PREPRINT

Author-formatted, not peer-reviewed document posted on 06/04/2022

DOI: https://doi.org/10.3897/arphapreprints.e84924

Halyomorpha halys invasion front jumps 1,500 kilometres to reach the Canary Islands; a framework for rapid response, identification of urgent questions, and assessment of potential impacts

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Halyomorpha halys invasion front jumps 1,500 kilometres to reach the Canary Islands; a framework for rapid response, identification of urgent questions, and assessment of potential impacts

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Keywords: brown marmorated stink bug, Tenerife agriculture, invasive Pentatomidae, insect trapping

Abstract

Early detection and rapid response are cornerstones of effective invasive species management. However, these strategies can be challenging to implement when the arrival of a non-native species has not been predicted, as may be the case when a species is discovered large distances from known populations. Brown marmorated stink bugs *Halyomorpha halys* are rapidly spreading across much of the world, causing substantial economic losses to agriculture as well as nuisance when entering houses to overwinter communally. Multiple individuals were recently confirmed in the Canary archipelago, marking a dramatic range expansion into subtropical Atlantic areas and the northwest African region. The potential establishment of this major pest species in this region raises important questions on its ecological adaptation to new climatic and biotic conditions an as well as the unknown impacts and control effectiveness in novel host crop plants such as banana. Previous attempts to control *H. halys* elsewhere have been typically only partially successful but we suggest eradication in the Canary Islands might still be possible and a sensible goal. Within a conceptual framework we review potential management options and encourage local authorities and stakeholders to implement specific surveillance, control and biosecurity measures aiming to swiftly eradicate this species. Not doing so risks a potentially severe invasion by this species across the region and significant damage to the local agricultural and ornamental plant economy. Our framework provides a basis for rapid

response and management in other scenarios where an unexpected non-native species is detected.

Introduction

It is well-established that a comprehensive approach to invasive species management involves early detection and rapid response (Reaser et al., 2020). Development of such a strategy requires effective predictions of future invaders so that appropriate, species-specific measures for surveillance and management can be implemented. For invasive species that are spreading along known pathways or by recognised vectors, horizon-scanning can be an effective tool in identifying and prioritising future invaders (e.g. Roy et al., 2014). However, when non-native species are transported large distances from historical locations the stakeholders in recipient geographies may be ill-prepared for species that have been overlooked as potential threats. Here we report the unexpected discovery of a high risk invader 1,500 km away from its previously known distribution, and set-out a framework for rapid response and management that could be applied under similar scenarios for other discoveries of unpredicted non-native species.

The brown marmorated stink bug *Halyomorpha halys* (Stål, 1855) is a highly polyphagous, mobile, and damaging invasive hemipteran of global concern that has been spreading in the past two decades from its native east and south Asia to much of the USA, parts of South America (Chile) and large parts of continental Europe, from Russia and Georgia in the east to Portugal in the west, as reviewed by Kriticos et al. (2017) and Leskey & Neilsen (2018). In southern Europe, including Spain where it has been recorded in the Catalunya region since 2016 (Dioli et al. 2018), the species is bivoltine and occupies farmland and Mediterranean forested habitats. In such mild climate areas rapid increases in abundance and sometimes extensive crop damage have been observed within less than five years post-establishment (Bariselli et al. 2016; Costi et al. 2017; Pajač Živković et al. 2021).

H. halys has an extensive host range exceeding 300 plant species and can severely impact a large variety of fruit crops, row crops, vegetables and ornamental plants (Bergmann et al. 2016; Kriticos et al. 2017; Leskey & Neilsen 2018). For example, in Italy the species has locally caused up to 50% or even 80% fruit crop losses in some sites (Costi et al. 2017; Maistrello et al. 2017). Damage is caused via feeding injuries and injecting digestive enzymes that produce necrotic plant tissue, wilting and deformities, which is further aggravated by the feeding behaviour of adults that move frequently between individual plants and different crop types (Bariselli et al. 2016). It can also transmit plant pathogens, such as witches' broom disease *Paulownia tomentosa* (Kriticos et al. 2017). In addition, its tendency to form extensive overwintering aggregations in buildings and the pungent, unpleasant smell produced when disturbed, makes it a significant urban nuisance pest (Lee et al. 2013). It has shown multi-pesticide resistance and, once established, farmers have had to substantially increase insecticide applications, for example four-fold increase in the aftermath of *H. halys* outbreaks in USA apple orchards (Leskey et al. 2012), causing supplementary chemical pollution, higher production costs and damaging integrated pest management, especially as most insecticides available to growers for *H. halys* control are broad-spectrum (Kuhar and Kamminga, 2017).

Under controlled conditions average *H. halys* egg mortality was 100% at 12.5 °C but dropped to 1.3% at 30 °C (Haye et al. 2014) and optimal development temperatures for *H. halys* have been estimated at 25-30°C, with maximum feeding at 16-17°C, meaning large parts of the Southern Hemisphere, Central America, northwest and sub-Saharan Africa are considered suitable for the species (Kriticos et al. 2017; Leskey et al. 2018). However, despite its high invasive potential in many subtropical and tropical regions, where it could exhibit continuous activity throughout the year and have even shorter generation time the species has so far remained largely absent in such areas (Leskey et al. 2018). In the warm climate of its native southern China the species was reportedly able to produce up to 4-6 annual generations in by Hoffmann (1931) but more generally it is known to produce 1-2 generations per year (Leskey & Neilsen, 2018).

In December 2021 multiple individuals of *H. halys* were detected in an urban setting on the island of Tenerife (Figure 1). This marks a southern expansion of around 1,500 km, well beyond the range of self-sustained flight from the closest known existing populations in the Iberian Peninsula, and into subtropical areas. The strong Atlantic influence in the Canary Islands' climate results in an "eternal spring", nearly constant 18-24°C temperature at sea level but with wide differences in rainfall between, and within, islands due to complex island morphologies. Large parts of the eastern islands of Lanzarote and Fuerteventura might be too hot and dry for *H. halys* development, but the areas used for agriculture across the islands are likely suitable. It is unknown how the lack of a defined cold season may influence diapause in *H. halys* as the species was shown to breed late into autumn in southern Europe but photoperiod, which is assumed to be a critical diapause cue, might delay development and female reproductive maturity at such low latitudes (Leskey et al. 2018).

These *H. halys* observations in the Canary Islands are very recent and to date individuals have been found only in a very localised site, indicating the possibility of early-stage invasion. The aim of this paper is to discuss this range expansion, the potential risk to Tenerife and the Canary Islands, identify urgent research questions, discuss possible management opportunities and consider how this example may provide a framework for rapid responses to discoveries of other invasive species a long distance from previous records.

Methods

A live and active adult brown marmorated stink bug was observed on 17th of December 2021 on the external wall of a building in the coastal town of Costa Adeje in south Tenerife (Figure 1) and flew away while taking pictures to confirm species identification. Once the invasive data range was checked from citizen science records and the scientific literature, the images and location were made public that day on INaturalist to alert interested scientists. Following expert confirmations that this is probably the first record of this species in the Canary Islands, repeated transect surveys were started the following day and the local government health plant agency was alerted.

An area of approximately 400 m in length around the site of the first observation was surveyed twice daily, at 8-9am and at 8-10pm until 24th of December. Additionally, visual sampling in the nearby area using 1-2 min observations of 50 randomly chosen trees and shrubs was started by inspecting leaves, flowers, fruits and woody parts between 0.5 and 2 m above the ground, as well as searches of neighbouring built-up areas (e.g. garden and building walls with similar surfaces and orientations within a 1 km radius). An additional 40 ornamental street-lining trees, mostly palms and flamboyant trees *Delonix regia*, were visually checked following the same protocol in three other nearby urban sites (Adeje, La Caleta and Los Cristianos), at distances of 2-6 km from the original site.

Results

During repeated surveys an additional five individuals were located by the 24th of December 2021. All individuals were found at the same site, on eastern facing external building walls and open-sided corridors bordering a public park with palm trees and mature shrubs. One individual was observed landing on the external wall on the third floor of a building and then captured. Most individuals (4) were recorded on the same day (December 19th); three were recently dead, apparently stepped on by people on the external paved surface.

All six recorded *H. halys* individuals were adults, with three females and at least one male provisionally identified based on external morphology of the ventral area. Two live and two freshly dead individuals were collected as record specimens and to allow genetic analysis to establish their probable origin. These specimens were passed on to the Plant Health agency.

Local gardening and cleaning personnel working at the site of the first observations indicated they had seen stink bugs several times recently in the same place but could not say if this had been going on for more than 2-3 weeks. However, another Pentatomidae species, which is similar in shape and size but not in colour (an adult of the Canary Islands endemic *Acrosternum rubescens*) was observed live at the same location during surveys and staff could not specify which of these species they had seen. Despite a generally low abundance of insects in the area, several live moths (*Palpita vitrealis* and *Herpetogramma licarsisalis*) and the syrphid *Eristalinus taeniops* were also found during visual surveys on the same building walls, suggesting an influx of flying insects at the site, perhaps due to prevalent wind direction and the position, facing the park.

The vegetation and building wall searches within the 1km radius and the randomised 40 trees checked in other urban areas did not produce any further *H. halys*. The park at the original site was briefly searched for *H. halys* adults or nymphs on December 21st and focusing on trees and palm trees, but none were found.

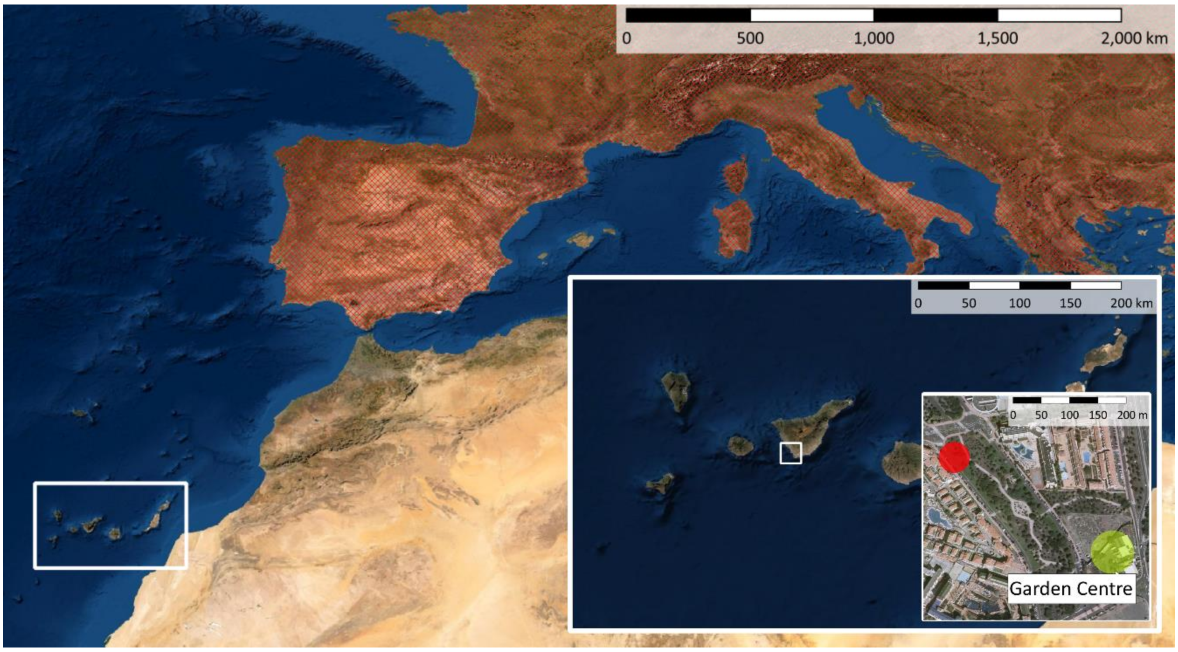

Figure 1. Overall area highlighting the position of the Canary Islands, the location of the records in SW Tenerife and a detailed map of the *H. halys* observations (red dot) plus the proximity to a garden centre (green dot). Shaded areas in continental Europe show occupied range by *Halyomorpha halys* at national scale. Shading of some Mediterranean islands (e.g. Corsica and Sardinia) indicates known occupied range of the species.

Discussion

The identified *H. halys* individuals might have congregated from multiple sites or from considerable distances. However, a mixed open-air and enclosed garden centre located at the edge of the park (Figure 1) and selling a variety of cut flowers, potted garden plants and garden décor could be a potential point of accidental introduction for the species via undetected hitchhiking on live plant imports or garden objects. The garden centre was not surveyed but its potential relevance was raised with the Plant Health agency.

We suggest these highly clustered observations should be the urgent focus of rapid response management and we offer a potential framework for consideration.

Significance of *H. halys* in the Canary Islands and potential for impact and spread

Tenerife is the largest (2,034 km^2) and highest (3,718 m asl) of the Canary Islands, located near the centre of the archipelago, which would make *H. halys* expansion across the region feasible given the combination of the relatively small distances between the seven Canary Islands (15-100 km) and that it can fly up to 100km (Wiman et al. 2015). Human-assisted colonisations between the islands should be expected if the species becomes locally established due to the frequent daily movements of goods, vehicles and people between the islands. While the distance to the African mainland is around 100km from the island of Fuerteventura, there are also discussions to reinstate the currently suspended direct ferryboat to Tarfaya in Morocco.

Tourism is the largest economic activity in the Canary Islands but agriculture plays an important economic, social and cultural role, with an estimated value of 674 million euros in 2019, especially from bananas (9.095 ha and 420.144 tones in 2020), tomatoes, potatoes, avocado and fruits but there are also 6,000 ha of vineyards and over 500 ha of ornamental plants and flower nurseries (Estadistica Agraria y Pesquera de Canarias, 2019; Gobierno de Espana, 2020), all of which could be impacted by *H. halys*. In addition to cumulative impacts of feeding on grapes at different stages, *H. halys* can also affect wine quality by releasing its chemical defence compounds if collected with grapes (Mohecar et al. 2017).

Invasive species management is often difficult after entry and establishment. Many management strategies focus on temporary and localised control, and models to assess optimal strategies decisions to eradicate or to control are now available (Baker & Bode 2021). Yet, the current invasion in Tenerife might offer the potential for eradication, given that all individual *H. halys* were found in a single urban location in the vicinity of a potential importation point and not detected elsewhere. Urgent and targeted control measures would allow a realistic chance for successful eradication.

Early detection and rapid response

H. halys was apparently eradicated in Australia (Horwood et al. 2019) and this demonstrates that a combination of early detection and rapid response can prove effective for this high-risk species. We present a conceptual framework (Figure 2) and briefly review the evidence for possible rapid response measures for *H. halys* invasion in Tenerife. Early detection refers to the process of “surveying for, reporting, and verifying the presence of a non-native species before it becomes established or spreads so widely that eradication is no longer feasible” and rapid response as measures aiming to eradicate the non-native founding population from a specific location (Reaser et al. 2020). Details for how each of the key response options in Figure 2 can be implemented in Tenerife are given below.

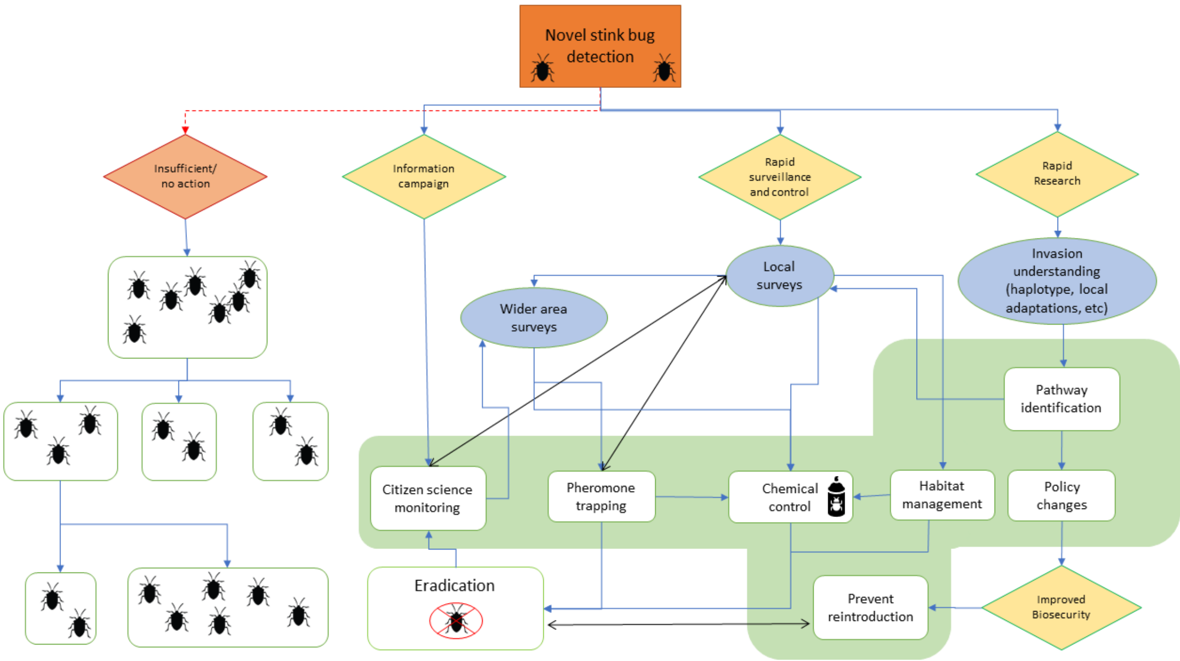

Figure 2 Flowchart of rapid response measures and scenarios to address the early detection of multiple brown marmorated stink bugs in an isolated new region.

1) Rapid surveillance Professional local surveys using visual checks and trapping (see below) should progressively increase the area of surveys from a 1km radius. Optimal allocation of survey effort can be calculated as a function of probability of occurrence (higher in the proximity of the initial detection and decreasing thereafter), the benefits of detection (maximum in the early stage when eradication is still a realistic goal) and local detectably of the invasive species (depending on life stage, variability in seasonal activity, habitat type and detection method used) (Hauser & Raut, 2017). Efforts should be concentrated in the areas with the highest likelihood of stink bug arrival and establishment as well as microhabitat considered optimal and suitable (e.g. specific or general plant and tree vegetation, specific artificial structures such as those involved in the original detections). Advances in technology including artificial intelligence, “web crawlers”, computer vision and eDNA (e.g. via fruit rinsing and water testing) could significantly improve the surveillance of populations (Martinez et al 2020; Valentin et al 2018). Combined surveys and a public information campaign (see below) could help to determine invasion status, whether the individuals originated from a recent accidental introduction, whether breeding has occurred, how close their distribution is to a means of arrival (e.g. a garden centre) or if the invasion has been undetected for some time and populations are now established.

2) Information campaign Professional surveys could be supplemented with a multi-media public information campaign asking people at the original locality as well as across Tenerife and other Canary Islands to check for, and report sightings of, this species (Pawson et al, 2020). A smart phone reporting app could be considered but any type of verifiable reporting should be encouraged and facilitated (e.g. social media, email form, phone message platform). Free existing platforms, such as INaturalist, could be used and promoted with sightings monitored and verified by the authorities. *H. halys* is an excellent candidate for citizen science monitoring being relatively recognisable, slow moving and easy to photograph: the first European observation originated from hobby photographs in Zurich, Switzerland in 2004 (Haye et al. 2015). Adult *H. halys* can disperse into crops in time for reproduction, but trees and shrubs may be important intermediate hosts before crop invasion (Rice et al. 2014), thus allowing the collection of chance citizen science records at sites where they might be otherwise difficult to detect.

3) Rapid research could a) confirm the haplotype structure of individuals collected and b) investigate potential for local adaptation and spread (e.g. predict preference for particular areas or plant species, seasonal changes in distribution according to the local climatic conditions and the presence of habitat niches such as irrigated crop areas). Research could explore distribution modelling scenarios for this species in the Canary Islands to facilitate surveillance efforts and model potential spread in the absence of effective control. In addition, eradication can be costly to implement and is only a viable option if the likelihood of reintroduction is low. Otherwise, a different strategy may look at keeping populations low or focus on containment as this can still offer ecological and economic benefits, but this requires rapid research at an early stage. Identification and management of pathways might reduce the likelihood or reinvasion, in which case eradication can become more compelling. Haplotype analysis can provide important information and, at a global level, has indicated multiple introductions from China between eastern and western USA as well as southern Europe while the populations in Emilia Romagna in Italy resulted from a bridgehead invasion effect, introduced from eastern USA rather than directly from China (Valentin et al. 2017; Leskey & Neilsen 2018). This could assist pathway identification and, combined with import data, could allow targeting potential introduction points for surveillance effort and chemical control and, in the longer term, revising of policies and biosecurity protocols (Figure 2).

4) Trapping, chemical control and habitat management The feasibility of successful eradication depends upon characteristics of the invading species and the context in which it is detected, with a narrow window of opportunity for eradication (Simberloff et al. 2003). Capture and removal of any *H. halys* present is essential for eradication and pheromone trapping of the original site as well as other potential sites can offer crucial support. Pheromone luring and trapping has been intensively researched in the USA for this species and substantial progress was achieved once Khrimian et al. (2014) identified the male-produced aggregation pheromone following isolation of male-specific volatiles. Single males were found to produce more pheromone than groups and both adults and nymphs are attracted to pheromone. A variety of trap designs and pheromone lures have recently been tested for *H. halys* including various designs, colours and sizes of tree canopy and ground deployed traps, with ground-deployed black pyramid traps becoming the standard due to their higher capture rates (Leskey et al. 2021). Increasing trap loading with 2-stage aggregation pheromones increased overall captures, with variability of optimisation possible when considering both specific pheromone attraction and production costs (Leskey et al. 2021). However, *H. halys* are sometimes attracted to, but remain outside and in the vicinity of, the traps baited with pheromonal stimuli, indicating "trap spillage" and a need for careful and frequent searches. In Australia, rapid response to identification of *H. halys* within and on the perimeter of importation warehouses used insecticide fumigations of the interior (bifenthrin surface spray and pyrethrum fog), sweep-net sampling and visual observation of potential host plants within a 1km radius area as well as 4-5 month ongoing trapping using commercial pyramid traps, panel traps and sticky traps with MDT/murgantiol pheromone lures for this species, resulting in apparent eradication (Horwood et al. 2019). Similarly, trapping and control efforts for *H. halys* in Tenerife would require integrated surveillance to confirm effectiveness and successful eradication.

Habitat management is often employed to manage invasive species and has been tested for *H. halys* including via the use of attractant crops (e.g. sunflower) or management focus on field margins (Leskey et al. 2018) but results have been mixed given that the species is so mobile and polyphagous. However, in the drier climate and sparsely vegetated areas of Canary Islands it might offer new opportunities that should be explored.

5) Policy changes and biosecurity Understanding the invasion pathway using surveys and genetic tracing could offer important evidence for reviewing policies related to checks of imports and ultimately better targeted biosecurity. Island areas can maximise the advantages of their isolation to prevent invasions and the Canary Islands already have separate biosecurity importation checks for agricultural products to and from mainland Europe. However, *H. hays* has been imported in "low risk" goods, such as 38 live adults detected in an Australia in November 2017 from a shipping container carrying electrical components from Italy (Horwood et al. 2019).

In addition, biocontrol policies might be considered as part of longer-term biosecurity. For example, although *H. halys* is yet to establish in New Zealand, authorities have pre-emptively developed a biological control program for this species, which includes risk assessment of the egg parasitoid *Trissolcus japonicus* and approval of its conditional release if *H. halys* is detected (Charles et al. 2019). In the USA, both endemic *Trissolcus* species as well as *T. japonicus* were found to parasitise *H. halys* eggs in wooded habitats, although *T. japonicus*, which was accidentally introduced in the USA, was more successful (Leskey and Nielsen, 2018).

Urgent questions and factors to consider- December and January are the coolest and wettest months in Tenerife potentially suggesting that the observed brown marmorated stink bug individuals might have been attracted to urban areas and buildings in search of overwintering areas yet that seems unlikely as daily local temperatures in late December 2021 in South Tenerife were 23-25°C. In Italy, experiments indicated that overwintered female *H. halys* were all breeding and had high productivity (285 eggs/female ± 22.8 SE); only 13 of 15 summer generation females bred with lower mean lifetime productivity (214.7 eggs/female ± 30.6 SE) (Costi et al. 2017). How the ecology and productivity of this species might change and adapt to the constant, subtropical dry (southern Tenerife slopes or eastern group islands) or wet and humid (northern Tenerife slopes or western islands) climate of the Canary Islands remains unknown. Understanding and answering this question is however directly relevant for modelling species demographic outputs and an estimated speed of population expansion in the absence of eradication and could ultimately improve control measures by targeting specific areas, times of the year or life stages.

There are also numerous questions about preferred host ornamental plants or interactions with endemic Canary plant and insect species, but these are important given the very diverse local communities compared to Europe, USA or Asia.

Given the disproportionate importance of banana crops for local agricultural production there are critical and urgent questions for the local agricultural economy on the potential impact, crops losses and methods for control in banana farms as to our knowledge there are currently no studies detailing *H. halys* impacts on this crop. However, the species is fed banana fruits in captive conditions (Wong et al. 2021), suggesting high potential for targeting this crop plant as a host in the Canary Islands. Quantifying the impact of *H. halys* on this major global crop would be of broad relevance for other regions in the predicted expansion range. We urge researchers to rapidly evaluate such impacts and test a variety of trapping and lethal control methods in this crop.

Finally, there are unknown aspects relating to optimal trapping density for both *H. halys* surveillance and trap and kill protocols but these should not prevent the application of rapid response measures as these can be managed adaptively in the field.

Broader implications

The presence of *H. halys* in Tenerife represents a dramatic expansion in its range. The potential ecological and economic impacts of the species in the Canary Islands is difficult to extrapolate from experiences elsewhere because it will be relatively novel in comparison to native insects, and species and crops in the new locality are less likely to have evolved traits to cope with this new invader (Simberloff, 2009). Ricciardi et al. (2017) identified the importance of intercontinental trade as a growing pathway for the long-distance transport of stowaways. The relatively high transport volumes of goods to nations with overseas territories, such as from Spain to the Canary Islands, combined with the extension of free trade agreements (Genovesi, 2011) suggests that such trade routes may be especially important introduction pathways that deserve tighter biosecurity regulation. By proposing a structured action plan in response to the discovery of *H. halys* in Tenerife we provide a more general framework for managing new and relatively isolated invasion events.

Acknowledgements

Silviu Petrovan, Rebecca Smith and William Sutherland are generously supported by the David and Claudia Harding Foundation via the BioRISC initiative at St. Catharine’s College at

Cambridge. We are grateful to Roxy Popa and to Maya Petrovan for their patience, interest and assistance during surveys and data recording for stink bugs in Tenerife and to Mark Burgman and Estrella Hernandez Suarez for very useful discussions and comments on an earlier draft of the manuscript.

Availability of data and material

All the data and materials are available in the manuscript. All authors have contributed and approved the manuscript. We declare no conflict of interest and no animal testing or experiments were used in our study.

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