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MINI REVIEW

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Options for the biological and physical control of *Vespa velutina nigrithorax* (Hym.: Vespidae) in Europe: A review

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Abstract

Recently, the environmental economist J.M. Salles (Salles, 2016) declared that "the Asian hornet was likely to be the most threatening invader insect in France." Thirteen years after the accidental introduction in France, the Asian hornet (*Vespa velutina nigrithorax*) has invaded most west European countries. Little has been done to date to limit its progression and its economic, ecological and social impact. Although it is illusory to try to eradicate this species, it is known that a targeted control would limit its threatening trend. Current *V. velutina* control in France is mainly based on (i) high scale volunteer trapping by citizens and (ii) volunteer spotting of the nest. Evaluation of trapping strategies developed so far to control *V. velutina* expansion has highlighted their failure and has demonstrated the need to optimize nest detection techniques and to investigate on new control strategies. This review describes most of the means aimed to control predation and expansion of *V. velutina*, whether they have been scientifically assessed or only tested on field with decent success. Published prospective control methods and biological control techniques are also presented.

KEYWORDS

invasive species, nest finding, poisoning, prospective control means, trapping, yellow-legged hornet

1 | INTRODUCTION

Invasive alien species cost 12 billion €/year in the European Union (Karmenu, 2016). Invasive non-native Hymenoptera species, including the Africanized bee in the United States; the German wasp in New Zealand; and the Asian or yellow-legged hornet (*Vespa velutina*) in Europe, South Korea and Japan, represent a significant threat to the endemic insect fauna and the biodiversity.

Thirteen years after its accidental introduction in France from very few or possibly only one single multimated female (Arca et al., 2015), the yellow-legged hornet has colonized 87 of the 96 departments of metropolitan France and threatens to spread to all neighbouring countries in the coming years (Figure 1).

The challenges linked to the settlement of this predator are of several orders: (i) economic: bee pollination services are estimated at 1.5 billion €/year and direct loss for bee-keepers is calculated to be over a 100 million €/year, both for France only; (ii) environmental: damage to honey bees, pollinators and endemic insect fauna; and (iii) public health: several death/year although the number of cases does not seem to fit with *V. velutina* expansion yet (de Haro et al., 2010; Viriot, Sinno-Tellier, & de Haro, 2015). If it is illusory today to try to eliminate this species, it is clear that a focused control could reduce its expansion and thus its impact. There are currently no studies available on the impact of *V. velutina* predation on the activity of European bee colonies. Nevertheless, a study carried out in China showed that the presence of predator could reduce the foraging activity up to 79% (Tan et al., 2013).

Engaged in the control of *V. velutina*, French local authorities have recently implemented action plans for the destruction of the nests (an average of 150 k€/year for several of the 87 concerned departments), with little success. Indeed, the current control of the Asian hornet is based on visual location and suppression of the

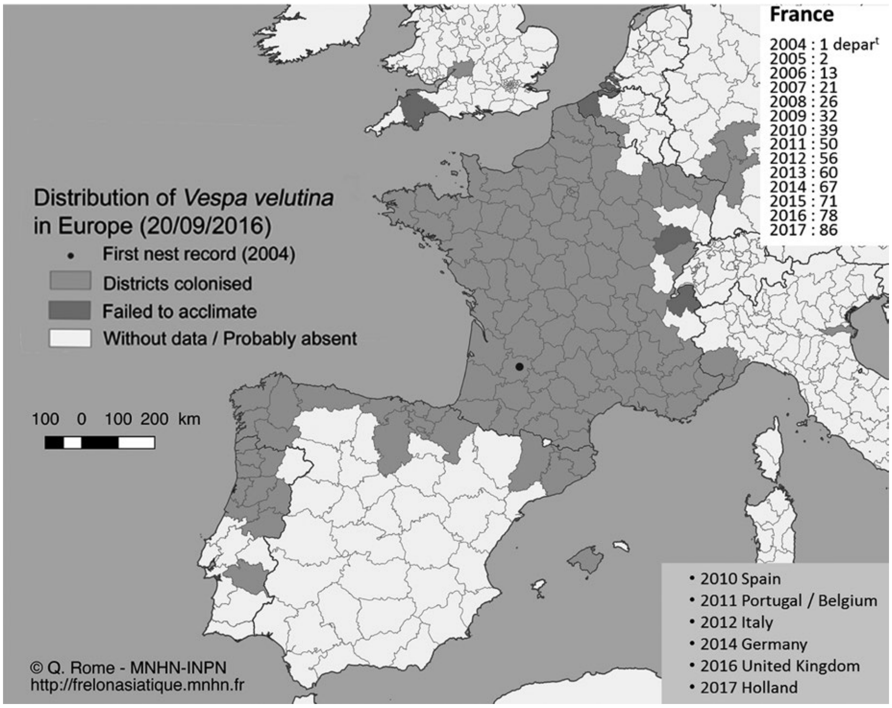

FIGURE 1 *Vespa velutina*'s distribution (October 2017). Black dot: first detected nest, dark grey: areas colonized in 2017, light grey: areas colonized before 2017, white: no available data/likely to be absent. Number of colonized French departments and colonized European countries are framed (From Q. Rome)

nests. It is limited by their preferred location high on the trees and low visibility in spring–summer due to foliage, such that <5% of hornet's nest are spotted (Robinet, Suppo, Darrouzet, & Diekotter, 2017). This targeted control should strongly limit the predation exerted by the *V. velutina* on apiaries and on sensitive sites (schools, fish/meat markets, beaches, etc.) and therefore limit its economic and social impact.

2 | BIOCIDE INJECTION

In much affected area in France, when a nest is spotted on the public domain, local authorities usually dispatch a contracted pest control technician on site to ensure it is indeed a nest of *V. velutina* and not of *Vespa crabro*. When *V. velutina* is identified, a pest control technician is sent to destroy the nest by injecting permethrin. As permethrin has a substantial remanence, technicians are obliged to unhook the nests after injection in order to avoid contamination of the environment and food chain. It should be recalled that according to European Directive 98/8/EC, the use of sulphur dioxide is not permitted for the destruction of hornet nests (98/8/CE, 1998). Nevertheless, at their request, the European Parliament may grant derogations for temporary use of sulphur dioxide for several months. This directive is very unfortunate because, if more dangerous for the user in the event of a leak in an enclosed space, sulphur dioxide is much less harmful to the environment than permethrin. In addition, it is much cheaper.

Other biocides, such as pyrethrum or diatomaceous compounds, with potentially less impact than permethrin, can also be considered in the destruction of hornet nests. In fact, pyrethrum, from the structure of which permethrin was synthesized, or diatomaceous compounds could advantageously replace synthetic biocides. They are likely to have a much lesser impact on the entomofauna and the environment (shorter remanence for pyrethrum and physical action for diatomaceous compounds) but still need to be fully assessed (Métayer & FDGDON-Manche, 2017).

3 | IMPROVISED FIELD TECHNIQUES

3.1 | Home-made syrup traps

3.1.1 | Hornet workers trapping

There are several types of traps to catch hornets. The most widespread traps are those intended to capture workers during the hunting season. They have been widely promoted by various bee-keeping syndicate and association. Their simple and rudimentary manufacture consists in cutting the upper third of a plastic mineral bottle, which is turned over and pressed into the lower part: this constitutes a creel in the bottom of which one will deposit a mixture of berry syrup, beer and white wine which is supposed to repel bees. The disadvantage of this kind of trap is its significant lack of selectivity with respect to the yellow-legged hornet which represents <1% of the average catch (Goldarazena et al., 2015).

This type of trap has been assessed regarding several parameters such as hornet trapping, bee foraging, productivity and colony mortality (Decante, 2015). The conclusion of the author was that the comparisons between the control apiaries without trapping modalities and those provided with them reveal no protective effect of trapping nor on the foraging activity nor on the development nor on the survival of the colonies.

To improve its selectivity, an updated version of that trap has been developed with a grid over the liquid attractant to prevent the drowning of non-hornet insects. In addition, 8.5-mm-diameter inlets (to prevent the entrance of insects bigger than hornets) and 5.5-mm outlets at the bottom of the bottle (to allow the bees and other small insects to be able to escape from the trap) have been added (Blot & Debellescize, 2017). These improvements have not been scientifically assessed yet, but should improve selectivity.

3.1.2 | Spring queen trapping

The queens build their nests in early spring. They usually start with a primary nest which is in 80% of cases located in shelters of gardens or buildings little used (Monceau & Thiéry, 2017). In this primary nest, the queen gives birth to approximately a hundred workers who may then help her to build a secondary nest if the primary nest location is not suitable. The secondary nests are generally built at the top of the trees such that they are often invisible and inaccessible. Thus, many bee-keeping syndicates recommend intensive trapping of queens in early spring with a trap identical to that described above. At least two arguments are against this method of trapping. Indeed, a large-scale study carried out in New Zealand showed that the trapping of queens of *Vespula germanica* and *Vespula vulgaris* had no impact on the number of nests installed in the following season (Monceau, Bonnard, & Thiery, 2012). Moreover, some authors describe an intraspecific competition between queens for the best sites nesting with the eastern yellowjacket *Vespula maculifrons* (MacDonald & Matthews, 1981). In fact, it is not uncommon to see several dead queens on the ground at the bottom of primary nests that are likely to result from fighting for the possession of the nest. Thus, randomly trapping the strongest queens may be counterproductive as these could kill several other queens claiming the same nest site (Monceau et al., 2012).

3.2 | Poisoned baits

While strictly regulated in Europe and banned in France, bee-keepers widely use several types of poisoned baits devices in their apiaries to target *V. velutina*. Although they all have the major disadvantage of releasing biocides into the environment and thus causing collateral damage, these poisoned baits have the obvious advantage of targeting and destroying nests remotely without having to locate them at advance. They have been used in the past in *V. germanica* control with clear success (Sackmann, Rabinovich, & Corley, 2001; Ward, 2014). They have never been scientifically assessed for *V. velutina* yet.

3.2.1 | Bucket poisoned bait

This very simple method consists in mixing a bait made from pieces of meat (beef heart or liver) or fish (sardines or mackerel) to a biocide. Workers will make a meat or fish ball soaked in the chosen biocide and return it to the nest to feed the larvae. The latter are thus quickly poisoned, which blocks their development and finally that of the colony. In this type of trapping, the choice of biocide is therefore obviously decisive. Indeed, depending on whether a fast acting or delayed biocide is used, the result may be different. For example, the use of Fipronil®, very frequent by bee-keepers, has the disadvantage of killing the hornet in a relatively brief time interval of the order of 1 hr. This has the disadvantage of quickly killing the workers which are accustomed to return regularly to their poisoned food supplies. On the contrary, if a biocide is used which does not have a direct effect on the workers such as a growth regulator (such as Fenoxycarb®), the workers can continue to feed the nest with the poisoned bait without self-poisoning. If any, this type of biocide is to be favoured especially as its toxicity is likely to be less important for ecosystems.

3.2.2 | Poisoned skewer

Rather than using a bucket containing poisoned bait, some prefer to use this bait in the form of skewer hanging vertically. It is then enough to deposit a few drops of biocide on the top and this one will flow overall the skewer. This system is more easily suspended around the apiary and avoids poisoning terrestrial animals (domestic animals, foxes, etc.). A cup placed at the bottom part of the skewer even avoids the flow of biocides to the ground.

3.3 | Beehive muzzle

The muzzle is a physical device allowing to block the access of the bee entrance to the hornets while allowing the bees to pass through (Figure 2). It consists generally of two boards placed on the sides of the east hive, on which is fastened a lattice with a mesh of 6 × 6 mm. The hornet ventures very rarely inside this muzzle as it will have difficulty to leave in an emergency and thus exposes itself to the guards. This system avoids the entry of hornets inside the hive but moves the problem of predation in a perimeter a little further away

FIGURE 2 Regular beehive muzzle (From A. Lavignotte)

FIGURE 3 Vertical beehive muzzle (From JC. Teissier)

than that of the bee entrance. However, it has the advantage of being very inexpensive and the bees get used to it very quickly.

A variant of this muzzle consists of a 4-cm-wide chimney vertical to the bee entrance (Figure 3). This set-up obliges the bees and a possible hornet to go down towards the hive entrance vertically. When the hornet ventures, it cannot escape if attacked by warriors.

3.4 | Badminton racket

The badminton racket is probably the most effective and environment-respectful tool to fight the Asian hornet for amateur bee-keepers currently. Very inexpensive, this method is nonetheless quite time consuming and cannot be used by professional bee-keepers. It is then appropriate to choose the best time to intervene and eliminate the hornets that are hovering in front of the hives. According to some authors, it seems that the predation peak of the hornets is the early morning (Tan et al., 2007) although this remains controversial (Monceau et al., 2013). In any case, it is preferable to intervene in the early morning because it allows to release the stress inflicted to the bees for the rest of the day. When one has a hornet's nest close to the apiary, this technique allows to eliminate up to 30–40 hornets in <15 min after which a clear decline in predation is usually observed for the rest of the day.

3.5 | Nests gunshot destruction

Some are promoting shotgun destruction of the nests (Jaffré, 2015). The objective is to place at least four hunters on each side of the nest and have them alternately shoot a total of at least 12,000 bird shots at the nest. This technique has the disadvantage of sometimes fragmenting the nests, not systematically killing the queen, and disseminating a lot of lead in the environment. The risk of accidents related to all hunting techniques is also to consider. This technique has never been scientifically evaluated.

3.6 | Hornet workers used as poison carriers

This method (also call Judakiller amongst French bee-keepers) consists in capturing a hornet with an insect net and depositing a few drops of biocide (permethrin) on its head and abdomen which it will then bring back to the nest and thus contaminate. More hazardous, because of the hornet catch, than the poisoned bait technique described above, this technique has nevertheless been the object of a marketing in kit (Subito®) recently. It has the disadvantage of requiring catching several hornet workers to treat a nest but it is highly specific as the only nest affected should be *V. velutina*'s nests.

Similarly, to the poisoned baits, this method has the major disadvantage to disseminate biocides as the nest's position remains unknown.

4 | PATENTED OR COMMERCIALIZED DEVICES

4.1 | Pheromone traps

Several groups have been working for several years on the isolation of pheromones from *V. velutina* (Couto, Monceau, Bonnard, Thiéry, & Sandoz, 2014; Gévar, Bagnères, Christidès, & Darrouzet, 2017; Wen et al., 2017; Ya-Nan, Ping, Shi-Hao, Ken, & Nieh, 2017). J. Nieh's group is developing a trap to attract yellow-legged hornet males very selectively using hornets sex pheromones. Its commercialization should take place in the coming year (Nieh, 2017).

4.2 | Electric trap

According to its designer, the Occitina® trap allows a great specificity (60%–80%) towards the yellow-legged hornet (Lubat, 2017). Attracted by a bait, the hornets are then held by a low voltage electric grid system which immobilizes them and makes them fall into a water tank. It is described to trap up to 100 hornets per day. The other insects continue their way through the trap and finally reach the exit. The trap is powered by a battery and is a connected object that allows to monitor it remotely. This sophisticated device is the subject of a patent which has not yet been exploited, and it has not been independently tested yet.

4.3 | Electric harp

The electric harp is aimed to electrocute hornets passing through two wires powered by a current generator. The spacing of the wires is such that a honeybee can fly through without touching them, while a hornet inevitably touches both, electrocutes and falls into a water basin underneath. The electric harp is placed between two hives because the hornets are used to circulate between the hives before hovering over the bee entrance. Nevertheless, in the ideal, it would be necessary to place a harp every two or three hives to be able to be effective. Considering the price of each commercially available device seems hardly feasible for large apiaries. Home-made electric harps plans are also available (Le Bervet, 2015).

4.4 | Passive trap

A passive trap (Apishield®) distributed by most online sellers of bee products consists of a thin box that is placed under the hive. Top and bottom are made a mesh and it is equipped with funnel-shaped entrances on each side which allows hornets to enter the trap but not get out. The hornets are attracted under the hive by the smell of bees, wax and honey. Hornets then engage in the conical inlets and enter the trap in which it remains blocked. This trap may seem interesting but it should be noted, however, that the stress pheromone released by the hornets that accumulate in the trap may generate stress to the bees living just above. Moreover, it is quite expensive and does not seem to be quite efficient (Decante, 2015).

Another type of trap, which does not meet with much success in France but which seems to give better results than the bottle/syrup trap described in 3.1 was developed in the past for *Vespa orientalis*. It uses glue placed as a circle on a board in the middle of which is a meat bait. The hornets attracted by the bait are stuck by the glue and die (Bacandristos, Papanastasiou, & Saitanis, 2006), but this trap does not discriminate amongst insects species or size.

5 | NEST LOCALIZATION TECHNIQUES

Several techniques are currently available to locate hornet nests but they are all tedious, extremely heavy and/or expensive.

5.1 | Triangulations

Triangulation is a technique that has been used in the past to locate wasp nests. This involves capturing at least three specimens, then releasing them at various locations and recording the direction of their flight. Captured and stressed hymenopteran tend to return in a straight direction to their nest. If the three individuals are from the same nest, there is a good chance that the three directions they took would intersect at a point that will give the nest position (Blot, 2008). An alternative is to release a hornet and then follow its direction for a few tens of metres, then to release another and to rectify the trajectory in function of that of the last released hornet. Thus, little by little, one is supposed to reach the nest. Unfortunately, in practice, this type of location is difficult to implement precisely because the landforms rarely allow it and the direction taken by the specimens is sometimes difficult to estimate. Although it is costless, this technique requires a lot of work and time and is therefore difficult to apply on a large scale.

5.2 | Visible tracking of tagged hornets

The tracking of a hornet marked with a very fine thread and a feather or a cotton attached to its end is a technique used by the Chinese in Yunnan to locate the hornet's nests in order to consume its larvae (Jeffs, 2008). This technique is therefore theoretically conceivable, but it is necessary that the hornet does not realize that a thread has been attached to it; otherwise, it will do everything to eliminate it. In practice, we tried this technique several times, but we could never attach a thread to the hornet without the insect noticing it. So, when the hornet notices that a thread is attached to its abdomen, it inevitably stops on the first branch and does everything to get rid of the thread. It usually ends up being attached to the branch. In fact, a hornet with any obvious anomaly will be excluded from the nest by the guards at the entrance. This behaviour is intended to protect the colony.

5.3 | Drones-assisted nest tracking

A theoretical study using several drones (unmanned aerial vehicle [UAV]) equipped with cameras capable of analysing an image of a hornet marked with a thread carrying a fluorescent styrofoam ball has recently been published (Reynaud & Guérin-Lassous, 2016). The authors believe that this system will be applicable to the location of nests. In practice and as described above, it is very difficult to mark a hornet with a thread linked to an object remotely detectable by a camera. The marked specimen will do everything to get rid of the thread and the styrofoam ball and will not return to the nest before it is done. Nevertheless, this study has the merit of establishing the basis of work which may make it possible in future to locate the nests in a fast and reliable manner.

5.4 | Harmonic radar

Described 2 years ago for the first time, the harmonic radar is certainly currently the most suitable device for the search of *V. velutina* nests (Milanesio, Saccani, Maggiora, Laurino, & Porporato, 2016). It is identical to that found on boats or on planes, using a radar and a transponder placed on the object to be tracked. It seems to work efficiently but has the disadvantage that it is not transportable because it is placed on the roof of a vehicle and has a large wingspan. A lighter version has recently been described but this portable radar still remains of quite high power which can possibly be detrimental to the health of the user in the long term (Milanesio, Saccani, Maggiora, Laurino, & Porporato, 2017). It is nevertheless a very promising way of research in the fight against the yellow-legged hornet.

6 | BIOLOGICAL CONTROL

Biological control of the yellow-legged hornet will probably be an unavoidable technique in future, but it will require significant material and human investments and must be considered in the long term. The reserves common to the use of all biological control agents will obviously have to be considered in the application of this technique to the case of *V. velutina*.

6.1 | Using parasitic insects

An endoparasitoid insect, the *Conops vesicularis* fly, has recently been described to infect larvae and adults *of V. velutina* (Darrouzet, Gévar, & Dupont, 2015). Unfortunately, *C. vesicularis* has only been observed on a very limited number of queens and this suggests that its use as a biological control auxiliary seems difficult, but this still needs to be further investigated.

Close cooperation with our Asian colleagues specialized in *V. velutina* studies or vespid parasites could lead to significant advances in the biological control of this insect. Indeed, because of its ancient presence on the Asian continent, it is a safe bet that there are many parasites there that were not imported into Europe during the introduction of this invasive exotic species. Nevertheless, there are at least three other potential parasitoid insects of *V. velutina*. Indeed, it was shown in 2010 that the insects of the Strepsipter family *Xenos moutoni* could infect hornet nests of the *Vespa analis* species in Japan (Makino, Kawashima, & Kosaka, 2011). Although approximately half of *V. analis*'s nests studied where contaminated, it seems that around 5% of the hornet nests were parasitized. This rate may be different in Europe and with *V. velutina* and should be further studied. Therefore, *X. moutoni* and the closely related species *Xenos vesparum*, which is also a parasitizing hymenopters (Beani et al., 2017), may also be good candidates for the biological control of *V. velutina*.

Another insect of the Hymenoptera order, *Sphecophaga vesparum*, was also described in 1995 parasitizing the nests of *V. orientalis* in Israel. It also makes it a suitable candidate for biological control (Barlow, Beggs, & Moller, 1998; Beggs, Rees, Toft, Dennis, & Barlow, 2008; Havron & Margalith, 1995). Havron and Margalith showed that *S. vesparum* has been found to attack up to 100% of the observed the *V. orientalis nests*. Within these nests, 2.5%–95.1% of host cells were parasitized by three to seven individuals. This make *S. vesparum* a good auxiliary for *V. velutina*'s control.

Finally, the syrfid diptera *Volucella inanis* are large flies which are for the most part mimetic of the social hymenopteran they parasitize. The known targets of these syrphids are the nests of bumble bees, hornets and wasps. The larva, of flattened form, is an ectoparasite of the hornet larvae entering their cells and eating them. New Zealand is currently investigating the possibility to use this fly to control *V. germanica* and *V. vulgaris* (Groenteman, 2016).

6.2 | Using nematodes

The nematode *Pheromermis vesparum* (Villemant et al., 2015) was discovered in two locations in France infecting *V. velutina*. It has a complex reproductive cycle mediated by larvae of aquatic insects. Hornets using the adult forms of these aquatic insects to feed their own larvae are then likely to transmit the nematodes, thus allowing their development in the abdomen of future adult hornets. This complex cycle of *P. vesparum* makes it a poor candidate to use for biological control.

Sphaerularia vespae and *Sphaerularia bombi* nematodes have also been described to parasitize the hornet gynes of the species *Vespa simillima* (Sayama, Kosaka, & Makino, 2013). More than 60% of the *V. simillima* gynes collected were contaminated with *S. vespae* in Japan (Kanzaki, Kosaka, Sayama, Takahashi, & Makino, 2007). In doing so, these nematodes sterilize the queens. Both nematodes are present in France, and their reproductive cycle is simple which suggests their potential use as a biological control agent. However, it potentially infects the bumblebee *Bombus terrestris*.

A second nematode *Steinernema Feltiae* has also been described to infect wasps (Gambino, Pierluisi, & Poinar, 1992). This type of nematode is also endemic in France and is even marketed to target several pests such as wolf larvae, orchard caterpillars, garden caterpillars or ants. Thanks to in-depth studies, its potential use in France should be feasible.

6.3 | Using entomopathogenic fungi

An entomopathogenic fungus, *Beauveria bassiana*, has been described to infect the common wasp *V. vulgaris* (Harris, Harcourt, Glare, Rose, & Nelson, 2000). This fungus is currently marketed in France for the control of palm weevil. It is therefore likely to infect other vespids such as *V. velutina*.

6.4 | Using acari

As part of New Zealand's nationwide struggle against *V. germanica* and *V. vulgaris* wasps, researchers have recently isolated *Pnemolaelaps niutirani* mites (Fan, Zhang, Brown, France, & Bennett, 2016). Very few mites species have been observed to date in vespids. New Zealand's wasp control services have founded much hope on this recent discovery.

7 | DNA TECHNOLOGICAL CONTROL

The use of DNA technology in insects control has developed considerably in recent years, not only for the control of pests but also for the control of the Anopheles mosquito (Gantz et al., 2015; Probal & Sajal, 2014).

7.1 | siRNA

RNA interference has been widely used for genetic research in insect (Mallikarjuna Reddy, Moises João, Guy, & Olivier, 2016). The use of RNAi has also developed in recent years by the generation of transgenic plants expressing RNAi directed against insect pests that feed on them. In a first step, it would of course be necessary to target genes encoding key proteins or enzymes of *V. velutina* (Scott et al., 2013). For example, the cotton bollworm, *Helicoverpa armigera*, is a moth whose larvae feed on a wide range of plants, including many important crops. Three dsRNAs targeting the lepidopteran chitin synthase (Chi), cytochrome P450 monooxygenase (P450) and V-ATPase genes were expressed in the chloroplast genome of tobacco plants. Large amounts of theses RNA were detected which significantly reduced transcription of the target genes in the insect midgut and reduced the weight of *H. armigera* larvae, its development and pupation rates drastically (Jin, Singh, Li, Zhang, & Daniell, 2015).

As the genome of *V. velutina* is not yet known, this approach would be carried out by PCR amplification of the gene of interest and search for *V. velutina* specific regions to design the RNAi. It will then be necessary to consider the mode of administration as *V. velutina* in the larval state is mainly carnivorous. It may therefore be considered to create a GMO fish, for example, expressing the hornet-targeted RNAi and which will be used as bait. Hornets larvae fed by workers with this RNAi-expressing GMO fish will then die. The RNAi-expressing GMO fish culture will obviously have to be tightly controlled to avoid any dissemination. The advantage of this technique will be its great specificity as the RNAi will be directed against a sequence specific to *V. velutina* that should not led to collateral damages.

7.2 | CRISPR–Cas9

Discovered as an adaptive bacterial immune system, CRISPR/cas9 is currently considered an attractive tool for genome editing. Because of its great specificity and applicability, this editing system has been used in a multitude of organisms and cells including insects, not only for basic research but also for applied research such as modification of organisms of economic importance.

Thanks to CRISPR/cas9 technology Hammond et al. have shown in 2016 that they can spread a recessive infertility gene in the *Anopheles gambiae* mosquito (Hammond et al., 2016). The character first progressed silently and then spreads at a lightning speed. The species is no longer transformed and is simply suppressed. One could also consider using gene drive to sterilize a population of *V. velutina*. It is of course necessary to assess upstream the risks induced by this type of genetic manipulation as, if the accidentally introduced European population were to disappear, it is also quite possible that this GMO hornet would be re-exported to China where it could also destroy *V. velutina*. Obviously, this could have unsuspected consequences on the territory of origin of *V. velutina*. However, the technique is no less attractive in the specific case of *V. velutina* in Europe.

8 | CONCLUSIONS

Since its arrival in 2004, the colonization of Europe by *V. velutina* has never slowed down. In Europe, this foreign invasive species only faces few predators such as the rare European honey-buzzard (*Pernis apivorus*). Although inbreeding was observed, and was supposed to reduce the population size, this has not happened so far (Darrouzet, Gévar, Guignard, & Aron, 2015). *Vespa velutina* is

TABLE 1 Comparison of the different control methods for *Vespa velutina*

Method	Efficiency	Side effect	Area	Cost	R&D
Trapping	Low	High (E)	Small	Low	No
Poisoned baits	High[a]	High (E, B)	Medium	Medium	Evaluation
Muzzels	Low	None	Apiary	Low	No
Racket	Low	None	Apiary	Low (time)	No
Gunshots	Low	Low	Small	Medium	No
Juda killer	Unknown	High (B)	Medium	Medium	Evaluation
Pheromone traps	Unknown	Low (?)	Small	Medium	Yes
Electric traps	Unknown	Low (?)	Small	High	Evaluation
Electric harps	Low (?)	Low	Apiary	Medium	Evaluation
Passive trap	Low	None	Hives	Medium	No
Triangulation	Low	None	Medium	Low (time)	No
Tagged horned	Low	None	Medium	None	No
Drones-assisted nest tracking	Unknown	None	Medium	High	Yes
Harmonic radar	Unknown	None	Medium	High	Yes
Biological control	Unknown	Low (?)	Very wide	High	Yes
siRNA	Unknown	None (?)	Medium	High	Yes
Crispr–Cas9	Unknown	Low (?)	Medium	High	Yes

Efficiency: efficiency (proven or field appreciation) to reduce hornet numbers; side effects: impact on environment (E) entomofauna and biodiversity (B) biocide dissemination; area: supposed size of the controlled area; cost: rough evaluation of the cost of the method; R&D: investment in research and development needed. Underlined control methods are those who can impact the whole nest without initially knowing its location. (?) Not evaluated for *V. velutina*.
[a]Only improved for *Vespula germanica* and *vulgaris*.

already very well adapted to the French biotopes (Villemant et al., 2011) and climate change projections made Europe and particularly France, the future best playfield of this invasive species (Barbet-Massin et al., 2013).

Despite warnings from the scientific community (Salles, 2016), the French and European authorities do not appear to be very concerned by the progression of this resilient predator-threatening pollinators (Santarém, 2016). Only a few research programs on the control *of V. velutina* (Decante, 2015; Milanesio et al., 2016) (IRBI-University of Tours, France; University of Turin, Italy; INRA-Bordeaux, France; MNHN-Paris, France) and some local institutional initiatives (notably the "Plan Frelon 06" of the Department Council of Alpes Maritimes) aimed to localize and destroy nests have been funded so far ("Plan Frelon CD06", https://www.departement06.fr/lutte-contre-les-especes-envahissantes/le-frelon-asiatique-9032.html). Meanwhile, our New Zealand colleagues have launched major research projects aimed at reducing the population of *V. germanica* and *V. vulgaris* (Barlow et al., 1998; Beggs et al., 2008; Fan et al., 2016; Ward, 2014), whose threat is probably not as great. This underlines the fact that serious investments in research should be made rapidly (Table 1).

All the techniques described here (Table 1) have their pros and cons but can be divided into two main categories: those who would affect *V. velutina*'s (Table 1, underlined methods) nest and larvae (nest localization, poisoned baits, biological control, DNA technology) and those who can only affect hornet workers (rackets, all traps, muzzles, etc.). Considering that a *V. velutina* nest holds 1,500–2,500 hornets and will produce 12,000–15,000 hornets during a season, it is obvious that methods aimed to localize or destroy the nests at distance should be privileged in terms of efficiency (Rome et al., 2015).

Nevertheless, depending on whether one takes the side of a bee-keeper looking for simple, fast and inexpensive solutions, or a citizen bothered by *V. velutina* or sensitive to the current threat to pollinators, or even a decision-maker who must make strategic choices, the choice of the best control method will be different. In fact, a combination of several of the techniques described here is often the best choice.

As far as bee-keepers are concerned, the cost of treatment (varroa mite, honeycomb moth, foulbrood, etc.) is already quite high, and additional investments in expensive traps or devices are difficult to envisage. Therefore, many of them use home-made traps or poisoned baits. As we have seen, these traps (paragraph 4.1) are not very selective and effective, even counterproductive, if they are placed near the hives. If a bee-keeper insists on placing traps, it would be useful to place them at distance from the apiary. Indeed, it seems that the hornets are attracted by the trap bait but quickly turn away for bees. Biocides-poisoned meat/fish baits are more selective in that they only concern carnivorous insects, if not accessible to terrestrial carnivorous animals or birds. However, their major disadvantage is that they can lead to the dissemination of the biocides used. Although the level involved are well below what is usually used in crop treatment, it remains that contaminated larvae can enter the food chain if the nests are not removed after being poisoned. Thus, in this case, low-remanence biocides will be preferred.

Citizens confronted to the hornet or aware of its harm must keep in mind that the little they can do without risking to threat the entomofauna or the environment is, in case of nest discovery, to inform their local administration (city hall, police station…) and the French Natural History Museum (MNHN), which is involved in a huge programme to map *V. velutina*'s invasion (MNHN nest reporting, P. Fiche de signalement. Retrieved from http://frelonasiatique.mnhn.fr/signaler-informations; MNHN). Nevertheless, in case of major inconvenience due to hornets, they may equip their gardens with a trap as selective as possible (home-made traps with exits for the smallest insects) as described by Blot and Debellescize (2017), but should be aware of possible side effects on the entomofauna. The use of poisoned traps is not recommended as it presents risks for users but also for possible collateral victims (wild animals, domestic animals, children). Commercial electric rackets normally intended for mosquitoes can be effective on the hornets, but it is necessary to crush the electrified hornet as it will recover quickly.

Finally, as far as the decision-makers are concerned, they can only be recommended to invest very quickly in finding solutions to search and cleanly destroy hornet nests. Indeed, this strategy is by far the most efficient, the least expensive and the safest for the environment as it allows biocide destruction by the nest incineration. Let us hope that national and European institutions will quickly become aware of the extent of this problem and will invest to limit the spread of yellow-legged hornets which now threatens the whole of Europe.

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CONFLICT OF INTEREST

Authors have no conflict of interest to declare.

AUTHOR CONTRIBUTION

L. Turchi and B. Dérijard wrote the manuscript. All authors read and approved the manuscript.

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