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ORIGINAL ARTICLE

Current distribution and spatial spread patterns of *Halyomorpha halys* in Germany

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Abstract

The brown marmorated stinkbug (*Halyomorpha halys* Stål) is a polyphagous insect from the Pentatomidae family that is originally from Asia. This contaminating (i.e. hitchhiking) species, often found in urban areas and along anthropogenic infrastructure, is fast spreading in Germany and other European countries. As a pest in those countries for agriculture and as a nuisance pest for the public it is important to have a solid database of the current distribution for spread modelling, risk assessment and further analysis to contain infestations and reduce or prevent further spread. The authors present here the current phytosanitary status and trends of distribution of the brown marmorated stinkbug in Germany.

Répartition géographique actuelle et dissémination d'*Halyomorpha halys* en Allemagne

La punaise diabolique (*Halyomorpha halys* Stål) est un insecte polyphage de la famille des Pentatomidae, originaire d'Asie. Cette espèce contaminante (i.e. « auto-stoppeuse »), souvent observée en zone urbaine et à proximité d'infrastructures anthropiques, se dissémine rapidement en Allemagne et dans d'autres pays d'Europe. Cette punaise est considérée en Europe comme un ravageur des cultures agricoles et une nuisance pour le grand public, il est donc important de disposer d'une base de données solide sur sa répartition géographique afin de modéliser sa dissémination, permettre des analyses de risque phytosanitaire ou toute autre analyse, dans le but d'enrayer les infestations existantes et de réduire ou d'empêcher sa dissémination future. Cet article présente la répartition géographique actuelle de la punaise diabolique en Allemagne, ainsi que ses tendances évolutives.

Текущее распределение и закономерности распространения в пространстве *Halyomorpha halys* в Германии

Коричнево-мраморный клоп (*Halyomorpha halys* Stål) - это многоядное насекомое из семейства Pentatomidae родом из Азии. Этот засоряющий вид, часто встречающийся в городских районах и вдоль объектов антропогенной инфраструктуры, быстро распространяется в Германии и в других европейских странах. В этих странах он является организмом, вредным для сельского

хозяйства и досаждающим населению. Чтобы сдерживать заражение, сокращать или предотвращать дальнейшее распространение организма, важно иметь надежную базу данных о его текущем распределении. Это необходимо для моделирования дальнейшего распространения, оценки риска и последующего анализа. Авторы представляют здесь текущий фитосанитарный статус и тенденции распространения коричнево-марморного клопа в Германии.

1 | INTRODUCTION

The spatio-temporal occurrence, abundance and phenology of new pests in a country are important pieces of information for various stakeholders ranging from farmers whose crops might be at risk, field ecologists setting up traps to monitor and describe a species, plant protection services, to risk analysts and modelers who are interested in simulating the spread and estimating the potential risk of the pest for a country. The brown marmorated stink bug (*Halyomorpha halys* Stål, Heteroptera: Pentatomidae) is an invasive hitchhiking pest from China, Japan, South Korea and Taiwan (Lee et al., 2013). The brown marmorated stinkbug was found in Europe for the first time in Liechtenstein in 2004 followed by Switzerland in 2007 (Wermelinger et al., 2008; EPPO, 2013; Haye et al., 2015). After its introduction to Liechtenstein/Switzerland the brown marmorated stink bug continued to spread to surrounding countries (EPPO, 2021). The first occurrences in Germany were in 2011 in Bremerhaven (where it was eradicated) and in Konstanz (Zimmermann et al., 2018). Due to its polyphagous feeding patterns the brown marmorated stinkbug has the potential to cause serious ecological and economic impacts (Haye et al., 2015). It occurs on many crops in urban areas, gardens, on balconies and on agricultural land. For overwintering, *H. halys* seeks shelter in buildings and can thus become a major nuisance for the public (Inkley, 2012; McPherson, 2017; Schulz, 2018). The temperature increase associated with climate change may lead to an expansion of the habitat and better growth conditions, and thus increase the above-mentioned risks in the future (Stoeckli et al., 2020).

2 | OBSERVATIONS/MATERIALS AND METHODS

The present study was carried out in Germany starting in 2019 (Heß et al., 2020), incorporating some data from 2017 and 2018 as well. The obtained data consist of the monitoring of pheromone insect traps, visual inspections, data from citizen science, databanks, literature and other relevant sources. A total of 5476 data points were collected, of which 3654 indicate the presence of the species.

2.1 | Pheromone traps

For the monitoring of *H. halys* traps can be a useful tool (Rice et al., 2014; Acebes-Doria et al., 2020). In this project, rocket-shaped RESCUE!® traps produced by the company Sterling International Inc. (Sokane, WA, USA) as well as so-called 'Fischer traps', a prototype provided by Andermatt Biocontrol AG (Grossdietwil, CH), were used (Figure 1). The pheromone dispensers were placed/hung in these traps and were replaced every 9–12 weeks depending on the minimum duration of pheromone effectiveness indicated by the manufacturer. The products used as lures were either PHEROCON® Stink Bug DUAL Lure or RESCUE!® Stink Bug Attractant from the companies Trécé Inc. (Adair, OK, USA) and Sterling International Inc., respectively. The traps equipped with the dispenser were hung from branches at an accessible height. The locations of the monitoring traps (Figure 2) were chosen to cover the type of places where the species has often been found in the past, and locations where it had not been detected in the previous year but was

FIGURE 1 Pheromone traps (rocket-shaped RESCUE!® trap at the top, Fischer trap on the bottom) used in the project for the monitoring of the brown marmorated stinkbug (©Lutsch 2021). [Colour figure can be viewed at wileyonlinelibrary.com]

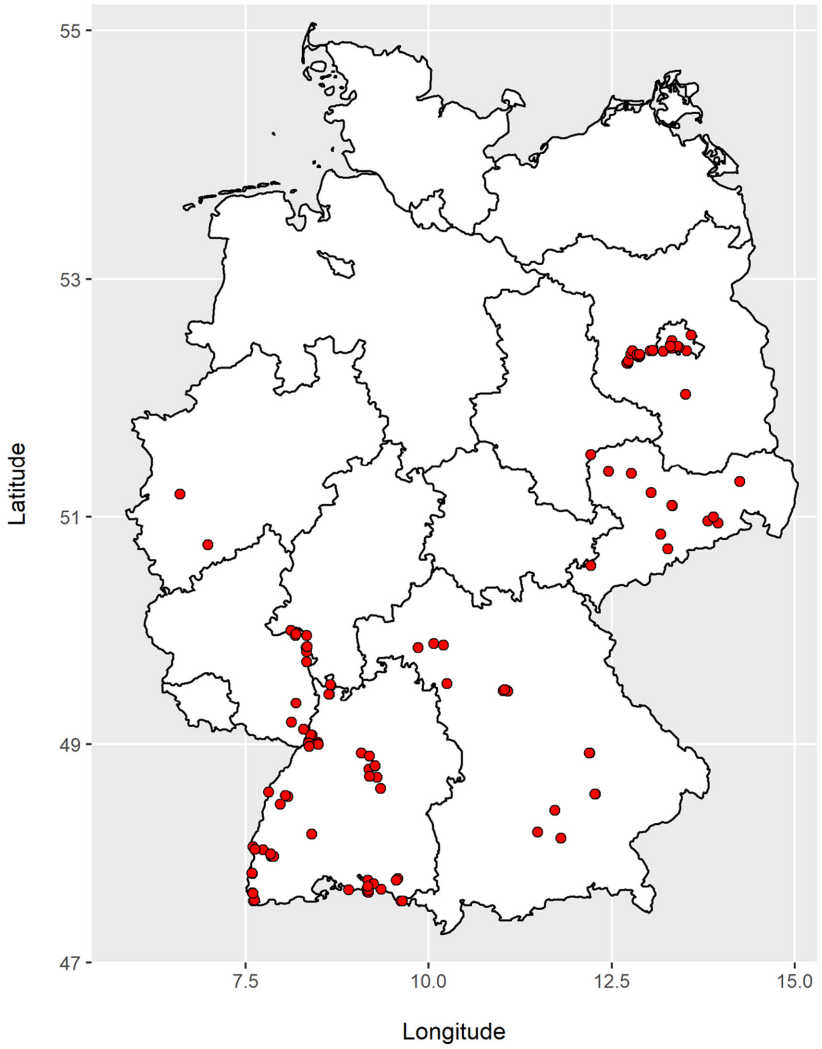

FIGURE 2 Map with the position of traps in the years 2017–2020. Some trap location points were used over several years [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Number of traps per year used to monitor the brown marmorated stinkbug

Year	Number of traps
2017	18
2018	23
2019	69
2020	70

very likely to occur. This includes gardens and parks in rural areas with high traffic volume (Haye et al., 2015; McPherson, 2017).

The traps were checked regularly, at least every 14 days. If no target organism was caught, then this date was entered in the table as 'absence'. When one or more individuals of the target organism were present, the infestation level/quantity, type of location (e.g. urban area, forest and vegetable cultivation), current development stage and mating status were noted in the table for that particular date and trap/location. The monitoring with traps was carried out from May/June until the end of September/October.

The pheromone traps have been managed by the project since 2019 (Table 1). However, a few traps were established earlier (18 in 2017 and 23 in 2018) and were taken over at the start of the ProgRAMM project (Heß et al., 2019).

2.2 | Visual monitoring

Visual monitoring with photographic documentation was carried out from May to November in 2019 and 2020 (Figure 3). In addition to date and location of discovery, host/feeding plants and number of individuals, other important information was recorded: end date of winter dormancy (first find of the year), mating information, oviposition, first occurrence of nymphs, emergence of the different nymphal stages up to adult and beginning of winter dormancy (retreat into protected areas, e.g. buildings). Catalpa trees (*Catalpa bignonioides*), from the

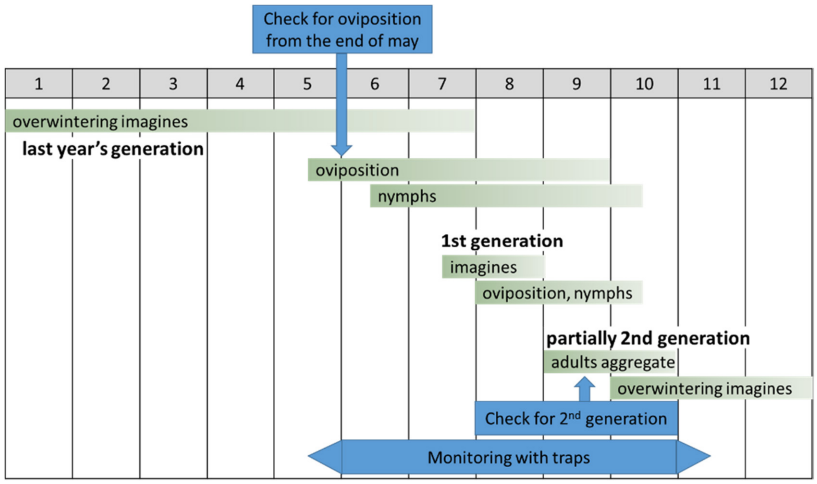

FIGURE 3 Developmental stages of brown marmorated stinkbug over the year (columns for 12 months) and time of monitoring activities [Colour figure can be viewed at wileyonlinelibrary.com]

family Bignoniaceae, turned out to be an important indicator tree in urban areas for the occurrence of *H. halys* because they are relatively rare and scattered over the urban area, but usually easily accessible, so that the extent of the spread of *H. halys* over an area can be estimated. Thus, the indicator trees are a good starting point when looking for a first find of the brown marmorated stinkbug in a new area. Catalpa trees were therefore primarily targeted during visual control. Other important indicator trees were Ailanthus trees, also known as Tree of heaven (*Ailanthus altissima*) of the Simaroubaceae family, the Princess tree (*Paulownia tomentosa*) of the Paulowniaceae family and the Cherry Laurel (*Prunus laurocerasus*) of the Rosaceae family. These trees are often found in parks and are thus easily accessible and permanent.

2.3 | Citizen science

Citizen science can be a substantial tool to improve monitoring programmes for *H. halys* (Malek et al., 2018). At public events, presentations and on the internet (LTZ Augustenberg, 2021), the public was asked to help in finding the brown marmorated stinkbug. The insects found by citizens were sent to LTZ Augustenberg or JKI, either the organism itself or a photo of it, together with information about the place and date of discovery and any host plants, for identification by qualified scientists. Citizen science databases were also included, amongst others iNaturalist, naturgucker.de and gbif (GBIF.org, 2021a, 2021b). All data points taken from the databases that are used in this manuscript, e.g. iNaturalist (https://www.inaturalist.org/taxa/81923-Halyomorpha-halys), were checked by a researcher to ensure high quality and correct identification of the species (Zimmermann et al., 2018). For these citizen science data points, the inhomogeneous distribution of observation opportunities (locations where people look for insects) as well as the presumably correlated inhomogeneous distribution of bugs with human presence/infrastructure (bugs look for hibernation sites in buildings and are unknowingly transported by humans (hitchhiker species) must be taken into account. This may result in a spatial bias of the actual distribution of the pest (Dickinson et al., 2010). The potential effect of the COVID-19 pandemic on citizen science and on distribution via 'hitchhiking' must also be kept in mind when comparing the data in time series (Basile et al., 2021).

TABLE 2 Data points with presence and absence of *Halyomorpha halys* by year

Year	Presence	Absence
2017	208	92
2018	878	217
2019	1189	844
2020	1325	621

TABLE 3 Number of presence data points gained from the different summarized sources by year

Source	2017	2018	2019	2020
Citizen science	49	614	562	858
External experts	91	113	314	125
Literature	6	36	35	0
LTZ	62	49	207	334
JKI	0	66	71	8

2.4 | Other sources

References used to complement the monitoring database included Hanselmann (2016), Haye and Zimmermann (2017), Morkel and Dorow (2017), Claerebout et al. (2018), Kott (2019) and Morkel and Renker (2019). Other sources

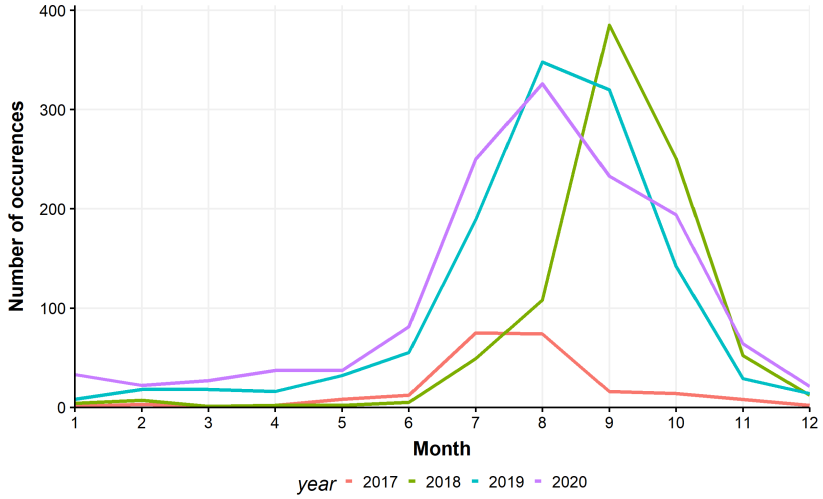

FIGURE 4 Number of verified brown marmorated stinkbug finds in each month for different years. [Colour figure can be viewed at wileyonlinelibrary.com]

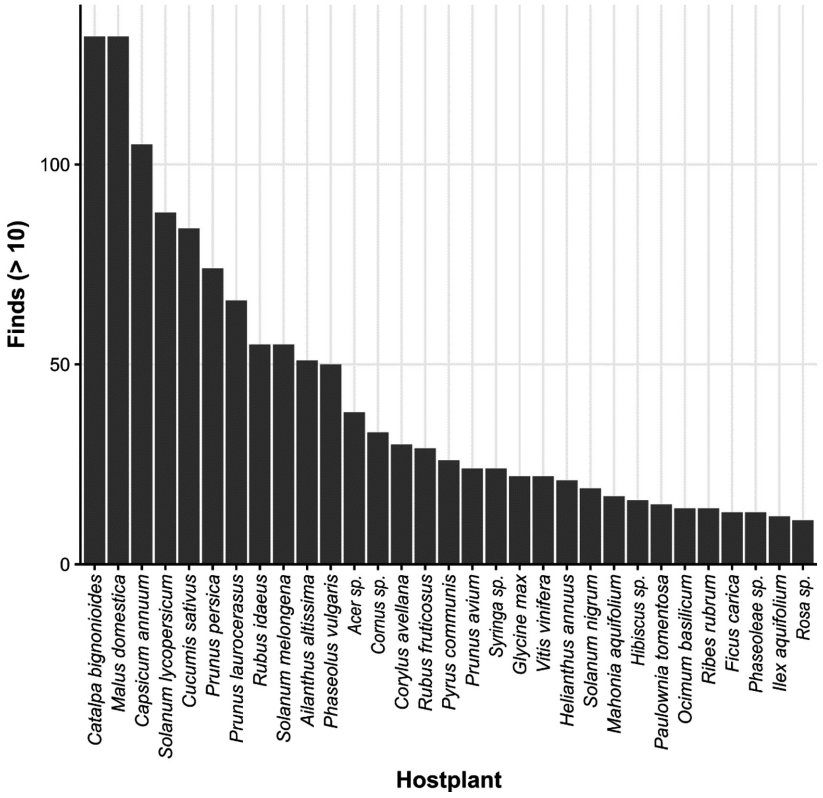

FIGURE 5 Host plant that the brown marmorated stinkbug was found on. Only plants with more than 10 occurrence points are shown

that contributed to the brown marmorated stinkbug database were reports of findings by universities, research institutes, phytosanitary services and external experts.

3 | RESULTS AND DISCUSSION

During the total monitoring phase (2017–2020) a total of 3600 occurrence points of the brown marmorated stinkbug were registered in Germany. The numbers show an increasing trend from 208 finds in 2017 to 1325 finds in 2020 (Table 2). Most occurrence points in 2017 were from the InvaProtect project (Stöckli et al., 2017) and identifications and excursions from the Center for Agricultural Technology Augustenberg (LTZ). It is possible that there were only few reports through citizen science in 2017 because the brown marmorated stinkbug was not well known at that time in Germany. In 2018, more than half of the occurrence data points were contributed through emails (citizen science). In 2019, the presence data points

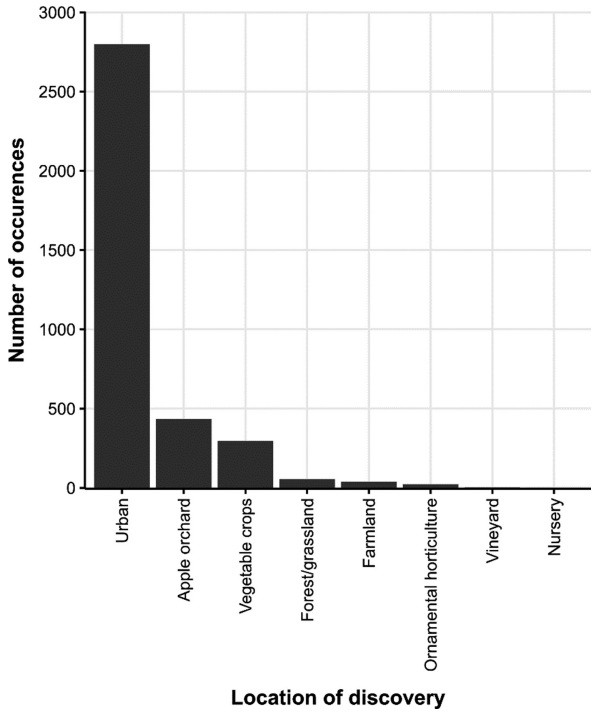

FIGURE 6 Location of discovery of the brown marmorated stinkbug

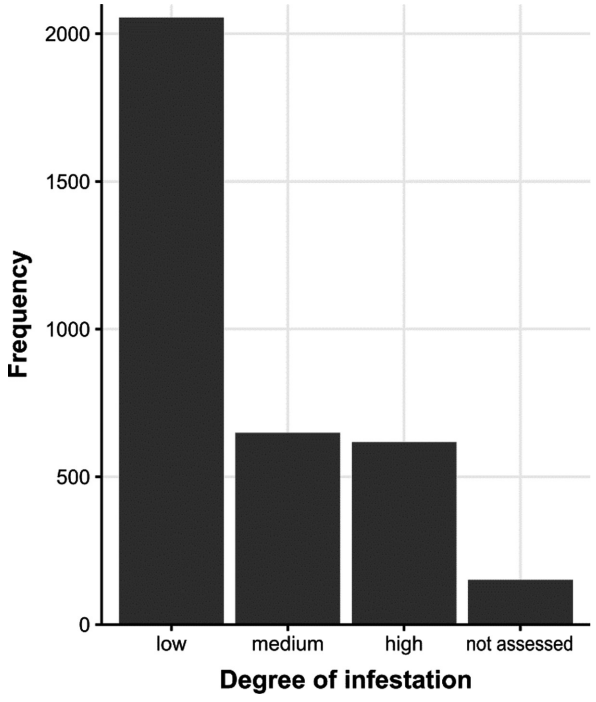

FIGURE 7 Degree of infestation for the single data points. Assessment categories: low (single animal), medium (one colony), high (more than 1 colony), not assessed, since data were not provided

from iNaturalist increased strongly as did the number of points from LTZ identifications and from excursions and external consultants. In 2020, most data points were contributed by citizen science, especially through websites such as iNaturalist, followed by data points from LTZ identifications and excursions (Table 3).

Most brown marmorated stinkbugs were found between July and November (for weekly resolution graphs see the Supporting Information), with a trend for abundance peaks occurring a few weeks earlier each consecutive year except for 2017, with only 202 finds in total (Figure 4). In 2018 most brown marmorated stinkbugs were found in September and October (385 and 251 finds, respectively), while in 2019 there was a strong peak in August and September with 348 and 320 finds. In 2020, the presence data points were distributed a bit more homogeneously, with the main peaks in July, August and September (250, 326 and 233 finds, respectively). Variations in the data for 2020 may be due to the COVID-19 pandemic and the associated travel restrictions, especially for citizen science (as mentioned in section 2.3) and for the monitoring data from external experts. In addition, inter-annual variations of environmental variables will affect the population development in a year and its subsequent spread.

The polyphagous feeding behaviour of the brown marmorated stinkbug could be observed in the wide range of host plants on which the insects were found (Figure 5). The brown marmorated stinkbug was most often found on Catalpa trees (*Catalpa bignonioides*) and apple trees (*Malus domestica*) (132 finds each). Peppers (*Capsicum annuum*) (105 finds) were the third most common plant that *H. halys* was found on, followed by tomato (*Solanum lycopersicum*) (88) and cucumber (*Cucumis sativus*) (84). In total, the brown marmorated stinkbug was found on more than 167 different plants. Many of the fruits mentioned are often grown in allotments in urban areas, which is also reflected in the high frequency of this location of discovery.

H. halys was most often found in urban areas (2799 finds). This confirms the occurrence in human settlements observed in various studies (Inkley, 2012; Hancock et al., 2019). The pest was also found in apple orchards (434) and vegetable crops (296). Other sites of discovery with some finds included forests and grasslands (55), farmland (39), ornamental horticulture (23), vineyards (3) and tree nurseries (2) (Figure 6).

Most finds were of only one single individual (2055). However, there were also finds of one (649) or more (617) colonies (Figure 7), where a colony means a group of individuals of an unspecified number. This pattern may be an indicator that the brown marmorated stinkbug is in an early stage of invasion in Germany and is still spreading in the country, having not yet reached the abundance to aggregate in big numbers (e.g. for overwintering) (Cira et al., 2016; Song & Lee, 2021).

The brown marmorated stinkbug has been progressively spreading in Germany over recent years (Figures 8 and 9). From its first discovery points in the Konstanz area in 2011, it has been spreading northwards throughout Germany. It appears to be not only

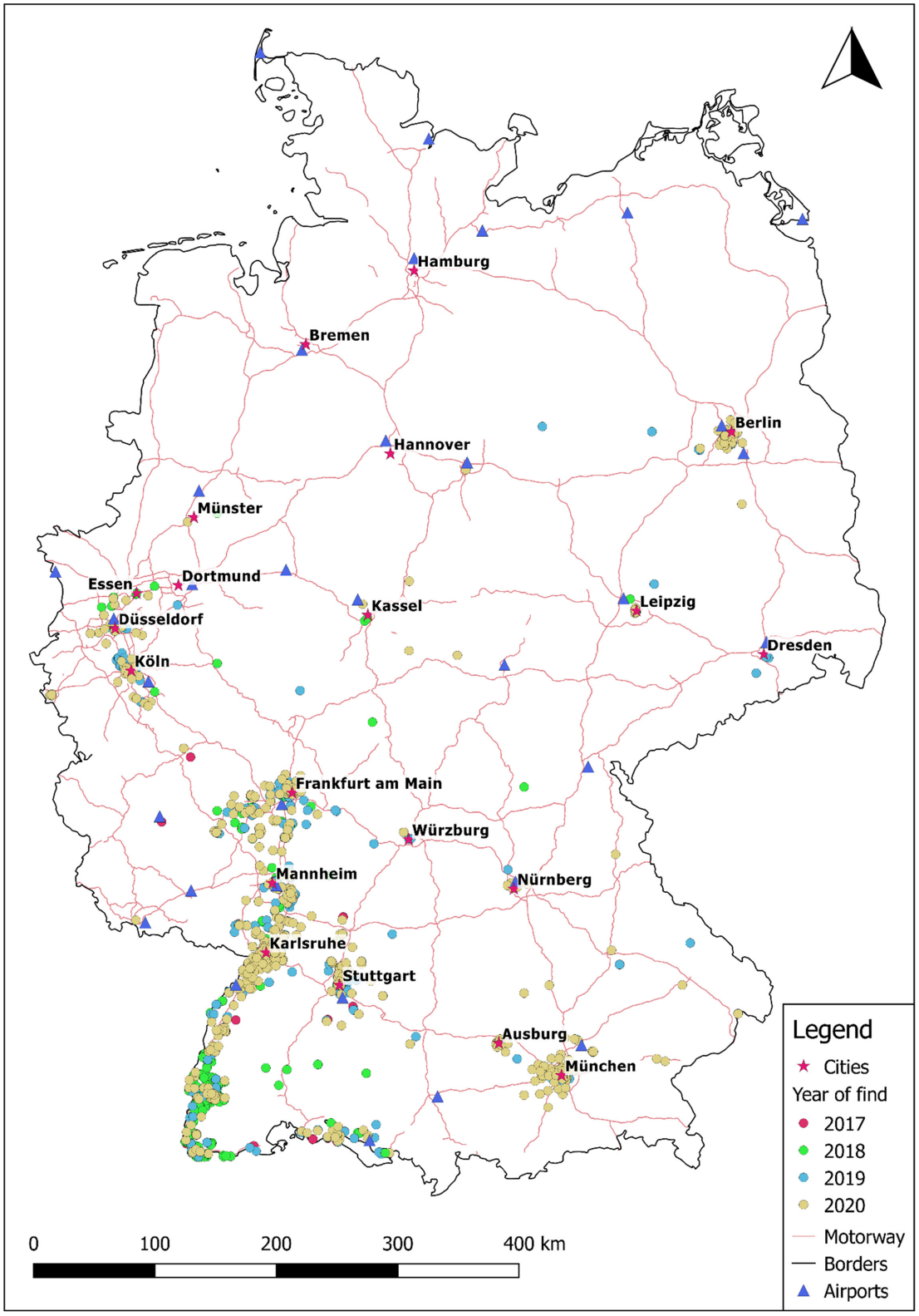

FIGURE 8 Illustration of the finds of *Halyomorpha halys* over the years 2017–2020. Main motorways in red, airports as blue triangles, borders of Germany in black; some major cities for reference as red stars. (Airport locations adapted from: OurAirports.com, Megginson Technologies Ltd. Public Domain, 2007; Motorways adapted from: OpenStreetMap, licensed under Open Database 1.0 License 2014) [Colour figure can be viewed at wileyonlinelibrary.com]

spreading actively, but also passively via humans through 'hitchhiking' with traffic and industrial transportation, hence more finds in the vicinity of roads and urban areas. By this means, long distances can be travelled each year. The current distribution of *H. halys* in Germany can be described as clustered in the warmer

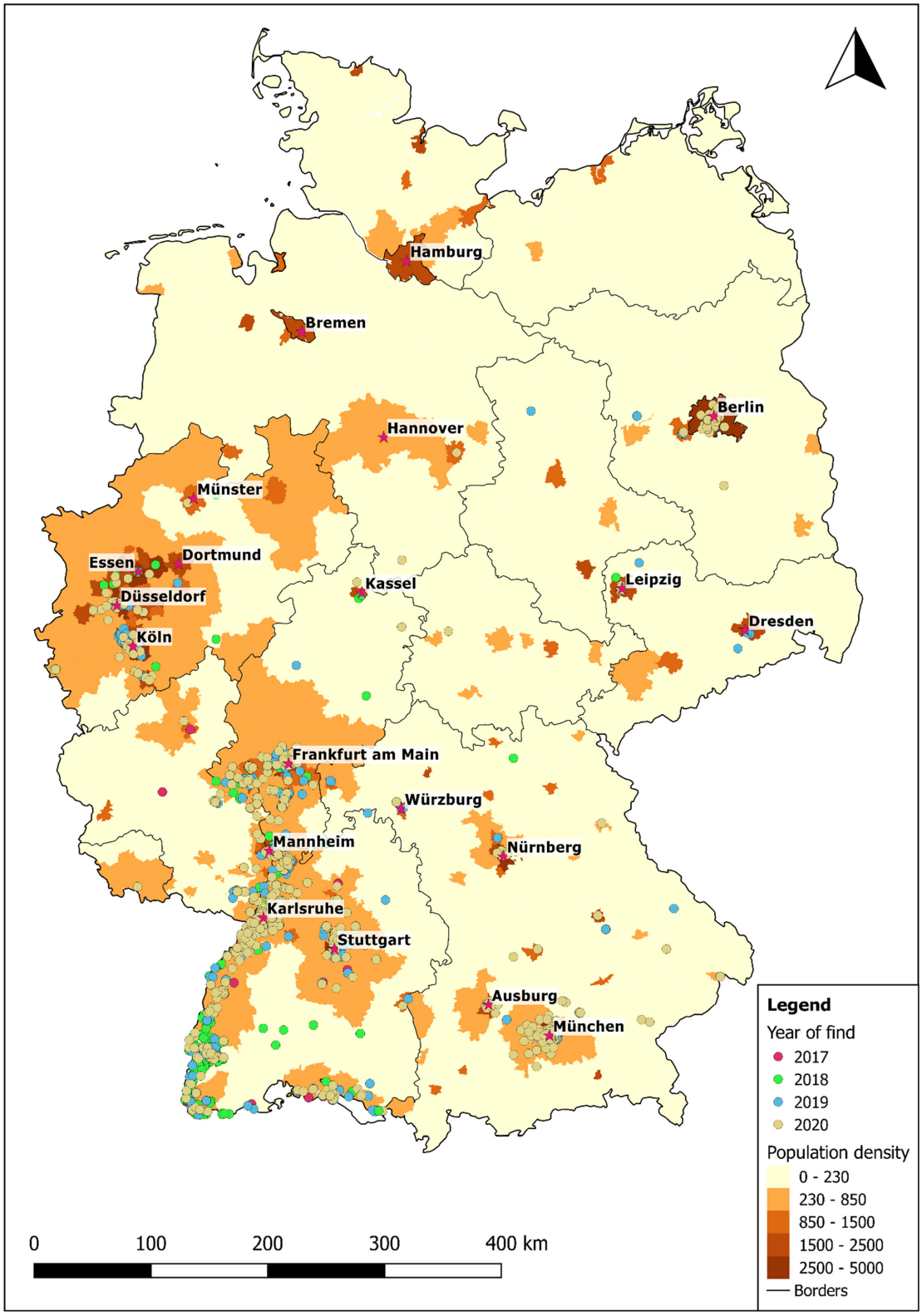

FIGURE 9 Illustration of *Halyomorpha halys* occurrence over the years 2017–2020 with the population density (inhabitants per km^2) in the background. Some major cities for reference as red stars. (Population density map adapted from: GeoBasis-DE/BKG, Statistisches Bundesamt (Destatis) 2020) [Colour figure can be viewed at wileyonlinelibrary.com]

southwestern region with smaller clusters in the east and west of Central Germany. The pest is particularly abundant in the warmest region in Germany, the Upper Rhine Rift, where a clear spread from south to north can be observed. Close to this main dispersal route, in the Lake Constance region, is another cluster of occurrence.

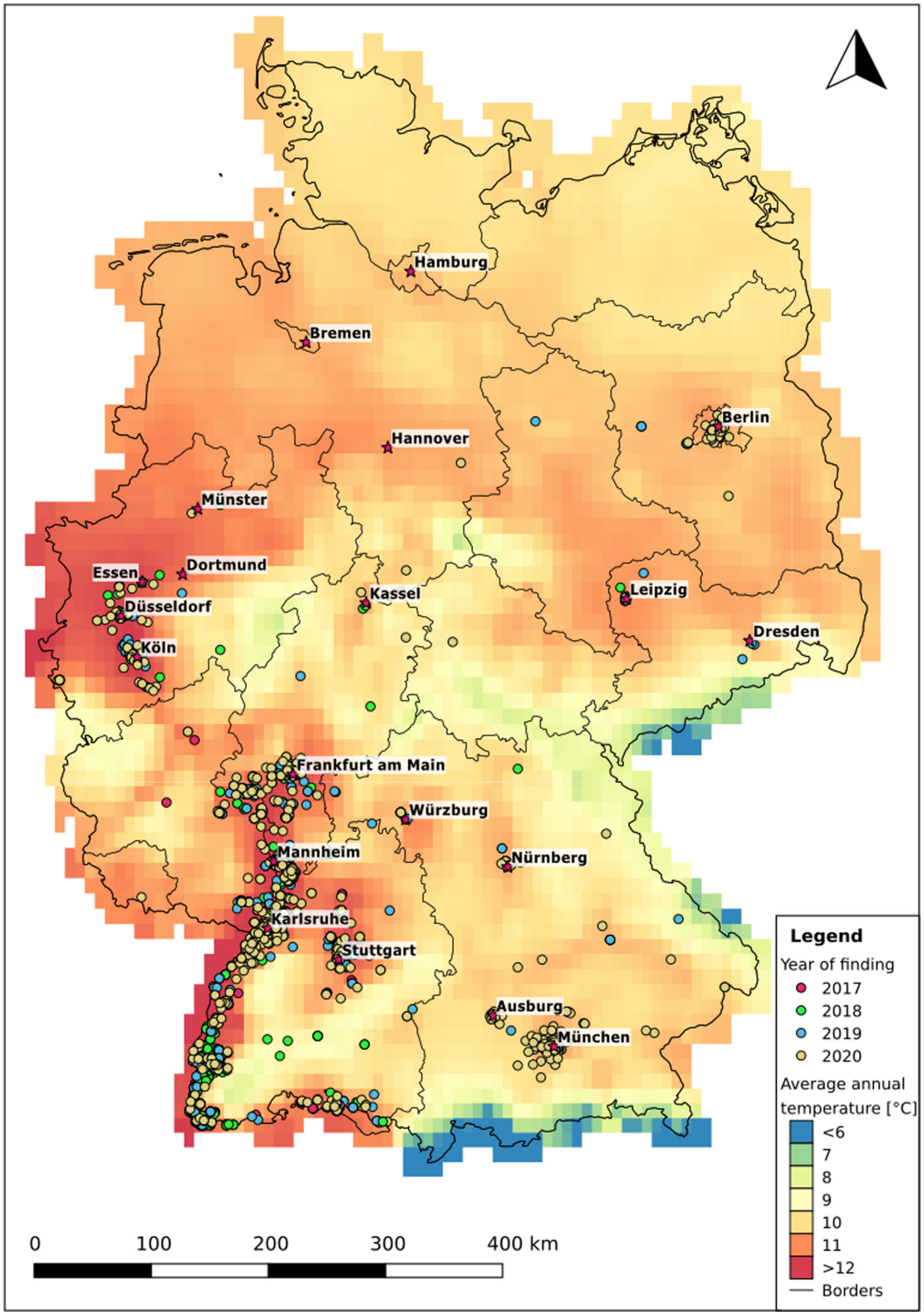

FIGURE 10 Illustration of *Halyomorpha halys* occurrence over the years 2017–2020 with the average annual temperature (°C) of the years 2017–2020 in the background. Some major cities for reference as red stars. (Temperature map calculations based on data from Deutscher Wetterdienst DWD) [Colour figure can be viewed at wileyonlinelibrary.com]

Here, the warm climate in combination with the temperature buffer function of the large lake as well as the warm winds from the Alpine *föhn* likely play a role in the creation of suitable environmental conditions for the establishment of the brown marmorated stinkbug. Since this is also a large fruit-growing area, the brown

marmorated stinkbug was likely to have found very attractive host plants. This may have increased the potential for reproduction and thus for a faster spread. There are also large clusters of *H. halys* finds in and around Berlin, Munich and Nuremberg. These may be connected to the high population densities (Figure 9) in relation to high traffic and travel volume in the areas. Another cluster of occurrence is in the Ruhr region. This region has one of the highest population densities in Germany and in addition many heavily frequented highways and a lot of border traffic, which may promote entry and spread of the brown marmorated stinkbug (Figures 8 and 9). Only single finds were registered in Central and Northern Germany. In accordance with Bebber et al. (2013) and Hickling et al. (2006), *H. halys* spreads from the southern, warmer regions towards the colder north (Figure 10). The increasing temperatures due to climate change may lead to better growth conditions, resulting in a higher number of generations per year as well as an increased fitness and may thus even accelerate these spread patterns. Due to its proximity to humans and human settlements (e.g. overwintering in basements or attics), it can be assumed that the cold temperatures during winter in Germany do not have as strong an effect on the brown marmorated stinkbug as they usually have on other insects. This promotes the brown marmorated stinkbug in its further population growth and spread, and could potentially lead to extreme accumulation infestations of residential and industrial buildings as has been observed in the United States (Schulz, 2018). Furthermore, high abundance could lead to more damage in the future, especially in orchards, as has been observed in Italy (Bariselli et al., 2016).

4 | CONCLUSION

The monitoring results indicate an increasing dispersal of the brown marmorated stinkbug in Germany. Further spread and increasing abundance are expected. The dispersal patterns appear to be correlated with temperature, human population density and infrastructures such as roads and airports. The limits of the spread are not yet clearly visible, which may be an indicator for potential further spread in Germany. Further monitoring is necessary to determine the exact limits of spread and to identify pest-free areas. As this species is both harming plants and a nuisance when overwintering in buildings, control is an important point to consider. The samurai wasp, *Trissolcus japonicus*, shows promising results for biological control of *H. halys*, but release is currently not permitted in Germany due to nature conservation issues. Since first populations of these parasitoid wasps have already been found in Northern Italy, Switzerland and Germany (Sabbatini Peverieri et al., 2018; Stahl et al., 2019; Dieckhoff et al., 2021), natural spread is expected.

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DATA AVAILABILITY STATEMENT

The dataset with anonymized monitoring data is provided as an excel file in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.

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