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Research article

Science communication is needed to inform risk perception and action of stakeholders

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ABSTRACT

Stakeholders are critical environmental managers in human-dominated landscapes. In some contexts, stakeholders can be forced to personally act following their own observations and risk perception instead of science recommendation. In particular, biological invasions need rapid control actions to reduce potential socio-ecological impacts, while science-based risk assessments are rather complex and time-delayed. Although they can lead to important detrimental effects on biodiversity, potential time-delayed disconnections between stakeholders' action and science recommendations are rarely studied. Using the case study of western European beekeepers controlling the invasive Asian hornet *Vespa velutina nigrithorax* for its suspected impact on honey bee colonies, we analysed mechanisms underlying personal actions of stakeholders and how they evolved in science disconnection. Personal actions of stakeholders were causal-effect linked with their risk observation but disconnected to time-delayed science predictions and recommendations. Unfortunately, these science-disconnected actions also led to dramatic impacts on numerous species of the local entomofauna. These results highlight the need to improve mutual risk communication between science and action in the early-stages of management plans to improve the sustainably of stakeholders' practices.

1. Introduction

The management of human-dominated landscapes involves the critical role of environmental managers, which represent a strong action and observation force (Shackleton et al., 2019a). Stakeholders can be defined as environmental managers who are affected by the decisions and actions they take, and who have the power to change their actions (Reed et al., 2009). Ideally, management plans should be established by environmental policies, following scientific risk assessment recommendations, and prior to stakeholders' opinion-based actions (Genovesi and Shine, 2004). However, the current rate of global changes can lead to time lags between the provided scientific recommendations and the emergency to act in the field. One common example implies biological invasions (Courchamp et al., 2017). Biological invasions have negative effects worldwide such as biodiversity loss and species extinctions and can threaten economy and public health (Bellard et al., 2017; Courchamp et al., 2017; Cole et al., 2019). Invasive alien species management implies three types of action: preventing the invasion from occurring (e.g. public awareness and border control of global market), reducing the impact magnitude (e.g. by controlling the expansion range through individual trapping or population eradication programs), or repairing the damages (e.g. restoration programs) (Bradshaw et al., 2016). The choice of the management plan depends on the invasion stage and the results from risk assessment studies (Campbell et al., 2015). Nevertheless, assessing the potential risk of a newly introduced alien species is extremely complex and time consuming; it depends on a combination of co-evolutionary processes, population dynamics, complex interspecific relationships, abiotic changes, and anthropogenic impacts (Liu et al., 2007; Heger et al., 2013; Shackleton et al., 2019b). Consequently, some studies have showed that risk assessment estimations can be time-shifted in regard to the rapid need –real or perceived– of stakeholders to take actions and control alien species (e.g. Matzek et al., 2015). Although stakeholders' risk perception and actions should be related to previously emitted science recommendations (Genovesi and Shine, 2004), the time gap without established scientific risk assessment can force stakeholders to personally make decision and act following their own observations

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and risk perception.

Risk perception consists in the importance that individuals give to an at-risk situation (Lamarque et al., 2011; Dewitt et al., 2015; Shackleton et al., 2019b). It is known that risk perception is determined by different social and environmental factors affecting individuals, such as the degree of knowledge they have and/or the environment in which they evolve (Martín-López et al., 2012). In the case of humans, someone's perception of an environmental risk will vary according to their relation to nature (i.e. hobby and/or professional activity dependent on nature) and the amount of knowledge obtained through communication networks (Martín-López et al., 2012; Shackleton et al., 2019b). Accordingly, risk perception of biological invasions can be radically different between citizens or even cause conflicts among them (Estévez et al., 2015; Tassin and Kull, 2015). This is the case, for example, of many tree species introduced massively around the world for forest production or aesthetic reasons. These introductions, which have sometimes led to invasions, crystalize sharp conflicts of interest between naturalists –aware of the environmental impacts of these exotic tree species– and forest managers (Dickie et al., 2014). Although the drivers of stakeholders' risk perception have been studied, the ways in which they decide to personally act in a science-disconnected context is still an open question.

In this study, we analysed the mechanisms underlying personal actions of stakeholders and how they evolved in a science-disconnected context. We used the case study of western European beekeepers controlling the invasive Asian hornet *Vespa velutina nigrithorax* (also called the Yellow-legged hornet) for its suspected impacts to their professional activity. First observed in 2004 in Southwest France, this species has rapidly spread across most of the French territory (Villemant et al., 2011; Robinet et al., 2017), and it has then established successively in several neighbouring countries, e.g. Belgium, Germany, Italy, the Netherlands, Portugal, Spain and the United Kingdom (Robinet et al., 2018; Rome and Villemant, 2019). The Asian hornet captures foraging western honey bees (*Apis mellifera*) at the beehive entrances during the critical pre-wintering season for honey bee colonies, and therefore may represent an additional risk factor involved in the winter mortality of currently weakened bee colonies (Leza et al., 2019; Requier et al., 2019a). Western honey bees are currently suffering collapse disorder (Potts et al., 2010; Goulson et al., 2015; Requier et al., 2018), a phenomenon manifested by high bee colony mortality rates during winter (Neumann and Carreck, 2010), and likely due to a combination of multiple stresses including parasites, pesticides, and lack of flowers (Potts et al., 2010; Goulson et al., 2015; Henry et al., 2017).

The Asian hornet, an additional risk factor for honey bees, has alarmed western European beekeepers and has motivated the rapid development of control methods over the past years (Turchi and Derijard, 2018). The use of passive traps with homemade syrup or poisoned (with insecticide) baits was the most common method used for the control of the Asian hornet (Rome et al., 2011; Rojas-Nossa et al., 2018). However, the risk from Asian hornet predation on honey bees has only recently been assessed (Requier et al., 2019a). This delayed estimation has postponed the spread of the science recommendations to control this risk (Requier et al., 2019a; but see also some general recommendations of management delivered before: French ministry of Agriculture, 2013). Therefore, western European beekeepers have mainly followed their own observations and perception of Asian hornet-related risk to assess the necessity to put into place management actions for the last 15 years. This time delay between beekeepers' action and scientific recommendations represents a great opportunity to analyse how risk perception and personal action of beekeepers (so-called stakeholders thereafter) evolved in a science-disconnected context.

We performed a national-wide stakeholder-based survey to record beekeepers risk observation, perception and personal actions taken against the Asian hornet over the French territory and prior to the first Asian hornet scientific risk assessment publication (Requier et al., 2019a). We then estimated the risk of honey bee colony mortality and the associated management action recommendations, based on a combination of science-based citizen science programs recording the presence of the risk factor (based on Rome and Villemant, 2019) and predicting colony mortality (based on Requier et al., 2019a). This information was then compiled to: (*i*) evaluate the causal links underlying drivers of stakeholder risk perception and action in a science-disconnected context, and (*ii*) analyse whether risk observation, perception and personal action of stakeholders are connected to post-assessed science predictions and recommendations. Moreover, given that accumulated evidences showed that trapping the Asian hornet does not represent a biodiversity-friendly control method and leads to the catch of non-targeted insect species (Rome et al., 2011; Rojas-Nossa et al., 2018; Turchi and Derijard, 2018; Requier et al., 2019b), we finally discussed how biodiversity (i.e. the local entomofauna) can be affected by the potential science-disconnected personal actions.

2. Methods

2.1. Long-term citizen science program of Asian hornet nest record

Since the introduction of the Asian hornet in France in 2004, a citizen science program has been implemented at a national scale to record its invasion range. For that, a web-platform was designed by the French National Museum of Natural History (Rome and Villemant, 2019), inviting people to register observations (i.e. nests and individuals), associated with a picture to proof the identity of the Asian hornet and the location of the observation. A taxonomist carefully approved all of the valid observations and excluded those without supporting proofs or based on other species (e.g. *Vespa crabro*, the native European hornet) (Rome and Villemant, 2017). The location of Asian hornet nests were then recorded in the French national biodiversity database (INPN) over the 2004–2019 years (Rome and Villemant, 2019), however, we restricted the dataset to the 2004 to 2013 period for the aim of this study, in order to match the other datasets (see below). This database provided 10,379 records of Asian hornet nests. We finally computed the sum of nests detected per township to get a single data at the municipality area scale, which is the spatial resolution of the study.

2.2. Estimating the Asian hornet risk for managed honey bees

We defined the Asian hornet risk as density dependant in both the predator abundance (i.e. the number of nests recorded) and the prey abundance (i.e. the number of honey bee colonies). Whilst the predator abundance was previously recorded through the citizen science program (see above), we used the national-wide dataset of honey bee livestock from the French ministry of agriculture (French ministry of Agriculture, 2017) to calculate prey abundance. This database is based on mandatory beekeeper declarations of the number of honey bee colonies per township across the whole French territory. We obtained and therefore used the data from the year 2013. Overall, the dataset ranged from 0 to 2377 honey bee colonies per township. We then computed a dilution factor of Asian hornet predation load according to the number of beehives per township. For that, we first converted the number of Asian hornet nests per township as a number of predating hornets (the risk factor *per se*). No information is yet available on the exact number of predating hornets per nest, however, we know that a nest of Asian hornets reaches in average 3000 individuals during the season of honey bee predation –from September to November– (Rome et al., 2015). We chose a conservative value of 1% of the Asian hornet nest population (i.e. 30 hornets) likely to predate simultaneously from a single nest on the beehives stock of the township. We then divided the number of predating hornets in a township by the number of managed colonies in the same area to estimate the Asian hornet load per beehive. This simple estimate is based on the hypothesis that hornets could reach any hive located in the same township from their nest. The flight range of hornets varies from 2 to 3 km (Rome and Villemant, 2017; Kennedy et al., 2018) and could physiologically reach until 30 km (based on laboratory tests, Sauvard et al., 2018), while the mean size of a French townships is a 3.87 km side length square (varying from 3 to 75,780 ha, with a mean area is 1500 ha).

2.3. Predicting the hornet-related risk of bee colony mortality

We used the mechanistic BEEHAVE model (Becher et al., 2014) to assess the risk probability of honey bee colony mortality related to Asian hornet predation. We performed 1000 simulations to predict the daily colony growth of a bee colony population from the beginning of January to the end of May of the following year. This time period was chosen to include a complete winter season. The model was calibrated following Becher et al's. (2014) initial colony settings, for which four key colony parameters were modified to increase stochasticity in the predictions and to improve representativeness of real field-condition variability (Requier et al., 2019a). We followed Requier et al. (2019a) method to simulate hornet impacts in BEEHAVE, consisting in altering the two parameters "forager mortality" and "the maximal foraging distance allowed for the colony" during the day 240 (August 28th) to the day 310 (November 6th). Along the 1000 computed simulations, we gradually decreased the maximal foraging distance allowed for the colony from the default value of 7299 km per day down to 0 (no foraging activity), and we increased the forager mortality rate from the default value of 1.00e-05 to 2.00e-05. Thus, each simulation involved a level of hornet impact ranging from low (0 hornets predating) to high impact (more than 20 hornets predating at the beehive entrance). Simulations were further classified based on whether they predict colony collapse during winter. Collapse events were defined following the two thresholds from Becher et al. (2014): (*i*) simulations that predict a population size smaller than 4000 adult bees during winter, and (*ii*) simulations that predict a total depletion of honey stock during winter. We then estimated the colony mortality probability related to Asian hornet predation in each township. This last step consisted in inferring the corresponding modelled mortality risk to the estimated number of Asian hornets predating on the beehives for each township of the French territory.

2.4. Estimating management recommendation

We followed Requier et al.'s (2019a) recommendations suggesting the application of control methods only in case of high hornet loads (i.e. more than 13.3 hornets predating at the beehive entrance). Low hornet loads do not lead to foraging paralysis (i.e. the most important factor of hornet-related colony mortality), while the hornet-based risk only concerns previously weakened colonies. At high hornet loads, the hornet-based risk of bee colony collapse results in a foraging paralysis of the bee colony and subsequently an over-consumption of honey stocks reserved for overwintering (Requier et al., 2019a). Requier et al.'s (2019a) suggested that in such conditions, controlling the hornet loads around the beehives could decrease the number of hornets overflying and help bee colonies to conserve their foraging activity. Thus, science-based recommendations of control were provided in the townships where the estimated hornet loads exceeded 13.3. Otherwise recommendations deter stakeholders from control action.

2.5. Stakeholder-based survey of risk observation, perception and personal action

We performed a stakeholder-based survey in 2013 (i.e. six years before the publication of the Asian hornet risk assessment including management recommendation, Requier et al., 2019a) to record the risk observation, perception and personal action of beekeepers against the Asian hornet over the French territory. We first designed a standardized questionnaire to invite beekeepers to notify their activities, including 11 questions designed to record:

(1) *Site of the operation* – the names and zip code of the municipality where more than 50% of the colonies are placed.
(2) *Operation size* – the total number of honey bee colonies managed at the date of the survey.
(3) *Education* – The starting year of beekeeping activity was asked. Education was then estimated as the number of years of beekeeping practiced, which corresponds to the amount of time elapsed between the date of the survey and the start of this activity.
(4) *Risk factor observation* – Observation of Asian hornet nests in the landscape surrounding the operation (i.e. in a range of 500 m around the apiary; two categories: yes or no)
(5) *Risk observation* – Observation of Asian hornet predating honey bees at the beehive entrance (two categories: yes or no)
(6) *Total winter mortality* – the total number of colonies dead during the winter season of 2009–2010, 2010–2011 and 2011–2012
(7) *Presumed hornet-related winter mortality* – The number of colonies dead, presumably due to the predatory behaviour of the Asian hornet during the winters of season of 2009–2010, 2010–2011 and 2011–2012. The risk perception was then estimated as the proportion of colonies lost due to the Asian hornet relatively to the total number of colonies lost, and then yearly averaged (Fig. 1).
(8) *Personal action* – The setting up of control method of the Asian hornet using traps (two categories: yes or no).
(9) Trap number – If (8) is yes, the number of traps established in the whole operation.
(10) *Trap design* – If (8) is yes, the type of trap used. Then summarized in two categories: commercial or home-made trap.
(11) *Bait composition* – If (8) is yes, the type of bait used. Then summarized in two categories: commercial or home-made-bait.

The questionnaire was then distributed in June of 2013 over the French territory through beekeeping social networks and national beekeeping journals. In particular, it was published in four national journals of beekeeping and entomology and was also available online across various web-platforms (e.g. the Asian hornet dedicated website of Tours university and beekeeping websites from provinces of Gironde, Dordogne and Indre et Loire). The beekeepers had until December of 2013 to send their answers, finish date of the survey. After a post-validation procedure was set (to exclude incomplete answers: 18 respondents), the responses of the 401 remaining respondents were used to analyse the drivers of beekeepers' action against the Asian hornet, and the relationship with science predictions. The responses came from beekeepers who were distributed throughout the whole country (Fig. 1).

2.6. Testing the role of social, environmental and economic contexts

Social, environmental and economic contexts can affect perception and actions of stakeholders (Martín-López et al., 2012). Such factors can also affect scientific predictions, given their role in biological invasion, in particular in the case of the Asian hornet (e.g. Robinet et al., 2017). We used the CORINE (Coordination of Information on the Environment) Land Cover 2012 dataset to record the environmental context for each township (European Environment Agency, 2010). This dataset is characterized by a high spatial resolution (i.e. 100 m^2) and is composed of 44 different land cover classes (hereafter habitat), each belonging to one of the four following broad categories: artificial surfaces (urban, roads, industrial units, etc.), agricultural areas (non-irrigated arable land, pastures, fruit trees, etc.), natural areas (coniferous forest, bare rocks, etc.) and wetlands and marine areas (estuaries, salines, etc.). Based on Fournier et al. (2017), we only retained the categories identified as suitable habitat to the Asian hornet, and computed the proportion of these habitats per township. We used the national-wide dataset of human population from the French ministry of agriculture (French ministry of Agriculture, 2017) to record the number of people living in

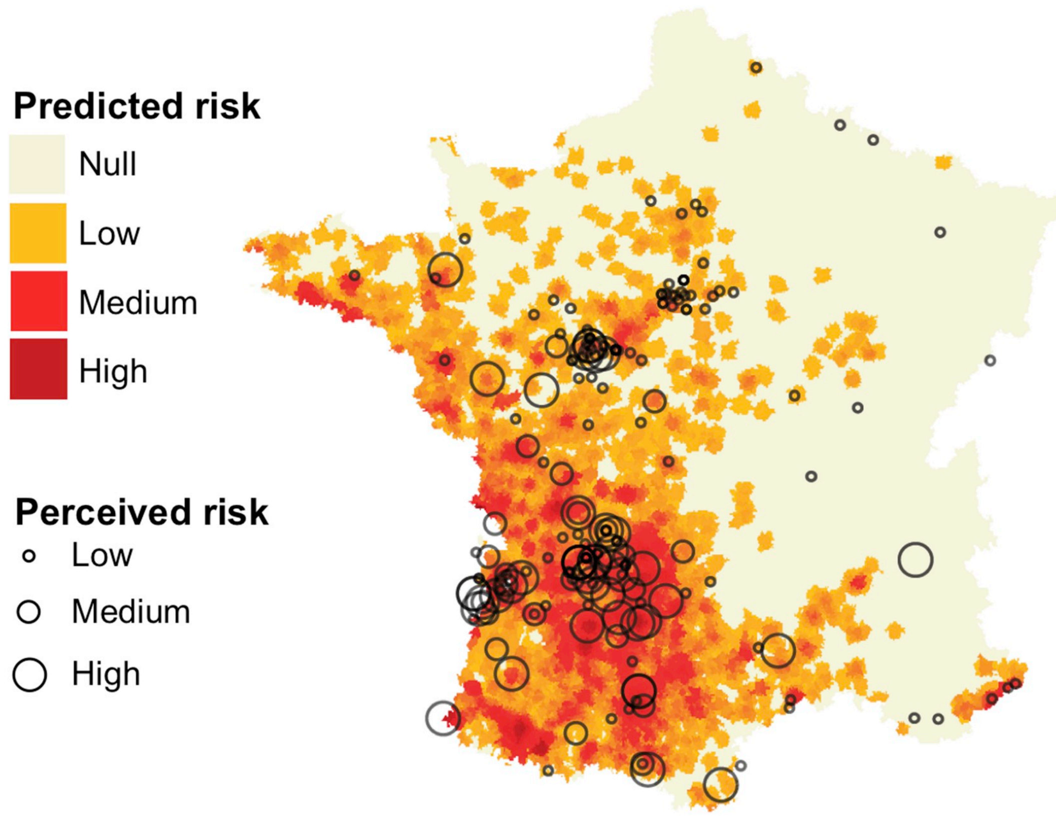

Fig. 1. Spatial distribution of two hornet-related risk evaluations: (1) Science-based predicted risk, obtained at the town scale, corresponding to the predicted number of hornets that can predate on beehives (colour gradient). This estimation was obtained based on online citizen declarations checked by a specialist. (2) Stakeholder-based perceived risk (black open circles). This estimation was obtained by inviting beekeepers (i.e. stakeholders) to declare on a standardized questionnaire their observation, perception and management of the Asian hornet. See methods for more details on the estimates. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

each township as an indicator of the social context. Indeed, the number of people living in an area could positively affect the probability to detect a nest, but could also influence stakeholder's personal actions through social interaction and group making decision (Traves et al., 2004; Behdarvand et al., 2014). Finally, we used the number of managed honey bee colonies per township (see above, French ministry of Agriculture, 2017) as an estimate of economic beekeeping level.

2.7. Statistical analyses

All statistical analyses were performed using the R Project for Statistical Computing version 3.3.3 (R Development Core Team, 2018).

Identifying causal links underlying drivers of stakeholder risk perception and personal action. We used path analyses (Shipley, 2009) to disentangle direct and indirect effects along the chains from risk observation to control action. Path analysis helps to disentangle the most plausible direct and indirect links in multivariate datasets by assessing conditional independence among indirectly linked variables. We applied the path analysis using the *PiecewiseSEM* R-package (Lefcheck, 2016). We first selected scientific predictions for all townships where we had collected beekeeper answers from the survey (n = 401, Fig. 1). We then built a basic path model that reproduced the mechanistic structure underlying stakeholder's action, linking risk factor observation (i.e. Asian hornet nest), risk observation (i.e. Asian hornet predating at the beehive entrance), risk perception (i.e. the proportion of colonies lost due to the Asian hornet) and personal action of stakeholders (application of control methods).

Analysing the link between risk observation, perception and personal action of stakeholders and post-assessed science predictions and recommendations. We built a similar basic path model that reproduced the mechanistic structure underlying science-predicted action recommendations, linking the risk factor (Asian hornet nest inventory), risk identification (predicted number of hornets predating at beehive entrance), risk estimation (predicted hornet-related colony mortality) and the science-based recommendations of management (recommendation of control). We then analysed the relationship between stakeholder data and science prediction (e.g. risk factor observation and risk factor inventory, respectively) to test for potential correlations. Each causal link in the path model was depicted as a linear model (LM) or a generalized linear model (GLM), using *lm* and *glm* function in the *base* R-package respectively, depending on the nature of the involved variables. We used GLMs with a binomial error structure for risk factor observation, the risk observation, the personal action of stakeholders, and the science-based recommendation. We used LMs with Gaussian error structure for other variables. All variables were standardized using Z scores, and the normal distribution of residuals of each model was checked. We then identified the simplest path model structure that did not deviate from the conditional independence expectations while including only significant links. The path analysis showed consistent causal links along and between the two chains from risk observation to control action, with indirect links that did not significantly deviate from conditional independency requirements (Fisher's $C = 35.27$, $P = 0.823$; Fig. 2). Coefficients and detailed P values underlying the path analysis are presented in the online Supplementary Materials (Appendix A).

Effect of stakeholder actions on biodiversity. We first evaluated the efficiency of trapping (i.e. the control action from stakeholders) on the targeted trapping of Asian hornet. For that we fit a GLM with a binomial error structure to test the logistic link between the number of traps established (log-transformed) and the collection of Asian hornets as a binary variable (yes = 1 or no = 0). We then evaluated the effect of

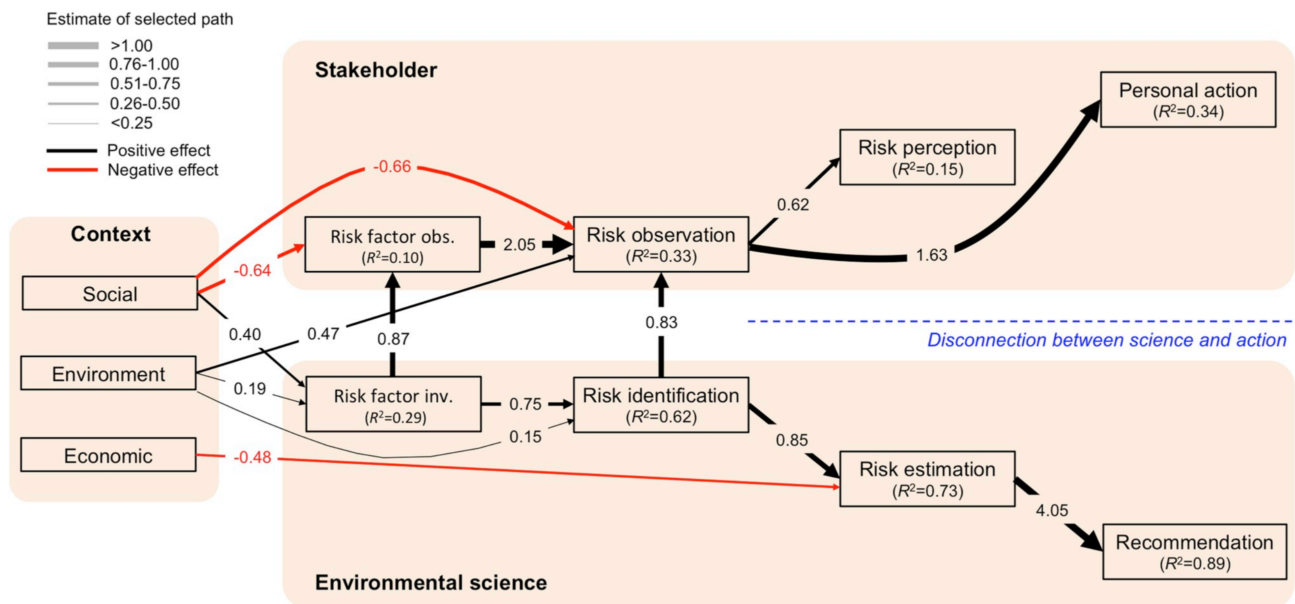

Fig. 2. Path analysis revealing the causal links identified between the observation, perception and management of the Asian hornet risk by beekeepers, and their relationship with science recommendation. Only significant links are shown. See online Supplementary Materials (Appendix A) for detailed statistical properties of the path model and links. Total explained variance (R^2) is indicated in the box for each response variable. The thickness of an arrow represents the magnitude of the (standardized) effect and the colour shows the correlation sign (positive or negative). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

trapping on the collection of non-targeted entomofauna (e.g. European hornet, other Vespidae, the Western honey bee *Apis mellifera*, Diptera, Lepidoptera, other insects). Thus, we fit a second GLM with a binomial error structure to test the logistic link between the number of traps established (log-transformed) and the collection of other insects than the Asian hornet as a binary variable (yes = 1 or no = 0). The model residuals were extracted and inspected against fitted values (residuals *vs.* fitted plot and normal Q-Q plot) to ensure the residual normality and the homoscedasticity assumptions were fulfilled.

3. Results

3.1. Drivers of stakeholder risk perception and personal action

Among the chain from risk observation to control action of stakeholders, the most notable links were between risk factor observation, risk observation and personal action (Fig. 2). Following the causal links, the personal action of stakeholders (the carried out of trapping) was positively affected by the risk observation (i.e. the observation of Asian hornet predating at the beehive entrance), and the risk factor observation (i.e. the observation of Asian hornet nests in the surrounding landscape of the apiary). The risk perception (i.e. the predicted hornet-related colony mortality) was positively affected by the risk observation but was not linked with the personal action. Finally, the social context (i.e. the number of people in the township) had a direct negative effect on the risk factor observation, and an indirect negative effect on the risk observation (Fig. 2).

3.2. Links between risk observation, perception and personal action of stakeholders and post-assessed science predictions and recommendations

On the other hand, the causal links showed that the science-based recommendation of control action was positively affected in cascade by the risk estimation (i.e. the predicted hornet-related colony mortality), the risk identification (i.e. the predicted number of hornets predating at beehive entrance), and the risk factor inventory (i.e. the inventory of Asian hornet nests). The environmental context (the suitable habitat for the Asian hornet) had a direct positive effect on the risk factor inventory, and an indirect positive effect on the risk observation (Fig. 2). In turn, the economic context (the number of managed beehives per township) had an indirect negative effect on the risk estimation. Such effects underlying the chain from risk factor inventory to control action recommendation confirm the integration of the science-based estimate processes in the path analysis.

Interestingly, the two chains (stakeholder and science) were linked between risk factor observation and risk factor inventory, and between risk observation and risk identification (Fig. 2), suggesting that stakeholder's observation are in accordance to science-based inventories and estimates (Appendix S1). However, the risk perception and the personal action of the stakeholders were disconnected to time-delayed science prediction (Fig. 1), suggesting that beekeepers had inaccurate perceptions of the Asian hornet risk and carried out trapping action when it was not needed, and vice versa (Appendix S1).

3.3. Effect of stakeholder actions on biodiversity

A total of 63.3% of the respondents (n = 274) carried out trapping of the Asian hornets. Based on stakeholder responses, the frequency of occurrence of trapped Asian hornets varied from 80% to 100% depending on the trap design and bait composition (Fig. 3). The most efficient combination was the home-made trap (based on plastic bottle) with commercial bait (Vétopharma® bait). However, this combination was also highly performing to trap the native European hornet *Vespa crabro* (*i.e.* with the same catch efficiency than that of the Asian hornet (Fig. 3)). Unfortunately, all combinations of trap designs and bait compositions led to detrimental effects on the non-targeted entomofauna, including honey bees in the cases of home-made traps filled with home-made bait (e.g. with wine, sugar, beer) and commercial trap (Vetopharma® bait) filled with commercial bait (Fig. 3). In average, the beekeepers used 7.4 traps on their operation, ranging from 1 to 180 traps. Although the establishment of a single trap led to less than 50% chances to catch the targeted Asian hornet, setting up more traps led to a strong increase of this probability (n = 274, $Z = 5.530$, $P < 0.001$; Fig. 4a). However, also based on stakeholder response, the number of

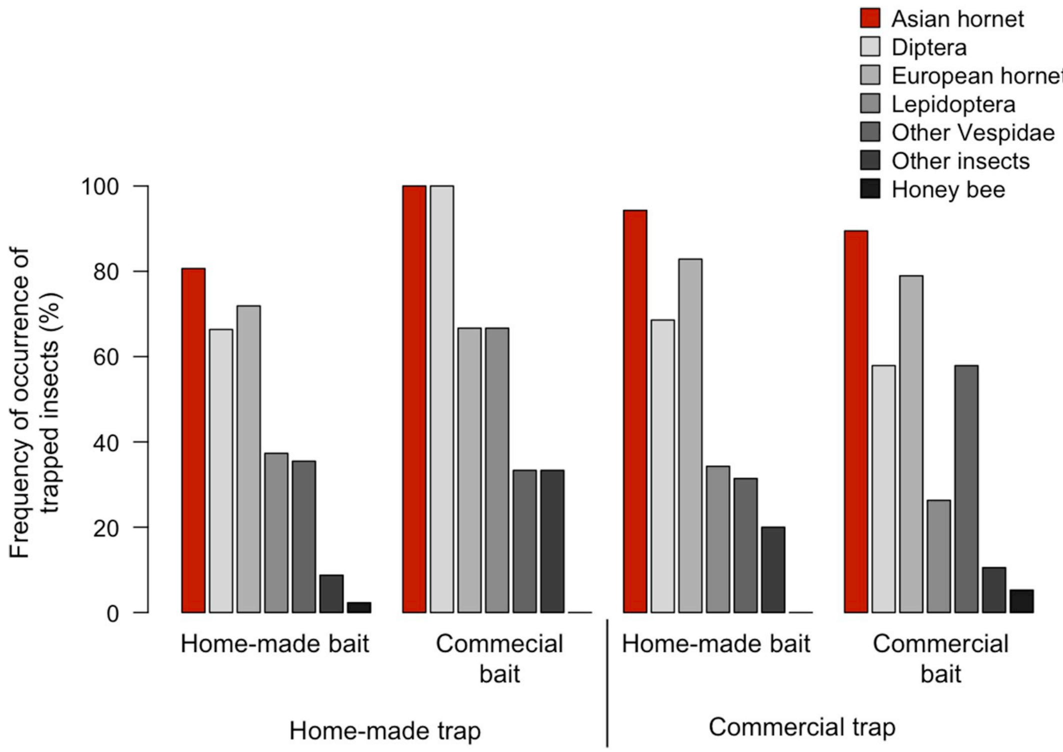

Fig. 3. Frequency of occurrence of the trapped insects in two different trap designs (home-made trap on the left and commercial trap on the right) and two different bait compositions (home-made bait and commercial bait). The probability to catch the targeted insect *Vespa velutina* is showed in red while the probability to catch different non-targeted groups of entomofauna (e.g. European hornet, other Vespidae, the Western honey bee *Apis mellifera*, Diptera, Lepidoptera, other insects) is presented within the grey gradient. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

traps did not affect the probability to catch other non-targeted insect species (n = 274, $Z = 0.478$, $P = 0.632$; Fig. 4b), with a significant high probability (>90%) to trap non-targeted entomofauna (model intercept: $Z = 5.126$, $P < 0.001$, Fig. 4b).

4. Discussion

Stakeholders manage the environment in human-dominated landscapes, ideally following management plans that were previously established by science-based environmental policies. Here, we showed that beekeepers had to personally act following their own observations and risk perception (the risk of bee predation by the Asian hornet) instead of following scientific recommendations that were time delayed. Their personal actions were related to their observations of the risk, but not related to their risk perception (i.e. the presumed hornet-related colony mortality). The results suggest that they practiced control action as preventive measures even in contexts where they did not perceive any direct risk for their production. While the risk observations were in accordance with science-based estimates, their risk perception and personal actions were disconnected to time-delayed science

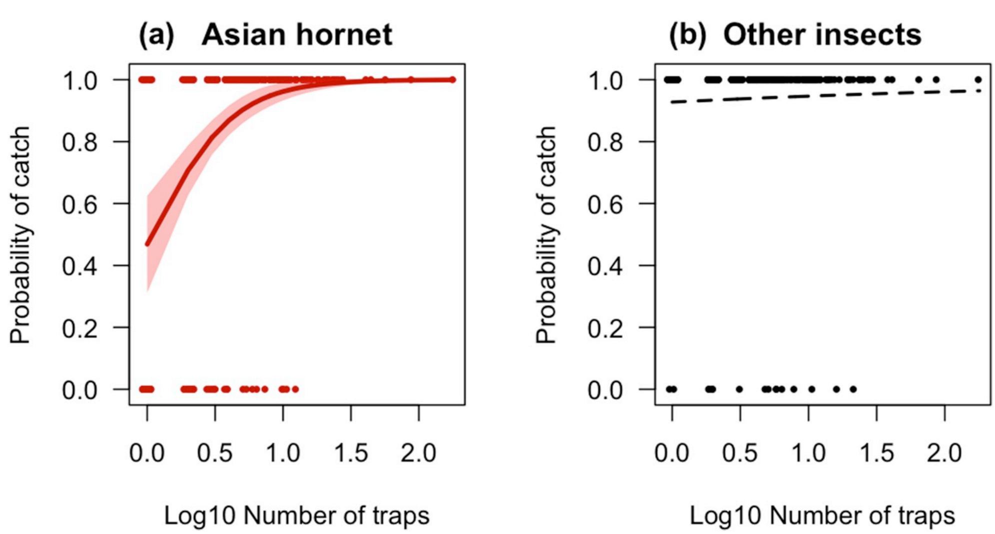

Fig. 4. Effect of the number of established traps on the probability to catch (**a**) the targeted Asian hornet or (**b**) other non-targeted insects. The number of established traps increased the probability to catch the targeted Asian hornet, but did not affect the high probability to catch other non-targeted insects. The dotted line shows non-significant relationship. Thick line shows the model predictions with shaded areas (presented if the model is significant) indicating the 95% confidence interval.

predictions and recommendations. These results suggest that beekeepers percept a risk when there is none and vice versa, and act when it is not necessary in contexts of science disconnection (e.g. trapping action in absence of hornet nests in the surrounding landscape). Unfortunately, these science-disconnected actions also lead to important impacts on local biodiversity. Trapping actions lead to the catch of non-targeted local entomofauna, already threaten by many factors and critically declining (Sánchez-Bayo and Wyckhuys, 2019).

This work highlights that stakeholders' risk perception and personal actions did not follow a biodiversity-friendly approach in a science-disconnected context. The general recommendations made before any formal risk assessment study were not sufficient to inform or to raise stakeholders' awareness concerning the detrimental effects on biodiversity to trap Asian hornets. A potential explanation could be that stakeholders applied control methods for the purposes of risk prevention. Indeed, the Asian hornet was rapidly predicted as likely to expand all over the French territory as well as to eventually spread further in Western Europe (Villemant et al., 2011). Yearly records of the expansion range of the Asian hornet have confirmed the rapid spread of this invasive species over the French territory (Rome and Villemant, 2019) and further in the neighbouring European countries (Rome and Villemant, 2019). This could affect stakeholder's risk perception towards the requirement of control actions even if the risk factor is not yet present in an area, and even with methods that may be detrimental for biodiversity. Indeed, the common use of simple passive traps with homemade syrup or poisoned baits are known to fail to sustainably reduce the populations of Asian hornets (Beggs et al., 2011; Turchi and Derijard, 2018) and represent a low-efficiency method to control Asian hornet-related impacts on honey bees (Monceau et al., 2012; Requier et al., 2019a,b). Although the environmental impacts of common trapping on the numerous species of the local entomofauna was established before the risk assessment study (e.g. Dauphin and Thomas, 2009; Beggs et al., 2011; Rome et al., 2011), more biodiversity-friendly methods are now tested and/or available for beekeepers. For instance, more species-specific trapping systems based on sex pheromone attraction are currently in process of development and could allow the specific catch of the Asian hornet without trapping other insects (Couto et al., 2014; Cheng et al., 2017; Gévar et al., 2017; Wen et al., 2017; Turchi and Derijard, 2018). Moreover, the use of beehive muzzle –a mesh placed around the beehive's flight board allows bee workers to continue foraging even in the presence of hovering hornets– can reduce the foraging paralysis and thus positively affects the survival of hornet-stressed colonies (Requier et al., 2019b). Given the multiple evidences of negative effects in the use of common trapping methods on the local entomofauna (Rome et al., 2011; Rojas-Nossa et al., 2018; Turchi and Derijard, 2018; Requier et al., 2019b) that the present study confirms, we recommend that beekeepers prioritize the use of biodiversity-friendly methods such as species-specific trapping systems and beehive muzzles for the control of the Asian hornet.

Reconnecting science and action is one of the 21st century priorities (Nisbet and Scheufele, 2009; Groffman et al., 2010; Shackleton et al., 2019a). Generally, biological invasions is a very complex topic when it comes to risk communication, as it is marked with strong duality of opinions among the need of control actions –to reduce the threat on the native biodiversity due to an invasive species– and the recommendation of no action due to direct risk of impact of control methods on native biodiversity (Courchamp et al., 2017). The results of this study highlight the need to improve the quality and quantity of risk communications between science and action in the early-stages of management plans, in order to improve the sustainably of stakeholders' practices. Over the last years, there has been an increase in the practice of citizen science programs and other community-based projects in conservation biology (Bryce et al., 2011; Follett and Strezov, 2015; Requier et al., in press). These allow, in socio-ecological systems, to connect researchers, citizens and stakeholders around common environmental issues. For instance, a recent citizen science study in the United States has shown broad public interest in pollinator conservation issues (Wilson et al., 2017). This study showed that conservation efforts require significant public support and that any program aimed at stopping or mitigating the decline of pollinators should include awareness and education measures. Citizen science programs and other community-based projects could also facilitate human interactions and education concerning other topic of biodiversity conservation and environmental management, such as risk communication on invasive species issues. Overall, scientists have to communicate with stakeholders and vice versa, sharing explicit information on the risk, the hypothesis made, the methodological framework used, and the uncertainty that comes with the risk predictions, in order to ensure co-constructed, coherent and acceptable management recommendations (Schmolke et al., 2010; Voinov and Bousquet, 2010; Shackleton et al., 2019a).

Our results help fill a knowledge gap regarding how personal actions of stakeholders evolve in a science-disconnected context. In particular, our results provide evidence that mutual communication between stakeholders and researchers though, before, during and after the risk assessment process, is one component that needs to be reinforced to ensure its usefulness for biological invasion management and policies (Theobald et al., 2000; Jönsson et al., 2015; Shackleton et al., 2019a). Moreover, involving stakeholders in invasions management programs is central to not only ensure their success, but also enhance their acceptability and avoid situations where such programs result from a single actor involved (Liu et al., 2011; Verbrugge et al., 2013). This requires interacting works between stakeholders and researchers in the drafting, conduction and final evaluation of co-managed programs (Crowley et al., 2017; Novoa et al., 2018; Shackleton et al., 2019a). For instance, web-based forums and round-table discussions could promote such a mutual communication. New ways of communication are also needed, to (1) establish a two-ways link between researchers and all stakeholders involved in the invasions management process and (2) to address this disjunction between science and action, for which citizen science programs and other community-based projects can help. Beyond risk communication, considering the knowledge, the experience and the perception that people and stakeholders have of a situation, a risk, or a system, in the scientific process of risk assessment can ensure the usefulness and acceptability of biological invasion management.

Authors' contributions

FR, AF and ED conceived the study; ED led beekeeper-based survey; QR led the long-term citizen science program of Asian hornet nest record; AF ran the national-wide prediction of Asian hornet density; FR simulated the national-wide colony mortality risks and associated management action recommendations; FR performed statistical analyses, interpreted the results and wrote the manuscript; All authors provided several corrections to subsequent drafts and gave their final approval for publication.

Research data

The data presented in this manuscript are available in the online Supplementary Materials (Appendix A).

Declaration of competing interest

No conflict of interest was reported by the authors.

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Appendix A. Supplementary data

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