

Communication

Monitoring 2.0: Update on the *Halyomorpha halys* Invasion of Trentino

Robert Malek ^{1,2,*} , Livia Zapponi ² , Anna Eriksson ², Marco Ciolli ^{1,3}, Valerio Mazzoni ² , Gianfranco Anfora ^{2,3} and Clara Tattoni ^{1,4} 

¹ Department of Civil, Environmental and Mechanical Engineering, University of Trento, 38123 TN, Italy; marco.ciolli@unitn.it (M.C.); clara.tattoni@unitn.it (C.T.)

² Research and Innovation Center, Fondazione Edmund Mach, San Michele all'Adige, 38010 TN, Italy; livia.zapponi@fmach.it (L.Z.); anna.eriksson@fmach.it (A.E.); valerio.mazzoni@fmach.it (V.M.); gianfranco.anfora@unitn.it (G.A.)

³ Center for Agriculture, Food and Environment (C3A), University of Trento, San Michele all'Adige, 38010 TN, Italy

⁴ Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, University of Florence, 50144 FI, Italy

* Correspondence: robertnehme.malek@unitn.it; Tel.: +39-0461-615-509

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Abstract: “BugMap” is a citizen science mobile application that provides a platform for amateur and expert scientists to report sightings of two invasive insect pests, the tiger mosquito *Aedes albopictus* Skuse (Diptera: Culicidae) and the brown marmorated stink bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae). The latter is a notorious pest of fruit trees, vegetables, ornamentals, and row crops, inflicting severe agricultural and ecological disturbances in invaded areas. Our approach consists of coupling traditional monitoring with citizen science to uncover *H. halys* invasion in Trentino. The project was initiated in 2016 and the first results were reported in 2018. Here, we revisit our initiative four years after its adoption and unravel new information related to the invader dispersal and overwintering capacity. We found that our previous model predicted the current distribution of *H. halys* in Trentino with an accuracy of 72.5%. A new MaxEnt model was generated by pooling all reports received so far, providing a clearer perspective on areas at risk of stink bug establishment in this north Italian region. The information herein presented is of immediate importance for enhancing monitoring strategies of this pest and for refining its integrated management tactics.

Keywords: citizen science; northern Italy; invasive insect pests; crowdsourcing; long-term monitoring; brown marmorated stink bug

1. Introduction

Disentangling a species' invasion requires extensive sampling and surveys across large spatial and temporal scales, which can be challenging and costly for a small group of scientists trying to track invasive species. Citizen science is a potentially powerful means to overcome some of these challenges, whereby it enlists the public in collecting a large amount of data across an array of habitats and locations [1]. Another major strength of citizen science is that it can aid in raising public awareness regarding local ecological issues and promote a more active scientific citizenship [2]. Catalyzed by access to technology and the internet, citizen science is on the rise, with thousands of projects worldwide [3], yet, few involve agricultural pests [4]. Numerous projects have been initiated in the USA and UK to monitor the species richness of “Lady Beetles” [5–7]. Another example is the Monarch Larva Monitoring Project (MLMP), a trinational long-term project concerning the monarch

butterfly, *Danaus plexippus* that involves volunteers from across the United States, Canada, and Mexico in monarch research [8].

The brown marmorated stink bug *Halyomorpha halys* is an invasive pest that feeds on over 300 plants including economically important fruit trees, vegetables, and row crops as well as ornamentals [9,10]. This insect is native to Eastern Asia, but its occupied range has expanded outside of its areas of origin, probably due to global anthropogenic forcing [11], thus spreading through most of the United States, Canada, and numerous European and Eurasian countries [12]. In the Southern Hemisphere, it has been recorded in Chile [13] and intercepted many times in Australia [14] and New Zealand [15]. Feeding by *H. halys* results in deformed, symptomatic produce with indents on the surface and corky spots in the flesh, hampering marketability [16]. Severe crop losses have been registered in the USA and Europe, reaching millions of dollars per year [17] as well as serious nuisance problems due to large *H. halys* aggregations in man-made structures [18]. Some of the most acute agricultural and nuisance problems were recorded in Italy [19,20]. Aside from its polyphagy, *H. halys* is capable of long-distance flight [21] and hitchhiking on both animate and inanimate objects alike, making it a harder to control and monitor landscape level pest.

About four years ago, we attempted to couple traditional monitoring strategies with a citizen science approach, whereby students, farmers, technicians, and everyday citizens could report sightings of *H. halys* via ‘BugMap’, a freely available mobile application. The collected data were then employed to forecast its predicted distribution and to identify areas at risk in Trentino, instructing technical monitoring and management efforts. This tactic permitted the uncovering of *H. halys* seasonal invasion dynamics, phenological patterns, and potential management methods in this North Italian region. Monitoring 2.0: coupling traditional monitoring and citizens science, has thus proved effective in unraveling *H. halys* invasion in Trentino [22]. The objective of this update is to utilize the newly recorded data points to verify the accuracy of our previously calculated model on the projected distribution of the invasive bug in Trentino. We also reveal new information regarding the seasonal activity of the bug, namely its overwintering capacity in areas of high economic interest. We also aimed to verify and highlight the far-reaching capacity of citizen science in such an initiative, spanning all Italian territories.

2. Materials and Methods

2.1. Study Area and BugMap Campaign

Our study focuses on Trentino, North Eastern Italy, which is characterized by a continental climate, covering 6214 km² south of the Alps. The BugMap team has been generally advertising for the mobile application across the whole of Italy, with special attention to Trentino. Several social media platforms were used to actively disseminate information on the pest and the application, thus engaging followers year-round. This initiative was further circulated in several scientific and socio-technical events that took place in museums as well as national and international conferences (Table 1).

Table 1. A summary of main events revolving around the BugMap campaign.

Type of Event	Audience	Interactions
Social media platforms	Local and International users	- BugMap Facebook: https://www.facebook.com/Bugmap-1926843807640177/ - BugMap Instagram: #bugmap #citizenscience #halyomorpha #downloadbugmap #cimice #stinkbug
Scientific gatherings	Researchers, PhD students and conference participants	- “Arbovirosis: emerging diseases”: scientific workshop, Trento, Italy 2019 - “CitSci2019”: international citizen science conference, Raleigh, North Carolina, (USA) 2019 - “The First Italian Citizen Science Conference”, Rome, Italy 2017 - “IPM 3.0” Riva del Garda, Italy, 2017
Scholastic events	Students and pupils of various schools in Trento province	- “Citizen science for kids! Alla scoperta della cimice asiatica” - “hands-on activities on invasive insect species” - “Let’s make goals! The week of sustainable goals” - “Trentino for Biodiversity”
Technical days and outreach activities	Citizens, researchers and journalists	- “La Giornata Tecnica “Frutticoltura delle Valli del Noce” - “Green Week”: Natural History museum of Trento - “The European Research Night of Trento”: Natural History museum of Trento - “Porte Aperte”: Fondazione Edmund Mach - “Trento Economy Festival 2019”: Aliens without borders - “Magazine article”: Cassa rurale della Valsugana
Television and radio appearances	National and international citizens	- RaiTre Geo, October 2017

2.2. Citizen Reports and Seasonal Classification

Since the initiation of this mobile application, the BugMap team, which includes technicians, computer scientists, science communicators, modelers, and entomologists, has been receiving citizen feedback and constantly working toward enhancing citizen involvement. Even though the steps to follow are the same as the ones described in Malek et al. [22], registering an *H. halys* sighting was made easier by refining map visualization, image upload, and ameliorating overall user-experience.

Recorded sightings between February 21, 2018 and October 1, 2019 were seasonally classified according to the North Italian climate. In Trentino, 799 valid BugMap reports were obtained during that period, and were projected in QGIS (version 2.18.16) on the *H. halys* distribution model that we previously generated. These new 799 records of the species were used to validate the first model, developed using 144 records from the previous survey.

To generate the BugMap reports’ map of Italy and to compute the new MaxEnt model, we utilized all valid datapoints recorded thus far, spanning from May 2016 to October 2019.

2.3. *Halyomorpha Halys* Maxent Species Distribution

Using the same environmental predictors applied in Malek et al. [22] such as digital elevation models, land-use, hydrography, road networks, and forest tracks, along with all valid BugMap reports obtained so far, we modeled *H. halys* distribution in MaxEnt (v. 3.3.3) and ran the Jackknife test to determine the variables that reduced the model reliability when omitted. The latter software attempts

to estimate a probability distribution of species occurrence that is closest to uniform while still subject to environmental constraints [23].

In order to increase the model performance, we followed the recommendations of Fourcade et al. [24], who suggested undertaking a systematic sampling of the records when the data are biased according to travel time. Performing a systematic sampling over a 500 m grid was found to be the best method to account for BugMap sampling bias [22], and we again randomly selected a single point for each mesh of the grid. In the end, we ran the model using a total of 699 presence locations: 490 points were used to train the model and 209 (30%) for testing.

In order to determine the optimal cut-off value, we followed the ROC (receiver operating characteristic) plot-based approach, allowing us to identify the point that maximized the sensitivity of our model against 1-specificity [23,25,26].

3. Results

3.1. Model Accuracy

The logistic output of the previously generated map from MaxEnt was then classified according to the cut-off value into two classes: unsuitable habitat below 0.26 of the logistic output, and suitable habitat above that value. Projecting the new BugMap reports on the old model, we found that it predicted the distribution of the bug in Trentino with 72.5% accuracy, with 580 out of 799 new reports falling in the projected distribution range (Figure 1).

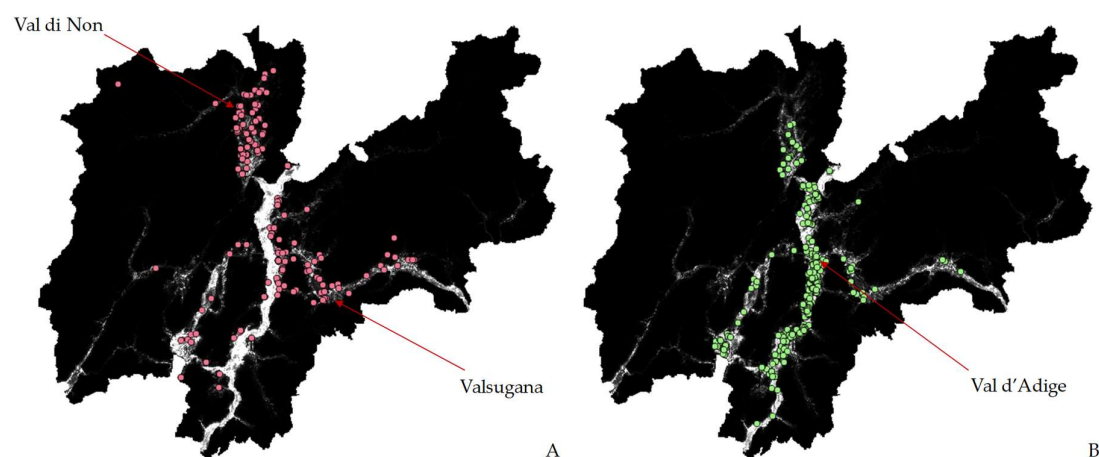


Figure 1. Maps showing the new BugMap reports falling outside (A) and inside (B) the previously predicted distribution range of *H. halys* in Trentino.

3.2. Seasonal Distribution

Halyomorpha halys was reported all year round from most urban and agricultural areas of Trentino. In spring 2018 and 2019, 146 reports were recorded from Trentino (Figure 2), reflecting a seven-fold increase when compared with reports recorded in 2016 and 2017. During the summer of 2016 and 2017, 49 reports were registered, compared with 260 reports in 2018 and 2019. Summer and autumn seem to be the seasons when both citizens and technicians recorded the most *H. halys* sightings, with 32.5% and 40.9% of reports, respectively. During spring and summer, most reports were registered from the highly suitable Val d'Adige, while in autumn, an upsurge of BugMap reports was noted from Val di Non, an economically important agricultural area. Scattered sightings of the bug were registered during winter from all urban and agricultural valleys of the North Italian region.

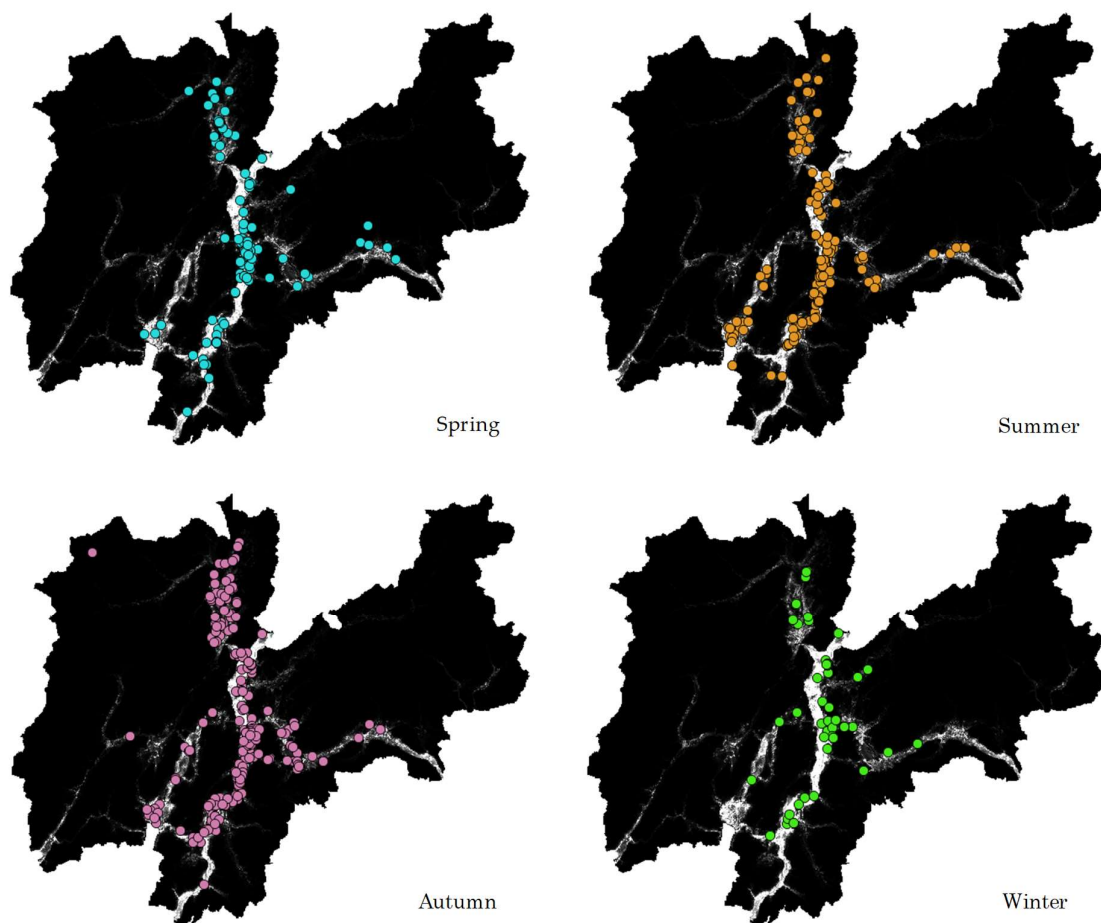


Figure 2. Seasonal distribution of *H. halys* in Trentino, according to traditional monitoring and new BugMap reports. Spring and summer maps show the 2018 and 2019 records, while the autumn and winter maps show records from 2018.

3.3. Italian Distribution

Halyomorpha halys reports have been increasing throughout the Italian territories, with 259 new recordings obtained from Italian regions other than Trentino in 2019, compared with 62 recorded reports in 2017 and 2018 (Figure 3). Adjoining North Italian regions such as Veneto and Lombardy have seen an upsurge in recordings of the invasive stink bug when compared with the previous years. Valid BugMap reports were also registered for the first time in Umbria, Marche, Abruzzo, Molise, Puglia, Calabria, Sicily, and Sardinia. Sporadic reports have also occurred from nearby countries such as Switzerland, Slovenia, Croatia, and Hungary.

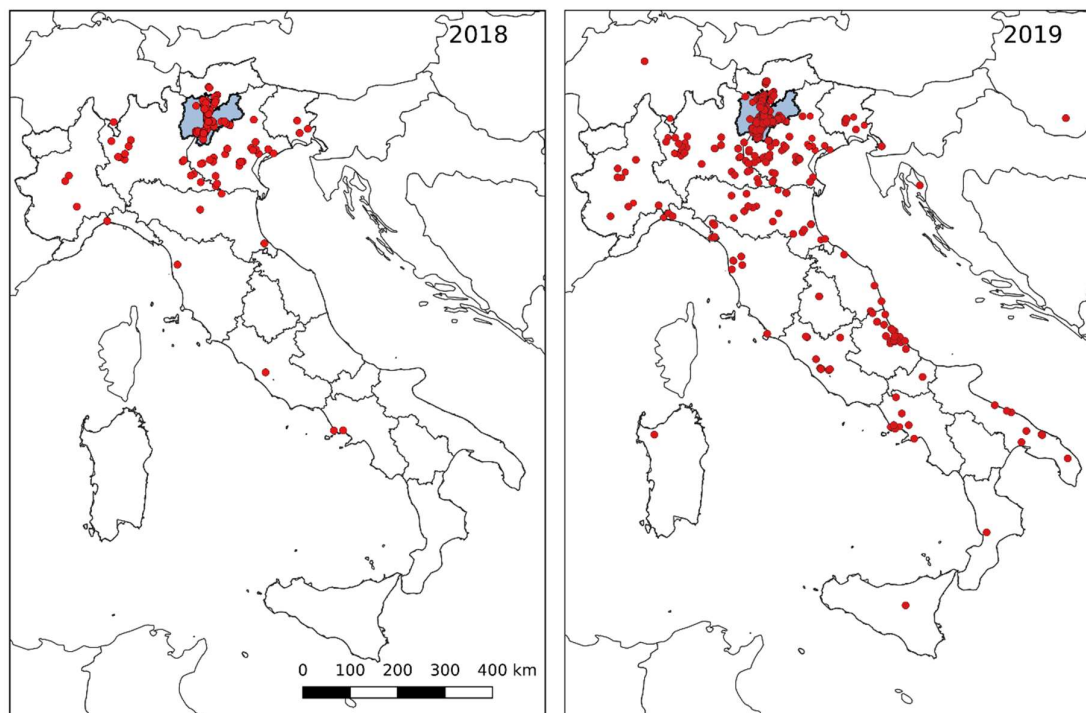


Figure 3. Map of Italy and neighboring countries, showing reports since the initiation of BugMap until February 2018 (left) and until October 2019 (right).

3.4. New Maxent-Generated Suitability Map

The occurrence data collected on our platform were treated for travel-time bias by systematic sampling of random points over a 500 m grid. For training the model, 490 points were used while 209 records were used for testing it, the model had an AUC for training data of 0.956 and the test data was 0.943. The 2018 and 2019 suitability maps are shown below (Figure 4). The Jackknife test for assessing variable contribution revealed that the parameters that most affected the dispersal of the bug were the digital terrain model, land use, and distance from houses and from streets.

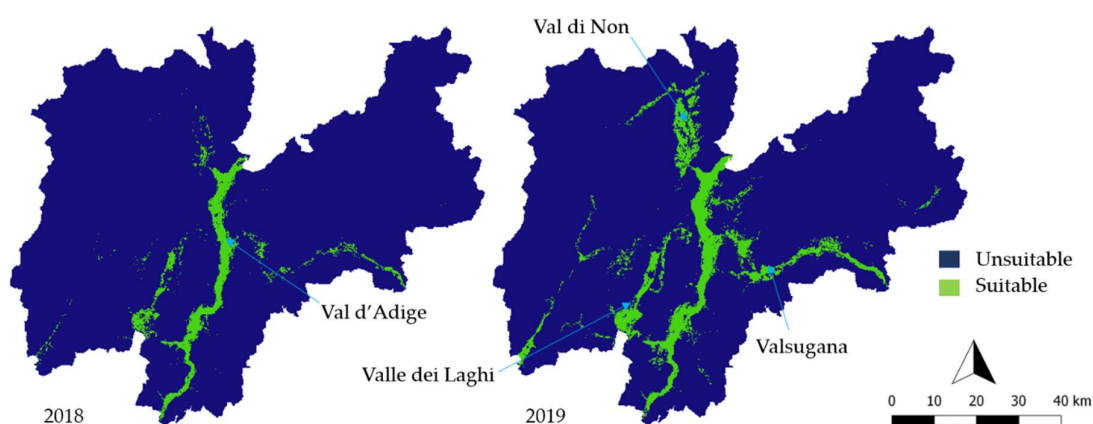


Figure 4. Comparative MaxEnt models of the 2018 and 2019 *H. halys* projected distribution in Trentino, highlighting suitable and unsuitable areas at risk of pest establishment.

4. Discussion and Conclusions

BugMap is the only citizen science initiative specifically designed to monitor *H. halys* in Italy while employing a highly accessible, user-friendly, and freely available mobile application that facilitates

volunteer participation and involvement. The only comparable system that was adopted by researchers in the central Italian region of Emilia Romagna also integrated systematic sampling and crowdsourcing. Maistrello et al. [20] worked in close collaboration with amateur entomologists, university students, phytosanitary services, and volunteers of the general public, encouraging them to collect *H. halys* specimens and/or take high quality photographs and send them to project leaders along with a detailed annotation. In a more recent study, they referred to *H. halys* as a sneaking hitchhiking alien pest [27], a denomination well-earned as 13 sightings of both adults and nymphs were recorded via BugMap in different means of transportation (cars, tractors, and train stations). The capacity of this pest to go unnoticed in such means facilitates its fast spread and passive diffusion along urban and agricultural landscapes, increasing the risk of establishment in diverse territories.

Our previously generated MaxEnt model [22] successfully predicted the current distribution of *H. halys* in Trentino with a 72.5% accuracy. Mainly, our 2018 model projected a scattered suitability for Val di Non (Figure 1) as an area at risk of *H. halys* establishment. This is probably due to the high altitudinal gradient in this agricultural valley, with elevations ranging from 268 to 2999 m. We previously speculated that *H. halys* would probably be incapable of overwintering there, but it would rather have a source to sink population dynamic, with seasonal re-infestations from the highly suitable Val d'Adige. The continuing BugMap reports shed new light on this issue, showing that all year long numerous *H. halys* sightings were recorded from this northernmost region of Trentino with 81.8% of winter reports originating from buildings, thus rectifying our previously held assumptions. As has been suggested by several researchers [28,29], the latter finding highlights the crucial *H. halys* association and aggregation in man-made structures in maximizing survivorship and perhaps reducing the Allee effect. Kistner [30] projected that the impacts of global warming may cause a northward expansion of *H. halys* invasion and an increase in the number of annual generations. Therefore, the rise of BugMap reports from Val di Non might also be due to more favorable environmental conditions in 2018–2019 and better climatic suitability when compared with the first years of our monitoring.

Val di Non is an area of high economic importance due to the prevalence of about 9000 hectares of apple orchards. After the generation of our previous model [22], we organized technical days and training for farmers from the area, stressing the necessity of intensifying monitoring activities. Therefore, the increase of BugMap reports from Val di Non might be due to an *H. halys* population increase in the past two years, to a more active citizen involvement, or to both. This observation shows the importance of translating citizen participation and effort into practical agricultural advice to properly orient monitoring and management. All the other main regions of Trentino predicted to be suitable for *H. halys* establishment, namely Val d'Adige and Valle dei Laghi, have seen a great increase in the bug population in spring, summer, and autumn (Figure 2). Climatic suitability, agricultural-urban interfaces, host plant availability, and diffusion via human transportation are all factors that may contribute to the establishment and expansion of *H. halys* in the aforementioned-regions.

Our new MaxEnt model, generated using all BugMap reports registered thus far, revealed an expansion of the area under risk of stink bug establishment in Trentino (Figure 4). The territorial spread and landscape correlates are in accordance with a study by Wallner et al. [29], who found that the *H. halys* range expansion is associated with urban land use, agricultural/urban interfaces, and human habitat. Specifically, the main agricultural regions of Trentino, Val di Non, and Valsugana are now seen as highly suitable for *H. halys*, suggesting that in the coming years, the damage inflicted on crops is expected to rise there. A means to avoid increasing crop losses could be to adopt pre-emptive measures based on our model, instructing increased monitoring in critical periods of the year. Specifically, early detection during spring and implementation of appropriate control measures as adults emerging from overwintering are more susceptible to insecticides [31]. Additionally, the first appearance of nymphs is considered a key point in the management strategy to prevent *H. halys* from establishing in orchards early in the growing season [32]. Global *H. halys* distribution models are indeed useful for predicting areas climatically suitable and offering host plants that facilitate the establishment of this invader [33,34]. However, our fine scale-model presents information of direct concern to farmers and

citizens in affected areas, while accounting for urban and agricultural land use and extreme altitudinal variation in this mountainous North Italian region.

In the course of time spanning from February 2018 until October 2019, valid BugMap reports were registered for the first time from numerous Italian regions (Figure 3). Northern, Central, and Southern Italian regions are now threatened by *H. halys* establishment and accompanying damage to agricultural and ornamental industries. Although the hands-on training provided by the BugMap campaign was focused primarily in Trentino, however, the general public from other Italian regions positively reacted to social media posts and exhibited increased awareness and interest in taking part in this issue of local and national concern. Zhu et al. [33] indicated that the entire Italian peninsula is suitable for *H. halys* establishment and for setting up breeding populations. Therefore, the surge of reports from these regions could then be linked to an increased public engagement or to the stink bug's expansion throughout Italian territories, or both.

Crowdsourcing geospatial information on *H. halys* has proven efficient for predicting its distribution and for instructing decision making in geographical areas ravaged by this invader. So much so that in 2018, we applied the stink bug approach to the invasive tiger mosquito, aiming to better its monitoring and management in this region. Notwithstanding geographical limitations, BugMap was adopted by volunteers all around Italy in a show of elevated environmental awareness and a high scientific citizenship. Elements that contributed to its success are a user-friendly platform for facilitating stink bug reporting, an active informative campaign, close collaboration among amateur and expert scientists, and the transformation of long-term monitoring into a time- and cost-effective reality. The BugMap approach can now be regarded as a model that may be applied in other communities struggling with their own biological invasions, ranging from invasive plants, lizards, mammals, insects, and other environmental hazards.

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