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

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Key words:	invasive species, citizen science, crop and nuisance pest, population abundance, Brown Marmorated Stink Bug
Abstract:	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. Yet, 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 crop-threatening pests globally. A four-year survey that combined active search and a crowdsourcing approach, made the tracking of its spread and investigation of its spatio-temporal dynamics possible, showing the functionality of coordinated multi-actor approach in data collection.

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

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Abstract

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. Yet, in order to obtain good-quality data,

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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 crop-threatening pests globally. A four-year survey that combined active search and a crowdsourcing approach, made the tracking of its spread and investigation of its spatio-temporal dynamics possible, showing the functionality of coordinated multi-actor 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

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introduced pest are essential to phytosanitary officers and agricultural stakeholders to undertake timely decisions on their management.

Many stink/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 non-professionals in the process of creating new scientific knowledge, offer the great advantage of obtaining datasets that would otherwise be infeasible to generate (Bonney et al. 2014). Examples of using crowdsourcing dataset to detect new alien species early and to monitor their spread in newly-invaded areas are provided by Bodilis et al. (2014) and Andow et al. (2016).

The present study is the outcome of a four-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 dataset, we were able to obtain the map 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 where records were gathered intensively with constant effort, we derived information on the spatio-temporal 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

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crops. It is also a dwelling nuisance, due to 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 on 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, as 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:

1) Involvement of volunteers via multimedia channels (details 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 send/email them to the survey coordinators (L. Maistrello,

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P. Dioli, M. Dutto), together with details on the collection/sighting. Volunteers were solicited by: a) issuing press-releases (once a year, in early autumn) published in many paper/online newspapers; b) 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; c) issuing specific extension flyers, distributed in public areas and also published on the websites of regions and municipalities; d) alerting professional and amateur entomologists, naturalists, photographers, using social networks and specific web forums; e) organizing public conferences; f) giving interviews for local broadcasting units and newspapers; g) 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/naturalists, allowed the study to reach a considerable amount of people (more than 1500), particularly from northern Italy.

2) 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/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 used also 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.

3) 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, presence of BMSB was checked by purposely-trained PPOs personnel in April-September 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 ha in size)

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where the crop was close (< 20 m) 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/farm) baited with aggregation pheromones lures (Rescue®, Sterling International Inc., Spokane, WA) were used as monitoring techniques.

Data validation

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

Data organization

All records were stored in a database indicating: a) date of collection; b) geographic information (locality and street); c) number of specimens observed/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); d) context of detection (open field = crops or uncultivated land; rural = isolated country farmhouses; country village = small residential area in the countryside; urban = cities with a population of over 45,000 inhabitants; wild = forests, natural parks/reserves); e) place of detection (house/building, terrace, urban green, garden-vegetable garden, crop, park, means of transport); f) plant species, if the bug was found on plants; h) detector name and category (researcher = investigator in university or other research institution; museum = natural history museums

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personnel; ento/nat = entomologist/naturalist; phytosan = phytosanitary services personnel; student = university student; farmer; citizen = citizen not belonging to previous categories); i) additional observations if any. For each year, the positive records were used to obtain the percentages of occurrence of BMSB according to: a) the occurrence in different seasons; b) the presence in different contexts and places; c) the category of the survey participants.

Data analysis

Collected data were imported into a geographic information system using QGIS 2.18 software in order to obtain a map of all the records. To investigate the spatio-temporal pattern of BMSB invasion in Italy, a 150 x 304 km area was considered and adopted as 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) where the pest was originally reported in Italy and where 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. Data falling within the study area and used for the spatio-temporal analysis range 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 x 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 the

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points belonging to that cell rounded to the nearest integer. A cell with no population (state 0) is considered Empty (E), while 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 is 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. Based on the BMSB activity, the within-year occupancy dynamics is followed between April and September (the favorable season). All the data reported from September of a year to March of the following year are considered as estimates of the population abundance at the end of the favorable season, since the sampled BMSB in autumn and winter are overwintering individuals. Therefore, the occupancy in September of a year is the sum of all 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 one year) has been performed. Denoting by X_n the abundance state of a cell at year n, X_n can take 5 possible values: 0, 1, 2, 3, 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).

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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 records) and that central Italy records a few occurrences (1.6% of the survey), whereas only occasional records (0.4%) are reported for southern Italy and in the islands, showing a huge increase compared to the initial investigation, that 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 are concentrated along the main road/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 US (Wallner et al. 2014). BMSB was also reported at high altitudes (1100-1830 m a.s.l.) 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 highlighted by Acebes-Doria et al. (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

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bugs are easily noticeable within buildings by all people in any setting. Summer was the second best season for BMSB detection, as the present study also included records from the phytosanitary personnel (see supplemental figures S4), whereas in a crowdsourcing survey by Hahn et al. (2016), records were lowest in summer, since the majority of citizen reports were from homeowners.

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; afterwards the cases involving crops started to increase and peaked in 2016. Occurrences in green areas were similar over all years. Compared to Maistrello et al. (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 hitch-hiking aliens

Overall, BMSB was detected 22 times inside cars, 5 times in train stations, one in a port and one in an airport (figure 3). The detection along main roads and/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/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 US, intercepted both in New Zealand (Ken Glassey, Biosecurity and Environment Group, Ministry for

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Primary Industries, New Zealand, personal communication, since 9 February 2016 on) and in Australia (Adam Broadley, Department of Agriculture and Water Resources, Australia, personal communication, since 19 September 2016 on), 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 hitch-hiking, thus 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, e. g., *Megacopta cribraria* Fabricius (Plataspidae), a native Asian stinkbug that threatens legumes and other horticultural crops in the USA (Ruberson et al. 2013).

Spatio-temporal 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 to fit the within-year data (considered in the period April of a year – March of the following year). Since 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, while it is near 1 for 2016. This is due to the fact that, in the last case, the dataset taken into consideration is limited to 7 December 2016. Thus, the number of occupied cells in September 2016 is underestimated. The fact that the number of occupied cells towards 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.

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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 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.

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 to the previous year. Using data projected for 2016-2017 we have again estimated the exponential

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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 considerations:

a) Transition probabilities, as expected in an initial phase of invasion, are time-dependent leading to a time inhomogeneous Markov chain.

b) For all 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 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, since 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.

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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/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, as besides curiosity and understanding the importance of the study, they engage in a competition as "who best notices this 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, as 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.

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

The crowdsourcing approach presents issues related to data reliability, since 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 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 since 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 dataset 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 to 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 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 the necessary details, guaranteeing the accuracy of the dataset, also useful for the analysis of the spread patterns. 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

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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. Thus, 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 et al. (2016) in a project of invasive species detection, who noticed that volunteers who experienced a learning module were more likely to recruit new volunteers than those that received an invitation letter.

Usually citizen science data are focused on reporting the occurrence of the species, without taking into account the abundance, as in a study by Hahn et al. (2016). An example of integration of citizen science based on presence/absence data with other techniques is given by Fletcher et al. (2016). In our survey we moved a step forward, also taking into account the magnitude of infestation for the analysis of the spatio-temporal spread of this invasive pest. Availability of abundance data allowed the estimation of the time lag of four 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 like 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.

Conclusion

The present work demonstrated the functionality of the multi-actor 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 dataset with the data

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obtained by the stakeholders (PPOs, farmers) integrated with those obtained by researchers, naturalists, students and citizens allowed us to obtain information on the spatio-temporal 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. Further 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 spatio-temporal 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.

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Figure captions

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

Figure 2. Relative percentage of *Halyomorpha halys* detected on different landscape contexts for each year of the survey. Numbers on top of columns indicate the total number of records for each period.

Figure 3. Relative percentage of *Halyomorpha halys* detected on different places for each year of the survey. Numbers on top of columns indicate the total number of records for each period.

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

Figure 5. Between-year change in the number of cells occupied by *Halyomorpha halys* population

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in the study area. The occupancy is fitted with an exponential curve. Asterisks represent the total number of the occupied cells in the period April of a year – March of the next year, that is the number of cells occupied in September of every year appearing in figure 4.

Figure 6. Exponential fit of number of cells occupied by *Halyomorpha halys* population in the study area in the period 2016-2017. The number of cells occupied in September is obtained as projection of the exponential fit in figure 5.

Figure 7. Relative percentage of *Halyomorpha halys* detected by the different categories of participants, for each year of the survey. Numbers on top of columns indicate the total number of records for each period.

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Tables

Table 1. Features of the dataset used for the study. Positive records = validated as *Halyomorpha halys;* Negative records = cases of misidentified species or cases where *Halyomorpha halys* was actively searched but never detected in the considered period.

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

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Table 2. Transition matrices of *Halyomorpha halys* population abundance from a year to the next in the period 2013/2014 to 2016. The first number in cell (*i*, *j*) to move from state *i* to state *j*; the number in brackets denotes the number of cell that moves from state *i* to state *j* that has been used to compute the corresponding transition probability.

Transition matrix from year 2013/2014 to 2014/2015					
STATE	*j*=0	*j*=1	*j*=2	*j*=3	*j*=4
i=0	0.5714 (4)	0.4286 (3)	0	0	0
i=1	0.05 (1)	0.15 (3)	0.4 (8)	0.25 (5)	0.15 (3)
i=2	0	0.6667 (4)	0.1667 (1)	0.1667 (1)	0
i=3	0.1667 (1)	0	0.1667 (1)	0.5 (3)	0.1667 (1)
i=4	0	1 (1)	0	0	0
Transition matrix from year 2014/2015 to 2015/2016					
STATE	*j*=0	*j*=1	*j*=2	*j*=3	*j*=4
i=0	0.875 (7)	0.125 (1)	0	0	0
i=1	0.05 (1)	0.35 (7)	0.2 (4)	0.3 (6)	0.1 (2)
i=2	0.05 (1)	0.2 (4)	0.35 (7)	0.3 (6)	0.1 (2)
i=3	0	0	0.1429 (1)	0.8571 (6)	0
i=4	0	0	0	0	1 (2)
Transition matrix from year 2015/2016 to 2016					
STATE	*j*=0	*j*=1	*j*=2	*j*=3	*j*=4
i=0	0	0	0	0.5 (1)	0.5 (1)
i=1	0	0.2308 (3)	0.3077 (4)	0.2308 (3)	0.2308 (3)
i=2	0	0.125 (1)	0.375 (3)	0.375 (3)	0.125 (1)
i=3	0	0.2 (1)	0	0.4 (2)	0.4 (2)
i=4	0	0	0.3333 (1)	0.3333 (1)	0.3334 (1)

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Table 3. Number of cells (and percentage of cells) in each state in different years. The number of cell in state *i* is given by the number of cell classified with *i* in the year considered.

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

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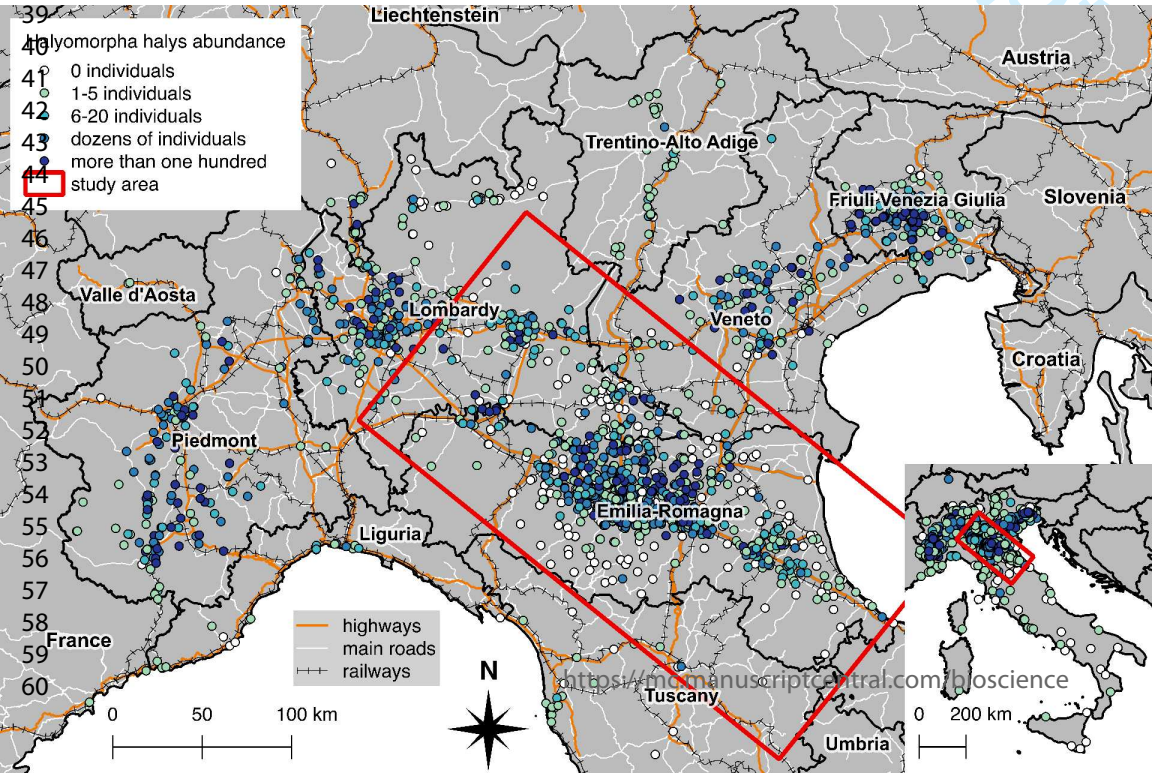
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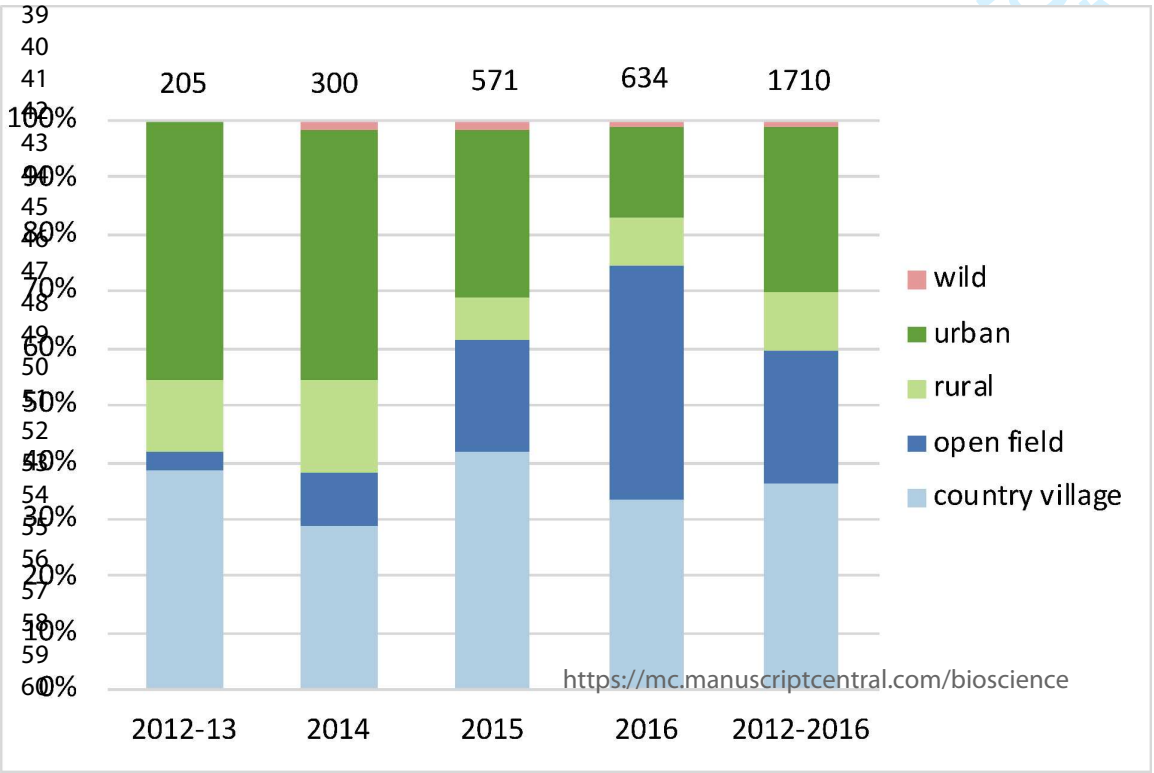
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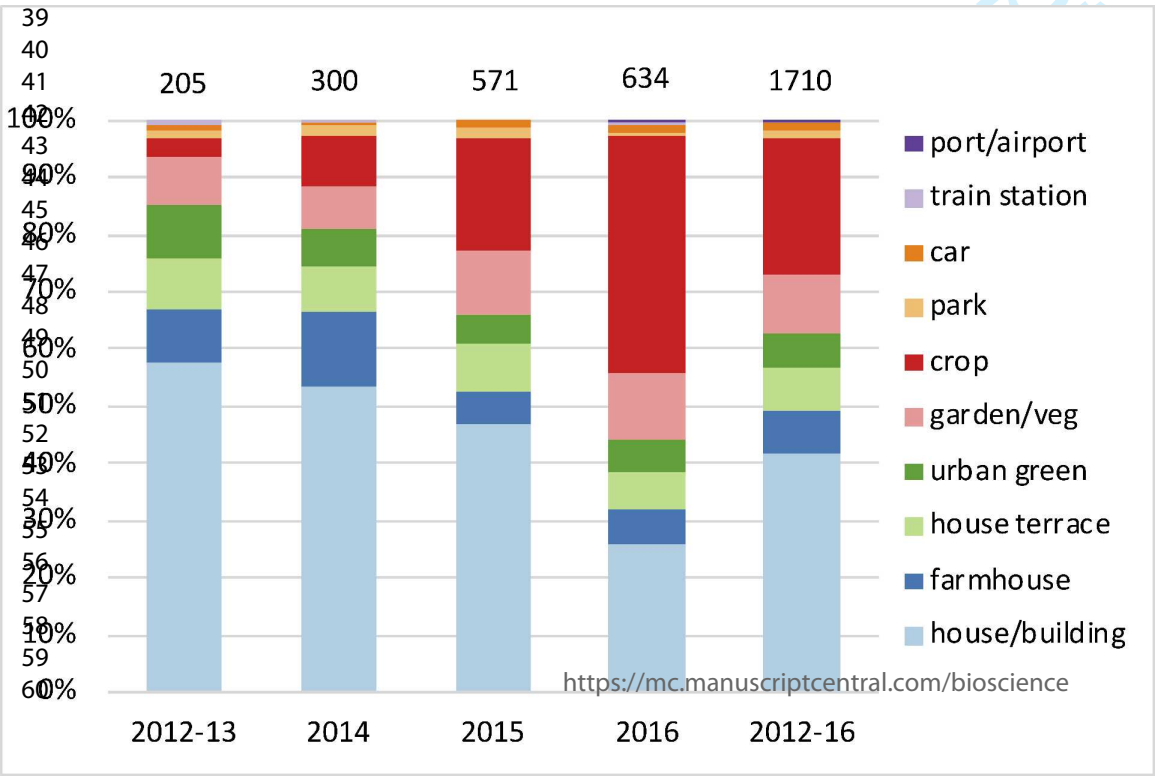


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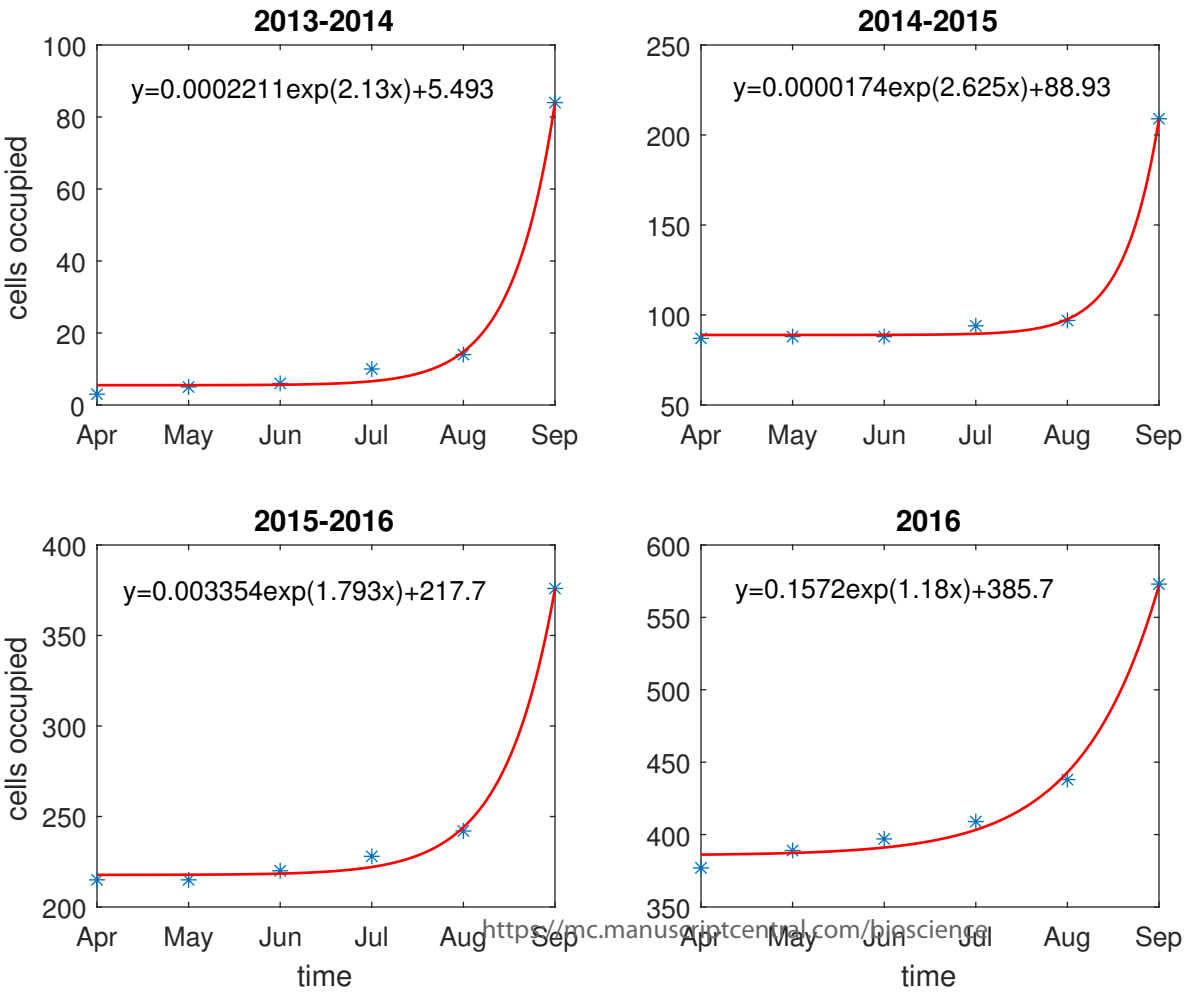
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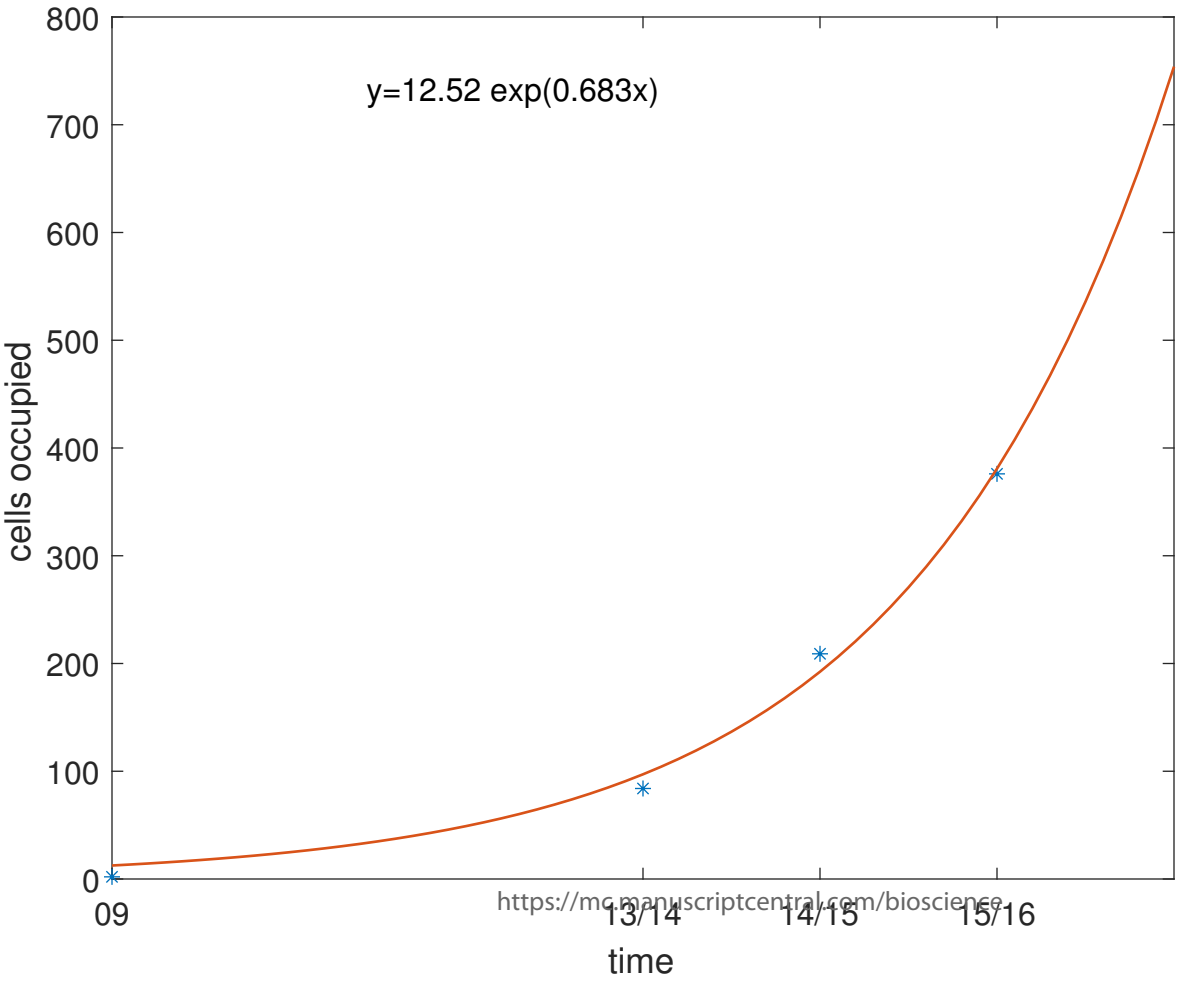


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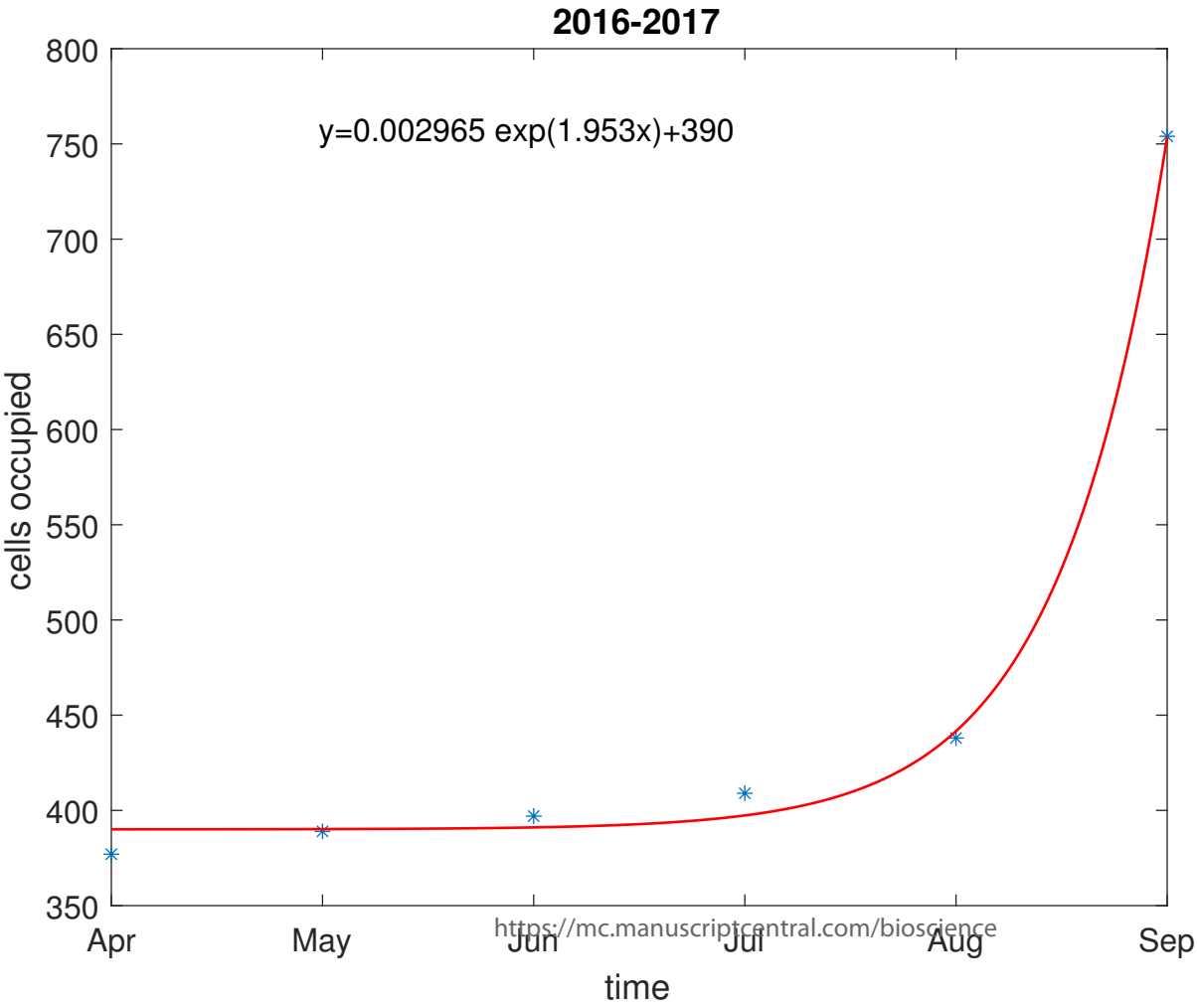
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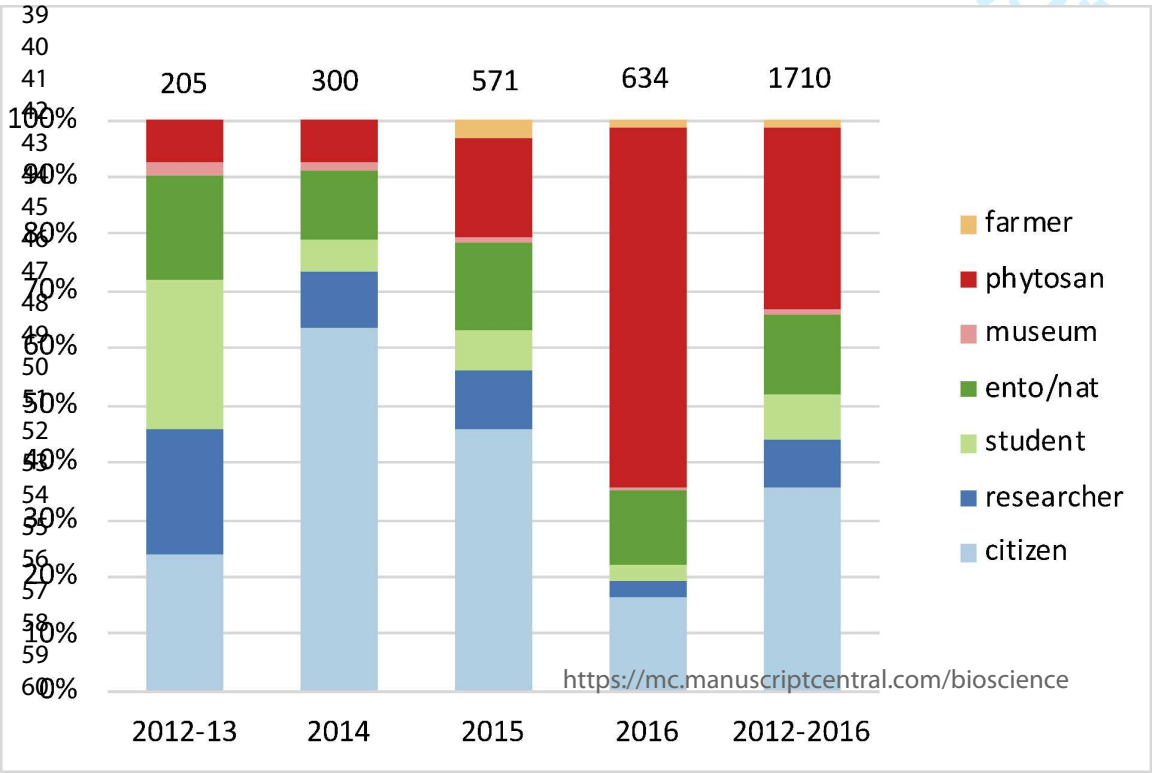


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S1

- Supplemental material for: BioScience
- Title: Tracking the spread of sneaking aliens by integrating crowdsourcing and spatial modelling: the Italian invasion of *Halyomorpha halys*
- Authors: Lara Maistrello, Paride Dioli, Moreno Dutto, Stefania Volani, Sara Pasquali, Gianni Gilioli
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Details on the crowdsourcing actions using multimedia channels

Type of action	Responsible of the action	Time frame	Initial territorial range	Target	Impact
a) issuing press-releases, published also on the UNIMORE website	UNIMORE[a] press office	once a year, in early autumn	local (Modena and Reggio Emilia cities) and nation-wide	all national and local press/online newspapers; offices of television networks; UNIMORE personnel and students; general public	- mainly local in the 1st year, northern Italian regions in the 2nd-3rd year, national in the 3rd-4th year; - website impact[b]
b) publishing alerts on the respective websites with a specific downloadable form with the request for all information	- Regional Plant Protection Service of Emilia-Romagna; - municipalities; - sanitary offices	since 2013 on	mainly regional (Emilia-Romagna)	farmers, IPM technicians and other plant protection stakeholders, general public	- on the 1st year only close to areas of first detection, then gradually extended to close by areas: since 2014 in nearby northern Italian regions (Piedmont, Lombardy, Veneto, Friuli-Venezia Giulia, Trentino) - website impact[b]
c) issuing specific extension flyers, distributed in public areas, also published on the websites reported in b)	Regional Plant Protection Service of Emilia-Romagna	2013-2014	regional (Emilia-Romagna region)	farmers, IPM technicians and other plant protection stakeholders, general public	- regional (Emilia-Romagna region) - website impact[b]
d) using social networks and specific web forums to alert and intercept the posts of entomologists, naturalists, nature photographers	- the survey coordinators and the moderators of the forums	since 2013 on	mainly national	professional and amateur entomologists, naturalists, nature photographers	- national - website impact[b]

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e) organizing public conferences	- Regional Plant Protection Service of Emilia-Romagna; - local affiliations of plant protection services - other plant protection stakeholders (associations of IPM technicians and/or farmers)	since 2013 on	regional (Emilia-Romagna region)	farmers, IPM technicians and other plant protection stakeholders, general public	on the 1st year only close to areas of first detection, then gradually extended to close by areas: since 2014 in nearby northern Italian regions (Piedmont, Lombardy, Veneto, Friuli-Venezia Giulia, Trentino)
f) giving interviews for local broadcasting units and newspapers, also published on the respective websites	local broadcasting units and newspapers	since 2013 on	regional (Emilia-Romagna region) and nearby provinces in northern Italian regions	general public	- regional (Emilia-Romagna region) and nearby provinces in northern Italian regions - website impact[b]
g) collecting reports by the public health services and the Italian Forestry Corps	the survey coordinators	since 2013 on	regional (Emilia-Romagna and Piedmont) for public health services; national for the Italian Forestry Corps	general public	mainly northern Italian regions

[a]UNIMORE= University of Modena and Reggio Emilia

[b]All the cited websites are public and available to anybody. They were accessed mainly at local level but could be accessed virtually by anybody in the world

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S2

• Supplemental material for: BioScience
• Title: Tracking the spread of sneaking aliens by integrating crowdsourcing and spatial modelling: the Italian invasion of *Halyomorpha halys*
• Authors: Lara Maistrello, Paride Dioli, Moreno Dutto, Stefania Volani, Sara Pasquali, Gianni Gilioli
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Descriptive features of BMSB occurrence

The negative records with misidentified species were related to *Rhaphigaster nebulosa* (54%), followed by *Nezara viridula* (22%), *Arma custos* (4%) and other pentatomids.

Most detections occurred in Emilia-Romagna (48% of total detections), with most records of highest abundance concentrated along the main highway/road/railway line that cross the region from southeast to northwest, in open field crops (mainly the fruit orchards typical of this area: pear, apple, peach, grapevine) and in the adjacent countryside villages in the northern part of the region.

In Lombardy (19% of total detections), cases with the highest abundance occurred mainly in the urban areas of Milan and Brescia, and along the lines connecting Italy to Switzerland. It seldom occurred in open field crops (pear, peach, apple, soybean, corn, small red fruits, grapevine, hazelnut, pepper).

In Friuli-Venezia Giulia (10% of total detections) and Veneto (6% of total detections), where *Halyomorpha halys* was first detected in 2014, most of the records with highest abundance were from crops (mostly apple/pear/kiwifruit orchards and soybean) and nearby countryside villages.

In Emilia-Romagna, Veneto and Lombardy, records of high abundance and crop damage were detected also in olive grows.

In Piedmont (10% of total detections), the highest abundance records were in the urban area of Turin and in the urban greenery (*Paulownia* sp. and *Clerodendrum trichotorum* are ornamental

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species with high presence of BMSB) and open field crops of the province of Cuneo (peaches/nectarines, nashi, apple, pears, cherry, hazelnut, small red fruits, corn, pepper, bean, corn). In this region, the species was detected also at high altitudes in Valle Maira (1155 m a.s.l.), Valle Varaita (1828 m a.s.l.), Valle Vermenagna (1465 m a.s.l.), and Valle Roya (1200 m a.s.l.). In the first three sites the findings were related to adults detected in summer in touristic areas close to the parking lots for cars and campers, whereas in Roya valley adults and nymphs were detected on the building material inside a construction site on *Arthemisia* sp plants and nearby.

The records from Trentino-Alto Adige (3% of total detections) are all related to 2016 and they were found in the packaging of phytosanitary products produced in Lombardy and along the main line crossing the region, particularly inside the traps in apple orchards.

Regarding central Italy, in Tuscany (1% of total detections), where first records date back to 2015, most cases are from Livorno city and Pisa countryside and the highest abundance record is in the city of Florence. In Lazio (0.35 % of total detections), three records are from the city of Rome since 2015, and three records from the province of Latina. Single BMSB individuals were detected also in Abruzzo (2014) and in Marche (2015) regions.

Regarding southern Italy, in Apulia (Barletta) one BMSB was spotted at a train station; in Campania one BMSB was detected in Naples airport; in Calabria (Catanzaro) one BMSB was found in the countryside; in Sicily, one BMSB was found during the unpacking of appliances manufactured from northern Italy; in Sardinia BMSB was detected inside two different houses (Dioli et al. 2016).

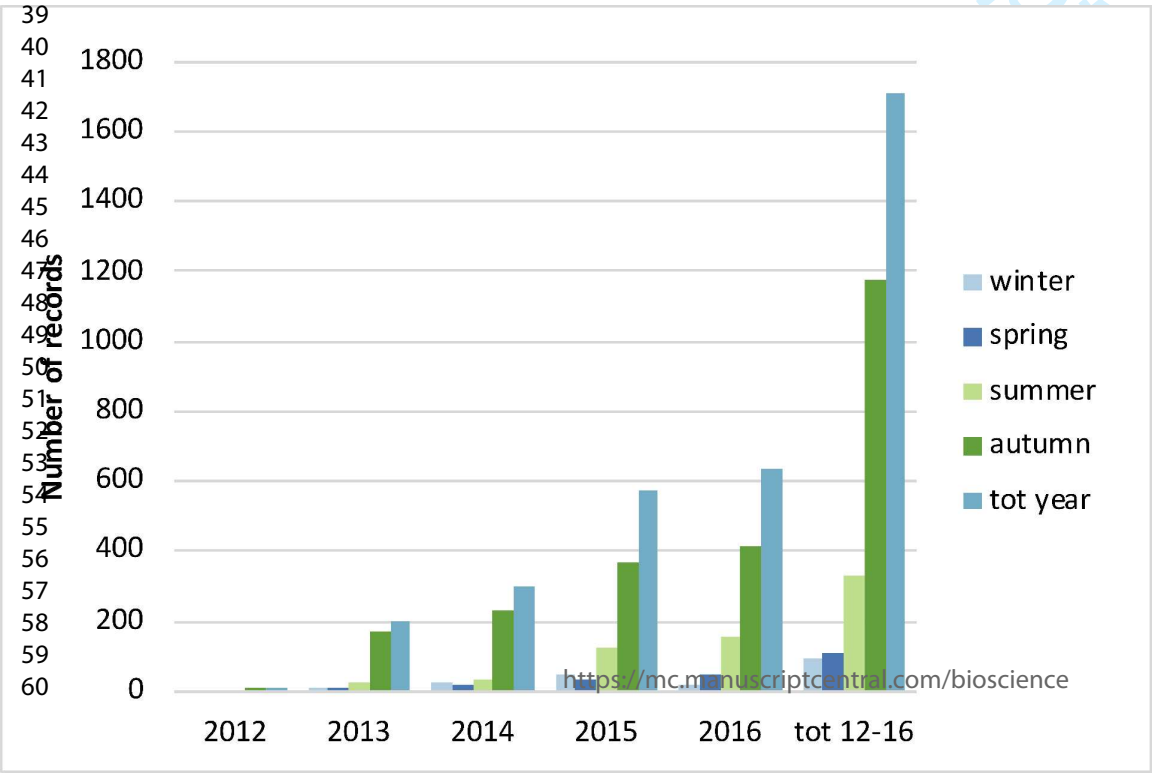
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S3

- Supplemental material for: BioScience
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- Authors: Lara Maistrello, Paride Dioli, Moreno Dutto, Stefania Volani, Sara Pasquali, Gianni Gilioli
- Corresponding author: Gianni Gilioli E-mail: gianni.gilioli@unibs.it, Phone +39 030 3717712, Fax+39 030 3717409

Number of validated positive records of *Halyomorpha halys* according to the year and season of detection

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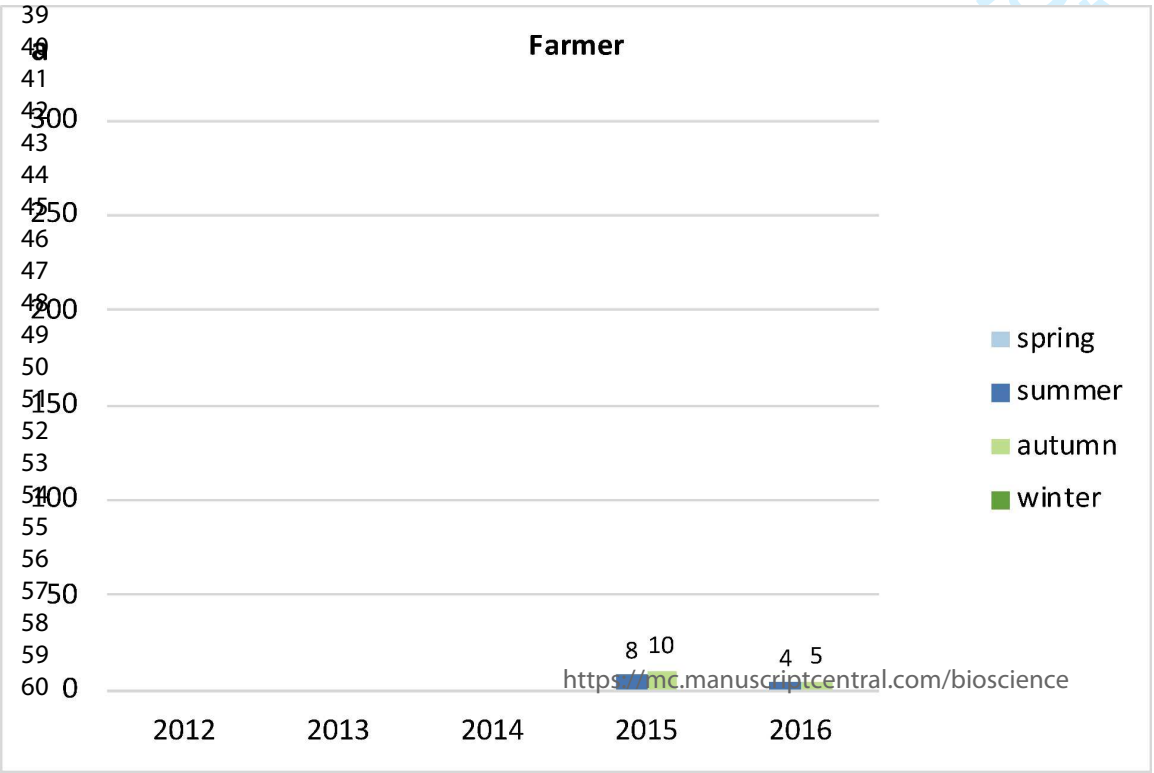
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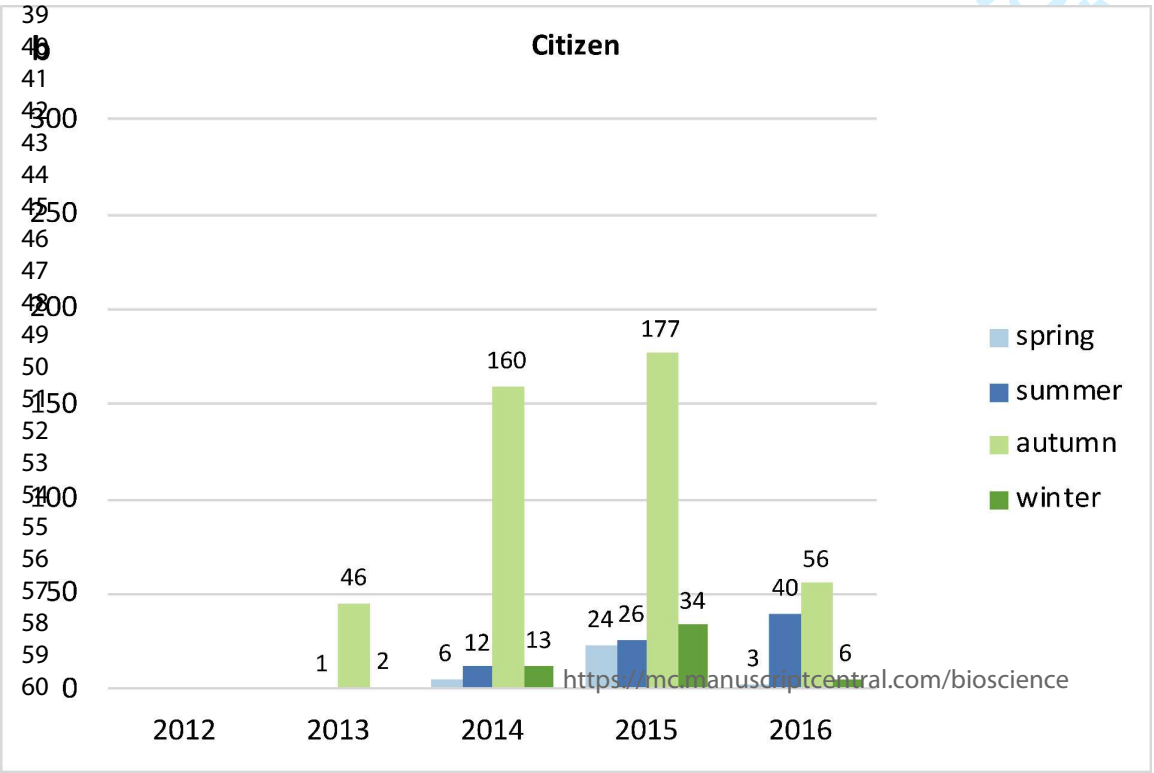
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Number of records by detector category according to year and season

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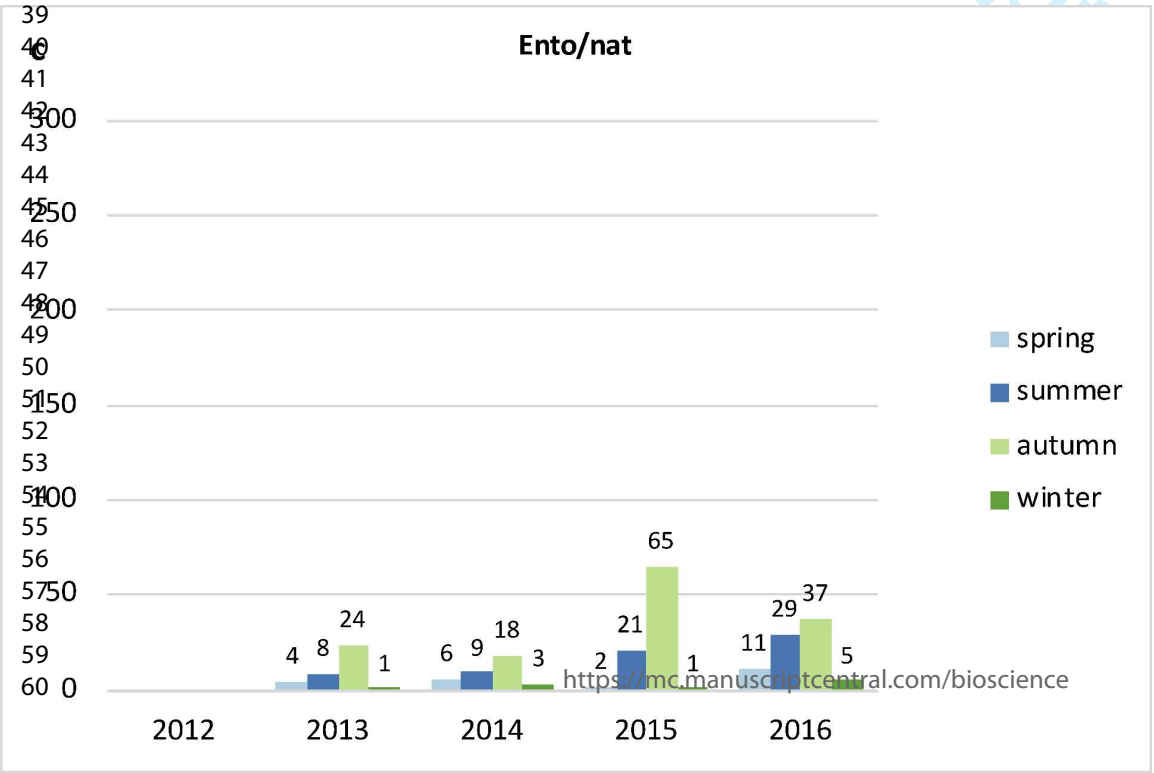


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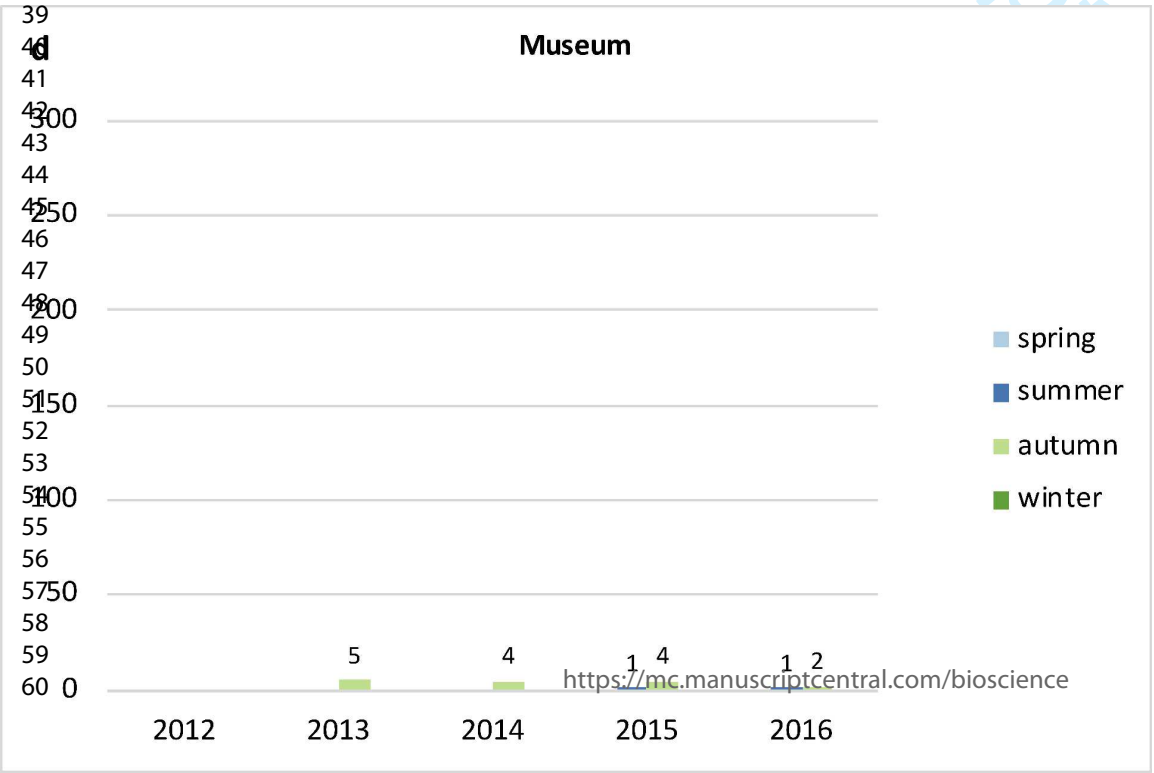


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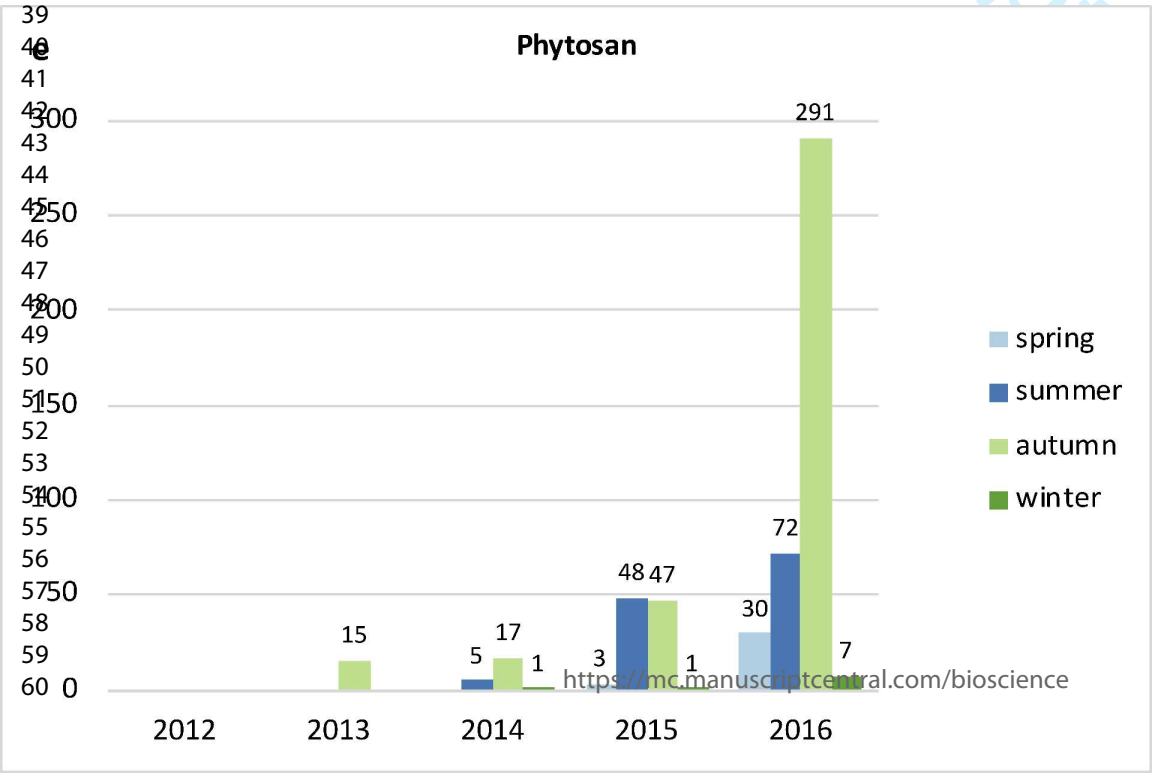
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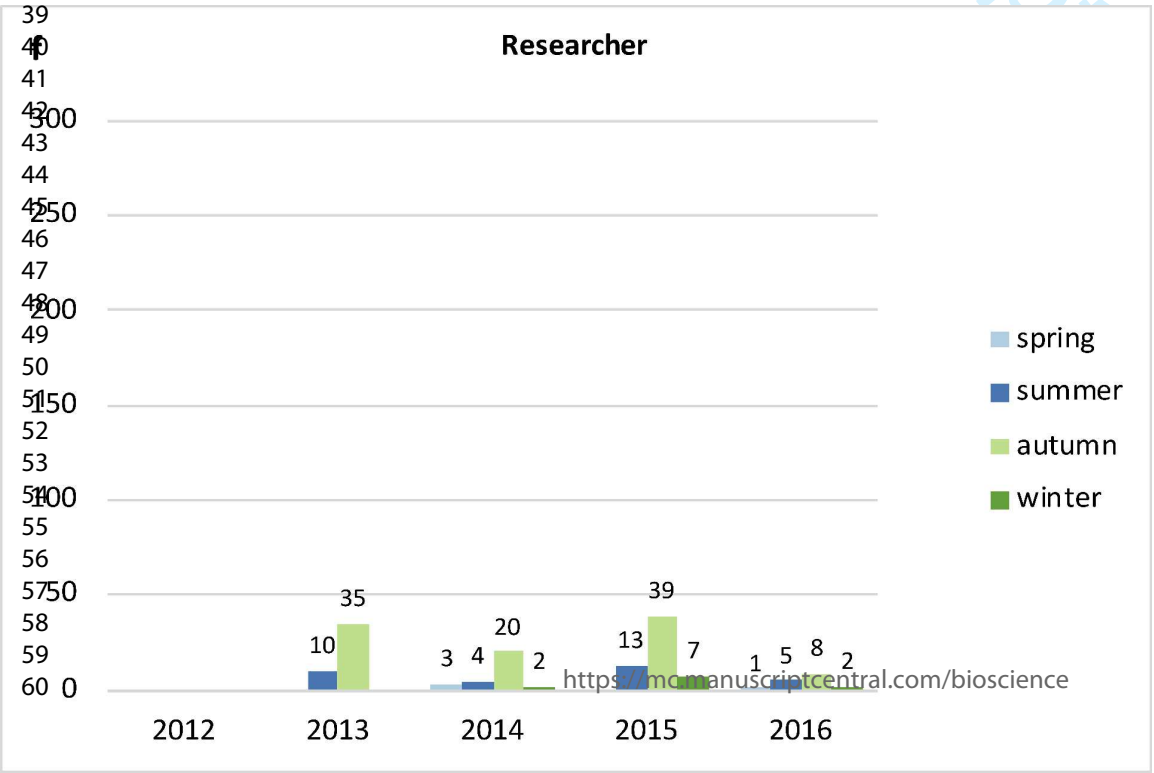
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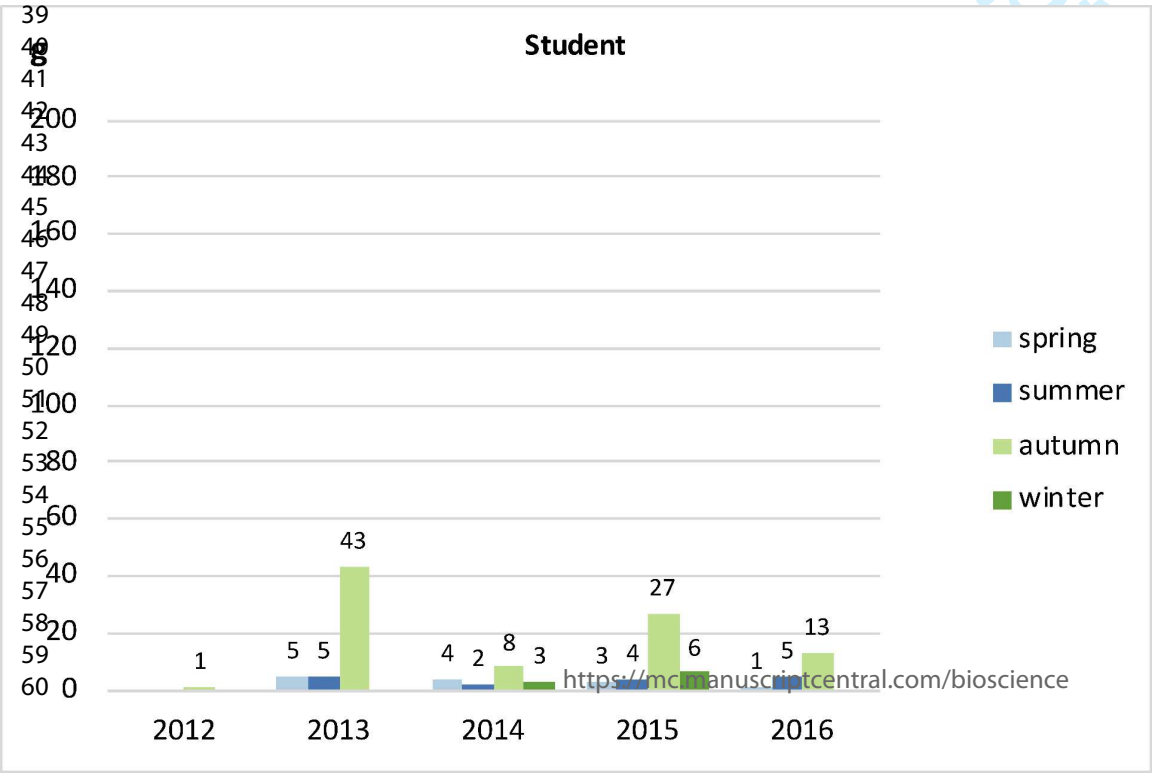


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