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The economic cost of control of the invasive yellow-legged Asian hornet

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Abstract

Since its accidental introduction in 2003 in France, the yellow-legged Asian hornet *Vespa velutina nigrithorax* is rapidly spreading through France and Europe. Economic assessments regarding the costs of invasive species often reveal important costs from required control measures or damages. Despite the rapid invasion of the Asian yellow-legged hornet in Europe and potential damage to apiculture and pollination services, the costs of its invasion have not been evaluated yet. Here we aimed at studying the costs arising from the Asian yellow-legged hornet invasion by providing the first estimate of the control cost. Today, the invasion of the Asian yellow-legged hornet is mostly controlled by nest destruction. We estimated that nest destruction cost €23 million between 2006 and 2015 in France. The yearly cost is increasing as the species keeps spreading and could reach €11.9 million in France, €9.0 million in Italy and €8.6 million in the United Kingdom if the species fills its current climatically suitable distribution. Although more work will be needed to estimate the cost of the Asian yellow-legged hornet on apiculture and pollination services, they likely exceed the current costs of control with nest destruction. It could thus be worth increasing control efforts by aiming at destroying a higher percentage of nests.

Keywords

biological invasions, IAS, Invasive alien species, yellow-legged hornet, impact

Introduction

Invasive species are one of the greatest threats to biodiversity and ecosystem functioning (Bellard et al. 2016) and part of global environmental change (Simberloff et al. 2013; Lewis and Maslin 2015). As globalisation keeps increasing, so does the amount of successful invasions (Seebens et al. 2017). Besides their negative impact on biodiversity and ecosystems, invasive species are also very costly to the global economy (Marbuah et al. 2014; Bradshaw et al. 2016). Indeed, invasive species can be very costly to goods and services such as agriculture (Paini et al. 2016), forestry (Aukema et al. 2010), aquaculture, tourism, recreation and infrastructure (Su 2002), but also to human health (Gubler 1998). Categorising and estimating these costs is not an easy task, so frameworks have been developed to categorise them, especially in ecology (Bradshaw et al. 2016). Bradshaw et al. (2016) suggest a framework that categorizes costs of species invasions into prevention, damage and response costs, but also into goods and services, human health, ecosystem processes and ecology. They estimated that "invasive insects cost a minimum of US$70.0 billion per year globally" in goods and services, "while associated health costs exceed US$6.9 billion per year", although these estimates are believed to be much underestimated (Bradshaw et al. 2016). Amongst the invasive species for which no cost has been estimated yet, the yellow-legged hornet *Vespa velutina nigrithorax*, the invasive sub-species of the Asian hornet, is considered an important threat to both biodiversity and apiculture and the importance of the damage it causes is regularly invoked in the media.

Vespa velutina nigrithorax is an Asian hornet native to China that invaded South Korea in 2003 and France in 2004. The species was first identified in 2003 in the southern part of South Korea (Kim et al. 2006). Introduced from China, it invaded most of the peninsula at an approximate rate of 10-20 km per year and became more abundant than other native *Vespa* species (Choi et al. 2012). The invasive hornet was then introduced into Japan: in Tsushima Island in 2012 (Ueno 2014) and Kyushu Island in 2015 (Minoshima et al. 2015). In France, *V. velutina nigrithorax* was first observed in south-western France in 2004 (Haxaire et al. 2006) after its accidental introduction from China (Arca et al. 2015). It spread rapidly, colonising most of France at an approximate rate of 60-80 km per year (Rome et al. 2015; Robinet et al. 2016) and progressively invading other European countries: Spain in 2010 (López et al. 2011), Portugal (Grosso-Silva and Maia 2012) and Belgium (Rome et al. 2013) in 2011, Italy in 2012 (Demichelis et al. 2014), Germany in 2014 (Witt 2015) and, finally, the UK where it was first recorded on 20 Sept 2016 (Budge et al. 2017). The rapid spread of the species in France and Europe is not necessarily a consequence of human-mediated dispersal, indicating that the species can rapidly spread on its own (Robinet et al. 2016), although human-mediated dispersal is not uncommon (Bertolino et al. 2016). Both climate and land-use have been shown to influence the spread of *V. velutina nigrithorax* (Villemant et al. 2011; Bessa et al. 2016; Fournier et al. 2017).

The yellow-legged hornet is believed to have several negative consequences on apiculture, biodiversity and, thus, on human well-being. Indeed, within its native and invasive range, *V. velutina nigrithorax* actively feeds on honeybees (Tan et al. 2007;

Monceau et al. 2013, 2014; Arca et al. 2014; Choi and Kwon 2015). Besides, the species could also have a negative impact on ecosystems by feeding on wild insects (Beggs et al. 2011) and contributing to the current global decline of pollination services and honey production (Villemant et al. 2011; Arca et al. 2014; Rortais et al. 2017). Given that nests are often found in urban areas (Franklin et al. 2017; Fournier et al. 2017), stings to humans are possible. Although multiple stings can be dangerous for humans, very few cases have been reported so far (de Haro et al. 2010), but the size of the hornet and its reputation for aggression make its presence dreaded and nest destruction systematically requested when the nest is close to human habitations or human activities. All of these negative impacts of the yellow-legged hornet invasion are likely to have an important economic cost, although such costs have not yet been estimated. Besides these potentially high cost, controlling the species in the already invaded areas and preventing the species further spread also have an economic cost that has not been estimated either.

The control of *V. velutina nigrithorax* invasion is mainly undertaken by nest destruction and bait trapping (Monceau et al. 2014), although neither of these methods are sufficient to achieve eradication even in a limited area when the yellow-legged hornet population is already too dense (Beggs et al. 2011). Several attractants have been used for bait trapping (Kishi and Goka 2017) but their efficiency is very limited as baits catch individuals rather than colonies. Moreover, they do not target *V. velutina nigrithorax* exclusively (Monceau et al. 2012). A previous study concluded that the most efficient strategy for controlling the yellow-legged hornet invasion remains to identify its presence early in new areas (with the help of predictions) and locate the nests for their systematic destruction (Robinet et al. 2016). In this study, we aimed at providing the first cost estimates for the control of the yellow-legged hornet invasion associated with nest removal. As these costs are not readily available for the entire invaded area, we did so by identifying potential correlates of the cost of nest destruction and extrapolated its total cost in the already invaded area, as well as in its potential invaded area.

Methods

The economic costs of invasive insects can be divided into three main categories: costs related to the prevention of invasion, the cost of fighting the invasion and the costs of the damage caused by the invasion (Bradshaw et al. 2016). There is no simple relationship between these cost categories. As the invasion is already underway, the costs related to the prevention of the invasion are non-existent. The costs of the damage caused by the invasion will be addressed in another study, as they require very specific data and methods. The main identifiable cost of fighting the invasion of yellow-legged hornets is the cost of nest destruction and will be the focus of this study. This first step, when combined with a subsequent estimation of damage costs, will allow the assessment of cost effectiveness, return on investment and similar indicators which will be useful indicators for decision-making frameworks for the use of funds for control programmes.

Data gathering regarding the cost of nest destruction

Estimating the average price of destroying a yellow-legged hornet nest would, in principle, be possible by surveying the many businesses providing such a service. However, as our aim is to estimate the total cost of nest destruction in the entire invaded range yearly, we also needed to know the total number of nests being destroyed each year. It seemed quite testing to gather such data exhaustively within a large enough spatial unit to then make reliable extrapolations. Therefore, we chose to focus our effort on identifying cities and departments subsidising nest destructions, as they were likely to have data, such as the number of nests destroyed and the total amount it costs them yearly. Indeed, given the rapid spread of the yellow-legged hornet, the administration of some French cities and departments decided to subsidise the destruction of the yellow-legged hornet in order to fight off the invasive species and the mechanism of the subsidy obviously encourages all the actors to be recognised by these administrations. To identify such cities and departments, we ran an internet search (using google.fr) with the key words "subvention", "destruction", "nid" and "frelon asiatique" or "*vespa velutina*" (i.e. "subsidy", "destruction", "nest" and "Asian hornet"). All cities and departments, identified as subsidising the yellow-legged hornet nest destruction, were then contacted to obtain data regarding the total yearly cost of nest destruction, as well as the number of nests that were destroyed.

Extrapolating the cost of nest destruction spatially

To take into account invaded areas with no subsidy of nest destruction, we aimed at spatially extrapolating this cost by identifying potential correlates of the cost of nest destruction. As potential correlates, we chose to investigate the surface area and the human population size of the spatial unit for which we were able to gather cost information. As we could only gather a reduced dataset, potential correlations were investigated through simple models – a linear model and a log-log linear model: for each potential correlate, we fitted the two following models (1) y~x and (2) log(y)~log(x).

Spatial extrapolation to countries other than France, need to be adjusted to *per capita* GDP (in purchase power parity terms), i.e. to the cost of living in a given country. To do that, we gathered the 2015 *per capita* GDP (PPP) of all countries and calculated their ratio to the one of France. The spatially extrapolated cost in a given country is then adjusted by multiplying it by this ratio.

However, if the yellow-legged hornet is rapidly spreading, we must limit our spatial extrapolation to areas it currently occupies and to climatically suitable areas it could likely invade in the next few years. As we aim at providing information useful for managers and decision-makers now, we will not account here for climate change of the next decades. We thus need to predict the potential distribution of the yellow-legged hornet.

Modelling the potential distribution of the yellow-legged hornet

Presence data of the yellow-legged hornet in its native and invaded ranges

Presence data of the yellow-legged hornet from the native Asian range was obtained by gathering information on museum specimens, published records and hornet sampling performed in China (Villemant et al. 2011). As for the invaded range in Europe, data from the French part of the invaded range came from the INPN database that aggregates all validated French records (https://inpn.mnhn.fr/). To this French database, we added the recent locations reported in other European countries (Spain, Portugal, Italy, Belgium and Germany) (López et al. 2011; Rome et al. 2013; Porporato et al. 2014; Witt 2015; Goldarazena et al. 2015; Bertolino et al. 2016). Overall, we obtained 10,395 records in the European invaded range observed from 2004.

Climate data

We used the same eight climatic variables as in previous studies for the niche modelling of the yellow-legged hornet (Villemant et al. 2011; Barbet-Massin et al. 2013). We considered: (1) annual mean temperature, (2) mean temperature of the warmest month, (3) mean temperature of the coldest month, (4) temperature seasonality, (5) annual precipitation, (6) precipitation of the wettest month, (7) precipitation of the driest month and (8) precipitation seasonality. The seasonality is the coefficient of variation of the monthly means. Current data were downloaded from the worldclim database (Hijmans et al. 2005) (http://www.worldclim.org/) as 2.5 arc-min grids (subset of the 19 bioclim variables). These data are interpolations from observed data representative of current climatic conditions.

Climate suitability modelling

Climate suitability of the yellow-legged hornet was modelled by running eight different modelling techniques implemented within the *biomod2* package (3. 3-7 version) (Thuiller et al. 2009) in R (R Core Team 2015): three regression methods (GLM, GAM and MARS), two classification methods (CTA and FDA) and three machine learning methods (ANN, BRT and RF). As no absence data were available for the species, pseudo-absences were randomly drawn (Barbet-Massin et al. 2012) from the South-East part of Asia and from Europe. We used 10,000 random pseudo-absences, with the total weight of presences being equal to the total weight of pseudo-absences (Barbet-Massin et al. 2012). As results might depend on the choice of pseudo-absences, models were replicated three times (with different pseudo-absences selection) (Barbet-Massin et al. 2012). To obtain a consensus distribution, we used an ensemble forecast technique (Marmion et al. 2009): the consensus distribution was calculated as the average of all distributions across modelling techniques and pseudo-absences replicates. Model predictive accuracy was evaluated through cross validation by splitting the data into training data (70%) and evaluation data (30%). The data split for cross validation was repeated five times.

Results

Through our data search, we were able to obtain data on total cost of nest destruction (as well as the number of nests being destroyed) for 10 administrations (two departments and eight cities, Fig. 1). Human population was found to be a strong predictor of the total cost of nest destruction, better so than the surface of the area studied (Table 1). The linear model was better than the log-log linear model, so it was selected for further extrapolation. Spatial extrapolation of potential cost of nest destruction given the population was then realised, based on a gridded population of the world (Center for International Earth Science Information Network – CIESIN – Columbia University 2016) and adjusted to *per capita* GDP (PPP) (Table 1). This spatially extrapolated cost was only applied where the climate is suitable for the yellow-legged hornet. The predicted climate suitability is a continuous value (from 0 to 1). A 0.5 threshold is frequently applied to transform the continuous suitability into binary output (suitable vs. non suitable). However, the yellow-legged hornet is unlikely to be at equilibrium in its invaded area, so we chose a less conservative threshold of 0.3 as the predicted climate suitability might be underestimated. Climate suitability below 0.3 was forced to 0. Not all climatically suitable areas have been invaded yet (Figure 2). To obtain a potential spatial cost of nest destruction in all areas suitable for the yellow-legged hornet, we can multiply the hornet climate suitability by the spatially extrapolated cost. This is the estimated yearly cost once the hornet has established. In Europe, the main yearly costs, once the hornet has colonised all its climatically suitable distribution, are estimated for France (€11.9M), Italy (€9.0M) and the United Kingdom (€8.6M) (Fig. 3 and Table 1). In Japan and South Korea, where the species has already been observed, the total yearly cost of nest destruction is estimated at €19.5M and €11.9M respectively (Fig. 3 and Table 1). If the species has been accidently introduced into the countries that have not yet been invaded, the yearly cost of nest destruction could be important in some countries, such as the USA (€26.9M), Australia (€3.6M), Turkey (€3.5M), Argentina (€2.6M) and Brazil (€1.8M) (Fig. 3 and Table 1). All these estimated costs are contingent on successful invasions.

In France, the hornet is already successfully spreading at a very fast rate and we know which year each department was invaded. So, we estimated the yearly cost of nest destruction since the start of the invasion, by only considering costs within invaded departments each year (a department was considered as successfully invaded when the tenth individual was observed). In 2006, only two years after the hornet was first observed in France, three departments were already invaded and the cost of nest destruction was estimated at €408k (Fig. 4). Since then, the estimated yearly costs have been increasing by ~€450k each year (Fig. 4), as the hornet keeps spreading and invades new departments. Overall, we estimated €23M as the cost of nest destruction between 2006 and 2015. If this temporal trend can be extrapolated for the next few years (i.e. if the hornet keeps spreading at a similar rate), we expect the yearly cost of nest destruction to reach an estimated value of €11.9M (given all suitable areas are invaded) by 2032.

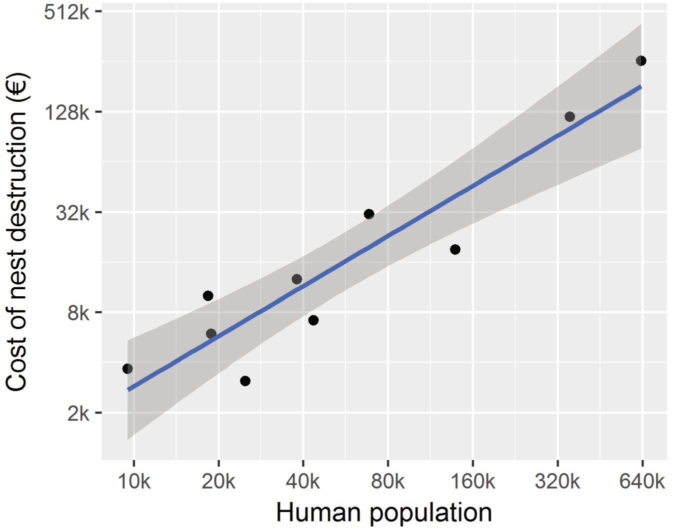

Figure 1. Relationship between population and the cost of nest destruction. The blue line represents the selected linear model (model 3 in Table 1). The darker grey area represents the confidence interval of the regression curve. Note that both axes are logarithmic.

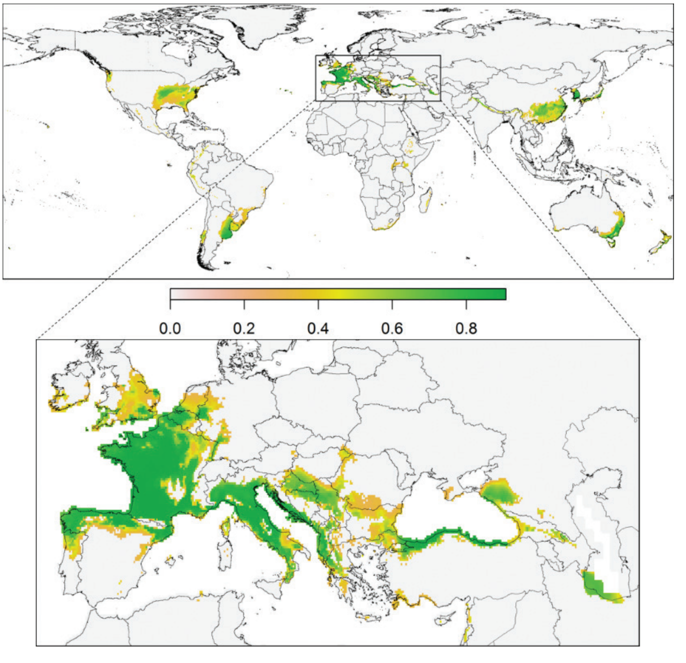

Figure 2. Consensus climate suitability of the yellow-legged hornet predicted from species distribution modelling. The climate suitability can be interpreted as a probability of having a suitable climate. The mean cross-validation TSS (respectively AUC) of all models considered to compute the consensus is 0.90 ± 0.07 (respectively 0.97 ± 0.03).

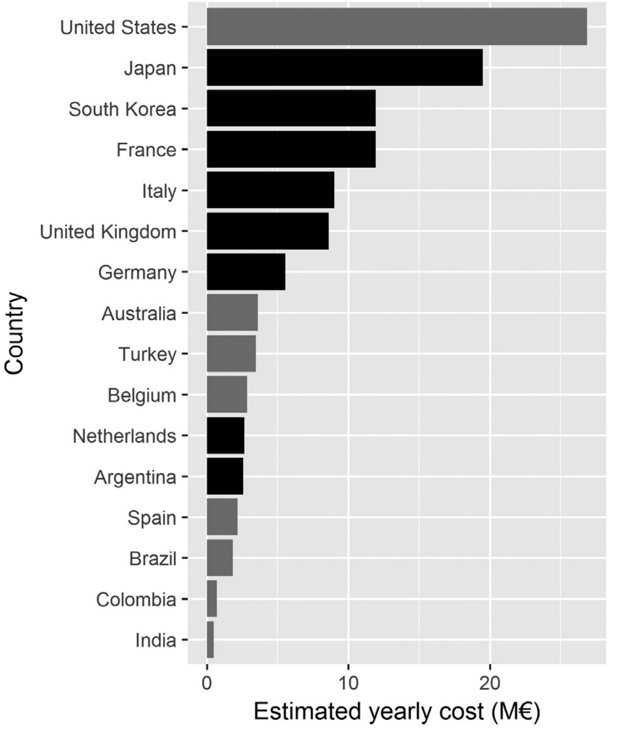

Figure 3. Estimated yearly cost of nest destruction if climatically suitable areas are fully invaded. Bars are coloured in black if the species is already invading the country and in grey for countries where the species has not established yet.

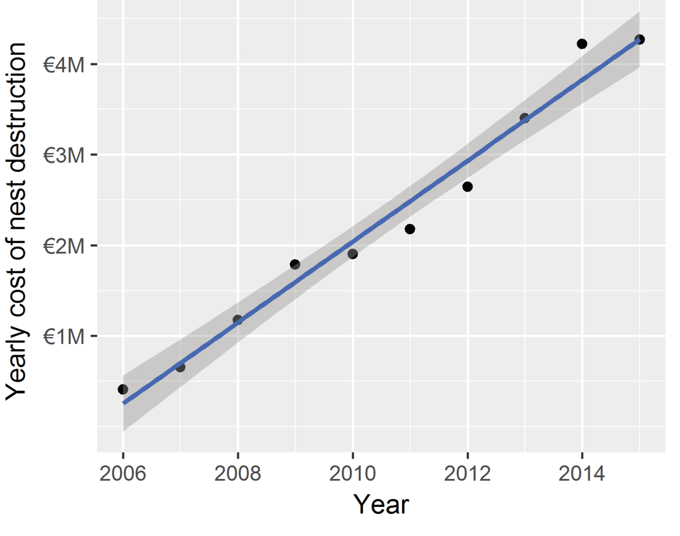

Figure 4. Estimated yearly cost of nest destruction in France since the start of the invasion given the yearly invasive range. The darker grey area represents the confidence interval of the regression curve. The increase results from the spread of the species.

Table 1. Results of the four models tested the potential influence of population and surface on the cost of nest destruction.

Model	Intercept	Slope	R^2	F	df	p-value
Cost~Population	$-6.49e^{3}$	0.39	0.97	303.2	8	$1.2e^{-7}$
Cost~Surface	8767	28.6	0.88	61.32	8	$5.09e^{-5}$
log(Cost)~log(Population)	-1.23	0.99	0.86	54.3	8	$7.82e^{-5}$
log(Cost)~log(Surface)	6.93	0.58	0.82	40.95	8	$2.09e^{-4}$

Discussion

As of today, nest removal remains the main strategy for efficiently controlling the yellow-legged hornet population. Indeed, even though European parasitic flies or nematodes can infect *V. velutina nigrithorax* (Darrouzet et al. 2014; Villemant et al. 2015), they seem to have a limited impact on the species colony survival (Villemant et al. 2015). Besides, intraspecific competition was shown to be unlikely as a potential mechanism for population regulation (Monceau and Thiery 2017), so there is no indication that the rapid spread of the species in Europe will lessen if control strategies do not improve and are not reinforced. Climate change may, on the contrary, worsen the invasion in the near future (Barbet-Massin et al. 2013) and, therefore, the overall economic costs. Nest removal thus currently remains the main strategy for controlling the spread and the population density of the yellow-legged hornet and we suggest it should be maintained or intensified (see below). It could also be combined with trapping individuals with more selective traps and more selective attractant, in order to make the control more efficient (Robinet et al. 2016). Successful case studies with *Vespula* wasps suggest the possibility of toxic baiting for the control of *V. velutina nigrithorax* (Kishi and Goka 2017), but further research is needed. As of today, the effort put into nest removal is not sufficient to prevent the spread of the species. Indeed, it has been estimated that only an average of 30-40% of detected nests have been destroyed each year in France (Robinet et al. 2016). The number of nests being destroyed does not result from a control strategy aiming at destroying all or a given percentage of detected nests, but rather from nests being destroyed because of their being potentially harmful to human (nests close to human habitations) or beekeeping activities (nests close to beehives). However, enforcing a control strategy that would aim at doubling the number of nests destroyed – thus potentially doubling the estimated yearly cost of nest destruction, to €23.8M if the cost per unit of control is constant- could reduce the spread (rate of dispersal) of the species by 17% and its nest density by 29% (Robinet et al. 2016). Further destroying 95% of the detected nests – thus tripling the estimated yearly cost of nest destruction, to €35.7M – could reduce the species' spread by 43% and its nest density by 53%. Our study thus provides the first estimates of the costs for nest destruction following the yellow-legged hornet invasion. These results can further be used to estimate the costs/benefits of different control strategies involving nest removal. If a more systematic nest destruction is considered for better control of the yellow-legged hornet invasion, public awareness campaigns need to be raised and nest removal could be required by a country's regulation. Furthermore, in order to reach a higher percentage of nests being detected and localised, new detection techniques need to be implemented.

As our cost estimates rely on scarce data, they therefore have to be interpreted with caution. Although our data were concentrated in western France, there is no reason to believe that the population – cost correlation would differ in another region. Despite a low amount of data, we were able to detect a strong correlation between the cost of nest destruction and human population within a given spatial unit. The cost of destroying a nest can vary significantly with local circumstances; but the quality of this correlation tends to show that, for a minimum area, the aggregate cost is not affected by this variability (there is no spatial correlation of the cost heterogeneity). Given the standard error of the correlation coefficient estimate, the confidence interval around extrapolation estimates should be ~10% of the extrapolated estimate. For example, the confidence interval for the estimated €11.9M yearly cost in France is €11.2M-€12.6M. The population – cost correlation, found by the authors, is not that surprising, given that the yellow-legged hornet was shown to favour urban and anthropised habitats (Franklin et al. 2017; Fournier et al. 2017). Besides, a nest is most likely to be destroyed if it is close to human habitations or activities, so it seems logical that larger numbers of nests are destroyed in areas with higher population density.

For a better understanding of the costs/benefits of different potential control strategies, it will also be important to compare the costs of nest removal strategies with the economic costs due to the negative impacts of the yellow-legged hornet, such as a potential decrease in the beekeeping activity or a decrease in pollination services or health costs. If the health costs are not currently available, the apiculture revenue was €135M in France in 2015. Given that half of France is currently invaded by the yellow-legged hornet, approximately 50% of this revenue can be at risk from the yellow-legged hornet. If the invasive species were to cause a 5% decrease in honey production, there would be an associated yearly cost of €3.3M. This is a broad estimate that would require data regarding the spatial distribution of honey production and the impact of the yellow-legged hornet on honey production to be refined. The yearly pollination services to agriculture were estimated at €2 billion in France (Gallai et al. 2009), so, if the yellow-legged hornet were to cause a 5% decrease in pollination services over half the territory, there would be an associated yearly cost of €50M. Obviously further research is needed to refine these estimates and, in particular, to assess the percentage of honey production and pollination services affected, but comparing it to the yearly €11.9M of nest destruction gives an idea about the order of magnitude of relative costs of damage and damage prevention. If more stringent control measures aiming at tripling the number of nests being destroyed were to be implemented, they would still be less costly than the cost of potential damage to apiculture and agriculture if the yellow-legged hornet causes more than a 5% decrease in honey production and in pollination services.

Estimates of costs associated with surveillance or prevention would also be very informative. Indeed, given the potential high costs associated with the yellow-legged hornet invasion to goods and services and given how difficult and costly it can be to control it once well established, preventing the species introduction into new countries will likely be less costly. We thus advise monitoring efforts to target areas projected as climatically suitable, especially on islands such as the UK and Japan (Robinet et al. 2016). Indeed, if the yellow-legged hornet were only observed a few times in the UK, a rapid nationwide colonisation is possible, even from a single invasive site (Keeling et al. 2017) and control would be less cost-effective than invasion prevention for other regions in the country. Moreover, various records in new areas took place in the vicinity of train station, port and airport cargo areas (e. g. northern Parisian suburb train freight station in 2009 and airport in 2011, near Viana do Castelo port, Portugal in 2011, Burela port in Galicia, Spain 2012, near Bristol port, UK in 2016) suggesting that commercial transport also plays a significant role for long-distance spread and, above all, for the creation of new foyers of dissemination and its impact on the spread of the invasive hornet must not be neglected. Monitoring efforts should, therefore, strongly focus on commercial and human transport crossroads. Other countries, such as the US, Australia, Turkey and Argentina, appear to be climatically suitable for the species, even if the yellow-legged hornet has not yet been observed there. Given their distance to the native and current invasive range of the species, it is unlikely that the species will disperse in these countries on its own. However, given the estimated costs of damage related to nest destruction alone, it is worth implementing surveillance programmes to prevent human-mediated dispersal in these countries in order to avoid the high economic impacts of the yellow-legged hornet if the species were to establish there.

Our study provides the first estimates of economic costs resulting from the yellow-legged hornet. We were able to estimate the cost of nest destructions – used to control the spread of the species and limit its presence close to human habitations and activities – and extrapolate these costs to all areas which are climatically suitable for the species. Although more studies will be needed to estimate other costs related to the yellow-legged hornet invasion (in particular, the cost of its impact on apiculture and pollination), the destruction of nests already cost €23M in France alone and a further €11.9M each year at least, with a likely increase as the species keeps spreading.

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