RESEARCH ARTICLE

How to eradicate an invasive forest pest without clear-cutting

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Abstract

1. The pine wood nematode (PWN), *Bursaphelenchus xylophilus*, is an invasive species causing high pine mortality in invaded areas outside its native range. European Union (EU) regulations stipulate a 500-m radius clear-cutting around infested trees to prevent the spread of PWN by the vector beetle *Monochamus galloprovincialis*, yet this measure is costly and not fully effective.

2. We used an individual-based model describing the dispersal of the insect vector and its transmission of PWN to compare the cost-effectiveness of clear-cutting and selective cutting of only the PWN-infested trees for three different methods for surveillance: visual ground surveys, aerial surveys and insect trap networks.

3. Both strategies eradicated PWN if intensive aerial surveillance was conducted at a time that all infested trees showed symptoms. Selective cutting reduced costs by up to a factor of 200 compared to clear-cutting, mainly due to the preservation of healthy trees. Additionally, selective cutting reduces environmental and societal costs. However, eradication is unlikely if symptom expression of infectious trees is incomplete at the time of survey.

4. *Policy implications.* The results show that selective cutting applied together with modern remote sensing surveillance methods is an environmentally friendly alternative to the mandatory clear-cutting for PWN control in the EU.

KEYWORDS
bioeconomic analysis, containment, *Monochamus galloprovincialis*, non-native, outbreak management, pine wilt disease, surveillance

1 | INTRODUCTION

The pine wood nematode (PWN) *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle is the causal agent of the pine wilt disease. The nematode is native to North America (USA and Canada) and has invaded Japan, China, Korea, Portugal and Spain, where it can cause up to 80%–90% tree mortality, leading to huge economic impacts to the forest sector in these countries (Seidl

et al., 2018; Soliman et al., 2011). Recently, PWN was detected for the first time in southwestern France (Folcher et al., 2026). In China alone, annual losses from PWN, including costs of prevention, control and PWN management, are estimated at 1 billion USD per year (Zhao et al., 2020). *Pinus* species are the main hosts for PWN, with *Pinus pinaster* Ait. being one of the most susceptible species in Europe (Nunes da Silva et al., 2015).

PWN is transmitted from tree to tree by longhorn beetles of the genus *Monochamus* (Coleoptera: Cerambycidae: Monochamini). In Europe, the species *Monochamus galloprovincialis* (Olivier) is the only known vector of PWN. The average spread rate of PWN in Portugal is currently about 5.3 km/year (de la Fuente et al., 2018). However, *M. galloprovincialis* may fly up to 4.3 km per hour (David et al., 2014), it may be carried by wind, and a beetle can disperse multiple times (Etxebeste et al., 2016). Hence, an individual may disperse more than 60 km during its adult life and thereby spread PWN over much longer distances than the observed average spread rate of 5.3 km/ year, making outbreaks extremely difficult to contain and eradicate (David et al., 2014; Robinet et al., 2019).

To slow down the spread of PWN, EU regulations mandate immediate eradication by felling all host trees within a 500-m-radius clear-cut area around any infested tree (European Commission, 2012, 2018). In a modelling study, Robinet et al. (2020) found that a 500-m-wide clear-cut would reduce PWN transmission by only 0.6%–11.5% and would not stop the spread of PWN in a large area with pines. Current measures have indeed been insufficient to halt the spread of PWN in Portugal and Spain (Sousa et al., 2012). According to Robinet et al. (2020), eradication would require a cutting radius of 14–38 km around infested trees, but this would be ecologically and economically unacceptable.

While clear-cutting is found to be ineffective for eradication, the costs of this strategy are high in terms of healthy trees lost. There is therefore a need to explore alternatives. A possible strategy to eradicate PWN would be selective cutting on a tree by tree basis, that is only removing the PWN-infested trees (Kwon et al., 2011), which then would have to be actively searched by intensive surveillance to ensure timely detection before spread occurs (Robinet et al., 2020). This approach may limit epidemic spread at lower cost if the costs of intensive survey and tree by tree selective cutting are less than the costs of lost healthy trees with clear-cutting. The cost-effectiveness and feasibility of tree by tree selective cutting have not been assessed.

Currently, in Europe, survey for trees with wilting symptoms is carried out by road surveillance. Once declining trees are detected, wood samples are tested for PWN in the lab (Mariette et al., 2023). New technology for remote sensing combined with image analysis may provide options for improved detection of symptomatic trees (Qin et al., 2021). Alternatively, the presence of PWN-infested trees in an area may be inferred from pheromone trapping of *M. galloprovincialis*, and testing with molecular markers to determine whether beetles are carrying PWN (Sanchez-Husillos et al., 2015). Thus, emerging technologies may facilitate replacing clear-cutting with

more targeted strategies, based on intensive surveillance and selective tree removal.

It is difficult to test alternative PWN control strategies in the field because of the costs of large scale experiments as well as EU regulations (Sun et al., 2023a). Hence, we used modelling to compare the cost-effectiveness of the two strategies: (1) the statutory 500-m-radius clear-cutting and (2) selective cutting on a tree by tree basis. Both strategies were evaluated in combination with three surveillance strategies: (i) visual ground surveillance, (ii) visual ground surveillance combined with trap networks and (iii) aerial surveillance.

We simulated PWN spread within a 20 km × 20 km contiguous maritime pine area, using an individual-based model for the movement of its vector *M. galloprovincialis* and its transmission of PWN. The research question was: Which strategy, clear-cutting or selective cutting, is the most cost-effective for controlling PWN, and how is this affected by surveillance method and symptom visibility? Our hypotheses were: (1) selective cutting is more cost-effective than clear-cutting because it reduces the costs associated with cutting healthy trees provided sufficient infested trees can be detected; and (2) higher symptom visibility and more intensive surveillance increase eradication success for both strategies.

2 | METHODS

2.1 | Simulation

We simulated a 20 km × 20 km area containing 4,004,001 mature maritime pine (*P. pinaster*) trees, evenly spaced at 10 m intervals, representative of 'Les Landes de Gascogne' (the largest planted forest in Europe, located in southwestern France). All trees were assumed healthy at the beginning of May. To simulate disease spread, we used an individual-based model for the introduction of the disease and its spread by introduced and resident adults of the native vector *M. galloprovincialis*. Resident adults are hereafter referred to as 'patrolling beetles' to distinguish them from the introduced beetles. Different strategies for surveillance and eradication were implemented in combination with different assumptions on the introduction process. The cost and effectiveness of each scenario in each modality were then calculated. Details for each component are provided below.

2.2 | PWN–vector–host system

2.2.1 | Initial inoculum

We distinguished three modalities for the introduction of PWN in a healthy forest (Methods S1). The three modalities of introduction differed in the number of initial PWN-carrying beetles and the probability that the resulting infested trees would subsequently be colonized by patrolling beetles already present in the area. These patrolling beetles are attracted to lay eggs on trees in which the

introduced PWN-carrying beetles previously laid their eggs, and the offspring of both the introduced beetles and patrolling beetles attracted to the PWN-infested trees could thus become PWN-carrying beetles. In the main body of the paper, we present the results for a single log introduced into the 20 km × 20 km study area. From this log, an average of 50.5 beetles emerge following a uniform distribution from 1 to 100 beetles (so called 'baseline'), 91% of which carry PWN (Naves et al., 2006). Further description of modalities of introduction is given in Methods S1.

2.2.2 | Life cycle of the vector

Adults of *M. galloprovincialis* begin to emerge in early May, with emergence peaking in mid-July and continuing until early September (Naves et al., 2008). After emergence, beetles feed on green shoots of healthy pine trees to mature. They typically remain on a tree for about 1 day before moving to another (Robinet et al., 2020). Females start oviposition between 20 and 53 days after emergence (Naves, Camacho, et al., 2007; Robinet et al., 2020), preferring weakened or recently dead trees for egg laying (Schröder et al., 2009). Females generally resume flight 5 days after oviposition. Once reproduction is completed, adults gradually die off by October. The larvae complete the larval and pupal stages inside the wood until the next generation of adults emerge from May to September of the following year (Naves, Camacho, et al., 2007; Naves, De Sousa, & Quartau, 2007).

We simulated the flight season of *M. galloprovincialis*, which extends from May to October (Figure 1), during which adults disperse, feed, mate and lay eggs. A detailed parameter description of vector dispersal can be found in Methods S2.

2.2.3 | PWN transmission

Adult beetles transport the nematodes within their tracheae from the infested trees from which they emerged to healthy trees. The flight period is from May–October. There are two principal pathways of transmitting the nematode to trees: via feeding wounds on the pine shoots and twigs of healthy trees by adult beetles during maturation feeding, and via oviposition wounds made by females on the trunk of decaying trees (Schröder et al., 2009). Successful overwintering larvae in PWN-infested trees could become an infection source of the next year. A detailed description of PWN transmission and the parameters of transmission can be found in Methods S2.

2.2.4 | Host

When a tree becomes infested by PWN, it stays asymptomatic for a certain period (incubation time). In the most favourable areas for PWN, pine trees show symptoms of decline about 30 days after inoculation by PWN (University of California, 2023; Zhao et al., 2008). It was assumed that trees infested with PWN remained alive during the 6-month simulation period (May to October). Since trees get infested over the course of 5 months, not all infested trees show symptoms simultaneously. Given that symptom expression is a condition for detection, we explored how the timing of surveillance affects the performance of the surveillance strategies. We assumed a range of symptom expression, from 100% to 20% with steps of 20% (Figure 1). The symptomatic trees are randomly selected among the infested trees. See Methods S3 for more details.
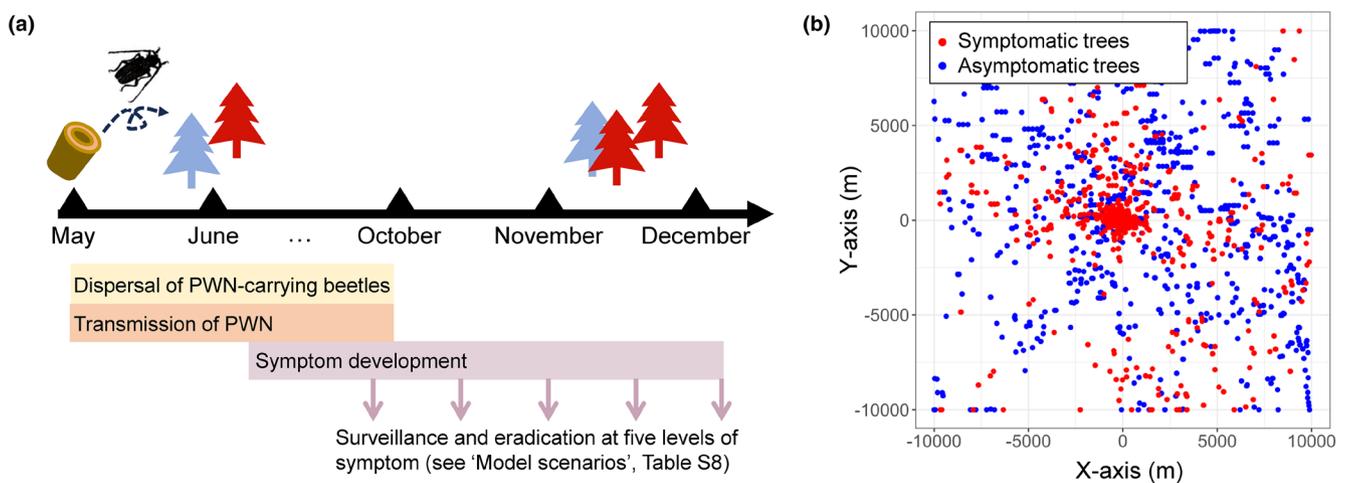

FIGURE 1 Conceptual timeline illustrating the dispersal of pine wood nematode (PWN)-carrying beetles from an infested log, subsequent transmission of PWN, symptom development in host trees and timing of surveillance and eradication efforts (a). An example of the distribution of PWN-infested symptomatic trees and asymptomatic trees in a 20 km × 20 km pine forest (b). This example is based on a single simulation with 36 initial emerging beetles, in which 50% of the infested trees are symptomatic at the time of surveillance. Red and blue trees in (a) represent symptomatic and asymptomatic trees, respectively. Black triangles on the horizontal axis in (a) represent the beginning of each month. Details of the modelling algorithm are in Figure S1.

2.3 | Surveillance

We modelled three surveillance methods: (i) visual ground surveillance from vehicles, (ii) visual ground surveillance in combination with vector trap networks and (iii) aerial surveillance. Visual ground surveillance and aerial surveillance were assumed to be conducted after the end of the beetle flight season, that is in October or later (Figure 1a).

2.3.1 | Visual ground surveillance

We implemented a square grid of 40 roads running north–south and 40 roads running east–west, each road at 0.5 km distance from the nearest parallel road, representing the road density and distribution in the study area. The number of roads to be surveyed was randomly selected, ranging from 10 to 40 in increments of 10 in each direction. The parameters regarding visual ground surveillance are listed in Methods S4.1.

2.3.2 | Ground surveillance combined with trap networks

We assumed that 25 traps were homogenously distributed in our 400 km^2 model landscape, consistent with a density of one trap per 16 km^2 (Nunes et al., 2021). Traps were installed in May, at the start of beetle dispersal, with monthly beetle collection and pheromone replacement until October. *Monochamus* beetles would be collected from the traps and tested on the presence of PWN in the laboratory (Nunes et al., 2021). At the end of the simulated dispersal, we calculated the theoretical origin of the infested beetles using a weighted barycenter method, where the coordinates of the traps were weighted by the number of PWN-infested beetles caught in each trap (Nunes et al., 2021). Visual ground surveillance was then simulated around this inferred source location. The symptomatic tree nearest this location was then removed as being the source of the nematiferous beetles. The parameters of trap density and trap efficiency are described in Methods S4.2.

2.3.3 | Aerial surveillance

Declining trees can be detected on images that are captured by cameras mounted on an aircraft. Surveillance efficiency is defined as the probability that a declining tree is detected during a survey. We used an aerial surveillance efficiency of 0.91 per air flight as the base efficiency following Jactel et al. (2023) and Qin et al. (2021). To take into account the variation of aerial performance in practice, we tested a range of aerial surveillance efficiencies that were lower than 0.91, that is 0.71 and 0.51 per flight. We considered one, two and three subsequent air flights assuming the same efficiency per flight and the same percentage of symptomatic trees during the three flights. The detection efficiency of aerial surveillance is described in Methods S4.3.

2.4 | Wood sampling

After the detection of declining trees by visual ground or aerial surveillance, wood samples are taken from the trees to confirm the presence of PWN by DNA tests in the laboratory, and exclude, for instance, that symptoms are caused by bark beetles or other pathogens.

2.5 | Eradication strategies

Two eradication strategies, clear-cutting and selective cutting, were compared. Following the EU regulations, in the clear-cutting scenario, a 500-m radius clear-cutting zone was delimited around every detected declining and confirmed PWN-infested tree, and all host trees (pines) within the clear-cutting zone were cut and chipped. In selective cutting, only the detected declining and confirmed PWN-infested pine trees were cut and chipped.

2.6 | Cost-effectiveness analysis

We considered surveillance costs, wood sampling costs, eradication costs (logging and chipping) and revenue loss in the overall cost assessment (Table 1).

2.6.1 | Surveillance methods

Visual ground surveillance
The costs of visual ground surveillance comprise costs for vehicle, labour and daily allowance costs. The costs ranged from €1491 for sampling 20 roads to €5930 for sampling 80 roads in the study area (Table 1; Methods S4.4).

Aerial surveillance
The costs of aerial surveillance comprised the costs of flights over the study area and the costs for the analysis and storage of the images taken. These surveillance costs corresponded to a total amount of €80,000 per air flight (Table 1).

Pheromone trapping
The costs of trap surveillance comprise the costs of traps and lures, the labour and equipment costs related to trap installation and checking, and the costs of analysing the collected samples in the lab. The total costs of trap surveillance were €16,505 (Table 1; Methods S4.4).

2.6.2 | Wood sampling

Costs of wood sampling and testing were calculated, including costs of labour, equipment and materials. Total costs for sampling and testing were estimated at €57 per wood sample (Table 1; Methods S4.4). The number of wood samples depended on the

TABLE 1 Input parameters for calculating the costs of surveillance and management activities related to pine wood nematode. Values were provided by experts from the French Forest Health Department and INRAE. The equations used to estimate costs are provided in Methods S4.4.

Parameter description	Value	Unit
Visual surveillance		
Vehicle cost per kilometer (fuel cost, maintenance cost)	0.4	€/km
Daily allowance (ex: meal expenses of field workers)	17	€/day
Labour cost per hour	64	€/h
Speed of ground surveillance	20	km/h
Max distance traveled per day	160	km/day
Number of roads sampled in each direction	[10–40]	—
Length of a single road	20	km
Aerial surveillance		
Flight over 20 km × 20 km ~10 days timespan per flight	25,000	€/flight
Image analysis for 20 km × 20 km (flight day)	50,000	€/flight
Data storage in the cloud	5000	€/flight
Trap networks		
Price of a pheromone trap for *Monochamus*	45	€/trap
Cost of pheromone lures (Dispenser Galloprotect Pack) each time the lure is replaced	40	€/dispenser
Number of traps to be installed	25	—
Number of times the lure is replaced	4	—
Number of traps installed	10	day^{-1}
Number of traps with lures replaced each time the lure is replaced	15	day^{-1}
Working time	8	h/day
Daily allowance	17	€/day
Labour costs per hour	64	€/h
Costs of sending samples to the lab each time the lure is replaced	30	€/trap
Costs of PWN identification each time the lure is replaced	35	€/trap
Wood sampling		
Costs of sampling the wood of a declining tree	23	€/sample
Costs of DNA confirmation of tested wood sample	34	€/sample
Tree removal		
Logging	10	€/tree
Chipping	12	€/tree
Revenue loss		
Timber value (ready to be harvested)	60	€/tree

number of declining trees detected by surveillance (Table 1; Methods S4.4).

2.6.3 | Tree removal

The total costs of tree removal depend on the number of trees cut and the costs of logging and chipping a tree. Labour and equipment costs were accounted for. The costs for logging and chipping a tree were estimated at €22 (Table 1; Methods S4.4).

2.6.4 | Revenue loss

With clear-cutting, the opportunity costs (revenue foregone) of cut healthy trees were accounted for. The timber value of a healthy tree is €60 (Table 1; Methods S4.4). We assumed that the infested trees that have been logged and chipped have no value.

2.7 | Effectiveness

We used the yearly multiplication factor, also called the net reproductive number (R), as an indicator of the effectiveness of the eradication strategies in the long term (Heesterbeek, 2002). Eradication requires that $R < 1$. We calculated the yearly multiplication factor of the number of infested trees at the start of the beetles' second growing season, R_{cases}, to characterize the epidemic growth of PWN. We define R_{cases}:

$$R_{cases} = \frac{T_{inf,t=1}}{T_{inf,t=0}} \tag{1}$$

where $T_{inf,t=0}$ is the number of initially PWN-infested trees by initial PWN-carrying beetle at the start of the growing season of the first year (equal to 1; Methods S3) and $T_{inf,t=1}$ is the number of PWN-infested trees at the start of growing season of the second year. To analyse the contribution of patrolling beetles to R_{cases}, we also calculated R_{cases} assuming no PWN-carrying patrolling beetles are present (Figures S5 and S6). This estimate of R_{cases} is the number of trees infested with PWN by the offspring of the initial PWN-carrying beetles, divided by $T_{inf,t=0}$.

We calculated measures of sensitivity and specificity of each eradication strategy to characterize the proportion of infested trees removed (sensitivity) and the proportion of healthy trees retained (specificity). These proportions were calculated for the whole 20 km × 20 km forested area:

$$Sensitivity = \frac{Cut\ infested\ trees}{Total\ infested\ trees} \tag{2}$$

$$Specificity = \frac{Preserved\ healthy\ trees}{Total\ healthy\ trees} \tag{3}$$

2.8 | Model scenarios

A scenario was defined as a combination of the (1) eradication strategy (clear-cutting or selective cutting); (2) the surveillance method (four different visual surveillance intensities, four visual surveillance + pheromone intensities and nine different aerial surveillance intensities); (3) the modality of introduction (three different modalities; Methods S1); and (4) the proportion of trees showing symptoms at the time of surveillance (100%, 80%, 60%, 40, 20%; Table S8). Thus factorially combining these four factors resulted in 510 scenarios. Additionally, we explored the consequences of several specific assumptions: (1) when surveillance is near-perfect, that is four air flights at 0.91 detection efficiency per air flight under the baseline of 1–100 initial emerging beetles for both strategies. This investigation resulted in 10 additional scenarios; (2) when we assumed no patrolling beetles would carry PWN, leading to 340 additional scenarios; (3) when the number of infested trees was lower (1% and 10% relative to the baseline) than that in the baseline of 1–100 initial emerging beetles, which resulted in 2416 ± 189 infested trees. This resulted in 340 additional scenarios. This scenario is relevant to check how robust our assessment is when disease spread and/or symptom development is slower than considered in the baseline. Each scenario was simulated with 50 replicates. This study involved only modelling and secondary data analysis and did not require ethical approval or permits.

3 | RESULTS

3.1 | Cost and effectiveness of the two eradication strategies

Clear-cutting or selective cutting combined with ground survey did not reduce R_{cases} below one in any of the tested scenarios, indicating eradication is not possible with ground survey (Figure 2a; Figure S2i). In contrast, clear-cutting and selective cutting in combination with intensive aerial surveillance reduced R_{cases} below one if all the infested trees showed symptoms at the time of survey (Figure 2a). To achieve this, clear-cutting needed to be combined with at least two flights with 0.91 detection efficiency, while for selective cutting four or more flights with 0.91 detection efficiency were needed (Figure 2a; Figure S2ia). Clear-cutting and selective cutting reduced R_{cases} below one when not all trees were symptomatic (at 75% and 98% for clear-cutting and selective cutting, respectively) only when intensive aerial surveillance was performed (two air flights, 0.91 detection efficiency) and no native patrolling beetles carrying PWN were present (Figures S5ia and S12). Thus, only under these highly restrictive conditions could eradication be achieved.

When comparing the two cutting strategies under the cheapest surveillance strategies that still achieved eradication, clear-cutting was far more expensive. Clear-cutting combined with two air flights cost about €237.8 million (Figure 2b), which was on average 198 times more costly than selective cutting combined with

four air flights (~€1.2 million). When at least 60% of infested trees were symptomatic at the time of survey, selective cutting with aerial surveillance achieved a similar level of effectiveness as the standing practice of clear-cutting with visual ground surveillance, but at total costs that were on average 86 times lower (€74.9 million for clear-cutting and €0.87 million for selective cutting; Figure S2ia–c). If less than 60% of the infested trees showed symptoms, selective cutting with aerial surveillance achieved a similar level of effectiveness as clear-cutting only if clear-cutting was combined with low intensity visual surveillance (Figure S2id,e).

Clear-cutting always led to lower R_{cases} (Figure S2ia–e) and lower sensitivity (Figure S2iia–e) than selective cutting for the same surveillance method. However, selective cutting resulted in a higher specificity and lower costs (Figure S2iiia–e). The other two modalities for introduction (Figures S3 and S4) and two lower levels of infested trees (Figures S7 and S8) led to qualitatively the same conclusions.

3.2 | Effect of the two eradication strategies on the number of cut trees

In the baseline of 1–100 initial emerging beetles, on average 2416 trees became infested. Clear-cutting removed substantially more trees, including both infested and healthy trees, than selective cutting at the same intensity of surveillance (Figure 3). For instance clear-cutting removed on average 2056 infested trees and missed 15% of the infested trees (360 out of 2416) if ground surveillance was done when all PWN-infested trees showed wilt symptoms. Under the same assumptions, selective cutting cut on average 694 infested trees, while missing 71% of the infested trees (1722 out of 2416) (Figure 3). Therefore, selective cutting left more infested trees than clear-cutting. On the other hand, clear-cutting with visual ground surveillance resulted in an average of ~1.8 million cut trees (SE ±111,417) (that is 3% of all trees) of which only 0.1% were infested (~1800 on average). Under selective cutting, no healthy trees were removed. Scenarios with other surveillance methods (Figure 3), other modalities for introduction (Tables S9–S11) and two lower levels of infested trees (Tables S21–S23) led to qualitatively similar conclusions. Therefore, selective cutting in combination with conventional ground surveillance saved a lot of healthy trees but resulted in poor control.

3.3 | Efficiency of surveillance methods

Aerial surveillance was much more efficient in detecting infested trees than conventional ground surveillance (Figure 4). With the baseline of 1–100 initial emerging beetles and surveillance when all PWN-infested trees showed wilt symptoms (Figure 4; Table S9), visual ground surveillance detected on average 19% of the infested trees (448 out of 2416), ranging from 8% (191 ± 16) to 29% (694 ± 54), depending on the intensity of visual ground surveillance (10–40 roads surveyed in each north–south and east–west direction). Including
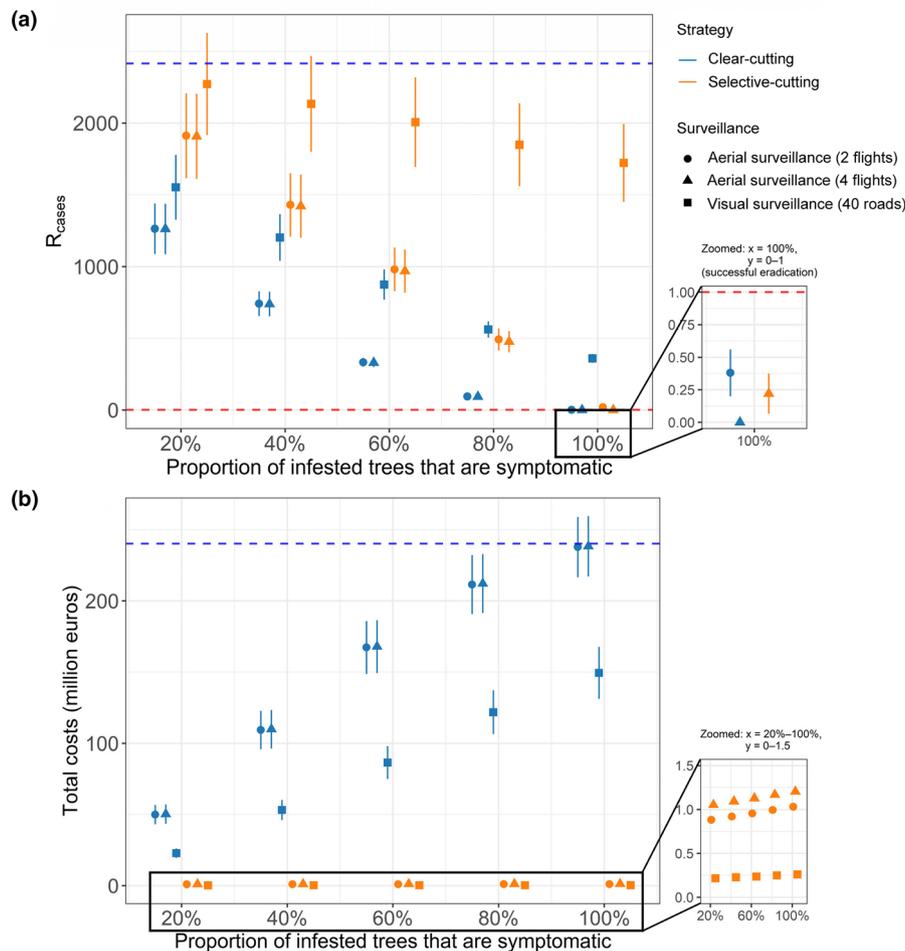
FIGURE 2 Relationships between the proportion of infested trees that are symptomatic at the time of surveillance and R_{cases} (a) and total costs of control (million euros) (b). The evaluated control strategies are based on standing practice of clear-cutting with visual ground surveillance and the alternative selective cutting with intensified aerial surveillance in the presence of patrolling beetles. R_{cases} represents the yearly multiplication factor of pine wood nematode (PWN)-infested trees. Symbols represent the mean of 50 simulations, which are jittered on the x-axis to improve visibility. Error bars represent confidence intervals of the mean for 50 simulations. The dashed orange line in (a) represents $R_{cases}=1$, below which eradication is achieved. The dashed blue line in (a) represents R_{cases} without management while the dashed blue line in (b) represents the timber value of the whole forest. The (a) inset zooms in on the point at $x=100\%$ to indicate the scenarios when eradication is successful ($y=0-1$), and the (b) inset zooms in on the low-cost range ($y=0-1.5$) to make costs between scenarios clearer. Results for other scenarios are presented in Figure S2.

trap networks did not help detect more infested trees (Figure 4). In contrast, aerial surveillance detected on average 85% of the infested trees (2056 out of 2416) across detection efficiencies of 0.51, 0.71 and 0.91 per flight and different numbers of flights, ranging from 51% (1233±96) to 100% (2416±189) (Table S11).

3.4 | Relevance of cost components within the two strategies

Selective cutting with intensive aerial surveillance would have significantly smaller costs than the standing practice of clear-cutting with ground surveillance for similar R_{cases} when eradication is not feasible and the objective is containment (Table 2). Revenue loss represented on average 73% of the total costs across surveillance methods with clear-cutting, whereas revenue loss due to lost trees was negligible

with selective cutting (Table 2; Tables S12–S20). Additionally, total costs were substantially higher with clear-cutting than with selective cutting (Table 2). For selective cutting, wood sampling costs constituted a large proportion of the total cost (on average 83% versus 0.5% in clear-cutting) (Table 2; Tables S12–S20). The other two modalities of introduction led to qualitatively the same conclusions (Tables S24–S29).

4 | DISCUSSION

The results of this study show that both clear-cutting and selective cutting are effective in eradicating PWN ($R_{cases} <1$) when intensive aerial surveillance is used and when 100% of infested trees show symptoms at the time of surveillance. Selective cutting required more surveillance flights than clear-cutting to achieve eradication
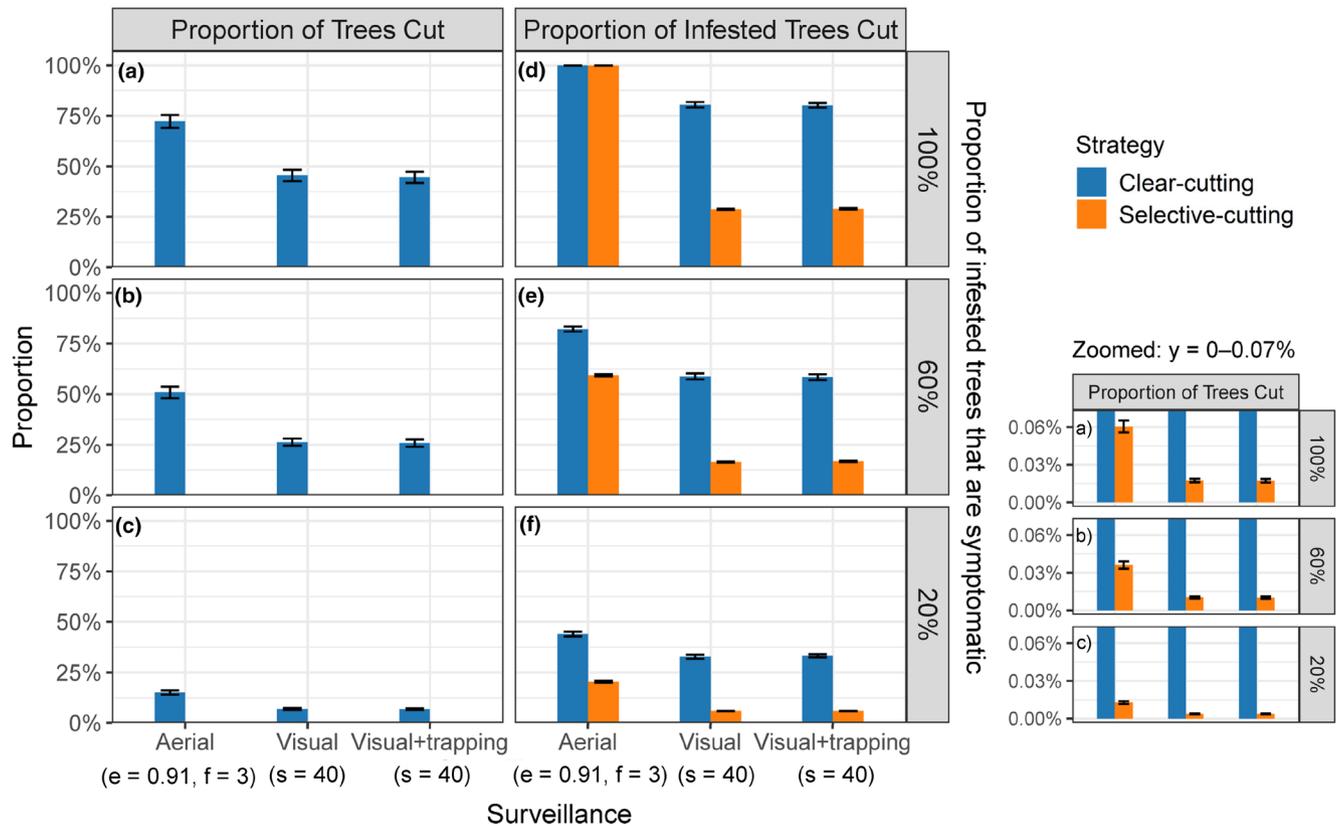
FIGURE 3 Proportion of trees cut (a–c) and proportion of infested trees cut (d–f) in clear-cutting (*blue bars*) and selective cutting (*orange bars*) when using aerial surveillance (leftmost two bars in each panel), visual ground surveillance (middle two bars in each panel) and visual ground surveillance combined with trap networks (rightmost two bars in each panel) when 100% (a, d), 60% (b, e) or 20% (c, f) of the infested trees are symptomatic. The zoomed panels on the right highlight values from the main plots (panels a–c) that are extremely small (close to 0%). This baseline simulates 1–100 initial emerging beetles, resulting in an average of 2416 (SE ±189) infested trees out of 4,004,001 trees in the forest at the time of survey. Scenarios with ground surveillance are shown for $s=40$, representing 40 roads surveyed in each north–south and east–west direction. Aerial detection efficiency was $e=0.91$, and $f=3$ flights were conducted, resulting in overall efficiency of 0.999 ($1-0.91^3$), that is about one in 1000 infested trees would be missed. *Bars* represent the average value ± standard error based on 50 simulations per scenario. Results for other intensities of surveillance, modalities for introduction and lower levels of infested trees are presented in Tables S9–S11 and S21–S23.

(four versus two, based on the introduction of a single infested log). It thus doubled the costs of surveillance flights but reduced total costs of control approximately 200-fold by avoiding the removal of a large number of healthy trees. Eradication was not achieved even if only a small proportion of trees did not show symptoms at the time of survey. Selective cutting with aerial surveillance achieved a given level of effectiveness at approximately 86-fold lower costs on average than the standing practice of clear-cutting with visual ground surveillance if at least 60% of infested trees showed symptoms at the time of survey.

4.1 | Effectiveness

Our results indicate that, under the current PWN regulation (European Commission, 2012, 2018) of a 500-m-radius clear-cutting zone, eradication is not feasible in a large landscape of pine forest plantations (e.g. 20 km × 20 km) if surveillance is only done on the ground, by visual inspection alone or combined with pheromone trapping of the vector. In these cases, R_{cases} always exceeds one, even if 100% of the infested trees show symptoms (Figure 2), due to the difficulty of finding all symptomatic trees by ground survey. In contrast, repeated aerial surveillance when 100% of infested trees are symptomatic, would lead to R_{cases} below one for both strategies. However, assuming that 100% of infested trees are symptomatic at the time of surveillance and before they have become a source of new infection in the next growing season is likely unrealistic (Carrasquinho et al., 2018; Soliman et al., 2011). Hence, aiming for containment of PWN may be more realistic than aiming for complete eradication. But this can be achieved by selective cutting, according to the simulations shown, without the dramatic impacts that clear-cutting has.

The multiplication factor of the number of cases of PWN in the absence of control results in a very high requirement for survey effectiveness to reach eradication of PWN, which is then nearly impossible. The high multiplication factor is due to the presence
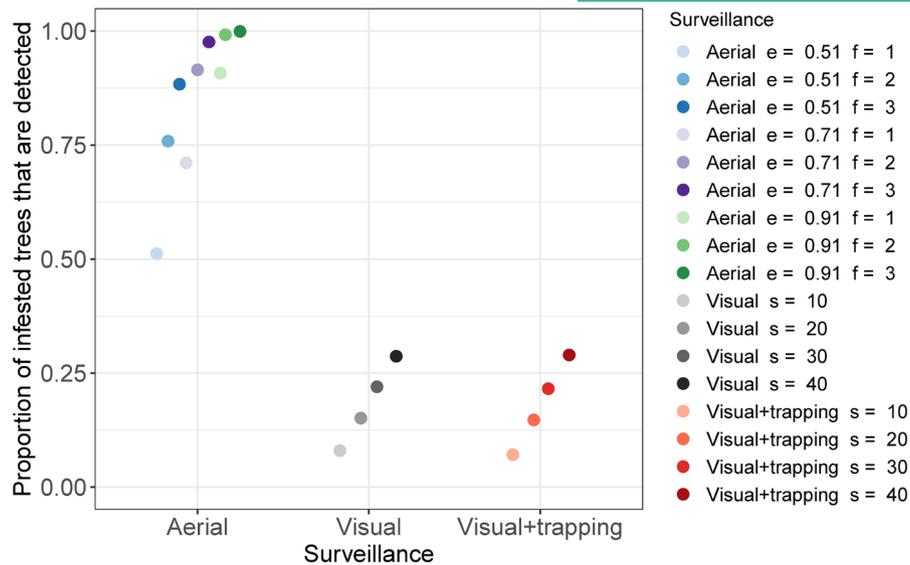
FIGURE 4 Proportion of detected infested trees (y-axis) in relation to surveillance method (x-axis). Circles (jittered along the x-axis) represent the mean of 50 simulations. Confidence intervals of the mean from 50 simulations are smaller than the markers and not visible. e indicates aerial detection efficiency per flight, f represents the number of air flights, and s indicates the number of roads sampled in each north–south and east–west direction.

TABLE 2 Cost components for the evaluated control strategies.

	CC + visual	SC + aerial	SC + aerial	SC + aerial
	$s = 40$	$e = 0.91, f = 1$	$e = 0.91, f = 2$	$e = 0.91, f = 3$
R_{cases}	561 ± 28	650 ± 51	492 ± 38	477 ± 37
Surveillance costs	$0.059^{[a]}$	$0.83^{[a]}$	$1.66^{[a]}$	$2.49^{[a]}$
Total wood sampling costs	2.30 ± 0.03	7.19 ± 0.08	7.85 ± 0.08	7.91 ± 0.08
Total eradication costs	326 ± 21	0.39 ± 0.03	0.42 ± 0.03	0.43 ± 0.03
Total revenue loss	889 ± 56	0	0	0
Total costs	1218 ± 77	8.41 ± 0.11	9.93 ± 0.12	10.82 ± 0.12

Note: This analysis is based on standing practice of clear-cutting (CC) with visual ground surveillance and the alternative strategy of selective cutting (SC) with intensified aerial surveillance when 80% of the infested trees are symptomatic. This comparison is intended to identify the most cost-effective strategy under similar levels of R_{cases}. The numbers represent mean costs $\pm$ standard error in 0.1 million euros. e indicates aerial detection efficiency per flight, f represents the number of air flights and s indicates the number of roads sampled in each north–south and east–west direction.
[a]Constant value; no variation across replicates.

of native patrolling beetles. As soon as PWN is introduced into an area, the resulting declining infested trees attract egg laying by native patrolling beetles. Their offspring become infested with PWN and contribute to the spread of PWN. The contribution of patrolling beetles accounts for 97% of R_{cases} according to our simulations and the patrolling beetles hence can be held responsible for the high reproductive factor of the disease in the absence of management. Our results indicate that without patrolling beetles, clear-cutting with aerial surveillance could eradicate PWN already if at least 75% of infested trees were symptomatic, while selective cutting with aerial surveillance would require at least 98% of the infested trees to show symptoms to achieve eradication (Figures S5i and S12). Therefore, eradicating PWN may be possible only when native patrolling beetles are at very low density, so that not every infested

tree infested by initial PWN-carrying beetles would attract native patrolling beetles. When the patrolling beetle population is at high density, as in southwestern France, and middle and eastern Spain (EPPO, 2021; GBIF, 2025), both strategies should be accompanied by additional measures to control the beetle population. However, effective control is hardly feasible. For example, mass trapping is not recommended as the trapping rate is about 2% and thus not efficient enough to reduce beetle population density (Jactel et al., 2019). Their main value would lie in detecting initial sources of infection: when several traps capture beetles carrying PWN, the location of infested trees may be identified (Nunes et al., 2021). This makes trap networks more useful in colder regions where the incubation period is long and visual or aerial surveillance may fail to detect symptomatic trees.

The effectiveness of control increases as more infested trees show symptoms of wilting at the time of surveillance as more sources of spread may be removed before the next generation of beetles emerges. This highlights the need for precise timing of surveillance because when applied too early one would miss infested not yet symptomatic trees, while delaying too much could mean that PWN-carrying beetles have already emerged from the infested trees and started spreading the disease further. Available information suggests that most trees show symptoms before the next episode of spread. In southwest France, 90%–95% of the infested trees would show wilting symptoms by December and the remaining 5%—10% would be symptomatic the next spring before the dispersal of newly emerging PWN-carrying beetles (Carrasquinho et al., 2018; Gruffudd et al., 2016; Soliman et al., 2011). This provides a window of opportunity for intensive surveillance, preferably at multiple times, combined with selective cutting and hence effective containment of the epidemic. In principle, survey should be late enough to allow all infested trees to show symptoms, but early enough to allow appropriate action when such trees are found. The more resources are available for logging and chipping infested trees, the later the survey might be conducted, and the more effective the control would be. But the risk of early emergence of some beetles in the spring needs to be considered.

When few infested trees show symptoms before the next beetle season, for example when PWN is introduced into cool areas in which symptom expression is slow (Gruffudd et al., 2016), or when detection resources are insufficient, clear-cutting may still be an option. Clear-cutting consistently yielded lower R_{cases} and higher sensitivity (proportion of infested trees that is removed) than selective cutting for the same surveillance intensity, as it removes asymptomatic trees surrounding detected infestations thus avoiding the necessity to detect all symptomatic trees. This advantage of clear-cutting was slightly inflated as we used reflecting boundaries in the simulations, leading to some clustering of infested trees near the forest edge (Figure 1b). Clear-cutting is effective as long as infested trees are clustered in the landscape (Figure 1b; Figures S10 and S11). Importantly, clear-cutting becomes less effective when the density of infested trees is lower as undetected trees are less likely to fall within the cutting radius (Figure S9). This suggests that, especially early on in the epidemic, selective cutting with enhanced surveillance is the preferred option.

A negative side-effect of clear-cutting that was not incorporated in this study is that clear-cutting in a large area will likely force beetles to fly longer distances looking for host trees (Nunes et al., 2021), reducing the potential benefit of clear-cutting. On the opposite, the existence of pine trees preserved by selective cutting, may enable a larger proportion of emerging insects to be retained on site (e.g. for maturation feeding) and thus could slow PWN spread.

4.2 | Cost-effectiveness

Cutting a large number of healthy trees implies enormous economic losses on market services (timber and non-timber forest products),

but also on non-market services (recreation, carbon sequestration, landscape, watershed protection, protection of biodiversity and soil erosion) (Lopes, 2013; Torres et al., 2021). For example, we estimated that clear-cutting in the 20 km × 20 km study area would release on average ~19 kilotons more carbon than selective cutting based on the difference in the number of cut healthy trees (1.3 million across all scenarios; Tables S9–S11) and carbon stored per tree (Schulz, 2023; Seidl et al., 2018). Clear-cutting would also cause an additional non-market loss of ~€2308 per hectare (Lopes, 2013). The high costs of clear-cutting in terms of revenue forgone and effects on ecosystem services imply that high investments are needed to improve detection and enable more selective cutting that would offset these costs (Robinet et al., 2020).

In this study, we assigned the costs of surveillance and wood sampling exclusively to PWN control. However, in practice, other pests could be detected when surveilling PWN. As the surveillance can potentially be shared with other forest health programs besides PWN control and serve as an early warning system, the estimated surveillance and wood sampling costs attributable to PWN control might be lower than was estimated here. If surveillance and wood sampling costs were not fully attributable to PWN control, this would further increase the relevance of improved detection and selective cutting because the costs of surveillance and wood sampling make up most of the costs in this strategy (97% of total costs) while they are minor cost items (<1% of total costs) in the clear-cutting strategy.

The assumption that trees remain alive throughout the simulation period is simplistic. Mortality may occur earlier in highly susceptible trees, especially when combined with other stressors. This could increase the detection probability, whether through ground surveys or remote sensing. Achieving higher detection probability would, in turn, reduce R_{cases} without affecting costs, thereby increasing the effectiveness of both control strategies.

Aircraft and satellites equipped with imaging technology represent the future of monitoring to survey PWN-infested forest. By combining them with deep learning (AI), the efficiency of detection can be high (Fedoniuk et al., 2025; Li et al., 2023; Luo et al., 2023; Ren et al., 2025). For example, a recent study utilizing high resolution earth observation satellite imagery achieved an accuracy exceeding 98% (Zhou et al., 2022). Unmanned Aerial Vehicles (UAVs) are also powerful tools; however, their utility for use over large areas depends on legislation. For instance, in France, UAVs may not be used out of sight of the operator. Therefore, we considered aircraft rather than drones because the latter would fly out of sight in our simulated landscape. In the long run, we expect that satellites will replace aircraft, which would greatly reduce costs (Zhou et al., 2022) and allow a more frequent surveillance of forested areas. Such technological progress would enhance the feasibility and economic benefit of surveillance with selective cutting.

Our analysis is broadly applicable to other invasive pests managed by clear-cutting, but details will differ. Therefore, similar studies might be useful for other pest-vector-plant or pest–plant systems to develop control methods that have less environmental impact

than clear-cutting. Such modelling studies may, for instance, be warranted for *Xylella fastidiosa*, *Aromia bungii*, *Fusarium circinatum*, *Phytophthora ramorum*, *Anoplophora glabripennis* and *Anoplophora chinensis* in Europe (Branco et al., 2021), *Plum pox virus* and *P. ramorum* in America (Gougherty et al., 2015; Rizzo et al., 2005), Citrus canker in Australia and South America (Sharma & Sharma, 2009) and Cocoa pod borer in Australia (Business Queensland, 2019). As such, there is huge scope for further studies on more targeted approaches for management of invasive forest pests to evaluate strategies that may replace current strategies that sometimes have dramatic environmental and economic costs.

5 | CONCLUSION AND OUTLOOK

In conclusion, this work demonstrates that (1) selective cutting can, similar to clear-cutting, eradicate PWN by using intensive aerial surveillance when 100% of infested trees are symptomatic; (2) Since it is unlikely that all infested trees show symptoms and are detected at time of surveillance, containment (i.e. slowing the spread of the pest) is a more realistic goal, especially in areas where native vector beetles are abundant; (3) aerial surveillance is more effective at detecting PWN than ground surveillance; (4) selective cutting is more cost-effective than clear-cutting for the similar level of effectiveness, as it saves the costs of cutting healthy trees. Overall, these results provide a basis for improved policies on PWN management to allow the more environmentally friendly selective cutting method.

AUTHOR CONTRIBUTIONS

Hongyu Sun and Christelle Robinet developed the model. Jacob C. Douma provided suggestions on data analysis and model structure. Monique Mourits contributed to the cost-effectiveness analysis. Manuela Branco and Hervé Jactel provided modelling parameter values and input on model design. Wopke van der Werf offered insights into indexing effectiveness and model simplification. Hongyu Sun analysed the data generated from the models and wrote the first draft of the manuscript. All authors contributed to revising the final manuscript.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Parameters used in the model for vector dispersal and PWN transmission.

Table S2. Model parameters for simulating surveillance and management.

Table S3. Input parameters for calculating the costs of visual surveillance.

Table S4. Input parameters for calculating the costs of aerial surveillance.

Table S5. Input parameters for calculating the costs for surveillance with trap networks.

Table S6. Input parameters for calculating the costs of wood sampling.

Table S7. Input parameters for calculating the costs of tree removal.

Table S8. Scenarios for PWN management.

Figure S1. Conceptual framework of modelling approach.

Figures S2–S4. Costs and effectiveness in the presence of patrolling beetles.

Figures S5 and S6. Costs and effectiveness in the absence of patrolling beetles.

Figures S7 and S8. Costs and effectiveness assuming fewer infested trees (1% or 10%) in the first modality of introduction.

Figure S9. Effects of the number of infested trees on the evaluation of the two strategies.

Figure S10. Proportion of infested trees in relation to their distance to the first infested tree assuming 1% or 10% of infested trees in the modality 1.

Figure S11. Spatial distribution of symptomatic trees and asymptomatic trees assuming 1% or 10% of infested trees in the modality 1.

Figure S12. R_{cases} in relation to the proportion of infested trees that are symptomatic when aerial surveillance is conducted with a detection efficiency 0.91 per flight and 2 flights, with modality 1 without PWN-carrying patrolling beetles present.

Methods S1. Three modalities for introduction.

Methods S2. Vector dispersal and PWN transmission.

Methods S3. Host.

Methods S4. Surveillance.

Tables S9–S11. Number of cut trees, and cut infested trees by visual ground surveillance, visual ground surveillance combined with trap networks and aerial surveillance.

Tables S12–S14. Cost components by the three surveillance in modality 1.

Tables S15–S17. Cost components by the three surveillance in modality 2.

Tables S18–S20. Cost components by the three surveillance in modality 3.

Tables S21–S23. Number of cut trees, and cut infested trees by the three surveillance assuming 1% or 10% of infested trees in modality 1.

Tables S24–S26. Cost components by the three surveillance assuming 1% of infested trees in modality 1.

Tables S27–S29. Cost components by the three surveillance assuming 10% of infested trees in modality 1.