and on specific details on BMSB biology. Therefore, an overall benefit for the whole community was gained in terms of increased awareness, and very often this also encouraged the participants to recruit other people to join the survey. A similar tendency was observed by Andow and colleagues (2016) in a project of invasive species detection, who noticed that the volunteers who experienced a learning module were more likely to recruit new volunteers than were those who received an invitation letter.

Usually, citizen science data collection is focused on reporting the occurrence of the species, without taking into account the abundance, as in a study by Hahn and colleagues (2016). An example of integration of citizen science on the basis of presence or absence data with other techniques is given by Fletcher and colleagues (2016). In our survey, we moved a step forward, also taking into account the magnitude of infestation for the analysis of the spatiotemporal spread of this invasive pest. Availability of abundance data allowed the estimation of the time lag of 4 years from the introduction to the detection of high abundance population level. This seems to be a reasonable period of time for a fast growing and invading pest species such as BMSB (Nielsen et al. 2016). This capacity to establish and build up dense population in a short time period, together with the high spread rate, has important consequences for the possibility to slow down the spread and makes almost impossible the eradication.

Conclusions

The present work demonstrated the functionality of the multiactor approach in facing the invasion of a particularly devastating species that threatens agricultural productions, but that is also a nuisance pest. The study showed that the effort of keeping an organized data set with the data obtained by the stakeholders (PPOs, farmers) integrated with those obtained by researchers, naturalists, students and citizens allowed us to obtain information on the spatiotemporal population processes at the basis of the fast spread of BMSB in Italy. The one-to-one approach used for the interactions with people resulted in an increase in both the reliability of the method and the awareness of the survey participants, which benefited the whole community. Furthermore, investigations are needed for a complete analysis of BMSB population dynamics. A more detailed description of the spatial processes, together with the consideration of data on life-history strategies, behavior (e.g., dispersal and host selection) and host plants susceptibility, could be considered to build a more accurate model of the spatiotemporal population dynamics that could be used to support the design of risk management schemes.

In times of increasing trade globalization, staff at customs and plant protection stakeholders have the challenging task of having to face the continuous arrival of organisms that could quickly become crop-threatening invasive pests. The approach we presented could be useful for early detection and to track the global spread of BMSB and of other species similarly associated to man.

Supplemental material

Supplemental data are available at *BIOSCI* online.

Acknowledgments

We thank the hundreds of citizens who participated to the survey and Ronni Paolinelli, Gruppo Modenese Scienze Naturali, Livio Mola, Giovanni Bianchi (www.entomologiitaliani.net, www.halyomorpha-halys.it), Margherita Norbiato, Alessandro Girodo (www.naturamediterraneo.com), Mauro Agosti (Condifesa BS), Martino Salvetti (Fondazione Fojanini di Studi Superiori, SO), teachers, students and trainees of UNIMORE-UNIMI-UNITO-UNIPD-UNIFI, Plant Protection Services of Regions Emilia-Romagna, Veneto, Piedmont, Lombardy, Toscana, Friuli-Venezia Giulia, Ticino (Switzerland), and of the provinces MO-RE-PR-PC-BZ, Consorzio Agrario Ravenna, Consorzio Agrario dell'Emilia, ASTRA, Agrisol, Fondazione Edmund Mach, APOFRUIT, CREA. This research was partially supported by grant no. 2013.065 (Fondazione Cassa di Risparmio di Modena) and by Programma Emblematici Maggiori 2014 (Fondazione Cariplo, Regione Lombardia).

References cited

Abram PK, Hoelmer KA, Acebes-Doria A, Andrews H, Beers EH, Bergh JC, Bessin R, Biddinger D, Botch P, Buffington ML, et al. 2017. Indigenous arthropod natural enemies of the invasive brown marmorated stink bug in North America and Europe. Journal of Pest Science 90: 1009–1020.

Acebes-Doria AL, Leskey TC, Bergh JC. 2016. Host Plant Effects on *Halyomorpha halys* (Hemiptera: Pentatomidae) Nymphal Development and Survivorship. Environmental Entomology 45: 663–670.

Andow DA, Borgida E, Hurley TM, Williams AL. 2016. Recruitment and retention of volunteers in a citizen science network to detect invasive species on private lands. Environmental Management 58: 606–618.

Bodilis P, Louisy P, Draman M, Arceo HO, Francour P. 2014. Can citizen science survey non-indigenous fish species in the eastern Mediterranean Sea? Environmental Management 53: 172–180.

Bonney R, Shirk JL, Phillips TB, Wiggins A, Ballard HL, Miller-Rushing AJ, Parrish JK. 2014. Next steps for citizen science. Science 343: 1436–1437.

Cesari M, Maistrello L, Ganzerli F, Dioli P, Rebecchi L, Guidetti R. 2015. A pest alien invasion in progress: Potential pathways of origin of the brown marmorated stink bug *Halyomorpha halys* populations in Italy. Journal of Pest Science 88: 1–7.

Cesari M, Maistrello L, Piemontese L, Bonini R, Dioli P, Lee W, Park C-G, Partsinevelos GK, Rebecchi L, Guidetti R. 2018. Genetic diversity of the brown marmorated stinkbug *Halyomorpha halys* in the invaded territories of Europe and its patterns of diffusion in Italy. Biological Invasions 20: 1073–1092.

Costi E, Haye T, Maistrello L. 2017. Biological parameters of the invasive brown marmorated stink bug, *Halyomorpha halys*, in southern Europe. Journal of Pest Science 90: 1059–1067.

Daume S. 2016. Mining Twitter to monitor invasive alien species: An analytical framework and sample information topologies. Ecological Informatics 31: 70–82.

Dioli P, Leo P, Maistrello L. 2016. Prime segnalazioni in Spagna e in Sardegna della specie aliena *Halyomorpha halys* (Stål, 1855) e note sulla sua distribuzione in Europa (Hemiptera, Pentatomidae). Revista gaditana de Entomología 7: 539–548.

Fanfani R, Pieri R. 2016. Il sistema agro-alimentare dell'Emilia-Romagna. Rapporto 2015. Bologna: Unione regionale delle Camere di commercio dell'Emilia-Romagna Regione Emilia-Romagna, Assessorato agricoltura, caccia e pesca.

Faúndez EI, Rider DA. 2017. The brown marmorated stink bug *Halyomorpha halys* (Stål, 1855; Heteroptera: Pentatomidae) in Chile. Arquivos Entomolóxicos 17: 305–307.

Fletcher RJ, McCleery RA, Greene DU, Tye CA. 2016. Integrated models that unite local and regional data reveal larger-scale environmental relationships and improve predictions of species distributions. Landscape Ecology 31: 1369–1382.

Funk JL, Matzek V, Bernhardt M, Johnson D. 2014. Broadening the Case for Invasive Species Management to Include Impacts on Ecosystem Services. BioScience 64: 58–63.

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

Gilioli G, Pasquali S, Tramontini S, Riolo F. 2013. Modelling local and long-distance dispersal of invasive chestnut gall wasp in Europe. Ecological Modelling 263: 281–290.

Gilioli G, Schrader G, Baker RHA, Ceglarska E, Kertész VK, Lövei GL, Navajas M, Rossi V, Tramontini S, van Lenteren JC. 2014. Environmental risk assessment for plant pests: A procedure to evaluate their impacts on ecosystem services. Science of the Total Environment 2014: 475–486.

Hahn NG, Kaufman AJ, Rodriguez-Saona C, Nielsen AL, LaForest J, Hamilton GC. 2016. Exploring the spread of brown marmorated stink bug in New Jersey through the use of crowdsourced reports. American Entomologist 62: 36–45.

Haye T, Gariepy T, Hoelmer K, Rossi J-P, Streito J-C, Tassus X, Desneux N. 2015. Range expansion of the invasive brown marmorated stinkbug, *Halyomorpha halys*: an increasing threat to field, fruit and vegetable crops worldwide. Journal of Pest Science 88: 665–673.

Haye T, Weber DC. 2017. Special issue on the brown marmorated stink bug, Halyomorpha halys: An emerging pest of global concern. Journal of Pest Science 90: 987–988.

Inkley DB. 2012. Characteristics of home invasion by the brown marmorated stink bug (Hemiptera: Pentatomidae). Journal of Entomological Science 47: 125–130.

Kriticos DJ, Kean JM, Phillips CB, Senay SD, Acosta H, Haye T. 2017. The potential global distribution of the brown marmorated stink bug, *Halyomorpha halys*, a critical threat to plant biosecurity. Journal of Pest Science 90: 1033–1043.

Leskey TC, Hamilton GC, Nielsen AL, Polk DF, Rodriguez-Saona C, Bergh JC, Herbert DA, Kuhar TP, Pfeiffer D, Dively GP, et al. 2012. Pest Status of the Brown Marmorated Stink Bug, *Halyomorpha halys* in the USA. Outlooks on Pest Management 23: 218–226.

Levins R. 1969. Some Demographic and Genetic Consequences of Environmental Heterogeneity for Biological Control. Bulletin of the ESA 15: 237–240.

Liebhold AM, Tobin PC. 2008. Population ecology of insect invasions and their managemen. Annual Review of Entomology 53: 387–408.

Macavei L, Băețan R, Oltean I, Florian T, Varga M, Costi E, Maistrello L. 2015. First detection of *Halyomorpha halys*, a new invasive species with a high potential of damage on agricultural crops in Romania. Lucrari Stiintifice Seria Agronomie 58: 105–108.

Maistrello L, Dioli P, Bariselli M, Mazzoli GL, Giacalone-Forini I. 2016. Citizen science and early detection of invasive species: Phenology of first occurrences of *Halyomorpha halys* in Southern Europe. Biological Invasionsasions 18: 3109–3116.

Maistrello L, Dioli P, Vaccari G, Nannini R, Bortolotti P, Caruso S, Costi E, Montermini A, Casoli L, Bariselli M. 2014. Primi rinvenimenti in Italia della cimice esotica *Halyomorpha halys*, una nuova minaccia per la frutticoltura. Pages 283–288 in Atti delle Giornate Fitopatologiche, vol. 1. CLUEB.

Maistrello L, Vaccari G, Caruso S, Costi E, Bortolini S, Macavei L, Foca G, Ulrici A, Bortolotti PP, Nannini R, et al. 2017. Monitoring of the invasive *Halyomorpha halys*, a new key pest of fruit orchards in northern Italy. Journal of Pest Science 90: 1231–1244.

Maurel JP, Blaye G, Valladares L, Roinel E, Cochard PO. 2016. *Halyomorpha halys* (Stål, 1855), la punaise diabolique en France, à Toulouse (Heteroptera; Pentatomidae). Carnets natures 3: 21–25.

Mityushev IM. 2016. First record of marmorated bug detection in Russia. Zashchita i Karantin Rasteniĭ 3: 48.

Nielsen AL, Chen S, Fleischer SJ. 2016. Coupling developmental physiology, photoperiod, and temperature to model phenology and dynamics of an invasive heteropteran, *Halyomorpha halys*. Frontiers in Physiology 7: 165.

Rabitsch W, Friebe GJ. 2015. From the west and from the east? First records of *Halyomorpha halys* (Stål, 1855)(Hemiptera: Heteroptera: Pentatomidae) in Vorarlberg and Vienna. Beitr. Entomof. 16: 115–139.

Ross S. 1996. Stochastic Processes. 2nd Edition. Ch. 4, Pages 163–230. Wiley.

Ruberson JR, Takasu K, David Buntin G, Eger JE, Gardner WA, Greene JK, Jenkins TM, Jones WA, Olson DM, Roberts PM, et al. 2013. From Asian curiosity to eruptive American pest: Megacopta cribraria (Hemiptera: Plataspidae) and prospects for its biological control. Applied Entomology and Zoology 48: 3–13.

Šeat J. 2015. *Halyomorpha halys* (Stål, 1855; Heteroptera: Pentatomidae) a new invasive species in Serbia. Acta Entomologica Serbica 20: 167–171.

Shigesada N, Kawasaki K, Takeda Y. 1995. Modeling stratified diffusion in biological invasions. American Naturalist 146: 229–251.

Simov N. 2016. The invasive brown marmorated stink bug *Halyomorpha halys* (Stål,1855; Heteroptera: Pentatomidae) already in Bulgaria. Ecologica Montenegrina 9: 51–53.

Starr J, Schweik CM, Bush N, Fletcher L, Finn J, Fish J, Bargeron CT. 2014. Lights, camera … citizen science: Assessing the effectiveness of smartphone-based video training in invasive plant identification. PLOS ONE 9 (art. e111433).

Toyama M, Ihara F, Yaginuma K. 2011. Photo-response of the brown marmorated stink bug, *Halyomorpha halys* (Stål; Heteroptera: Pentatomidae), and its role in the hiding behavior. Applied Entomology and Zoology 46: 37–40.

USDA-NIFA SCRI. 2017. Stop BMSB. Biology, ecology, and management of brown marmorated stink bug in specialty crop. Stop BMSB. http://www.stopbmsb.org.

Wallner AM, Hamilton GC, Nielsen AL, Hahn N, Green EJ, Rodriguez-Saona CR. 2014. Landscape factors facilitating the invasive dynamics and distribution of the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), after arrival in the United States. PLOS ONE 9 (art. e95691).

Wiman NG, Walton VM, Shearer PW, Rondon SI, Lee JC. 2014. Factors affecting flight capacity of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). Journal of Pest Science 88: 37–47.

Lara Maistrello is a researcher and professor in general and applied entomology at the University of Modena and Reggio Emilia, in Reggio Emilia, Italy. Paride Dioli is an insect taxonomist at the Natural History Museum of Milan, Italy. Moreno Dutto is an entomologist consultant in urban and agricultural entomology. Stefania Volani is a research fellow specialized in GIS at the University of Brescia, Italy. Sara Pasquali is a researcher in probability and mathematical statistics at the CNR-IMATI of Milan. Gianni Gilioli is an associate professor in general and applied entomology at the University of Brescia.