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POLICY DIRECTION

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Effectiveness of clear-cuttings in non-fragmented pine forests in relation to EU regulations for the eradication of the pine wood nematode

Christelle Robinet[1] | Philippe Castagnone-Sereno[2] | Manuel Mota[3] | Géraldine Roux[1,4] | Corinne Sarniguet[5] | Xavier Tassus[6] | Hervé Jactel[7]

[1]INRAE, URZF, Orléans, France; [2]INRAE, Université Côte d'Azur, CNRS, ISA, Sophia Antipolis, France; [3]NemaLab-ICAAM, Universidade de Evora, Evora, Portugal; [4]Université d'Orléans, COST, Orléans, France; [5]ANSES, Nematology Unit, Le Rheu, France; [6]ANSES, Expertise and Biological Risk Unit, Angers, France and [7]INRAE, Université de Bordeaux, BIOGECO, Cestas, France

Correspondence
Christelle Robinet
Email: christelle.robinet@inrae.fr

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Abstract

1. The invasive pine wood nematode (PWN) *Bursaphelenchus xylophilus* is one of the most serious threats to pine forests across the world. Detected in Europe in 1999, it has largely spread despite containment measures.
2. Following the European Union regulations, the requested eradication measure is to fell, remove and dispose of all susceptible plants within a clear-cut zone (CCZ) of a radius of 500 m around any infected tree. This measure is controversial since its effectiveness is questioned.
3. An individual-based model, describing the dispersal of the nematode vector and the nematode transmission, was used to estimate the relationship between the radius and the effectiveness of the CCZ at eradicating the PWN.
4. Clear-cutting of a 500-m radius is poorly effective in non-fragmented pine forests since it reduces the number of PWN transmissions by only 0.6%–11.5%. To significantly reduce the number of transmissions, the radius should be between 14 and 38 km, which is not technically nor ethically feasible.
5. *Policy implications*. Our results, based on model simulations at a fine spatial scale, prove that clear-cutting susceptible trees 500 m around any infested tree—as requested by EU regulation to eradicate the PWN—is not effective in large and continuous pine forests. Instead, strengthened surveillance and sanitation felling could be explored.

KEYWORDS

biological invasion, *Bursaphelenchus xylophilus*, clear-cut, dispersal, emergency plan, eradication, Europe, *Monochamus galloprovincialis*

1 | INTRODUCTION

The pine wood nematode (PWN) *Bursaphelenchus xylophilus* (Steiner & Buhrer, 1934) Nickle 1970 is one of the most serious threats to pine forests across the world as it can kill a tree within a few weeks (Webster & Mota, 2008). Native to North America, it has spread to Japan, China, Korea, Portugal and Spain (Robertson et al., 2011; Zhao, Futai, Sutherland, & Takeuchi, 2008). The PWN requires an insect vector to disperse and be transmitted from one susceptible tree to another. The vector is a cerambycid beetle

from the genus *Monochamus*. In Europe, *M. galloprovincialis* is the only known species to carry the PWN (Sousa et al., 2002). Besides, the PWN can spread at long distance with the transportation of infected wood products. In Portugal, the PWN has locally spread at 5.3 km/year on average (De la Fuente, Saura, & Beck, 2018) but it can propagate further through human-assisted dispersal (on average at 150 km; Robinet, Opstal, Baker, & Roques, 2011).

The detection and eradication of infected trees is complex because of a latency period between nematode inoculation and apparition of wilting symptoms. Consequently, infected trees could be asymptomatic during a given period (Futai, 2003). To prevent the spread of the PWN in Europe, the EU regulation (Implementing Decision 2012/535/EU) requires the Member States to implement emergency measures. They consist of annual surveys for PWN detection, an eradication measure to eliminate the nematode where it is present, and a containment measure to prevent a further spread of the nematode where it cannot be eradicated. The requested eradication measure is to fell, remove and dispose of all susceptible trees within an area, called clear-cut zone (CCZ), of a minimum radius of 500 m (that may be reduced to 100 m subject to derogations) around any PWN-infected tree. This measure is controversial because it is expensive, difficult to implement in dense forests and its effectiveness is questioned. Indeed, removing host trees within a radius below 30 km could not stop the spread in Portugal (De la Fuente et al., 2018). Assessing the relationship between the size and the effectiveness of CCZ at the landscape scale based on the latest knowledge about the flight capability and behaviour of the insect vector is therefore a crucial step to improve PWN management.

The effectiveness of clear-cuttings depends not only on the dispersal capacities of the insect vector, but also on the purpose of their application (Jactel et al., 2015). These clear-cuttings could be done:

- To prevent the dispersal of infected vectors the following year in case that some of them remain after the removal of the infected pines (Scenario 1, 'preventive action'; Figure 1a) or
- To eliminate host trees potentially infected in the same year (Scenario 2, 'curative action'; Figure 1b).

In both cases, we assume that the detection is done at the end or after the vector flight season, and clear-cuttings are done before the flight of the following generation (before the following spring) as imposed by the EU.

In Scenario 1, we distinguish two sub-cases: the CCZ has no effect on the dispersal behaviour (Scenario 1-1, 'strategy of non-avoidance of the CCZ'; Figure 2a) or the beetle tends to exit the CCZ and not enter it again (Scenario 1-2, 'strategy of avoidance of the CCZ'; Figure 2b) because *Monochamus* beetles are known to be attracted by visual and chemical cues emitted by host pines (Giffard, David, Joubard, Piou, & Jactel, 2017). In Scenario 2, because the clear-cutting occurs after the beetles have dispersed, CCZ cannot affect the past dispersal behaviour of the insect vector. In all the cases, we assume that all the products resulting from the clear-cuttings (e.g. stems and branches) are removed or chipped.

In this study, we tested the effect of CCZ radius on the effectiveness of eradication under the three above-mentioned scenarios. For this purpose, we modified a process-based model that describes the dispersal of *M. galloprovincialis* at a fine scale (Robinet, David, & Jactel, 2019) to include the transmission of PWN to healthy trees. We

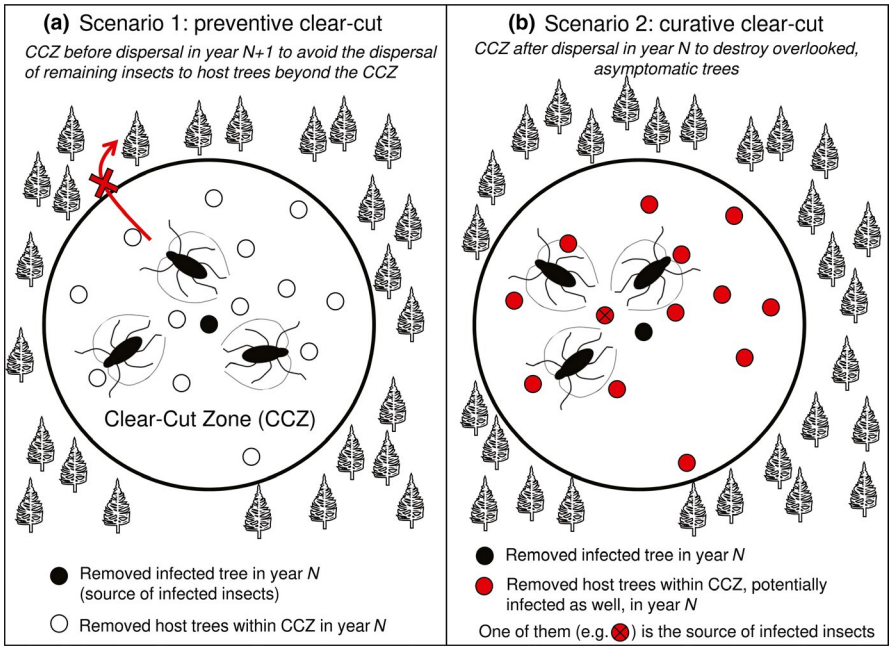

FIGURE 1 Illustration of the two objectives of clear-cutting for pine wood nematode eradication. (a) In Scenario 1, the clear-cutting is done preventively to avoid the dispersal of remaining infected insects to neighbouring host trees. (b) In Scenario 2, the clear-cutting is done to remove overlooked, asymptomatic trees

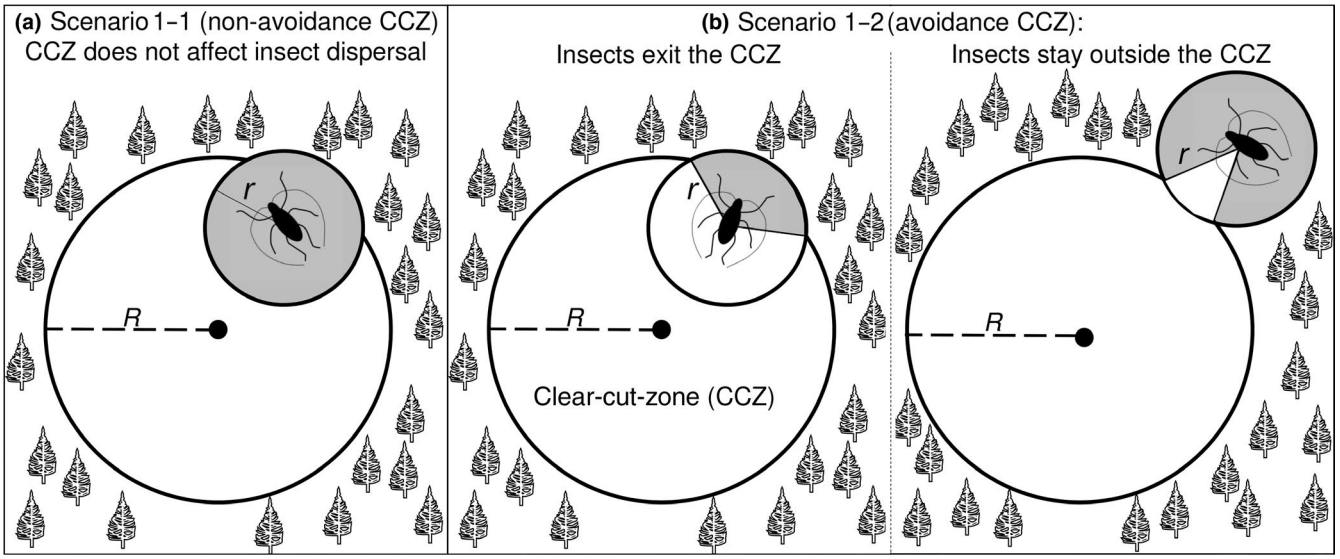

FIGURE 2 Illustration of the effects of the clear-cutting zone (CCZ) on the dispersal behaviour of insect vectors in Scenario 1. In Scenario 1-1, *Monochamus galloprovincialis* beetles do not avoid the CCZ (a), while they try to exit the CCZ and not enter it again in Scenario 1-2 (b). The authorized angles when flying are represented in grey area, *R* indicates the CCZ radius and *r* the dispersal distance

simulated both dispersal and transmission processes in a non-fragmented pine forest, and applied theoretical clear-cuts of various radii to estimate the resulting proportion of PWN transmissions avoided.

2 | MATERIALS AND METHODS

2.1 | Vector dispersal

We simulated the flight dispersal of the vector along its adult life span (120 days) using the individual-based model developed by Robinet et al. (2019). The dispersal distance was randomly chosen according to a negative exponential kernel. Then, the flight direction was set up to depend on beetle's behaviour and the scenario considered (Figure 2; see Appendix S1). In Scenarios 1-1 and 1-2, if the repeated flights did not allow escaping the CCZ, we counted the number of days the beetle would remain inside the CCZ. We assumed that beetles would die there after 12 days (parameter *s* in Table 1) as they cannot survive such a long starvation period (Sánchez-Husillos, Etxebeste, Álvarez-Baz, & Pajares, 2013).

We assumed that pine forest landscape was not fragmented (e.g. pines were present everywhere, except in the CCZ).

2.2 | PWN transmission

At each stop between two successive flights, we assumed that infected beetles could potentially transmit the PWN while feeding on fresh pine shoots of healthy trees. The insect vector tends to transmit nematodes very frequently 1–6 weeks after its emergence, transmissions then decrease rapidly, reaching nearly 0 from the 9th to the 12th week (Naves, Camacho, Sousa, & Quartau, 2007a). In our simulations, we considered that transmission is possible only on days 1–77 (with a gap from day 64 to day 70) to cope with the experimental results of Naves et al. (2007a). PWN transmission can also be done, to a lesser extent, when females lay eggs on decaying trees (Naves, Camacho, Sousa, & Quartau, 2007b). The first egg can be deposited 20 days after insect emergence and oviposition can last about 30–44 days (Naves, Sousa, & Quartau, 2006), with a probability of 0.37 to transmit the nematode at this occasion (Naves et al., 2007b). In the simulations, we assumed that 50% of individuals were females, which could lay eggs from day 20 to day 53 (i.e. for 34 days). For each day of egg-laying, we chose at random whether the PWN was transmitted by the female, following a binomial law Bin (p = .37).

TABLE 1 Parameters used in the model to simulate dispersal (see Robinet et al., 2019 for details) and the effects of the clear-cut zone (CCZ)

Parameter	Definition	Values
α	Mean daily dispersal distance (in metres)	2,000
Δ	Delay response time (in days)	0
β	Rest between two flights (in days)	1
n	Number of beetles released	100
l	Adult longevity (in days since adult emergence)	120
m	Maturation age (in days since adult emergence)	20
p_{fm}	Daily probability of flying for mature beetles	0.61
p_{fi}	Daily probability of flying for immature beetles	0.45
s	Number of days a beetle can stay without feeding	12
R	Radius of the CCZ (in metres)	0–40,000

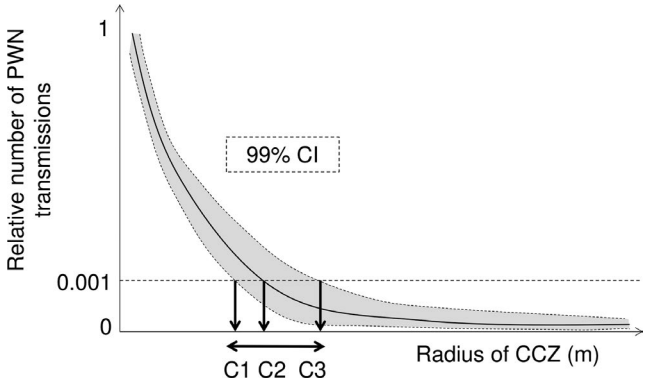

FIGURE 3 Calculation of the confidence interval (CI) for the recommended radius. The relative number of transmissions of the pine wood nematode (PWN) decreases with the clear-cut zone (CCZ) radius. C2 gives the radius to reduce the number of PWN transmission by 99.9% on average and [C1, C3] gives the confidence interval of the CCZ radius to ensure that the number of PWN number is reduced by 99.9% at the 99% CI

2.3 | Effectiveness of clear-cutting

We supposed that 100 infected beetles were initially present, able to disperse and transmit PWN. We tested the effects of clear-cutting trees on the PWN transmission for a CCZ with a radius varying from 0 to 40,000 m with an increment of 500 m and we additionally tested 100 m. Since the individual-based model is stochastic, 100 replications were done for each scenario and each radius value. The number of dispersing beetles is arbitrary in this study, but in reality it depends on local vector abundance. Additional simulations have shown that considering 100 beetles provides a representative outcome (see Appendix S2). In case that the number of beetles is lower (e.g. 10), unless conducting a higher number of replicates, stochasticity will increase and the results will be more variable.

To determine the effectiveness of clear-cutting, we calculated the number of PWN transmissions outside the CCZ (number of times the beetles stopped and inoculated nematodes). Then, we calculated the relative number of transmissions, which was defined as the number of transmissions obtained for a given CCZ radius divided by the number of transmissions without CCZ (radius of 0 m). We considered a CCZ successful at eradicating PWN when the relative number of transmissions was below 0.001 (0.1%). We estimated the size of CCZ radius allowing to reach this threshold value, and its confidence interval (at 99%) using the 100 replicates (Figure 3). Simulations and calculations were done in R (R Core Team, 2015; Robinet & Jactel, 2019) and the list of parameters is given in Table 1.

3 | RESULTS

The CCZ radius (and confidence interval, CI) required to obtain a relative value of nematode transmission of 0.001 (0.1%) was of (Figure 4; see Robinet & Jactel, 2019 for videos of the simulations):

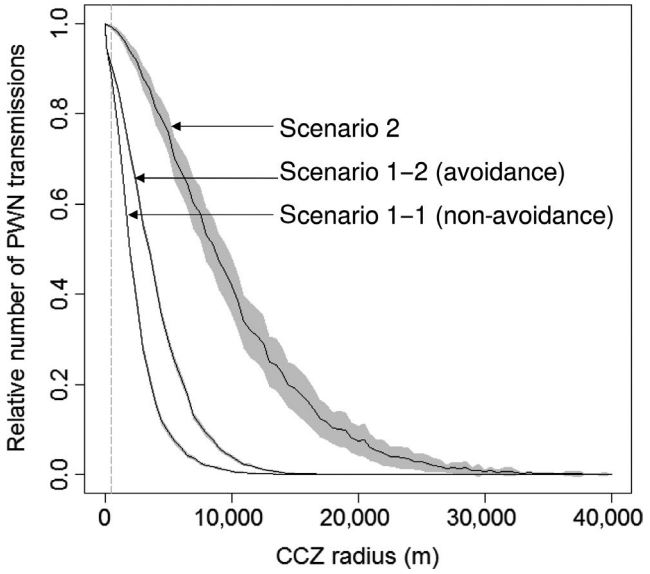

FIGURE 4 Effectiveness of the clear-cutting according to Scenario 1-1 (preventive action and avoidance strategy), Scenario 1-2 (preventive action and non-avoidance strategy) and Scenario 2 (curative action) with increasing radius of the clear-cut zone (CCZ). The mean and 99% confidence interval of the relative number of pine wood nematode (PWN) transmissions outside the CCZ are represented for the three scenarios (note that the confidence interval is almost not visible for Scenarios 1-1 and 1-2 because they are very narrow). The vertical dotted grey line indicates the radius of 500 m requested by the European Union regulation

- 14 km (CI = 14–15.5 km) in Scenario 1-1 (preventive action; no CCZ avoidance),
- 17.5 km (CI = 16.5–19 km) in Scenario 1-2 (preventive action; CCZ avoidance),
- 38 km (CI = 36.5–39.5 km) in Scenario 2 (curative action).

Consequently, to reduce significantly the number of PWN transmissions outside the CCZ, clear-cutting should cover from ca. 60,000 to 450,000 ha, according to the scenarios. A radius of only 500 m would reduce the number of transmissions outside the CCZ by only 0.6% in Scenario 2, 9.4% in Scenario 1-2 and 11.5% in Scenario 1-1.

4 | DISCUSSION

4.1 | Effectiveness of clear-cuttings

This study shows that the eradication measure requesting to cut, remove and dispose of all susceptible host trees within a radius of 500 m from infected trees is not effective to eradicate a PWN infection spot in non-fragmented pine forests. Clear-cuttings over larger radii (14–38 km) would be necessary but not practically and ethically feasible. This result is in agreement with that of De la Fuente et al. (2018) who estimated that a clear-cutting wider than 30 km was necessary to stop PWN spread. They fit their model on the

observed spread at the scale of Portugal, but this spread was not only the result of the vector dispersal but also of possible human-assisted dispersal via wood transport, and, of the effects of control measures. Our study refines the estimate as we actually describe the dispersal mechanism at a finer spatial scale, taking into account the dispersal capacity of the vector at immature and mature stages, and its ability to transmit nematodes over time. Despite differences in both methods, they provide very similar results and the conclusion is strengthened.

4.2 | Important factors to consider

Our study points out that the objective of the eradication method is important. To prevent further dispersal of insect vectors (Scenario 1), effectiveness of clear-cuttings is roughly the same irrespective of the insect behaviour (i.e. avoiding or not to fly through the CCZ). However, if some asymptomatic pines were not detected (Scenario 2), the CCZ may not be correctly centred on the insect vector source. In the worst case, the detected pine could be on the periphery on the infected area, and to remove all infected pines, the radius should be twice as large as the radius of a CCZ centred on the source. It is thus consistent that the recommended radius in Scenario 2 is approximately twice the radius in Scenario 1 (38 km vs. 2 × 17.5 = 35 km).

This modelling study also shows that two important processes should be considered: (a) PWN transmission and (b) insect flight capability and behaviour.

1. Regarding the PWN transmission process, many questions remained unanswered. It is unclear which PWN-load is carried and transmitted by the insect vector along its life span, what are the effects of PWN-load on insect flight capability and behaviour and which concentration of PWN is needed for a pine to show wilt symptoms. This study provides a solid baseline to test the effectiveness of clear-cuttings in various configurations as soon as these processes are better understood.
2. Regarding insect flight activity, there are still gaps in this knowledge as well, even if the insect dispersal has been thoroughly studied in previous years (David, Giffard, Piou, & Jactel, 2014; Torres-Vila et al., 2015). Etxebeste et al. (2016) performed mark-and-recapture experiments in continuous versus fragmented pine forests and found that insects could disperse far further in fragmented landscapes (up to 5,300 vs. 720 m). However, habitat fragmentation could instead increase the success of eradication, as has been shown with gypsy moth (Barron, Liebhold, Kean, Richardson, & Brockerhoff, 2019). Therefore, we need further data and model development to describe the dispersal behaviour of *M. galloprovincialis* adults in heterogeneous landscapes. Since clear-cuttings are poorly effective in non-fragmented pine forests, other eradication approaches should thus be investigated. Favouring the vector mortality by bird predation (De la Fuente & Beck, 2019) or mass-trapping (Jactel et al., 2015, 2019) would have insufficient effect to successfully control the nematode. Hereafter, we discuss more promising alternative methods.

4.3 | Alternative methods

Labour and financial costs saved if clear-cuttings were not implemented could be reallocated to a more intense surveillance of insect vectors and pine trees to detect the presence of PWN. Firstly, a higher number of traps could be installed in areas at risk and the insects caught in the traps could be checked for the absence of PWN with DNA methods. Secondly, host trees could be more extensively surveyed by visual detection from the ground and/or with remote sensing techniques (e.g. unmanned aerial vehicles or satellite images) with a special effort in areas at risk (e.g. in decaying pine forests, logging sites, wood-processing yards). Indeed, early detection has proved to be the best approach to increase the probability to eradicate invasive species rather than to eradicate them when already largely established (Liebhold et al., 2016).

Once the PWN is detected in a forest stand, sanitation felling of symptomatic trees (Waring & O'Hara, 2005) could be applied. With this method, contrary to clear-cutting, only decaying trees will be removed, one by one, so as to slow the development of the epidemics. This method is currently being tested in Portugal. Field surveillance and laboratory work (to confirm the presence of the PWN) would be more demanding, but it is the counterpart for safeguarding uninfected trees. In Korea, small clear-cuttings (radius of 10–50 m) appeared effective when combined with preventive nematicide-injection in the surrounding pine forests (Kwon, Shin, Lim, Kim, & Lee, 2011).

For trees with high heritage value (e.g. urban trees) or for trees located close to risk areas (e.g. ports and sawmills), the solution could be to inject nematicide into the trunk (e.g. emamectin benzoate; Sousa, Naves, & Vieira, 2013) or to use biological control agents such as the fungus *Esteya vermicola*, a method currently being tested with some success (S. Chang, personal communication, August 30, 2019). However, their implementation requires tedious tree by tree manual operations, which have to be repeated regularly, and this may result in phytotoxicity (e.g. by emamectin benzoate, Kuroda & Kenmochi, 2016).

5 | CONCLUSIONS

This study clearly demonstrates that the method of clear-cutting over radii of a few hundred metres is not relevant to eradicate the invasive PWN, at least in large non-fragmented pine forests. By quantifying the relationship between the radius and the effectiveness of the CCZ, we provide support to the new recommendations of the EPPO standard (EPPO, 2018), reducing the clear-cut radius to a minimum (e.g. 50–100 m) and re-enforcing the surveillance efforts.

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AUTHORS' CONTRIBUTIONS

All authors conceived the idea in a working group, corrected and approved the article. C.R. made the modelling part and wrote the article. C.R. and H.J. interacted to design relevant simulations. All authors gave final approval for publication.

DATA AVAILABILITY STATEMENT

R script available via zenodo at https://doi.org/10.5281/zenodo.3387267 (Robinet & Jactel, 2019).

ORCID

Christelle Robinet https://orcid.org/0000-0002-4933-4656

REFERENCES

Barron, M. C., Liebhold, A. M., Kean, J. M., Richardson, B., & Brockerhoff, E. G. (2019). Habitat fragmentation and eradication of invading insect herbivores. *Journal of Applied Ecology*, https://doi.org/10.1111/1365-2664.13554

David, G., Giffard, B., Piou, D., & Jactel, H. (2014). Dispersal capacity of *Monochamus galloprovincialis*, the European vector of the pine wood nematode, on flight mills. *Journal of Applied Entomology*, *138*, 566–576. https://doi.org/10.1111/jen.12110

De la Fuente, B., & Beck, S. A. (2019). Management measures to control pine wood nematode spread in Europe. *Journal of Applied Ecology*, *56*, 2577–2580. https://doi.org/10.1111/1365-2664.13486

De la Fuente, B., Saura, S., & Beck, P. S. A. (2018). Predicting the spread of an invasive tree pest: The PWN in Southern Europe. *Journal of Applied Ecology*, *55*, 2374–2385. https://doi.org/10.1111/1365-2664.13177

EPPO. (2018). PM 9/1 (6) *Bursaphelenchus xylophilus* and its vectors: Procedures for official control. *Bulletin OEPP/EPPO Bulletin*, *48*, 503–515. https://doi.org/10.1111/epp.12505

Etxebeste, I., Sánchez-Husillos, E., Álvarez, G., Mas, I., Gisbert, H., & Pajares, J. (2016). Dispersal of *Monochamus galloprovincialis* (Col.: Cerambycidae) as recorded by mark-release-recapture using pheromone traps. *Journal of Applied Entomology*, *140*, 485–499.

Futai, K. (2003). Role of asymptomatic carrier trees in epidemic spread of pine wilt disease. *Journal of Forestry Research*, *8*, 253–260. https://doi.org/10.1007/s10310-003-0034-2

Giffard, B., David, G., Joubard, B., Piou, D., & Jactel, H. (2017). How do sex and sexual maturation influence the response of *Monochamus galloprovincialis* to host odours? *Journal of Applied Entomology*, *141*, 551–560. https://doi.org/10.1111/jen.12374

Jactel, H., Bonifacio, L., van Halder, I., Vétillard, F., Robinet, C., & David, G. (2019). A novel, easy method for estimating pheromone trap attraction range–Application to the pine sawyer beetle, *Monochamus galloprovincialis*. *Agricultural and Forest Entomology*, *21*, 8–14. https://doi.org/10.1111/afe.12298

Jactel, H., Castagnone, P., Mota, M., Piou, D., Robinet, C., Roux, G., & Sarniguet, C. (2015). *Evaluation of emergency measures to prevent the spread of the PWN within the European Union*. ANSES opinion Collective Expert Appraisal Report. Retrieved from https://www.anses.fr/fr/system/files/SVEG2014SA0103RaEN.pdf

Kuroda, K., & Kenmochi, A. (2016). Risk of killing uninfected pine trees by the repeated trunk-injection of nematicides to prevent pine wilt. *Proceedings of the pine wilt disease international symposium* (p. 101) (2016 IUFRO Working Party 7.02.10), Seoul, Korea.

Kwon, T. S., Shin, J. H., Lim, J. H., Kim, Y. K., & Lee, E. J. (2011). Management of pine wilt disease in Korea through preventative silvicultural control. *Forest Ecology and Management*, *261*, 562–569. https://doi.org/10.1016/j.foreco.2010.11.008

Liebhold, A. M., Berec, L., Brockerhoff, E. G., Epanchin-Niell, R. S., Hastings, A., Herms, D. A., … Yamanaka, T. (2016). Eradication of invading insect populations: From concepts to applications. *Annual Review of Entomology*, *61*, 335–352. https://doi.org/10.1146/annurev-ento-010715-023809

Naves, P. M., Camacho, S., de Sousa, E. M., & Quartau, J. A. (2007a). Transmission of the PWN *Bursaphelenchus xylophilus* through feeding activity of *Monochamus galloprovincialis* (Col., Cerambycidae). *Journal of Applied Entomology*, *131*, 21–25. https://doi.org/10.1111/j.1439-0418.2006.01111.x

Naves, P. M., Camacho, S., de Sousa, E., & Quartau, J. A. (2007b). Transmission of the PWN *Bursaphelenchus xylophilus* through oviposition activity of *Monochamus galloprovincialis* (Coleoptera: Cerambycidae). *Entomologica Fennica*, *18*, 193–198. https://doi.org/10.33338/ef.84398

Naves, P., de Sousa, E., & Quartau, J. A. (2006). Reproductive traits of *Monochamus galloprovincialis* (Coleoptera: Cerambycidae) under laboratory conditions. *Bulletin of Entomological Research*, *96*, 289–294. https://doi.org/10.1079/ber2006422

R Core Team. (2015). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Robertson, L., Cobacho Arcos, S., Escuer, M., Santiago Merino, R., Esparrago, G., Abelleira, A., & Navas, A. (2011). Incidence of the pinewood nematode *Bursaphelenchus xylophilus* Steiner & Buhrer, 1934 (Nickle, 1970) in Spain. *Nematology*, *13*, 755–757. https://doi.org/10.1163/138855411x578888

Robinet, C., David, G., & Jactel, H. (2019). Modeling the distances traveled by flying insects based on the combination of flight mill and mark-release-recapture experiments. *Ecological Modelling*, *402*, 85–92. https://doi.org/10.1016/j.ecolmodel.2019.04.006

Robinet, C., & Jactel, H. (2019). Simulating the effectiveness of clear-cuttings to eradicate the pine wood nematode: R script and videos. *Zenodo*. https://doi.org/10.5281/zenodo.3387267

Robinet, C., Van Opstal, N., Baker, R., & Roques, A. (2011). Applying a spread model to identify the entry points from which the pine wood nematode, the vector of the pine wilt disease, would spread most rapidly across Europe. *Biological Invasions*, *13*, 2981–2995. https://doi.org/10.1007/s10530-011-9983-0

Sánchez-Husillos, E., Etxebeste, I., Álvarez-Baz, G., & Pajares, J. (2013). Physiological development of *Monochamus galloprovincialis* immature adults through shoot feeding. In T. Schröder (Ed.), *Pine wilt disease conference 2013* (pp. 26–27), Braunschweig: Julius Kühn-Institute (JKI) ISSN: 1866–590X.

Sousa, E., Naves, P., Bonifácio, L., Bravo, M. A., Penas, A. C., Pires, J., & Serrão, M. (2002). Preliminary survey for insects associated with *Bursaphelenchus xylophilus* in Portugal. *Bulletin OEPP/EPPO Bulletin*, *32*, 499–502. https://doi.org/10.1046/j.1365-2338.2002.00597.x

Sousa, E., Naves, P., & Vieira, M. (2013). Prevention of pine wilt disease induced by *Bursaphelenchus xylophilus* and *Monochamus galloprovincialis* by trunk injection of emamectin benzoate. *Phytoparasitica*, *41*, 143–148. https://doi.org/10.1007/s12600-012-0272-y

Torres-Vila, L. M., Zugasti, C., De-Juan, J. M., Oliva, M. J., Montero, C., Mendiola, F. J., … Espárrago, G. (2015). Mark-recapture *of Monochamus galloprovincialis* with semiochemical-baited traps: Population density, attraction distance, flight behaviour and mass trapping efficiency. *Forestry*, *88*, 224–236. https://doi.org/10.1093/forestry/cpu049

Waring, K. M., & O'Hara, K. L. (2005). Silvicultural strategies in forest ecosystems affected by introduced pests. *Forest Ecology and Management*, *209*, 27–41. https://doi.org/10.1016/j.foreco.2005.01.008

Webster, J., & Mota, M. (2008). Pine wilt disease: Global issues, trade and economic impact. In M. M. Mota & P. R. Vieira (Eds.) *Pine wilt disease: A worldwide threat to forest ecosystems* (pp. 1–3). Dordrecht: Springer.

Zhao, B. B., Futai, K., Sutherland, J. R., & Takeuchi, Y. (2008). *Pine wilt disease* (p. 459). Tokyo: Springer.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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