On the management of non-native plant pest outbreaks in the European Union

Hongyu Sun

Propositions

1. The management of non-native plant pest outbreaks has not received the level of scientific attention it deserves.
   (this thesis)
2. Delimitation of outbreaks is imperfect by design.
   (this thesis)
3. New energy vehicles are not sustainable when considering their entire life cycle.
4. The iterative nature of scientific work interferes with finishing on time.
5. Nervousness on stage is a result of evolution.
6. The most fundamental way to combat loneliness is to learn to be alone.

Propositions belonging to the thesis, entitled

On the management of non-native plant pest outbreaks in the European Union

Hongyu Sun

Wageningen, 7 October 2024

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Hongyu Sun

Thesis committee

Promotor

Dr W. van der Werf

Associate professor, Centre for Crop Systems Analysis

Wageningen University & Research

Co-promotor

Dr J.C. Douma

Assistant professor, Centre for Crop Systems Analysis

Wageningen University & Research

Other members

Prof. Dr Q. ten Bosch, Wageningen University & Research

Dr L. Hemerik, Wageningen University & Research

Dr J. Schans, Netherlands Food and Consumer Product Safety Authority, Utrecht

Dr S. Parnell, University of Warwick, UK

This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology & Resource Conservation.

On the management of non-native plant pest outbreaks in the European Union

Hongyu Sun

Thesis

submitted in fulfilment of the requirements for the degree of doctor

at Wageningen University

by the authority of the Rector Magnificus,

Prof. Dr C. Kroeze,

in the presence of the

Thesis Committee appointed by the Academic Board

to be defended in public

on Monday 7 October 2024

at 10:30 a.m. in the Omnia Auditorium.

Hongyu Sun
On the management of non-native plant pest outbreaks in the European Union,
194 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2024)
With references, with summary in English

ISBN: 978-94-6510-145-3
DOI: https://doi.org/10.18174/670692

Abstract

Non-native plant pests pose a significant threat to food production, ecosystem services, and biodiversity. Invasions of non-native plant pests are on the rise due to globalization and climate change. When entry cannot be prevented, non-native plant pests may establish in the invaded area and lead to an outbreak. Effective management of non-native plant pest outbreaks is critical. In this thesis I study how outbreaks are delimited and managed in practice and how this delimitation and management might be improved. In particular, I address the following three key research questions:

- Chapter 2: How are outbreaks of non-native plant pests managed in the European Union?
- Chapter 3: Which strategy is the most cost-effective for eradicating pine wood nematode: clear-cutting or tree-by-tree selective cutting?
- Chapter 4: Which strategy is the most effective for delimiting an infested zone: sampling inward or outward?

In Chapter 2, I reviewed 121 outbreak cases caused by 10 non-native insect species, 13 pathogen species, and 2 nematode species in the EU to understand how outbreaks of plant pests are managed in practice. Analysis revealed that an infested zone, buffer zone, and clear-cutting zone are commonly established, with the combination of an infested zone and a buffer zone being the most frequently implemented. This chapter highlights the need for evaluating existing zoning strategies and exploring more cost-effective alternatives by bioeconomic analysis.

In Chapter 3, I conducted a bioeconomic analysis using an individual-based model to compare the cost and effectiveness of regulatory 500-m-radius clear-cutting around infested trees with the alternative of only cutting infested trees on a tree-by-tree basis. The model simulated the spread and management of the pine wood nematode in a forest, and the cost-effectiveness of the management strategy was calculated based on the model's outcomes. I found that eradication could be achieved by both strategies only if intensive surveillance (aerial surveillance) was applied when all infested plants were symptomatic. When no less than 60% of the infested trees showed symptoms, tree-by-tree selective cutting with aerial surveillance allowed an average 88-fold reduction in costs compared to the standing practice of clear-cutting with visual ground surveillance, mainly by preserving healthy trees. Overall, tree-by-tree selective cutting is more cost-effective than clear-cutting.

In Chapter 4, I developed an individual-based model that combines pest spread and delimiting survey to compare the effectiveness and sampling effort of the inward and outward strategies when delimiting an infested zone. In the outward strategy, which is standing practice, sampling is done radiating out from the initial finding. In the inward strategy, sampling starts at a presumed frontier of the outbreak and either works inward or outward to map out the true frontier of the invasion. I found that both strategies for the parameter values tested achieved a high proportion of infested plants being within the delimited zone but did not delimit all infested plants. Which of the two strategies is better depends on the certainty about the estimate of the position of the frontier of the outbreak. The outward strategy is more cost-effective than the inward strategy if the position of the frontier is uncertain.

This thesis highlights existing gaps in the management of outbreaks of non-native plant pests. Modelling may be used as a tool to test outbreak management strategies in silico, but the management of outbreaks of plant pests has not drawn sufficient attention in science. Further research, requiring collaborative efforts between science, regulation, and practice, is essential to advance effective, resource-efficient and environmentally friendly management strategies. Implications of this thesis and specific suggestions for further improving outbreak management are provided in the general discussion (Chapter 5).

Keywords: Bioeconomic; eradication; European Union; outbreak management; plant pests; surveillance; zoning strategy

Table of contents

Chapter 1

General introduction

1.1 General background

Non-native plant pests threaten the health of plants that are important for securing food production, ecosystem services and biodiversity (Pyšek and Richardson 2010; Boyd et al. 2013; Cameron et al. 2016; Bellard et al. 2016; Branco et al. 2022). A non-native plant pest is "an alien species that by its establishment or spread has become injurious to plants, or that by risk analysis is shown to be potentially injurious to plants" (Table 1.1). The economic loss due to non-native plant pests is estimated at more than $US 25 billion annually in China (China News 2014). In 2007, the United States Department of Agriculture (USDA) allocated US$ 1.2 billion for management of non-native pest species, with approximately 22% directed towards early detection and rapid response activities (Yemshanov et al. 2017). It is estimated that non-native insects cost Europe at least US$ 3.6 billion per year in goods and services (Bradshaw et al. 2016). The invasion of non-native plant pests has accelerated, facilitated by globalization of trade and climate change (Hulme 2009; Ramsfield et al. 2016; Bonnamour et al. 2021; Singh et al. 2023). Considering the projected expansion of the human population to 9 billion by 2045 and the potential impact of non-native plant pests on food security and ecosystems, reducing losses from non-native plant pests is becoming increasingly important (MacLeod et al., 2010).

The invasion process of non-native plant pests is conceptually separated into four phases: entry, establishment, spread and impact (Fig. 1.1). In each phase, measures may be implemented. To prevent the entry of non-native plant pests, governments may impose phytosanitary measures, such as restricting movement of plants and plant products, or treatment requirements for traded plant products, such as fumigation (Fig. 1.1). However, these preventive measures do not completely block the movement of non-native species outside outbreak areas because phytosanitary measures are imperfect (White et al. 2017). For example, the number of non-native plant pest interceptions for the period 1995 – 2004 was 8,889 in Europe, with insects comprising the highest proportion at 76% (Roques and Auger-Rozenberg 2006). Fortunately, among those species that pass the border, only a minority of species become established and bring harm to the environment (Tobin et al. 2014, Fig. 1.1).

Once the prevention measures fail to prevent the entry of non-native plant pests, an outbreak might be detected just after the species has arrived into the new territory, has established or has spread (Fig. 1.1). In general, the International Plant Protection Convention (IPPC) defines an outbreak as "a recently detected pest population, including an incursion, or a sudden significant increase in an established pest population in an area" (Table 1.1). This definition of "outbreak" applies to both native and non-native plant pests, but in this thesis, I focus on outbreaks of non-native plant pests.

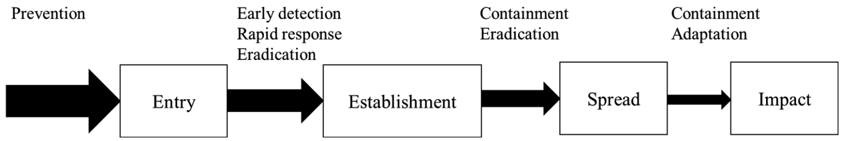

Fig. 1.1 Conceptual framework of four stages in an invasion process (boxes) and the corresponding management (text near arrows). The arrows represent the number of invasive species in each step (modified after Davis (2009)). An outbreak can be detected at any stage of the invasions after the pest enters

Table 1.1 Glossary of definitions based on or directly taken from FAO (2023)

Terminology	Definition
Containment	Application of phytosanitary measures in and around an infested area to prevent spread of a pest
Control	Suppression, containment or eradication of a pest population
Delimiting survey	Survey conducted to establish the boundaries of an area considered to be infested by or free from a pest
Eradication	Application of phytosanitary measures to eliminate a pest from an area
Non-native plant pest	An alien species that by its establishment or spread has become injurious to plants, or that by risk analysis is shown to be potentially injurious to plants
Pest entry	Movement of a pest into an area where it is not yet present, or present but not widely distributed and being officially controlled
Pest establishment	Perpetuation, for the foreseeable future, of a pest within an area after entry
Pest incursion	An isolated population of a pest recently detected in an area, not known to be established, but expected to survive for the immediate future
Pest introduction	The entry of a pest resulting in its establishment
Pest outbreak	A recently detected pest population, including an incursion
Pest spread	Expansion of the geographical distribution of a pest within an area
Suppression	The application of phytosanitary measures in an infested area to reduce pest populations
Surveillance	An official process which collects and records data on pest presence or absence by survey, monitoring or other procedures

Plant pests are managed with measures once an outbreak is detected. Eradication is always the initial goal, e.g. by destroying host plants in the infested area (Fig. 1.1). The goal might shift to containment if eradication is not feasible due to spread of the pest (Grice et al. 2020). Adaptation is the last strategy. It may be achieved by enhancing the resistance of host plants and releasing or augmenting natural parasites or predators (Pimentel 1991; Douglas 2018). However, it is not clear how outbreak measures are applied spatially.

1.2 Zoning strategies in outbreak management

When an outbreak is detected, its spatial extent is delimited by a National Plant Protection Organization (NPPO). The NPPO divides the area of and surrounding the outbreak into zones in which different measures are implemented to restrict the concerned organism within the delimited area, minimize the risk of the spread of the organism out of the delimited area, and to spatially allocate measures. Zoning strategies are applied to manage the outbreaks of both domesticated animal diseases and plant pests.

Animal diseases of non-native origin, such as swine fever or new strains of influenza, are characterized by outbreaks that prompt official control efforts to contain and eradicate the outbreak to prevent widespread harm. When an outbreak of an animal disease is detected (native or non-native), two main types of zones are established around the outbreak area: the exposed/infected zone, where infection of animals has been confirmed, and the surveillance zone, which surrounds the infected zone (USDA 2013). When aiming to contain a disease, in the infected zone, epidemiological investigation, biosecurity measures such as vaccination, and restricting movement of all animals, animal products, humans and vehicles are conducted (USDA 2013). However, when aiming to eradicate, in the infected zone, additional measures are implemented including killing all susceptible animals, and destroying animal products (European Union 2005). In the surveillance zone, measures are implemented such as tracing back of any infected animals, increasing awareness among animal health professionals, limiting the movement of all livestock, commerce and products out of this area, and restricting the public access to wildlife and animals (USDA 2013). For example, when an outbreak of Avian influenza was detected in the Netherlands in 2014, 150,000 animals were killed at the infected farm and all poultry and eggs were forbidden from being transported out of the Netherlands (EU Monitor 2014). Zoning strategies for animal diseases can be found in the literature (Farsang et al. 2013; Nickbakhsh et al. 2014; Lee et al. 2019). However, little information is available in the scientific literature on the principles of zoning for outbreak delimitation of plant pests.

Practical cases of how outbreaks of plant pests are managed in Europe can be found in the EPPO Global Database (EPPO 2021a). Those reports on the delimitation of zones are submitted by NPPOs based on their practices, where zoning is applied on a case-by-case basis. For example, in 2016, when *Xylella fastidiosa* was detected in Islas Baleares of Spain, a 100-m-radius infested zone and a 10-km-radius buffer zone were delimited (EPPO 2016). In the infested zone, all infested plants and host plants were burnt and the origin of the infestation was traced back. In the buffer zone, surveys were conducted and did not detect the bacterium (EPPO 2016). Therefore, the delimitation of plant pest outbreaks resembles that of animal disease outbreaks. Overall, the infested zone and buffer zone are often delimited following an outbreak of plant pests in practice. Additionally, a clear-cutting zone might be delimited with a radius around the detected infested plant or delimited infested zone. In this zone, all host plants are removed (European Commission 2012). However, the implementation of those zones varies between countries, between areas within countries, and over time. This variation in implementation reflects different ecological and socio-economic contexts, and also advances in insight gathered over time or from other places. There is a need for a scientific literature review of case-specific zoning strategies to identify principles of variation and pinpoint gaps in practical zoning strategies.

Strategies for delimiting zones are sometimes part of regulations of the EU. The EU regulates the zoning strategy of outbreaks of newly non-native plant pests depending on whether a new incursion is considered as an EU-wide threat or not. Depending on their presence and economic impact, non-native plant pests may be classified as either quarantine pests, or as regulated non-quarantine pests. The EU maintains measures related to plants and plant products to reduce the risk of introducing non-native plant pests to an acceptable level (European Union 2019). In this thesis, I analyze the literature and records in the EPPO Global Database concerning the plant pests listed in both the EPPO Global Dataset and the EU regulations. This is done to understand how zoning is practically implemented within the EU.

1.3 Importance of delimiting zones accurately

The determination of the sizes of zones is a key step following the decision on the type of zones to delimit. This is because making the size of delimited zones too small will allow pests to spread further, which contradicts the outbreak management goal of eradication or containment. Conversely, making the delimited zones larger than necessary to contain all the infested plants will result in a greater than necessary management effort and impact of the measures, leading to greater than necessary costs, both to authorities and to citizens. Zoning decisions during an outbreak balance different stakeholders' costs: stricter measures may reduce risks and thus lower costs for those outside the zone, but can increase costs inside the zone due to loss of valuable plants and decreased trade, often without compensation.

Accurately enclosing all infested plants within the infested zone is the basis for a zoning strategy. This is because the boundary of the infested zone determines the delimitation of other zones, e.g. buffer zone, thus affecting the spatial allocation of measures. In the current practice of delimiting outbreaks, a survey band is delimited and the surveyed area is enlarged with additional survey bands until no further subsequent detections are made (EFSA 2020). This is an "outward" strategy. This strategy can help practitioners conduct actions immediately but it may miss out infestations that are far from the focus. Alternatively, EFSA (2020) proposed that an infested zone may be delimited starting initially with a larger radius around the detection and then narrowed using survey bands, which could be called an "inward" strategy. In this approach, an initial guess of the size of the infested zone is made based on the spread distance of the pest since its introduction. This estimate is subsequently reduced as long as no detections are found, allowing for surveys to be conducted ahead of the frontier of the infestation. By doing so, more infested plants can be enclosed immediately. However, there is no study about which strategy outperforms in terms of the effectiveness of enclosing infested plants and sampling effort required.

1.4 Determination of the sizes of main zones

The determination of the sizes of the buffer zone and clear-cutting zone depends on many factors. When an outbreak is detected, the size of the delimited infested zone depends on the presence of the pest. The width of the buffer zone is based on the spread rate that is affected by the rate of reproduction and population growth of the pest, dispersal behavior of the pest or vector and local climate conditions (EPPO 2021b). Likewise, the radius of the clear-cutting is decided by the risk of transmission of the pest from the infested plants to the susceptible plants, and the acceptance of society (European Commission 2012). For example, the radius of the clear-cutting zone for eradicating the pine wood nematode is 500 meters (European Commission 2012). This radius could be adjusted to 100 meters if 500 meters are not accepted by society. Therefore, once the infested zone is delimited according to the presence of the pest, knowledge on the dispersal/spread of the pest is key to delimiting the clear-cutting and buffer zone. However, acquiring data on either dispersal or spread is not easy.

1.5 Challenges associated with acquiring data on pest dispersal and spread

When a non-native pest organism is first detected, the knowledge on the spread of the pest in the invaded area is lacking and it is challenging to obtain despite that this information drives decisions on the clear-cutting zone and buffer zone. Usually, approximate values are obtained by studying the dispersal of the pest or species with similar traits to the target pest in literature, combined with expert judgement (EPPO 2021b).

The dispersal of a pest is usually represented using a dispersal kernel, which is "a probability density function describing the distribution of the post-dispersal locations relatively to the source point" (Nathan et al., 2012). The dispersal kernel may be parameterized from field observations, e.g. mark release recapture studies, or laboratory measurements, e.g. with a flight mill (Carrasco et al. 2010; Nathan et al. 2012; Catton et al. 2014; David et al. 2014; Lopez et al. 2014; Etxebeste et al. 2016; Robinet et al. 2019; Bodino et al. 2020; GE et al. 2020; Hoddle et al. 2020; Antolinez et al. 2021; Dransfield et al. 2021). However, plant health risk assessments often encounter the challenge of lacking suitable data for estimating the dispersal kernel through literature review. In this case, expert knowledge elicitation (EKE) may be used to estimate the dispersal of the pest (James et al. 2010; Smith et al. 2012; EPPO 2021b). However, the impact of inaccuracies in expert knowledge on the effectiveness of zoning remains poorly understood. In my thesis, I take a first step and explore how uncertainty in estimates of critical parameters, specifically those underlying the radius of the initially infested zone, affects the performance of inward and outward strategies.

1.6 Use of modelling to evaluate the effectiveness of zoning strategies

To improve the effectiveness of current outbreak management strategies, scientific research is key. Especially modelling is a key tool as it can simulate the spatial and temporal dynamics of pest outbreaks and explore new control options. Spatial models encompass a broad spectrum, including metapopulation models, diffusion models, integrodifference equation models, and Neubert – Caswell models (integrodifference equation models including a structured population model), extending to spatially explicit individual-based models (Shea et al. 2000; Parry et al. 2006; Jongejans et al. 2008; Vinatier et al. 2012; Guichard et al. 2012; Rodrigues 2014; Rodríguez 2015; Lux 2018; Alexandridis et al. 2021). Individual-based models simulate the dynamics of ecosystems by modelling the behaviors and interactions of individual organisms. Individual-based models can incorporate a high level of detail regarding individual variability, and interactions with the environment and other organisms. Therefore, individual-based models offer an advantage when considering the complex interactions between plant pests, vectors (if they exist), and host plants.

Individual-based models are well-suited to determine the effectiveness of different zone widths or under different assumptions about the behavior of the pest (Carrasco et al. 2010; Robinet et al. 2020). As such, individual-based model simulation can help to assess the effectiveness and costs of outbreak management according to regulations and explore the room for improvement. For example, an individual-based model incorporating the dispersal and mortality of western corn rootworm indicated that increasing the EU regulatory focus zone from 1 km to 5 km, and safety zone from 5 km to 50 km is effective to eradicate western corn rootworm (Carrasco et al. 2010). An individual-based model that describes the interaction between the dispersal of the pine wood nematode vector and nematode transmission indicated that a 500-m-radius clear-cutting zone, as mandated by EU regulation, is insufficient to eradicate the pine wood nematode (EPPO 1999; de la Fuente et al. 2018; Robinet et al. 2020). To eradicate the pine wood nematode, the required radius of the clear-cutting shall be 14 – 38 km (Robinet et al., 2020). However, this radius may not be feasible in practice due to ethical and technical constraints. Instead of clear-cutting, an environmentally friendly alternative is needed to achieve eradication of PWN. Simulations can help to find such alternatives.

Integrating costs of detection, containment, and eradication measures in models offers the possibility to make an economic assessment of the performance of different management strategies. To incorporate the uncertainty in the invasion process and management strategies, stochasticity is added. This can be applied to both spatially explicit and implicit models (McCarthy et al. 2001; Cacho et al. 2006; Regan et al. 2006; Mehta et al. 2007; Tuomola et al. 2018). Given the complexity and uncertainty of interactions among pests, vectors, and host plants, as well as the implementation of measures in zones, I use stochastic individual-based models. Such models are suited to analyse pest outbreaks, surveillance, zone-based measures, and do bioeconomic analysis.

1.7 Objectives and research questions

My first objective is to clarify how zoning strategies for managing outbreaks of plant pests are implemented in practice, and to describe the variation in zoning strategies that exists across past outbreaks. This addresses the gap in knowledge regarding the implementation of zoning strategies in practice. The second objective is to compare the cost-effectiveness of a more environmentally friendly strategy of removing infested trees with the standard practice of clear-cutting around infested trees using the pine wood nematode as case study. The third objective is to evaluate different strategies for delimiting an infested zone.

Chapter 2 summarizes current practices of outbreak delimitation in the EU to describe the decision-making process at supra-national and national level for plant pests, the implementation of zoning strategies, the relationship between regulation and implementation of measures in practice, and the challenges and knowledge gaps in zoning strategies.

Chapter 3 compares the current mandatory clear-cutting strategy for eradicating the pine wood nematode with an alternative strategy that combines intensified surveillance with individual felling of infested trees, while preserving the healthy neighboring trees. I use an individual-based model incorporating biological interactions in the nematode-vector-host system, the surveillance methods, and clear-cutting or selective-cutting strategy, with economic analysis to explore which strategy is more cost-effective to eradicate the pine wood nematode.

Chapter 4 models two strategies for delimitation of the infested zone, inward and outward, to find out which strategy is more effective in enclosing infested plants with smaller effort of sampling. I develop a general individual-based model combing the spatial and temporal distribution of infested plants with the two strategies and use *X. fastidiosa* as an example for parameterization. Furthermore, I discuss the performance of two strategies when the EKE provides inaccurate estimates of the delimitation parameters.

Finally, Chapter 5 discuss the general findings of my research chapters. Here I first summarize main findings of the three research chapters. Second, I discuss the innovations in this thesis in the context of existing knowledge of zoning strategies. Third, I discuss the implications of my research for the management of outbreaks of plant pests in policy and practice. Then I list the limitations and indicate future research directions to further address the problems of zoning strategies. Finally, I give the main conclusions of my thesis.

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Chapter 2

Zoning strategies for managing outbreaks of non-native plant pests in the European Union: a review

Hongyu Sun [1], Jacob C. Douma [1], Martijn F. Schenk [2], Roel P. J. Potting [2], Donato Boscia [3], Antonio Vicent [4], Alan MacLeod [5], Wopke van der Werf [1]

[1] Centre for Crop Systems Analysis, Wageningen University and Research, P.O. Box 430, 6700 AK, Wageningen, The Netherlands

[2] Netherlands Food and Consumer Product Safety Authority (NVWA), P.O. Box 43006, 3540 AA, Utrecht, The Netherlands

[3] CNR, Istituto per la Protezione Sostenibile delle Piante (IPSP), Bari, Italy

[4] Centre de Protecció Vegetal i Biotecnologia, Institut Valencià d'Investigacions Agràries (IVIA), 46113, Moncada, Spain

[5] Department for Environment Food and Rural Affairs, Sand Hutton, York, YO41 1LZ, United Kingdom

This chapter has been published in Journal of Pest Science.

https://doi.org/10.1007/s10340-023-01591-y

Abstract

Managing outbreaks of non-native plant pests is key to preserving biodiversity and safeguarding crop production. Zoning strategies are applied by plant health authorities to tailor measures to the risk of spread in relation to distance from the outbreak epicentre and the biology of the pest. Here we synthesize information on outbreak management to evaluate the diversity and consistency of such approaches. We collected information on the zoning strategies of 121 outbreaks of 25 plant pests in the European Union (EU). According to the organism's presence and the measures applied, five zones were distinguished: an infested zone (83% of cases), a buffer zone (76%), a clear-cutting zone (28%), an eradication zone (1%) and a containment zone (1%). Infested zones and buffer zones were adjacent non-overlapping zones, while the clear-cutting zone, eradication zone or containment zone was within the infested zone or buffer zone. A combination of infested and buffer zones was used in 51% of recorded cases. Measures differed within different zones. Destruction of infested plants in the infested zone was done in 78% of the cases, while surveillance was always applied in the buffer zone. Regulation of an organism at EU level led to a convergence of zoning strategies applied by different member states. Regulations often prescribed the greatest widths used before regulations were issued. Further analyses are needed to explore the efficacy of different strategies including the costs of each strategy. Such analyses should combine insight from practice with bio-economic modelling.

Keywords Combination of zones, containment, eradication, phytosanitary measures, plant pests, widths of zones, zone diversity

2.1 Introduction

Non-native plant pests threaten plants that are important for ecosystem services and biodiversity and for agriculture. To prevent the entry of new plant pests, governments regulate trade with potential to introduce plant pests, e.g. by restricting imports of certain goods or by imposing phytosanitary requirements for traded plants, such as fumigation. However, these preventive measures do not completely prevent the arrival of new plant pests (Liebhold et al. 2012; Epanchin-Niell 2017), and thus, effort is also directed towards managing outbreaks of introduced or established plant pests with expected high impact (Barron et al. 2020). Here, we follow the definition of outbreak as used by the International Plant Protection Convention (IPPC) which is “a recently detected pest population, including an incursion, or a sudden significant increase of an established pest population in an area” (FAO 2021). Within this paper, we focus on outbreaks of non-native pests, i.e. those pests that have been newly introduced into an area.

Outbreak management needs to consider many aspects: what is effective given the biological properties of the plant pest and uncertainty in knowledge about these properties, what is required by the legal framework, what are the available resources to manage the outbreak and what is the social and geographical context in which the outbreak occurs (Ward 2016). In the European Union (EU), if a pest is not regulated at the EU level, a member state may manage a pest outbreak according to what is considered most appropriate. A non-regulated pest, i.e. a pest that is not explicitly mentioned in the EU plant health law (European Union 2019), does not need to be reported to supranational organizations. If a pest has an unacceptable economic impact, it may be regulated by the EU, resulting in a species specific legislation that specifies the required measures for surveillance and outbreak management, including the delimitation of zones, their widths and required control measures if an outbreak is detected (European Commission 2002, 2007, 2008a, b, 2018, 2019; European Union 2003, 2012a, 2015, 2016). For details regarding the legal framework for decision making of zoning strategies in the EU, we refer to Appendix S1 from Sun et al. (2023).

When outbreaks occur, the area around the findings may be divided into different zones to create clarity on which measures are applied where. Zones are delimited according to the presence of the pest in the area and are meant to isolate or separate populations of infested plants from populations of non-infested plants. The spread of a pest from an infested to a non-infested zone can be restrained by destroying infested or potentially infested host plants in the infested zone, and also by prohibiting movement of plant material from the infested zone to other zones. Furthermore, zoning allows measures to be limited to a specific zone, minimizing the impact of the measures. There is surprisingly little overview on zoning strategies in the domain of plant pests, except for some modelling literature which aims to evaluate the effectiveness of zones in case studies (Carrasco et al. 2010; White et al. 2017; Rimbaud et al. 2019; Robinet et al. 2020; Cendoya et al. 2022). There are also few published general guidance documents on zoning strategies for practitioners. Only recently, a guideline on the design and implementation of buffer zones was published (EPPO 2021a).

As a result, it is not well established for plant pests which type of zones are commonly used, what their widths are and which measures are commonly taken in each zone. It is therefore useful to make a synthesis of how zoning for management of outbreaks of plant pests is currently done in practice. In Europe, much information on the actual management of outbreaks of plant pests is described on a case-by-case basis in reports of plant protection organizations, such as the European and Mediterranean Plant Protection Organization (EPPO) and National Plant Protection Organizations (NPPOs), and published literature (MacLeod et al. 2004; Cannon et al. 2007; Vukadin 2010; Hérard and Maspero 2019; Eyre and Barbrook 2021). However, these reported zones are not always defined in a consistent way due to the occurrence of synonyms (different terms with the same meaning) and homonyms (a single term with multiple meanings). In outbreak reports, zones may be described implicitly by stating that zones were demarcated in accordance with the relevant EU legislation.

The aim of this paper is to provide a synthesis of how zoning is done in practice in the EU, and to identify potential targets for research to support evidence-based outbreak management. We focus in particular on the following questions: 1) What is the general outbreak management process for regulated plant pests? 2) Which zones are delimited and which combination of zones are used, and which terms are used, and which synonyms or homonyms are used for which zone? 3) What are the zone widths that are used and which measures are taken in various zones? 4) How do regulation and infestation size affect the zoning strategy? We answer these questions by reviewing the outbreak management reports provided by the EPPO Global Dataset, and by checking relevant EU regulations.

2.2 Methodology

First, we established a list of plant pests that could be used for our study. For early warning of emerging pests, EPPO maintains an A1 and an A2 list consisting of plant pests which potentially present a risk to EPPO member countries and are recommended for regulation as quarantine pests (EPPO 2017). The A1 list contains pests which are absent from the EPPO region while the A2 list includes pests that are present but not widely distributed in the EPPO region (EPPO 2020). Besides, EPPO maintains an EPPO Alert List to draw the attention of member states to pest species that are not (yet) recommended as quarantine pests but can be subjected to a Pest Risk Analysis (EPPO 2022). The EU maintains a list of quarantine pests and regulated non-quarantine pests, and associated measures on plants and plant products, to reduce the risk of non-native pest introduction to an acceptable level (European Union 2019). The EPPO A1 and A2 lists, the EPPO Alert List and the EU list are not identical although there is overlap. To search for outbreak cases of plant pests, we compiled a list of candidate plant pests that had outbreaks in the EU by combining the EPPO A1 and A2 lists, the EPPO Alert List and the EU list of regulated pests (European Union 2019; EPPO 2020). We searched the EPPO Global Database (https://gd.eppo.int/) for outbreak reports of the pests on this list. We concentrated on outbreaks that occurred between 1975 and 2020. Taxonomically, plant pests can be bacteria and phytoplasmas, fungi, insects, mites, molluscs, nematodes, parasitic and invasive plants, viruses and virus-like organisms that are damaging to plants or plant products. In our research, we focused on management of outbreaks of insects, pathogens (bacteria and phytoplasmas, fungi, viruses and virus-like organisms) and nematodes. We excluded mites, parasitic and invasive plants, and molluscs (*Pomacea*) because no outbreaks with information on zoning were available in the EPPO Global Database.

Second, to analyse outbreak reports in a consistent way, we formulated definitions of the infested zone, the buffer zone and the clear-cutting zone (Table 2.1). Using these definitions were able to identify the use of synonyms and homonyms in the naming of zones in the outbreak reports in the EPPO Global Database. We based our definition of an infested zone on the EU regulation for *Anoplophora glabripennis*: “an infested zone is the zone where the presence of the specified organism has been confirmed, and which includes all plants showing symptoms caused by the specified organism and, where appropriate, all plants belonging to the same lot at the time of planting” (European Union 2015). A buffer zone was defined based on the EU regulation, International Standards for Phytosanitary Measures (ISPM) 5 and measures in the buffer zone from EPPO reports as: an area with a specific radius beyond the boundary of the infested zone

(European Union 2015), aimed to minimize the possibility of spread of the target pest out of the infested zone (ISPM 5, FAO, 2021), and which may contain no known infested plants and, where at least surveillance is conducted and/or other phytosanitary measures, e.g. the execution of public awareness campaigns, can be included to verify the absence of pest in this area (EPPO 2021b). Based on the EU regulations, we defined a clear-cutting zone as: an area with a specific radius around an individual infested plant or around the infested zone where complete clearance of hosts is conducted (European Union 2012b, 2015).

Three steps were used to infer the zones that were used from reports. We refer to Fig. 2.1 for an explanation of the steps. From each outbreak report with information on zoning, we extracted information on species, status in the EU, location, country, date, infestation size, goal, EU regulation, inferred zones and on which step this inference was based (Fig. 2.1), alternative names for defined zones, measures in defined zones and their widths for the plant pests in our identified list (Table 2.2, Appendix S2 from Sun et al. (2023)). We derived a scheme of the general outbreak management process for regulated pests by reviewing the outbreak cases. We expected that the implemented zoning strategies would vary between member states before regulation of a pest but would converge after regulation. We used Pearson's chi squared tests ($\alpha = 0.05$) to determine if the proportion of cases that were delimited with the combination of zones prescribed in regulation differed before and after the regulation, and to determine if the proportion of cases that were managed with at least two zones varied with infestation size. Cases used for the analysis are listed in Appendix S2 from Sun et al. (2023).

Table 2.1 Definition of zones in this paper

Terminology	Definition
Infested zone	The zone where the presence of the specified organism has been confirmed, and which includes all plants showing symptoms caused by the specified organism and, where appropriate, all plants belonging to the same lot at the time of planting (European Union 2015)
Buffer zone	An area with a specific radius beyond the boundary of the infested zone (European Union 2015), aimed to minimize the possibility of spread of the target pest out of the infested zone (ISPM 5, FAO 2021), and which may contain no known infested plants and, where at least surveillance is conducted and/or other phytosanitary measures, e.g. the execution of public awareness campaigns, can be included to verify the absence of pest in this area (EPPO 2021b)
Clear-cutting zone	An area with a specific radius around individual infested plants or around the infested zone where complete clearance of hosts is conducted (European Union 2012b, 2015)

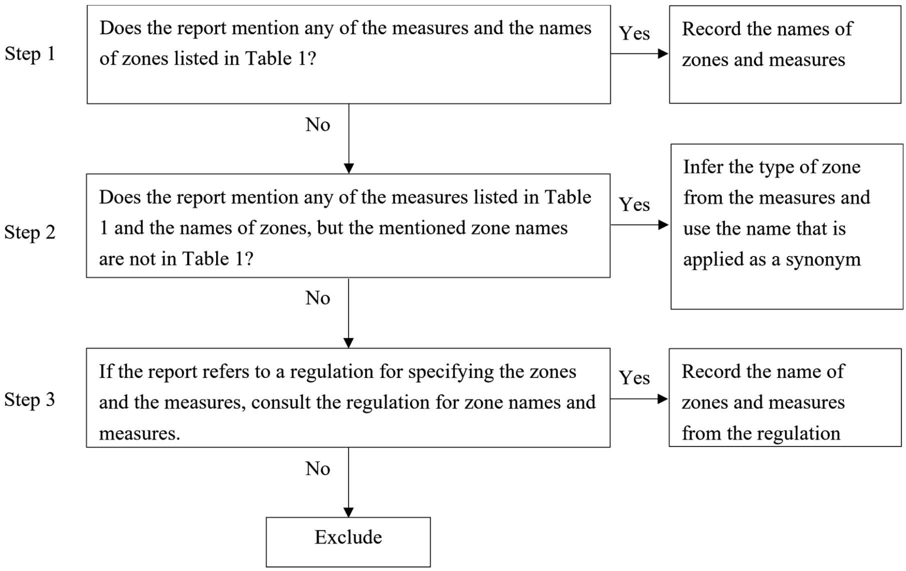


Fig. 2.1 Steps for inferring zoning strategies based on outbreak reports extracted from the EPPO Global Database (https://gd.eppo.int/) to interpret reported zones in a consistent way. Inconsistencies in reported zones may arise due to the use of synonyms, homonyms or implicit definitions on zones

Table 2.2 Variables extracted for each outbreak from the description in EPPO reports

Variable	Definition	Data type/Unit
Species	The scientific name of the plant pest that caused the outbreak in the EU	Text
Status in the EU	The regulatory status of the plant pest in the EU	Text
Location	The specific location of the detection	Text
Country	The country in which the outbreak was detected	Text
Date	The time at which the outbreak was detected	Date
Infestation size	The infestation size of the outbreak when it was detected	Continuous (m^2)
Goal	What should the outbreak management programme achieve	Text
EU regulation	The EU regulation in which harmonized measures were regulated to manage the outbreak of a plant pest	Text
Defined zones and based steps	Zones that were delimited to manage the outbreak of plant pests and the steps in Fig.2.1 that were used to infer defined zones	Text
Alternative names for defined zones	Alternative names for defined zones	Text
Measures in defined zones	Measures in defined zones	Text
Width of defined zones	The radial width of defined zones	Continuous (m)

2.3 Results

2.3.1 Species selection

Merging the EPPO A1 and A2 lists, EPPO Alert List and EU list of regulated plant pests resulted in a list of 295 insect species, 667 pathogen species and 39 nematode species. Of those species, 71 insect species, 49 pathogen species and 11 nematode species had outbreak reports in the EPPO Global Database. Of these, information on the actions taken was available for 55 insect species (337 outbreak reports), 39 pathogen species (300 outbreak reports) and 9 nematode species (42 outbreak reports). Information on the zoning strategy used was reported for 10 insect species (64 outbreak reports), 13 pathogen species (50 cases) and 2 nematode species (7 outbreak reports) (see Fig. 2.2 for a flowchart, Appendix S2 from Sun et al. (2023)). The proportion of pathogens and insects were comparable in the final set of selected cases and the set of excluded cases (41% vs 45% pathogens). The set of selected cases contained more regulated species (96%) than the 558 excluded cases (57%). However, the pest species in the two sets (include and excluded) were similar in terms of economic importance, introduction and spread risk.

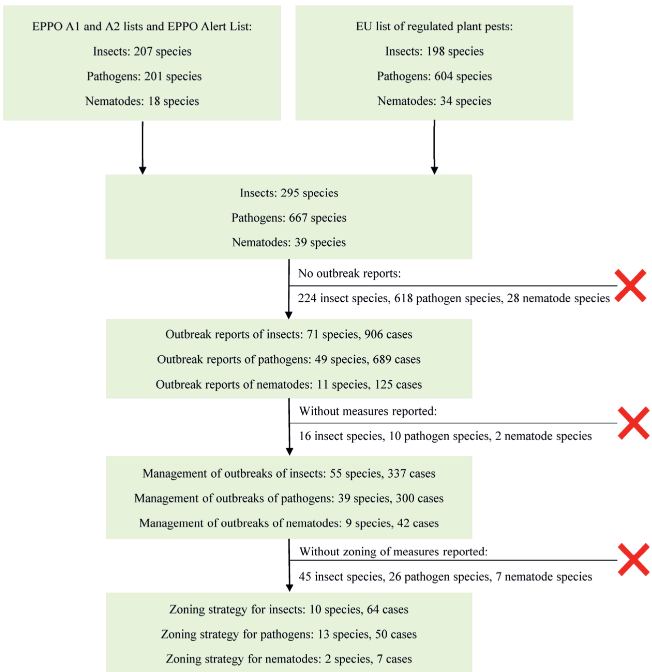


Fig. 2.2 Species selection. A plant pest list for data collection was compiled by merging the EPPO A1 and A2 lists, EPPO Alert List and the EU list of regulated plant pests. Zoning strategies for the outbreak cases of insects, pathogens and nematodes were extracted after excluding the cases without reports

2.3.2 The general outbreak management process for regulated pests in practice

We were able to describe zoning strategies for 121 outbreak cases on the basis of information in the EPPO Global Database (see Supplementary material Appendix S2 from Sun et al. (2023)). Of the 121 outbreaks, 118 outbreaks were caused by 24 EU regulated pests. Based on the 118 outbreak cases, we deduced the general outbreak management process for regulated pests (see Fig. 2.3 for a summary flowchart):

1) The initial goal of outbreak management for regulated pests is always eradication. The aim may shift to containment if eradication appears not feasible.

2) Once the goal of eradication is determined, the area surrounding an outbreak area is divided into zones, each with a different set of measures. Demarcated zones most often comprise an infested zone and a buffer zone. We found that an infested zone (implemented in 100 out 121 cases), buffer zone (92 out of 121 cases), clear-cutting zone (34 out of 121 cases), eradication zone (1 out of 121 cases) and containment zone (1 out of 121 cases) were delimited, in different combinations. Measures within each zone are elaborated in “The diversity of zoning strategies in practice” section.

3) Once a new finding is made in the buffer zone, the infested zone is expanded such that it includes the newly infested site. The buffer zone is also adjusted. If a new outbreak is detected outside the buffer zone, a new infested zone and buffer zone will be delimited around the new finding. Depending on the geographic location of the new infested site compared to the previous one and the width of the zones, the two infested zones could share one buffer zone around the two infested zones. This means that the contiguity of the old and new demarcated zones is related to the spatial position of the new outbreaks and the width of the existing zones.

4) Successful eradication is declared and demarcated zones are lifted if no detection occurs over a specified period, in accordance with the biology of the organism. The specified period is defined as at least one life cycle and some additional years. For example, to guarantee eradication of *Anoplophora chinensis*, demarcated zones can only be lifted if the pest is not detected for at least four consecutive years, which period includes one life cycle of three years plus one additional year (European Union 2012b). If a new detection is made in the demarcated zones and the evaluation shows that eradication is feasible, eradication measures would be implemented again.

5) If a pest becomes widely distributed and experience in other countries indicates that eradication may not be feasible, NPPOs can switch from eradication to containment and this switch is

specified in the EU legislation. For example, NPPOs were obliged to implement measures to eradicate *Xylella fastidiosa* in accordance with the EU regulation after it was first detected in Lecce province, Italy (Box 2.1). However, after several years it became clear that eradication in Lecce was not feasible and measures were adapted to aim for containment of *X. fastidiosa* in Lecce (European Union 2016).

2.3.3 The diversity of zoning strategies in practice

Zones delimited and synonyms and homonyms in naming zones

There was substantial variation in the zoning strategies applied in these 121 outbreaks. Synonyms and homonyms were used to describe different zones (Table 2.3). For example, the infested zone was also referred to as affected area, focus zone, safety zone, infected area/site/zone, outbreak area/site, infested area/site or quarantine area/zone. The buffer zone was also referred to as safety zone, focus zone and surveillance zone. The safety zone and focus zone that were delimited around the infested zone were special buffer zones for managing the insect pests *Diabrotica virgifera virgifera* and *Dryocosmus kuriphilus*, respectively, where surveillance was implemented to verify that the pest did not spread outside the infested zone. The term "surveillance zone" was used to describe the outer part of the buffer zone, which was used to detect further spread of the pest beyond the primary buffer zone where host plants were treated with insecticide when managing *Trioza erytreae* in Portugal, in 2020, and *X. fastidiosa* in Italy, 2015 (Appendix S2, ID 46, 82 from Sun et al. (2023)). The clear-cutting zone was also referred to as clearcut area when managing *A. glabripennis* in the Netherlands, 2012 (Appendix S2, ID 31 from Sun et al. (2023)), or focus zone when managing *Bursaphelenchus xylophilus* in Spain, 2008 (Appendix S2, ID 114 from Sun et al. (2023)). We found two homonyms, i.e. terms with multiple meanings: safety zone (either infested zone or buffer zone) and focus zone (either infested zone, clear-cutting zone or buffer zone).

Different zones described above were used in different combinations (Table 2.4). In total, ten different combinations were found, of which the combination "infested zone + buffer zone" was used most often (62 out of 121 cases). For the combination "infested zone + clear-cutting zone + buffer zone" (15 out of 121 cases), the clear-cutting zone was delimited either around individual infested plants (12 out of 15 cases) or around the infested zone (3 out of 15 cases). In some cases, a strict eradication measure of clear-cutting was implemented in the outer part of the infested zone to reduce the likelihood of the organism spreading into the buffer zone. In managing *X. fastidiosa*, this outer part of the infested zone was called the containment zone when the aim of the outbreak management was to contain the pest within the infested zone, while it was called the eradication zone when the aim of outbreak management was to eradicate the pest within the infested zone (Appendix S2, ID 82, 83 from Sun et al. (2023)).

Widths of the buffer zone and clear-cutting zone

The width of the clear-cutting zone was more variable before it was specified in the regulation than after the regulation (Table 2.5). For the 18 cases in which clear-cutting zones were delimited after a regulation for that species was in place, 17 cases were in accordance with the specified width in the regulation and in one case it was six times wider than the minimum width in the regulation. With one exception, the width of the buffer zone in the regulation was similar to the greatest width that was used in outbreak management before the regulation was put in place (Table 2.6). The exception was *Aromia bungii* for which the regulated width of the buffer zone was consistent with the smallest width used before regulation in practice.

Table 2.3 Terms used for outbreak management. The first column is the term of zones following the definition in Table 2.1. The second column refers to synonyms that were used; the third column contains the unique ID for each outbreak case to link to the outbreak reports in Appendix S2 from Sun et al. (2023). The homonyms of "safety zone" and "focus zone" are marked in italic

Type of zones	Synonyms	Case ID in Appendix S2 from Sun et al. (2023)
Infested zone	Affected area	7
	Focus zone	8, 44, 45, 49, 50, 55, 57, 58, 59, 60, 61, 62, 63, 64, 66, 86
	Infected area	70, 71, 72, 73, 74, 81
	Infected site	89, 111, 119, 120, 121
	Infected zone	94, 95
	Infested area	9, 10, 11, 14, 18, 20, 26, 28, 43, 47
	Infested site	5, 13, 19, 32, 100
	Outbreak area	28, 52
	Outbreak site	33, 96
	Quarantine area	17, 39, 48, 51, 54, 56
	Quarantine zone	21, 67, 68, 69
	Safety zone	65, 118
Buffer zone	*Safety zone*	45, 49, 50, 52, 53, 55, 57, 58, 59, 60, 61, 62, 63, 64
	Surveillance zone	46, 82
	Focus zone	38, 40
Clear-cutting zone	Clearcut area	31
	Focus zone	114

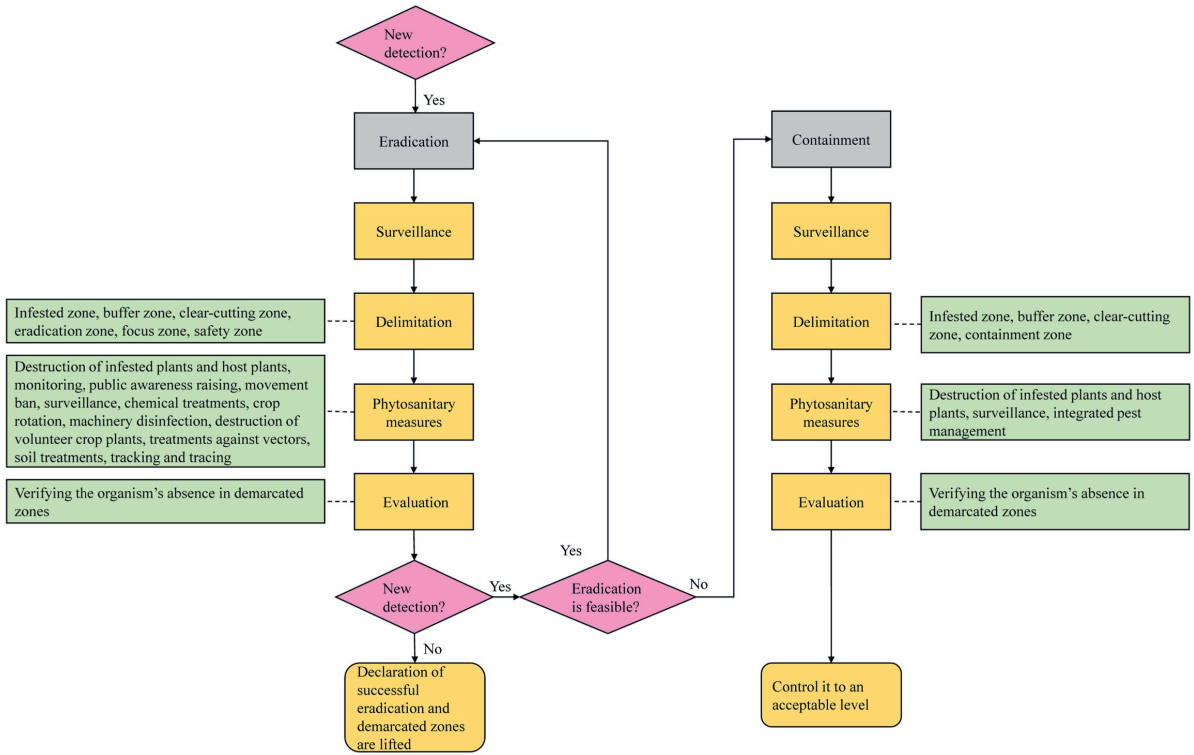


Fig. 2.3 Flow chart showing the implementation process of zoning strategies for managing outbreaks of regulated plant pests in the EU. *Grey rectangles* indicate the management goal, *yellow rectangles* indicate the components of implementation steps, *green rectangles* give further detail and actions taken, *pink diamonds* indicate decision-making, *arrows* indicate a causal or time sequential relationship, starting from the step of cause and pointing to the step of effect, and *dashed line*s indicate a parallel relationship, connecting general implementation steps (*yellow rectangles*) and the associated actions (*green rectangles*). The scheme is derived on the basis of reviewing outbreak reports of 24 regulated species with zoning strategies applied

Table 2.4 Graphical illustration of ten different combinations of five zones (infested zone, buffer zone, clear-cutting zone, eradication zone and containment zone) that have been used to manage outbreaks in the EU. Information was available for managing the outbreaks of 121 cases. *Red points* represent infested plants, *yellow circles* represent the infested zone, *blue circles* represent the buffer zone, *grey circles* represent the clear-cutting zone, *pink hatched lines* represent the eradication zone, and *yellow hatched lines* represent the containment zone. Infested zones and buffer zones were not overlapping. Clear-cutting zones were overlapping with either the infested zone or the buffer zone. Containment zones and eradication zones were overlapping within the outer part of the infested zone

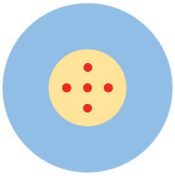
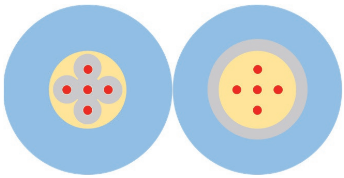
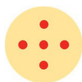
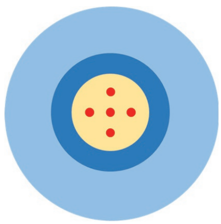
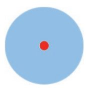
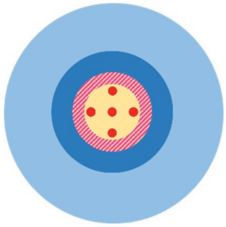
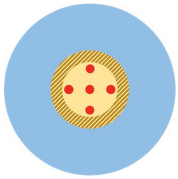
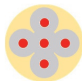
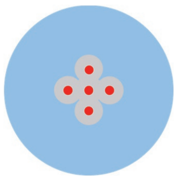
Combination of zones	**Illustration**	**Number of cases**
Infested zone (yellow) around infested plants (red dots) + buffer zone (blue)		62
Clear-cutting zone (grey)		17
Infested zone + clear-cutting zone[1] + buffer zone		15
Infested zone		11
Infested zone + primary buffer zone (dark blue) + secondary buffer zone (light blue)[2]		9
Buffer zone around a single infested plant		3

Table 2.4 (continued) Graphical illustration of ten different combinations of five zones (infested zone, buffer zone, clear-cutting zone, eradication zone and containment zone) that have been used to manage outbreaks in the EU. Information was available for managing the outbreaks of 121 cases. *Red points* represent infested plants, *yellow circles* represent the infested zone, *blue circles* represent the buffer zone, *grey circles* represent the clear-cutting zone, *pink hatched lines* represent the eradication zone, and *yellow hatched lines* represent the containment zone. Infested zones and buffer zones were not overlapping. Clear-cutting zones were overlapping with either the infested zone or the buffer zone. Containment zones and eradication zones were overlapping within the outer part of the infested zone

Infested zone + eradication zone[3] (pink hatched) + primary buffer zone + secondary buffer zone[2]		1
Infested zone + containment zone[4] (yellow hatched) + buffer zone		1
Infested zone + clear-cutting zone		1
Clear-cutting zone + buffer zone		1

[1]Clear-cutting zone can be delimited either around individual infested plants (12 out of 15 cases), or around an infested zone as a whole (3 out of 15 cases). The clear-cutting zone was delimited around an infested zone when managing *Anoplophora chinensis* in the Netherlands, 2009, *Bursaphelenchus xylophilus* in Portugal, 2008 and *B. xylophilus* in Spain, 2018 (Appendix S2, ID 12, 113, 117 from Sun et al. (2023)).

[2]The secondary buffer zone, i.e. the outer part of the buffer zone, is called the surveillance zone when managing *Trioza erytreae* in Portugal, 2020 and *Xylella fastidiosa* in Italy, 2015 (Appendix S2, ID 46, 82 from Sun et al. (2023)).

[3, 4]The position of the eradication zone and containment zone was within the infested zone and adjacent to the buffer zone when managing *X. fastidiosa* in Italy in 2015 and 2016, respectively (Appendix S2, ID 82, 83 from Sun et al. (2023)). The applied measures were different in these two zones (Box 2.1).

Table 2.5 Width of the clear-cutting zone in meters. Distinction is made between pest status, width in practical outbreak management before regulation, width as specified in the EU regulation and width in practical outbreak management after regulation. Numbers in brackets represent the frequency (number of outbreak case reports). Details are given in Appendix S3 from Sun et al. (2023)

Species	Status	Width in practice before the regulation (m)	Width according to the regulation (m)	Width in practice after the regulation (m)
Insects				
Anoplophora chinensis	A2	20 (1), 100 (2)	100	100 (3)
Anoplophora glabripennis	A1	50 (1), 100 (5), 500 (1)	100	100 (3)
Aromia bungii	A1		100	100 (1)
Oomycete				
Phytophthora ramorum (EU isolates)	A2	1 (1)	2	2 (7)
Insect-vectored pathogenic organisms				
Xylella fastidiosa	A2		100	100 (3)
Bursaphelenchus xylophilus	A2	100 (1), 3,000 (1)	500	3,000 (1)

Table 2.6 Width of the buffer zone in kilometers. Distinction is made between pest status, width in practical outbreak management before regulation, width as specified in the EU regulation and width in practical outbreak management after regulation. Numbers in brackets represent the frequency (number of outbreak case reports). Details are given in Appendix S3 from Sun et al. (2023)

Species	**Status**	**Width in practice before the regulation (km)**	**Width according to the regulation (km)**	**Width in practice after the regulation (km)**	**Width according to updated regulation (km)**	**Width in practice after the updated regulation (km)**	**Width according to (again) updated regulation (km)**
Insects							
Anoplophora chinensis	A2	1 (1), 2 (1)	⩾ 2	2 (3)			
Anoplophora glabripennis	A1	0.5 (1), 1 (5), 2 (2)	⩾ 2	0.5 (1), 2 (2)			
Aromia bungii	A1	2 (1), 4 (2)	⩾ 2				
Dryocosmus kuriphilus	A2	10 (1)	⩾ 10	10 (1), 15 (2)			
Rhynchophorus ferrugineus	A2	10 (2)	⩾ 10				
Fungi							
Fusarium circinatum	A2	1 (1)	⩾ 1				
Insect-vectored pathogenic organisms							
Xylella fastidiosa	A2	10 (5)	⩾ 10	10 (3), 11 (1)	⩾ 5	1 (1), 5 (4), 10 (1)	⩾ 2.5
Bursaphelenchus xylophilus	A2	20 (1)	⩾ 20	20 (1)			

Measures in various zones

Different measures were conducted in different zones (Fig. 2.4). In the infested zone, destruction of all infested plants (78 out of 100 cases) was most frequently applied, followed by destruction of all host plants (42 out of 100 cases). Crop rotation (2 out of 10 insect species) and soil treatments (2 out of 10 insect species) were only done for insects while treatments against vectors (2 out of 13 vectored pathogen species) were used when the outbreak was caused by vectored pathogens. Surveillance was in all cases (92 out of 92) carried out in the buffer zone to verify pest absence. Crop rotation (1 out of 10 insect species), machinery disinfection (1 out of 10 insect species) and chemical treatments (4 out of 10 insect species) were applied only for insects, while treatments against vectors (2 out of 13 pathogen species) and destruction of host plants (1 out of 13 pathogen species) were only used for pathogens. Measures in the infested zone and buffer zone used against insects were more diverse than those used against pathogens. In the infested zone, on average 3.7 (s.e. ± 0.2) different measures were taken for insects and 2.8 ± 0.2 for pathogens, and in the buffer zone on average 2.2 ± 0.1 different measures were taken for insects compared with 1.4 ± 0.1 for pathogens. Other, less frequently applied measures in the infested zone and buffer zone in relation to insects, pathogens and nematodes are listed in Fig. 2.4.

Measures were frequently used in combination. When destruction of infested plants was applied in the infested zone, it was most often combined with destruction of host plants in that zone (51%). In the infested zone, destruction of volunteer crop plants and machinery disinfection were usually combined (87% of the cases). In the buffer zone, the most commonly applied measure after surveillance was public awareness raising (30% of the cases). When crop rotation was applied in the buffer zone, it was often combined with machinery disinfection (50%). See Table 2.7 for the interaction between measures in the infested zone and Table 2.8 for the interaction between measures in the buffer zone

The combination of zones and their widths and the intensity of measures within each zone varied over time and from one country or place to another, even for one pest, depending on the local situation of pest spread, public acceptance, resources and the experience accumulated over time. See Box 2.1 for a presentation of two cases that illustrate this point.

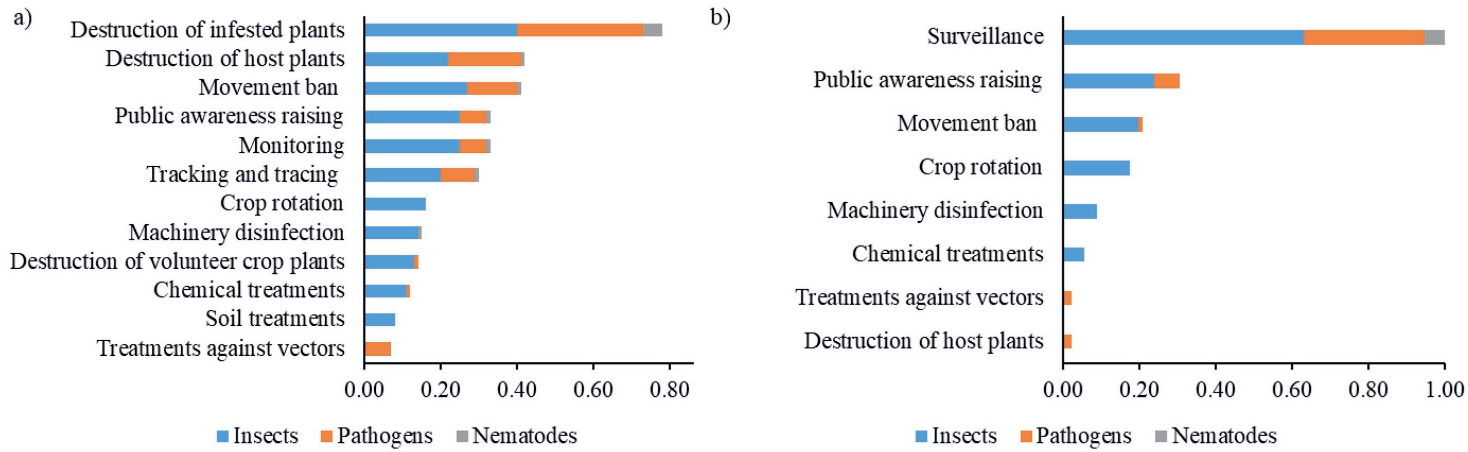


Fig. 2.4 Frequency of measures in the infested zone a) and buffer zone b) for insects (*blue bars*), pathogens (*orange bars*) and nematodes (*grey bars*). The frequency is calculated by dividing the number of cases with the measure applied for insects, pathogens and nematodes by the number of cases where an infested zone (100 cases) or a buffer zone (92 cases) was delimited

Table 2.7 Cross tabulation of measures in the infested zone. Numbers represent frequencies of measures occurring together. Numbers in brackets represent the conditional probability of the measure in a column if the measure in the row is carried out (i.e. the condition). For instance, 40 out of 78 cases with destruction of infested plants also had destruction of host plants. Bold numbers represent the frequency of the most frequent measure if the measure in a row is carried out

	Destruction of host plants	Movement ban	Public awareness raising	Tracking and tracing	Monitoring	Chemical treatments	Crop rotation	Machinery disinfection	Destruction of volunteer crop plants	Treatment against vectors	Soil treatments	Total cases
Destruction of infested plants	**40 (0.51)**	32 (0.41)	24 (0.31)	27 (0.35)	15 (0.19)	7 (0.09)	0 (0.00)	1 (0.01)	0 (0.00)	7 (0.09)	3 (0.04)	78
Destruction of host plants		14 (0.33)	12 (0.29)	**15 (0.36)**	7 (0.17)	2 (0.05)	0 (0.00)	0 (0.00)	1 (0.02)	1 (0.02)	1 (0.02)	42
Movement ban			11 (0.27)	**12 (0.29)**	9 (0.22)	7 (0.17)	7 (0.17)	6 (0.15)	5 (0.12)	7 (0.15)	7 (0.17)	41
Public awareness raising				10 (0.30)	**13 (0.39)**	3 (0.09)	8 (0.24)	8 (0.24)	8 (0.24)	2 (0.06)	2 (0.06)	33
Tracking and tracing					**10 (0.33)**	1 (0.03)	0 (0.00)	0 (0.00)	1 (0.03)	3 (0.10)	0 (0.00)	30
Monitoring						5 (0.15)	**16 (0.48)**	9 (0.27)	13 (0.39)	2 (0.06)	5 (0.15)	33
Chemical treatments							**3 (0.25)**	1 (0.08)	0 (0.00)	0 (0.00)	**3 (0.25)**	12
Crop rotation								**13 (0.81)**	**13 (0.81)**	0 (0.00)	5 (0.31)	16
Machinery disinfection									**13 (0.87)**	0 (0.00)	5 (0.33)	15
Destruction of volunteer crop plants										0 (0.00)	**5 (0.36)**	14
Treatment against vectors											0 (0.00)	7

Note: The conditional probability is calculated by dividing the number of cases with two measures executed in combination by the total number of cases with the measure in a row.

Table 2.8 Cross tabulation of measures in the buffer zone. Numbers represent frequencies of measures occurring together. Numbers in brackets represent the conditional probability of the measure in a column if the measure in the row is carried out (i.e. the condition). For instance, 28 out of 92 cases with surveillance also had public awareness raising. Bold numbers represent the frequency of the most frequent measure if the measure in a row is carried out

	Public awareness raising	Movement ban	Crop rotation	Machinery disinfection	Chemical treatments	Destruction of host plants	Treatment against vectors	Total cases
Surveillance	**28 (0.30)**	19 (0.21)	16 (0.17)	8 (0.09)	5 (0.05)	2 (0.02)	2 (0.02)	92
Public awareness raising		7 (0.25)	**8 (0.29)**	**8 (0.29)**	0 (0.00)	0 (0.00)	1 (0.04)	28
Movement ban			0 (0.00)	0 (0.00)	**2 (0.11)**	0 (0.00)	1 (0.05)	19
Crop rotation				**8 (0.50)**	2 (0.13)	0 (0.00)	0 (0.00)	16
Machinery disinfection					0 (0.00)	0 (0.00)	0 (0.00)	8
Chemical treatments						0 (0.00)	0 (0.00)	5
Destruction of host plants							0 (0.00)	2

Note: The conditional probability is calculated by dividing the number of cases with two measures executed in combination by the total number of cases with the measure in a row.

Box 2.1: Examples showing that for one pest, the zoning strategy differs

In the Netherlands, the intensity of measures taken to manage the outbreak of *A. glabripennis* in the town of Winterswijk differed from that in an industrial area near Almere (Appendix S2, ID 31, 32 from Sun et al. (2023)). In both cases, the clear-cutting zone had a radius of 100 m. However, the intensity of clear-cutting measures within the 100-m-radius clear-cutting zone was greater in Almere than in Winterswijk. In Almere, all trees with symptoms as well as host plants were destroyed within the 100-m-radius clear-cutting zone. In Winterswijk, all infested trees and all susceptible trees were eliminated in the first 50 m while in the range of 50-100 m only host plants of at least 2 meters in height were destroyed (EPPO 2010, 2012). This is because the outbreak in Winterswijk was much smaller and intensive clear-cutting was much harder to implement in a residential area where the public was more affected.

2-km-wide buffer zones were delimited in 2011 and 2016 to manage *A. bungii* in Rosenheim, Germany. These two zones were merged into a single 4-km-wide buffer zone in 2019 because of expansion of the two outbreaks (Appendix S2, ID 34 from Sun et al. (2023)).

Measures for the control of *X. fastidiosa* have evolved over time as a result of the accumulation of experience with the spread of the disease and also in response to evolving legislation and social pressures (Appendix S2, ID 81, 82, 83 from Sun et al. (2023)). At the first detection of *X. fastidiosa* in Puglia (Italy) in 2013, no demarcated area was defined. However, an eradication programme was launched as required in European Union, (2000). An infested zone, buffer zone, eradication zone and surveillance zone were delimited to eradicate the pest. In the infested zone, destruction of infested plants and movement ban were applied and destruction of host plants was implemented in the outer part of the infested zone, which was the eradication zone. In the buffer zone, surveillance, as well as destruction of host plants with a specific radius around the newly detected infested plants was applied. In the surveillance zone, host plants of insect vectors were treated with insecticide and surveillance continued in addition to the buffer zone. However, eradication appeared not feasible in Lecce due to the large number of infested hosts, epidemiological characteristics of the pest, various host plant species behaving as a reservoir of the bacterium, and a minimal implementation of the measures due to the public's objection to uprooting trees. In 2015, the aim of the outbreak management was changed to containment. Destruction of infested plants was not required anymore in the infested zone, but the outer part of the infested zone was delimited as a containment zone where clearance of infested plants should be applied to keep the organism within that area while destruction of host plants applied only in a zone with a specific radius within the buffer zone. The infested zone, containment zone and buffer zone were moved northward covering the subsequent outbreaks in Brindisi and Taranto province of Puglia region (Fig. 2.5). An infested zone (including a containment zone), buffer zone and surveillance zone adjacent to the buffer zone were delimited. All known host plants of the European isolates of *X. fastidiosa* within a radius of 100 m of each infested plant in the buffer zone were intended to be destroyed, shredded and treated to prevent further spread of the bacterium, together with insecticide treatments targeted on insect vectors. These measures, limited to infested plants, were also implemented in the containment zone.

Box 2.1 (continued):

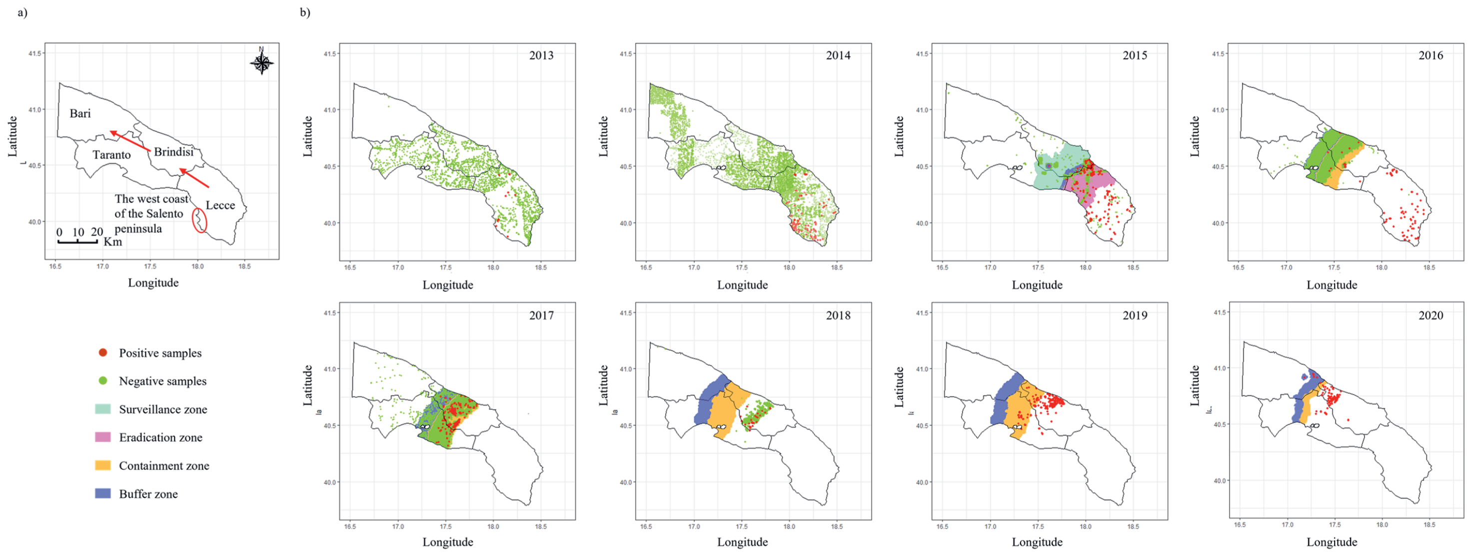


Fig. 2.5 a) Maps of Lecce, Brindisi, Taranto and Bari provinces in Puglia region, Italy. *Red oval* on the west coast of the Salento peninsula indicates where *Xylella fastidiosa* was first detected, *red arrows* indicate the direction of spread of *X. fastidiosa* from the South to the North in Puglia. b) The detection of positive plants and demarcated zones for managing *X. fastidiosa* in Puglia, Italy from 2013 to 2020 (https://www.emergenzaxylella.it). *Red points* represent positive infection, *green points* represent samples that are tested negative (with data available from 2013 to 2018), *light green area* represents the surveillance zone (2015), *pink area* represents the eradication zone (2015), *ochre area* represents the containment zone (2016-2020) and *blue area* indicates the buffer zone (2015-2020). There are overlaps between the tested negative area and demarcated zones in 2016 and 2017, when the surveillance programme covered almost the whole containment zone and buffer zone. The infested zone includes the eradication zone or containment zone and extends to the southernmost of Puglia

Effects of regulation and infestation size on zoning strategies

The implementation of a harmonized regulation and the size of infestation had a significant effect on the frequency of zones (Fig. 2.6). The percentage of cases that were delimited with the combination of zones prescribed in regulation differed before and after the regulation ($\chi 2 = 4.51$, df = 1, $p = 0.034$) showing that outbreak management strategies converged after imposing the regulation (5 out of 22 cases). The percentage of cases that was managed with only one delimited zone depended on the infestation size ($\chi 2 = 9.140$, df = 1, $p = 0.003$). NPPOs were more prone to delimit only one zone when the infestation size was smaller than 100 m^2 (21 out of 61 cases) than when the infestation size was larger than 100 m^2 (5 out of 50 cases).

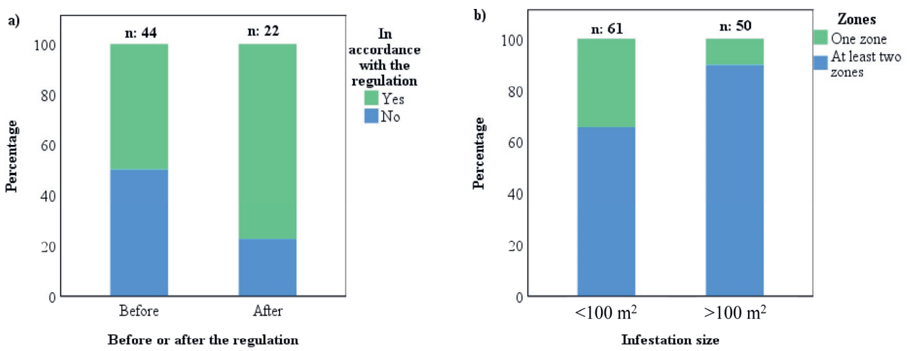


Fig. 2.6 a) Percentage of cases that used the combination of zones as was prescribed in the regulation before and after the regulation; b) Percentage of cases that were managed with only one delimited zone when the infestation size was smaller or larger than 100 m^2. The number above the bars represents the number of cases

2.4 Discussion

The aim of this paper was to review the zoning strategies that are used to manage outbreaks of plant pests in the EU. From reviewing 121 outbreak reports on the EPPO global database, we find that three main zones were delimited in practice: an infested zone, a buffer zone and a clear-cutting zone; other zones could be considered as special cases of one of these three zones. The eradication zone and containment zone were special cases in managing *X. fastidiosa.* The buffer zone and infested zone are adjacent to each other and non-overlapping. The clear-cutting zone is either located inside the infested zone surrounding the infested plants or inside the buffer zone and adjacent to the infested zone, while the containment zone and eradication zone are both inside the infested zone and adjacent to the buffer zone. Zones were used in different combinations, and the variation in zoning strategy used was larger before than after regulation.

Our study shows that most often the infested zone is delimited along with a buffer zone, although substantial variation exists. When the infestation size was small, i.e. there are only a few infested individuals, NPPOs tended to delimit either only an infested zone, a buffer zone or a clear-cutting zone. This is because the NPPO has made the assessment that the pest has not established beyond the infested plants (which are often the primary infestations, i.e. those originating from outside the area). If an NPPO concludes after surveillance that the incursion is isolated and the pest is not established, e.g. the pest is detected in an isolated infested plant, the NPPO might only delimit a buffer zone and apply surveillance measures in the buffer zone around the single infestation after destroying the infested plant. If they consider it is likely that the pest has established locally, even though only one infested plant was detected, they would additionally apply clear-cutting measures around this infested plant to eliminate host plants that may be infested but do not show any symptoms. Using infestation size as indicator to determine which zones to delimit may be useful practice as the likelihood of successful eradication decreases with the size of the outbreak (Pluess et al. 2012a; Tobin et al. 2014). A meta-analysis on outbreaks could possibly identify the optimal combination of zones that should be used in various circumstances, but to the best of our knowledge this is lacking.

Our study showed a close relationship between regulation and practice. The width of zones that were specified in a regulation was almost always the largest width that was used in managing one of outbreaks prior to the regulation. This is a relatively robust decision that builds on experience gained in outbreak management before regulation. Unfortunately, there were insufficient data to evaluate how the width of the buffer zones evolves with updated regulations.

Most cases implemented buffer zones and clear-cutting zones using the radius that was stipulated as a minimum in the regulation, and only a minority of cases implemented larger buffer zones and clear-cutting zones than was stipulated in the regulation. For example, to manage outbreaks of *X. fastidiosa*, despite a reduction in required width of the buffer zone from 10 km to 5 km, allowed by Commission Implementing Regulation (EU) 2020/1201 (European Union 2020), the NPPO in Puglia decided to keep the buffer zone at 10 km because previous experience indicated that 10 km is more effective in slowing pest spread than 5 km. Other evidence suggests that zone widths prescribed by regulations are lower than those needed to achieve eradication. For example, before the abolishment of the quarantine status of *D. virgifera*

virgifera in the EU, the results of an individual-based model that simulated the dispersal and mortality of *D. virgifera virgifera* showed that the management of *D. virgifera virgifera* would be improved by increasing the minimum width of the focus zone by 4 km and increasing the width of the safety zone by 45 km, as compared to the regulation (Carrasco et al. 2010). Similarly, a clear-cutting zone with a radius of 500 m, as stipulated in the EU regulation, was estimated to be insufficient to eradicate *B. xylophius* (Robinet et al. 2020). Additionally, four spatial Bayesian hierarchical models were used to evaluate the influence of different barriers in the distribution of *X. fastidiosa* in Alicante, Spain, showing that the minimum buffer zone of 2.5 km established by the regulation (European Union 2020) does not cover the entire area at risk of *X. fastidiosa*. Consequently, the plant health authority implemented an additional band of 10 km surrounding the demarcated area (Cendoya et al. 2022). A spatially explicit simulation model was built to model the control strategy for *X. fastidiosa* in Puglia, showing that increasing the width of the buffer zone decreases the infection risk (White et al. 2017).

Thus, the above modelling studies suggest that improved eradication would be achieved with a wider buffer zone or clear-cutting zone than that prescribed by the regulation. However, the required widths that are calculated to be optimal may not be technically nor socially feasible and compromises may need to be explored. For example, an alternative strategy could be to decrease the width of the clear-cutting zone around the infested plants and increase surveillance surrounding infested zones (Robinet et al. 2020). Alternatively, it could be cost-effective to increase surveillance at the European level and a few studies have been conducted to explore relationship between surveillance and eradication efforts (Bogich et al. 2008; Hauser and McCarthy 2009; Epanchin-Niell et al. 2014; Rout et al. 2014; Yemshanov et al. 2017a, b; Thompson et al. 2018). Increasing surveillance may lead to earlier detections of new incursions and higher detection rates of the targeted pest. As these incursions are more quickly discovered, they will have smaller infestation size and higher likelihood of successful eradication (Demon et al. 2011; Epanchin-Niell et al. 2014; Parnell et al. 2014; Bushaj et al. 2020), possibly leading to lower eradication costs. The fact that most eradication attempts are for regulated pests makes it difficult to ‘experiment’ with alternative management strategies and to explore the effectiveness of different management options. Modelling could help to explore the effectiveness of different combinations of zones under different circumstances and provide some insights into when which combination of zones is most effective (Cook et al. 2016).

The results of our analysis based on the definition on zones highlight that the most frequently applied measure was different between the infested zone, buffer zone and clear-cutting zone due to the functional difference between zones. In the infested zone, destruction of infested plants and host plants was the most frequently applied measure to eradicate the source of infestation. Surveillance was the most frequently applied measure in the buffer zone to verify that the pest is not spreading outside the infested zone, and take measures otherwise. In the clear-cutting zone, the most frequently applied measure was destruction of host plants to eliminate asymptomatic trees. Applying multiple measures in practice is useful because the success of eradication generally requires the combination of several measures applied on an area-wide basis (Suckling et al. 2016).

Even for the same pest, the zoning strategy changed over time and space. This is the result of the trade-offs between the costs and benefits of measures applied in a zone with a particular size, and the changing regulation. Intensive measures were applied against *X. fastidiosa* in Puglia at the frontier of invasion. This strategy is supposed to be effective because the frontier is the area with great infection potential, which should receive greater efforts to eradicate any potential invasions (Lodge et al. 2016). An important lesson with *X. fastidiosa* is that regulations should be flexible enough to cope with the particularities of each outbreak.

Finally, we found that synonyms are often used for the infested zone, buffer zone and clear-cutting zone, but homonyms are used rarely , i.e. in the case of the safety zone (either infested zone or buffer zone) and the focus zone (either infested zone, clear-cutting zone or buffer zone). Inconsistency in naming of different zones hampers the evaluation of the effectiveness of zoning strategies (Pluess et al. 2012a, b). Some case reports could not be used because of high uncertainty about what was done (Fig. 2.2). A systematic comparison of eradication programmes across countries worldwide is lacking, but it is likely that the eradication procedures are comparable among the countries or regions that follow the IPPC standard (see for example the case of Plum pox virus in Pennsylvania US; Gougherty et al. 2015) and hence could benefit from standardized terminology. This stresses the need for countries to use the term of buffer zone defined in ISPM 5 and to define other terms such as infested zone, and clear-cutting zone explicitly from the perspective of the pest presence, location of the zones in relation to the incursion and the measures taken within a zone. Analyses of past outbreaks and their management are facilitated if authorities report their management using standardized terminology. A map of demarcated zones is an effective tool to communicate the actual zoning approach followed. Finally, it would be advantageous if NPPOs report zoning strategies for non-regulated pests to enable a further analysis of differences in zoning strategies between regulated and non-regulated pests.

2.5 Conclusion

This synthesis demonstrates that three main zones were delimited for management of outbreaks of plant pests in the EU: an **infested zone** where the presence of the specified organism has been confirmed, and which includes all plants showing symptoms caused by the specified organism and, where appropriate, all plants belonging to the same lot at the time of planting (European Union 2015), a **clear-cutting zone** with a specific radius around individual infested plants or around the infested zone where complete clearance of hosts is conducted (European Union 2012b, 2015) and a **buffer zone** with a specific radius beyond the boundary of the infested zone (European Union 2015), aimed to minimize the possibility of spread of the target pest out of the infested zone (ISPM 5, FAO 2021), and which may contain no known infested plants and, where at least surveillance is conducted and/or other phytosanitary measures, e.g. the extension of public awareness campaigns, can be included to verify the absence of pest in this area (EPPO 2021b). The combination infested zone + buffer zone was used most frequently. Usually, only one zone was delimited when the infestation size was small. Zoning strategies became less diverse after a pest became regulated because regulations often prescribe the type and a minimum width for zones. The effectiveness of zoning strategies in practice needs to be evaluated, and guidelines on designing cost-effective zoning strategies could be explored by modelling pest spread, spatial allocation of measures and costs.

Acknowledgements

We thank M. Suffert for her participation in the interviews and her comments on earlier versions of the manuscript. This study was supported by the China Scholarship Council (China; grant number: 201906350034).

Data availability

All data generated and analyzed during this study are included in this published article and its supplementary information files.

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Chapter 3

Pine wood nematode control without clear-cutting: a scenario analysis

Hongyu Sun[1,*], Christelle Robinet[2], Hervé Jactel[3], Monique Mourits[4], Manuela Branco[5], Wopke van der Werf[1], Jacob C. Douma[1]

[1] Wageningen University and Research, Centre for Crop Systems Analysis, P.O. Box 430, 6700 AK Wageningen, The Netherlands

[2] INRAE, UR633 Zoologie Forestière, F-45075 Orléans, France

[3] Biogeco, INRAE, Univ. Bordeaux, F-33610 Cestas, France

[4] Wageningen University and Research, Department of Social Sciences, Business Economics Group, 6700 EW, Wageningen, The Netherlands

[5] Centro de Estudos Florestais, Laboratório Associado TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisbon, Portugal

Abstract

The pine wood nematode (PWN), *Bursaphelenchus xylophilus* is an invasive species that causes high mortality to pine forests in its non-native range. PWN is vectored by longhorn beetles of the genus *Monochamus*. European Union (EU) regulations stipulate a 500-m-radius clear-cutting around infested trees to prevent spread of PWN. However, this radius does not completely prevent the spread of PWN-carrying beetles while economic, environmental and societal costs of this measure are high. Here, we compared the cost-effectiveness of clear-cutting to an alternative eradication strategy based on cutting only PWN-infested trees. Both strategies were evaluated using three different methods for surveillance: visual ground surveys, aerial surveys, and insect trapping networks. We used an individual-based model to quantify the dispersal of *M. galloprovincialis* and the spread of PWN. Both strategies were able to eradicate PWN when conducting intensive aerial surveillance at a time when almost all infested trees show symptoms. The economic costs of selective cutting were thereby about 200-fold lower than those of clear-cutting. Eradication was not possible if the vector was abundant and not all trees showed symptoms at the time of surveillance. When no less than 60% of the infested trees show symptoms, for the same level of effectiveness, tree-by-tree selective cutting with increased surveillance allowed for an average 88-fold reduction in costs, mainly by preserving healthy trees. Additionally, it reduces unquantified environmental and societal costs. The results showed that there is a viable alternative to the mandatory clear-cutting for PWN control in the EU. Our model offers a general application to other pest-vector-plant or pest-plant systems, allowing for the exploration of alternative more environmentally friendly control strategies.

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

Significance

The pine wood nematode (PWN), *Bursaphelenchus xylophilus*, is one of the most damaging forest pests worldwide. Clear-cutting of host plants within a 500-meter-radius around the infested tree is mandatory in the European Union to eradicate PWN, but it is very costly, has large impact on the environment, and is often not effective enough. We evaluate the effectiveness of an alternative strategy involving intensive aerial surveillance and cutting of individual infested trees. Through modelling analysis, we conclude that selective cutting can reach the same effectiveness as clear-cutting although at much lower costs. Our results underline that with modern surveillance methods it may be possible to replace clear-cutting by cost saving and more environmentally friendly control strategies.

3.1 Introduction

The pine wood nematode (PWN) *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle is the causal agent of the pine wilt disease. PWN originates from North America (USA and Canada), and has been introduced in Japan, China, Korea, Portugal, and Spain where it causes 80% - 90% tree mortality, leading to huge economic impacts to the forestry industry and forest ecosystems (Soliman et al. 2011; Vicente et al. 2012; Seidl et al. 2018). In China only, the average economic loss of forest resources, the costs of prevention and control measures, and forest management expenditure due to the spread of PWN is currently estimated at one billion dollars per year (Zhao et al. 2020). Pine 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, *Monochamus galloprovincialis* (Olivier) is currently the only identified vector of PWN. The average spread rate of PWN in Portugal is currently about 5.3 km per year (de la Fuente et al. 2018). However, *M. galloprovincialis*, may fly up to 4.3 km per hour (David et al. 2014) and each individual may stop and resume its dispersal one or more times (Etxebeste et al. 2016). As a result, one individual may fly more than 60 km during its adult life and thereby spread PWN over a long distance (David et al. 2014; Robinet et al. 2019).

To slow down the spread of PWN, the European Union (EU) has adopted a series of regulations (European Commission 2006, 2012, 2018), which in particular prescribe that member states shall immediately implement a clear-cutting zone of a 500-m-radius around each detected PWN-infested tree. However, Robinet et al. (2020) found that a clear-cutting zone of 500 m would reduce the number of PWN transmissions by only 0.6% - 11.5% and would not stop the spread of PWN in a large contiguous landscape of pine plantations. The required radius for effective eradication by clear-cutting would be between 14 and 38 km, but such a wide zone of clear-cutting would result in unacceptable impacts, and would therefore be impossible to implement. Worse, clear-cutting may even accelerate the dispersal, as the lack of food resources would force the beetles to move further away (Schroeder 2019; Nunes et al. 2021). Thus, current measures are insufficient to halt the spread of PWN in Portugal (Sousa et al. 2012; de la Fuente et al. 2018).

An alternative strategy to eradicate PWN would be selective cutting on a tree-by-tree basis, i.e. only removing the PWN-infested trees (Kwon et al. 2011), which should be actively searched by intensive surveillance to ensure timely detection (de la Fuente et al. 2018; Robinet et al. 2020). This strategy may help curb the epidemic at a lower cost than clear-cutting because of lower cutting costs and preservation of the large numbers of healthy trees that lose their value when cut before the end of the forestry cycle. However, the effectiveness and costs of tree-by-tree selective cutting have not been rigorously assessed so far.

Trees with wilting symptoms, potentially attributed to the PWN, can be detected via road surveillance by forest health practitioners or by analysis of images that are captured by aerial remote sensing (Samalens et al. 2007; Deng et al. 2020; Qin et al. 2021; Zhang et al. 2021; Luo et al. 2023; Li et al. 2023). Once declining trees are detected, wood samples are collected to assess the actual presence of PWN through laboratory assays (Mariette et al. 2023). Alternatively, the presence of PWN-infested trees in an area may be inferred from pheromone trapping *M. galloprovincialis*, and testing with molecular markers whether beetles are carrying PWN (Sanchez-Husillos et al. 2015). If a trapping network is used and at least three traps succeed in trapping PWN-carrying beetles, the approximate location of the PWN-infested tree from which the insects emerged can be inferred by triangulation (Nunes et al. 2021).

New alternative PWN eradication strategies cannot be tested in the field because of limitations of designing controlled experiments as well as EU regulations (Sun et al. 2023). Therefore, we use modelling to compare the cost-effectiveness of two eradication strategies, 1) the statutory 500-m-radius clear-cutting and 2) a selective cutting on a tree-by-tree basis. Both strategies were applied in combination with different levels of surveillance intensity based on: i) visual ground surveillance (current practice), ii) visual ground surveillance combined with beetle trapping networks, and iii) aerial surveillance. Surveillance was implemented at the end of beetle flight season (mid-autumn). We simulated the spread of PWN in a 20 × 20 km landscape of pure maritime pine, using an individual-based model for the movement of its vector *M. galloprovincialis* (Robinet et al. 2019, 2020) and quantified the success of eradication of PWN upon its entry through an infested log in the area, leading to the release of PWN by 1-100 beetles (Naves et al. 2006). Two other entry scenarios were considered which yielded similar results to the baseline scenario (see Appendix, Methods S3.3). The costs and effectiveness of the two eradication strategies were tested for three different surveillance methods each with various intensities, along with varying proportions of symptomatic trees at the time of survey in our 20 × 20 km landscape. We additionally explored a near-perfect condition in which surveillance was implemented with near 100% detection efficiency when all PWN-infested trees showed symptoms, and an extremely favorable condition without native patrolling beetles, i.e. beetles that are present in the forest but not yet carrying the disease.

3.2 Results

3.2.1 Cost and effectiveness of two strategies

PWN can only be eradicated in the long term if the net reproductive number of infested trees is below one, such that the number of infested trees diminishes with each new generation. We calculated the net reproductive numbers of infested trees (R_{cases}, Eq. 3.1 in Materials and Methods), and of beetles carrying PWN (R_{vector}, Eq. 3.2 in Materials and Methods). We also determined from each simulation the proportion of infested trees that were cut (sensitivity, Eq. 3.3 in Materials and Methods) and the proportion of healthy trees that were preserved (specificity, Eq. 3.4 in Materials and Methods).

Clear-cutting was always more effective than tree-by-tree selective cutting in terms of the net reproductive numbers R_{cases} (Fig. 3.1A-E), and R_{vector} (Fig. 3.1F-J) as well as in terms of sensitivity (Fig. 3.2A-E) for the same surveillance method. However, tree-by-tree selective cutting resulted in a higher specificity and lower costs (Fig. 3.2F-J).

Importantly, if PWN was introduced through a log containing PWN-carrying beetles, resulting in 1 to 100 beetles emerging from the log of which 91% carry PWN (Naves et al. 2006), neither clear-cutting nor tree-by-tree selective cutting could reduce R_{cases} and R_{vector} below one when only ground survey was used (standing practice). In contrast, clear-cutting and tree-by-tree selective cutting in combination with intensive aerial surveillance could reduce R_{cases} below one when 100% of the infested trees showed symptoms (Fig. 3.1A). To achieve this, clear-cutting needed 2 or more air flights with 0.91 detection efficiency, while 4 or more air flights with 0.91 detection efficiency (Qin et al. 2021; Jactel et al. 2023) were needed for tree-by-tree selective cutting (Fig. 3.1A). This represents a near-perfect condition in which all infested trees showed symptoms and nearly all symptomatic trees were detected. R_{vector} dropped below one when the air flight number was increased to 5 (Fig. 3.1F) for tree-by-tree selective cutting. Clear-cutting and tree-by-tree selective cutting could make R_{cases} below one when not all trees were symptomatic (80% and 89%, respectively) only when no native patrolling beetles were present and intensive aerial surveillance was performed (3 air flights, 0.91 detection efficiency) (Appendix, Fig. S3.4i-a). Thus under these conditions eradication could be achieved for 1-100 initial emerging beetles.

When comparing the costs of eradication for scenarios that led to a $R_{cases} < 1$, the costs of clear-cutting (~ € 237.8 million) in combination with 2 air flights (Fig. 3.1A) were on average a factor 198 higher than that of tree-by-tree selective cutting (~ € 1.2 million) in combination with 4 air flights. When the proportion of symptomatic trees was no less than 60%, tree-by-tree selective cutting with aerial surveillance can achieve the same level of effectiveness as the standing practice of clear-cutting with visual ground surveillance at a cost that was on average 88 times lower. If less than 60% of the infested trees showed symptoms, tree-by-tree selective cutting with aerial surveillance can only achieve the same level of effectiveness as clear-cutting if clear-cutting was combined with low intensity visual surveillance (e.g. Fig. 3.1D and E).

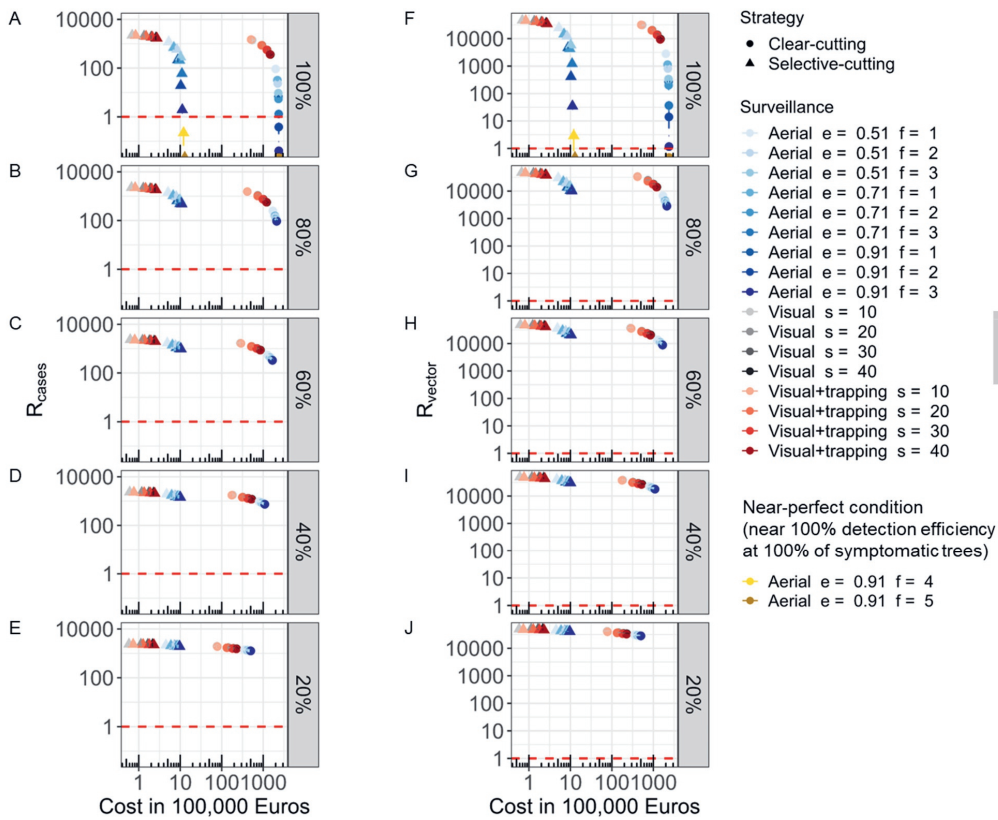

Fig. 3.1 Relationships between costs (x-axis) and the two performance metrics R_{cases} and R_{vector} (y-axis) of the evaluated eradication strategies based on clear-cutting and tree-by-tree selective cutting. R_{cases} and R_{vector} represent the yearly multiplication factors of the number of PWN-infested trees and the number of PWN-carrying vectors, respectively. Three methods for surveillance are considered: (1) aerial surveillance, (2) visual ground surveillance and (3) a combination of visual ground surveillance and trapping networks with pheromone traps to locate the first diseased tree. Surveillance is carried out when 100%, 80%, 60%, 40% and 20% (right side of each panel) of the infested trees are symptomatic. R_{cases} and R_{vector} and costs are presented on a log10 logarithmic axis. *Circles* represent clear-cutting, and *triangles* indicate tree-by-tree selective cutting. *Blue colors* represent aerial surveillance with aerial detection efficiency *e* per flight and *f* numbers of air flights, *grey colors* represent visual ground surveillance with *s* roads sampled, *red colors* indicate visual ground surveillance combined with trapping networks *s* roads sampled, and *yellow colors* represent the near-perfect condition of 100% of the infested trees showing symptoms and a near 100% detection efficiency. *Bars* represent confidence intervals of the mean for 50 simulations. *Dashed red lines* represent R_{cases} and R_{vector} values of 1. Results for the other two entry scenarios are presented in Appendix, Figs. S3.2 and S3.3

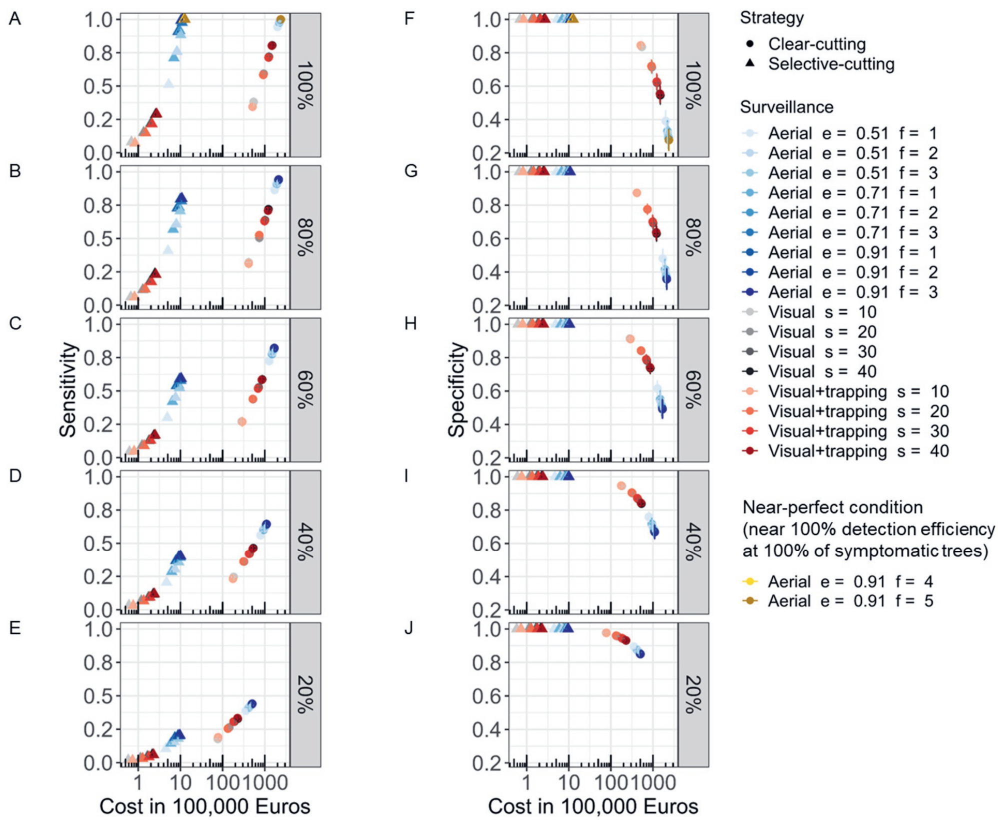

Fig. 3.2 Relationships between costs (x-axis) and the two performance metrics sensitivity and specificity (y-axis) of the evaluated eradication strategies based on clear-cutting and tree-by-tree selective cutting. Three methods for surveillance are considered: (1) aerial surveillance, (2) visual ground surveillance and (3) a combination of visual ground surveillance and trapping networks with pheromone traps to locate the first diseased tree. Surveillance is carried out when 100%, 80%, 60%, 40% and 20% (right side of each panel) of the infested trees are symptomatic. Costs are presented on a log10 logarithmic axis. *Circles* represent clear-cutting, and *triangles* indicate tree-by-tree selective cutting. *Blue colors* represent aerial surveillance with aerial detection efficiency *e* per flight by *f* number of air flights, *grey colors* represent visual ground surveillance with *s* roads sampled, *red colors* indicate visual ground surveillance combined with trapping networks with *s* roads sampled, and *yellow colors* represent the near-perfect condition of 100% of the infested trees showing symptoms and a near 100% detection efficiency. *Bars* represent confidence intervals of the mean for 50 simulations. Results for the other two entry scenarios are presented in Appendix, Figs. S3.2 and S3.3

3.2.2 The effect of eradication strategies on trees

According to the baseline scenario of 1-100 initial emerging beetles, more trees in total but also more infested trees were cut by clear-cutting than tree-by-tree selective cutting for the same intensity of surveillance (Fig. 3.3). For instance, if visual ground surveillance was done when all PWN-infested trees showed wilt symptoms, clear-cutting resulted in an average of ~ 1.8 million cut trees (s.e. ± 111,417) of which 0.1% were infested. Clear-cutting nevertheless retained 15% of the infested trees (360 out of 2,416). Tree-by-tree selective cutting resulted in an average of 694 ± 54 cut trees which were all infested, while 71% of the infested trees (1,722 out of 2,416) were not cut (Fig. 3.3). Therefore, tree-by-tree selective cutting left more infested trees than clear-cutting but saved a large number of healthy trees.

Aerial surveillance was more efficient in detecting infested trees than the currently implemented visual ground surveillance (Appendix, Tables S3.8-S3.10). Under the baseline scenario of 1-100 initial emerging beetles (Appendix, Table S3.8), and surveillance at the time when all PWN-infested trees showed wilt symptoms, visual ground surveillance detected on average 19% of the infested trees (448 out of 2,416), ranging from 191 ± 16 to 694 ± 54, depending on the intensity of visual ground surveillance. Including trapping networks did not help detect more infested trees. In contrast, aerial surveillance detected on average 85% of the infested trees (2,056 out of 2,416), depending on the detection efficiency, ranging from 1,233 ± 96 to 2,414 ± 189.

3.2.3 Cost components of two strategies

Revenue loss was the timber losses (revenues foregone) due to the cutting of non-infested trees, represented the largest proportion of total costs in clear-cutting (on average 73% of the total costs across surveillance methods) in contrast to zero in tree-by-tree selective cutting (Fig. 3.4, Appendix, Tables S3.11-S3.19). Additionally, logging and chipping costs were substantially higher with clear-cutting compared to tree-by-tree selective cutting. For tree-by-tree selective cutting, wood sampling costs constituted the largest costs (on average 83% compared to 0.5% in clear-cutting) (Fig. 3.4, Appendix, Tables S3.11-S3.19).

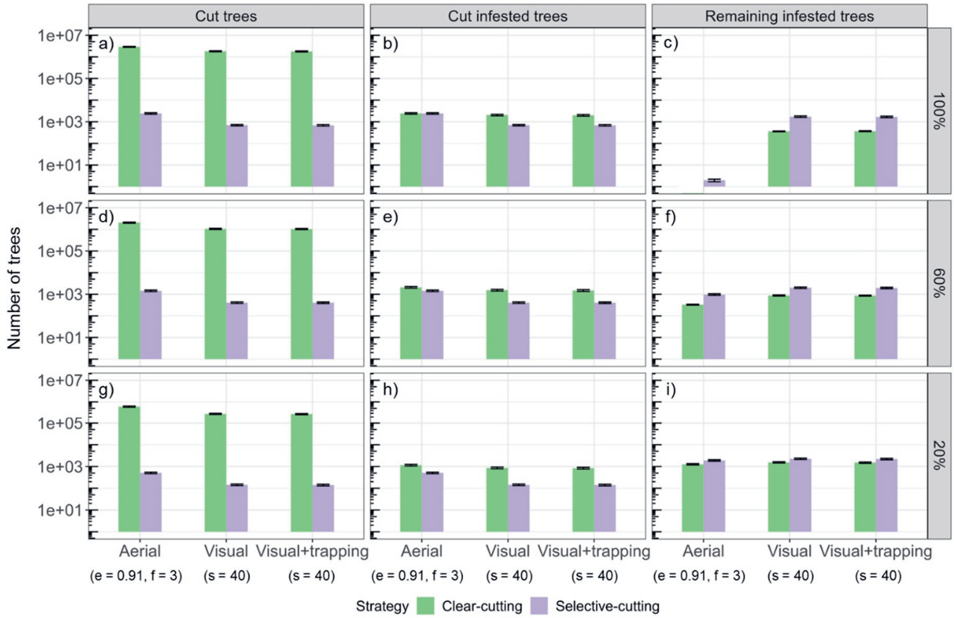

Fig. 3.3 The number of cut trees (a, d, g), cut infested trees (b, e, h) and remaining infested trees (c, f, i) in clear-cutting (*green bars*) and tree-by-tree selective cutting (*purple bars*) in terms of visual ground surveillance, visual ground surveillance combined with trapping networks, and aerial surveillance when 100%, 60% or 20% of the infested trees are symptomatic (right side of each panel). The symbol *s* indicates the number of sampled roads, *e* represents the aerial detection efficiency and *f* represents the number of surveillance air flights. The presented numbers represent the average value ± standard error based on 50 simulations per scenario. Results for other intensities of surveillance, and entry scenarios are presented in Appendix, Tables S3.8-S3.10

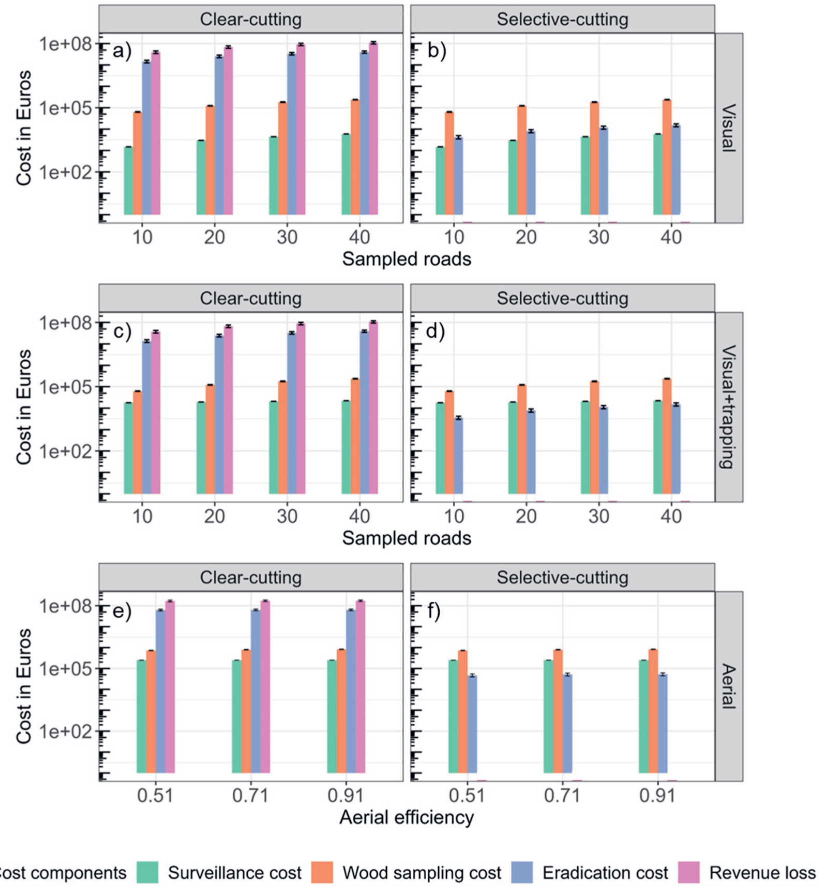

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Fig. 3.4 Cost components when eradication is implemented using visual ground surveillance (a, b), visual ground surveillance combined with trapping networks (c, d) and aerial surveillance (3 air flights) (e, f) under clear-cutting and tree-by-tree selective cutting in relation to the number of sampled roads and aerial detection efficiency, when 100% of the infested trees are symptomatic. Costs were expressed in Euros on a log10 scaled axis. *Bars* represent the mean ± standard error of 50 simulations. See Appendix, Tables S3.11-S3.19 for the costs when 80%, 60%, 40% and 20% of the infested trees are symptomatic, and the costs for the other two entry scenarios

3.3 Discussion

The results of this study show that both clear-cutting and tree-by-tree selective cutting are effective in eradicating PWN ($R_{cases} < 1$) only when aerial surveillance is used and when almost 100% of the infested trees show symptoms at the time of surveillance. Despite, tree-by-tree selective cutting required more flights compared to clear-cutting to achieve this (four compared to two), it reduced costs approximately 200 fold by avoiding the unnecessary removal of a large number of healthy trees. When no less than 60% of the infested trees show symptoms, tree-by-tree selective cutting with aerial surveillance can achieve a given level of effectiveness at approximately 88-fold lower costs on average compared to the standing practice of clear-cutting with visual ground surveillance.

3.3.1 Effectiveness

Our results indicated that, under the official EU PWN regulation of a 500-m-radius clear-cutting zone, eradication would not be 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 with pheromone trapping of the vector. In these cases, R_{vector} and R_{cases} would always exceed one (Fig 3.1). In contrast, aerial surveillance with almost perfect detection efficiency, implemented when almost 100% of the infested trees are symptomatic, would lead to a R_{cases} below one for both clear-cutting and tree-by-tree selective cutting. However, assuming that 100% of the 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 unrealistic (Soliman et al. 2011; Carrasquinho et al. 2018). Hence, aiming for containment of PWN may be more realistic than aiming for complete eradication.

The strict conditions described above indicated that achieving eradication of PWN is nearly impossible. This can be explained by the existence of beetles that are present in the forest which do not carry PWN (so called native patrolling beetles). Their offspring could become infested as native patrolling beetles are attracted to trees that have become infested by the initially PWN-carrying beetles during the maturation feeding or egg laying. This results in a high reproductive factor of the disease; they account for 97% and 99.96% of R_{cases} and R_{vector} respectively, and to the difficulty of detecting all infested trees before they act as sources. Our results indicated that without native patrolling beetles, clear-cutting in combination with aerial surveillance could eradicate PWN when at least 80% of infested trees were symptomatic while tree-by-tree selective cutting with aerial surveillance required at least 89% of the infested trees showed symptoms to achieve eradication (Appendix, Fig. S3.4). Therefore, eradicating PWN may be possible when native patrolling beetles are at low density, so that not every remaining infested tree would contain eggs of native patrolling beetles after implementing eradication strategies. When the patrolling beetle population are at high levels, tree-by-tree selective cutting should be accompanied with additional measures to control the beetle population which 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).

The more infested trees are showing wilting symptoms the more effective the surveillance becomes. 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 infested trees have become sources of PWN carrying beetles. If PWN were to be introduced in Southwestern 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 (Soliman et al. 2011; Carrasquinho et al. 2018). This gives a window of opportunity for intensive surveillance combined with tree-by-tree selective cutting, and hence effective eradication of the epidemic.

If infested trees do not show symptoms before the next beetle growing season, or if accurate detection is not possible, clear-cutting may be preferable. Clear-cutting consistently yields lower R_{cases} and R_{vector} and higher sensitivity compared to tree-by-tree selective cutting for the same surveillance intensity. This is because clear-cutting can remove potentially infested trees surrounding undetected infestations, thus eliminating the necessity to detect all symptomatic trees. Clear-cutting is effective as long as infested trees are clustered in the landscape (Appendix, Fig. S3.6). However, the high costs of clear-cutting should be considered.

Tree-by-tree selective cutting preserves a much larger number of uncut healthy trees compared to clear-cutting. Removing all trees (including healthy ones) in a large clear-cutting area will force beetles to fly longer distances looking for host trees (Nunes et al. 2021). On the opposite, the existence of pine trees preserved by tree-by-tree selective cutting, may enable a larger proportion of emerging insects to be retained on site (for maturation feeding, for example) and thus it would be more likely to slow the PWN spread.

3.3.2 Cost-effectiveness

When the proportion of symptomatic trees is no less than 60%, for the same effectiveness, tree-by-tree selective cutting with aerial surveillance could contain PWN at costs on average 88 times lower than the standing practice of clear-cutting with visual ground surveillance. 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 estimate that clear-cutting in our study area would release on average ~ 19 kilotons more carbon than tree-by-tree selective cutting based on the difference in the number of cut healthy trees between two strategies (1.3 million, Appendix, Tables S3.8-S3.10), and the amount of carbon stored per year per live pine tree (Seidl et al. 2018; Schulz 2023). We also estimated that clear-cutting will result in an additional non-market loss of on average ~ € 2,308 per hectare compared to tree-by-tree selective cutting given the difference in the number of cut healthy trees between two strategies, and the non-market value per tree (Lopes 2013). In agreement with the statement of Robinet et al. (2020) these costs saved could be reallocated to more intensive surveillance combined with tree-by-tree selective cutting.

Aircraft and satellites equipped with imaging technology represent the future of monitoring to survey PWN-infested forest. By combining them with deep learning algorithms, the efficiency of detection can be substantial (Deng et al. 2020; Qin et al. 2021; Zhang et al. 2021; Luo et al. 2023; Li et al. 2023). For example, a recent study utilizing high resolution earth observation satellite imagery achieved an accuracy of > 98% (Zhou et al. 2022). Unmanned Aerial Vehicles (UAVs) are also powerful tools (Deng et al. 2020; Qin et al. 2021; Zhang et al. 2021; Luo et al. 2023; Li et al. 2023), however, the utility in large areas is limited as they need to stay in sight of the operator. So in the long run, we expect that satellites will replace aircraft flights thus saving the flight costs (Zhou et al. 2022) and allowing a more frequent surveillance of forested areas. Instead of destructive clear-cutting, aerial surveillance in combination with immediate felling of detected infested trees can provide a more sustainable alternative to control PWN. Before PWN introduction, the costs of aerial surveillance, including the subsequent costs of wood sampling due to non-PWN symptomatic trees, (0.91 efficiency and 1 air flight) are currently on average € 3.2 million per year higher than the visual ground surveillance (20 roads sampled for which at least one infested tree could be detected). In this case, during the annual surveillance conducted before the arrival of PWN, a two-step procedure might be used to save costs. In the first step, visual ground surveillance with at least 20 sampled roads is used to identify whether any infested trees are present, and if this is the case, in a second step, intensive aerial surveillance is used to detect all.

In our cost calculation, the costs of surveillance and wood sampling were allocated to the control of PWN only. In practice, other pests could be detected when surveilling PWN. As the surveillance can potentially be shared with forest health programs other than PWN control and serve as an early warning system, we might have overestimated the surveillance and wood sampling costs. A reduction in surveillance and wood sampling costs would be beneficial to the tree-by-tree scenarios as they account for about 97% of the total costs. Total costs of clear-cutting scenarios are less sensitive to a change in surveillance and wood sampling costs as they only account for minor part (~ 0.6%) in the total costs.

Our analysis exploring alternative strategies to manage invasive pests has a general applicability to a wide range of species for which clear-cutting is implemented, e.g. *Xylella fastidiosa*, *Aromia bungii*, *Fusarium circinatum*, *Phytophthora ramorum*, *Anoplophora glabripennis* and *A. chinensis* in Europe (Branco et al. 2021; Sun et al. 2023), Plum pox virus and *P. ramorum* in America (Rizzo et al. 2005; Gougherty et al. 2015), Citrus canker in Australia and South America (Sharma and Sharma 2009), and Cocoa pod borer in Australia (Business Queensland 2019). In the case of PWN, we could rely on a broad literature studying the biology and dispersal of the vector. Similar studies are needed for other pest-vector-plant (e.g. *X. fastidiosa*) or pest-plant (e.g. *A. glabripennis*) systems to develop control methods that have less environmental impact.

3.4 Conclusion and Outlook

In conclusion, this work demonstrates that 1) tree-by-tree selective cutting could eradicate PWN, similar to clear-cutting, by using intensive aerial surveillance when almost 100% of the infested trees are symptomatic; 2) containment would be more realistic than eradication if PWN is introduced into the areas where native vector beetles are at high population level; 3) aerial surveillance is more effective at controlling PWN than ground surveillance; 4) tree-by-tree selective cutting is always more cost-effective than clear-cutting for the same level of effectiveness, as it saves the costs of cutting healthy trees.

3.5 Materials and Methods

3.5.1 General outline

The management of PWN outbreaks comprises four main steps: 1) detection of declining trees (that could be affected by PWN or other factors) through surveillance; 2) collecting wood samples on declining trees for confirming the presence of the PWN by morphological or DNA analysis (Schröder et al. 2009); 3) clear-cutting within a 500-m-radius around the detected tree(s); and 4) cutting and chipping of host trees.

We aimed to simulate the spatio-temporal distribution of symptomatic trees and asymptomatic trees that are infested by PWN during one flying season of its vector *M. galloprovincialis* (May to October). For this, we modified the individual-based model of Robinet et al. (2020) to explicitly consider the location of the pine trees and simulate the dispersal of *M.*

galloprovincialis carrying PWN, and the transmission of the nematodes to the trees during the maturation feeding of young adults or egg-laying by female *M. galloprovincialis.* Our in silico study area was a 20 km × 20 km landscape of pure maritime pine plantations (Appendix, Fig. S3.7), representative of the Landes Forest (the largest artificial forest in Europe, located in Southwestern France).

Three surveillance methods were considered in our study: visual surveillance of wilting symptoms from the ground, visual surveillance from the ground combined with *M. galloprovincialis* trapping networks, and aerial surveillance. Here, we used trapping networks to approximate the location of the most likely first PWN-infested tree, based on triangulation of locations of the traps where PWN-carrying beetles were captured. Hence trapping networks alone are not appropriate to detect all symptomatic trees. Two eradication strategies were compared, clear-cutting and tree-by-tree selective cutting. The aim of both strategies is to remove infested trees before they can act as sources of PWN-carrying beetles in the next spring (following Robinet et al. (2020)). The percentage of infested trees expressing disease symptoms is a function of time and varies with environmental drivers, mainly air temperature and drought stress (Evans et al. 2008). To explore the effects of the proportion of symptomatic trees infested by PWN on the costs and effectiveness of two strategies, the surveillance was simulated to be implemented when 100%, 80%, 60%, 40%, and 20% of PWN-infested trees were symptomatic.

We analysed the cost-effectiveness of different surveillance and eradication scenarios based on model outcomes. Costs comprise surveillance costs, wood sampling costs (field sampling and laboratory testing), eradication (logging and chipping) costs and revenue loss of timber value due to cutting healthy trees. Effectiveness was defined using four indicators: two proxies of the net reproductive numbers (R) in any epidemics in terms of infested trees (R_{cases}) and beetles with PWN (R_{vector}), the proportion of cut infested trees (sensitivity), and the proportion of preserved healthy trees (specificity). To measure cost-effectiveness, we plotted costs on the x-axis and effectiveness on the y-axis. This allows determining, for a given level of effectiveness, which strategy is least costly. Below, we describe each part of our model and analysis step by step. See Appendix, Materials and Methods for more details.

3.5.2 Host

We considered that maritime pine trees, *P. pinaster*, were distributed homogenously with a distance of 10 m between two adjacent trees in a 20 km × 20 km landscape, which resulted in 4,004,001 pine trees. We assumed that all trees were healthy at the beginning of the simulations. When a tree becomes infested by PWN, it stays asymptomatic for a certain period (incubation time). Trees begin to show wilt symptoms with needle discoloration (called symptomatic trees) after an incubation period that varies from 6-8 weeks to several months, depending on the temperature and tree physiological status after being infested (Fielding and Evans 1996). In our model, we assumed that the incubation time was 30 days. Due to our time frame of one year, we considered that all pines stayed alive (even if declining) during the simulated time regardless of their infection status. See Appendix, Methods S3.1 for more details.

3.5.3 Vector dispersal and PWN transmission

We built on an individual-based model that was developed by Robinet et al. (2020) to simulate the dispersal of beetles after adult emergence, describing feeding and oviposition activities, and PWN transmission along the vector's adult life span. In our model, the adults of *M. galloprovincialis* emerged from trees from the beginning of May and the emergence period lasted until September with a peak in July, which is representative of the flight in Portugal (Naves et al. 2008) and France. The detailed description of vector dispersal and PWN transmission can be found in Appendix, Methods S3.2.

3.5.4 Initial inoculum

We distinguished three different scenarios of how PWN is introduced in a healthy forest. The three scenarios differed on the number of initial beetles and the possibility of the infested trees being colonized then by native patrolling beetles present in the landscape. We presented the results of the baseline scenario of 1-100 initial emerging beetles in the main body, which depicted the entry of PWN through a log that originated from an area where PWN was present in the previous year. The other two entry scenarios gave similar results which were shown in Appendix, Figs. S3.2, S3.3, and S3.5. The detailed description of three entry scenarios can be found in Appendix, Methods S3.3.

3.5.5 Surveillance

Three surveillance methods were considered in our model: visual surveillance from the ground, visual surveillance from the ground combined with trapping networks, and aerial surveillance. Each surveillance is conducted for only once, followed by two eradication strategies. For aerial surveillance, several air flights work at one time given the aerial detection efficiency.

Visual surveillance from the ground

Visual ground surveillance is commonly done by driving with a car on roads through the forest. We therefore explicitly considered the road network of our study area. We implemented a grid pattern of 40 roads running north-south and 40 roads running east-west, each road at 0.5 km distance from the nearest parallel road, to represent the road density and distribution in Southwestern France. Roads were randomly selected ranging from 10 to 40 with an increment of 10. The parameters regarding visual ground surveillance are listed in Appendix, Methods S3.4.1.

Visual surveillance from the ground combined with trapping networks

A trap density of 1 trap per 16 km^2 is manageable to catch beetles and locate the tree where the initially PWN-carrying beetles emerge in Southwestern France (Appendix, Methods S3.4.2). Thus, we assumed that 25 traps were homogenously distributed in our model landscape. We assumed that traps were installed at the beginning of the dispersal season in May, and that both the collection of caught beetles and pheromone replacement were done every month until the end of the dispersal season in October. At the end of the simulated dispersal, we calculated the theoretical origin of the infested beetles. We used the weighted barycenter method (we weighted the coordinates of the traps by the number of PWN-infested beetles caught in each trap) and we assumed that the symptomatic tree infested by PWN closest to this theoretical origin was the putative origin. It was then assumed that visual ground surveillance around this location would be used to find the actual source. The parameters of trap density and trap efficiency are described in Appendix, Methods S3.4.2.

Aerial surveillance

Aerial surveillance can be used to detect declining trees from the images that are captured by cameras mounted on aircraft. Aerial surveillance is not a “routine approach” so far in France, but a prospective approach based on latest technology development. More precisely, we considered aircraft rather than drones because drones will fly out of sight in our landscape which is not allowed in France. We used an aerial efficiency of 0.91 per air flight as the base efficiency (Qin et al. 2021; Jactel et al. 2023). To take into account the variation of aerial performance in practice, we additionally tested a range of aerial surveillance efficiencies of 0.51 and 0.71 per air flight. We considered 1, 2 and 3 air flights for each efficiency (Appendix, Methods S3.4.3). To test the potential of both strategies, we considered 4 and 5 air flights for the best detection efficiency of 0.91 (leading to near perfect detection) when 100% of the infested trees are symptomatic, assuming the most likely scenario of PWN entry (with 1-100 initial emerging beetles). The detection efficiency of aerial surveillance is described in Appendix, Methods S3.4.3.

Wood sampling

After the detection of declining trees by visual 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.

3.5.6 Eradication strategies

Clear-cutting and tree-by-tree selective cutting were compared. In clear-cutting, a 500-m-radius clear-cutting zone was delimited around every detected declining and confirmed PWN-infested tree and all host trees within the clear-cutting zone were cut and chipped. In tree-by-tree selective cutting, only the detected declining and confirmed PWN-infested trees were cut and chipped.

3.5.7 Cost-effectiveness analysis

3.5.7.1 Costs

Surveillance costs, wood sampling costs, eradication (logging and chipping) costs and revenue loss were incorporated in calculating costs.

Surveillance methods

- Visual ground surveillance

The costs of visual ground surveillance accounted for the operational costs consisting of vehicle, labour and daily allowance costs, which depended on the number of roads sampled. Depending on the numbers of roads sampled (Appendix, Table S3.3 and Methods S3.4.4), the costs ranged from € 1,491 for sampling 10 roads to € 5,930 for sampling 40 roads on our area of 20 km × 20 km.

- Aerial surveillance

The costs of aerial surveillance covered the flight costs over the 20 km × 20 km area and the costs for the analysis and storage of the images that have been taken. Based on Appendix, Table S3.4 these surveillance costs corresponded to a total amount of € 80,000 per air flight.

- Trapping surveillance

The costs of trapping surveillance included the costs of the traps, the labour and equipment costs related to trap installation and checking, and the costs of analyzing the collected samples in the lab. Based on the input of Appendix, Table S3.5 and Methods S3.4.4, the total costs of trapping surveillance equaled € 16,505.

Wood sampling

Costs related to wood sampling and confirmation tests were calculated, including labour and equipment costs. Based on these values, the total costs for sampling and testing equaled € 57 per wood sample (Appendix, Table S3.6 and Methods S3.4.4). The number of wood samples depended on the number of declining trees that have been detected by the surveillance method (visual ground surveillance or aerial surveillance). See Appendix, Table S3.6 and Methods S3.4.4 for the calculation of the number of wood samples.

Eradication strategies

As the cost calculation of the eradication strategies only varied with the number of trees cut, the costs of both eradication strategies depended on the costs of logging and chipping a tree. To estimate these costs, calculations were performed considering labor and equipment expenses. The total costs for logging and chipping a tree equaled € 22 (Appendix, Table S3.7 and Methods S3.4.4).

Revenue loss

The opportunity value of the non-infested trees that were cut as part of the eradication strategy was aligned with the estimated standing value of a 'ready-to-be-harvest' tree. Revenue loss was the timber losses (revenues foregone) due to the cutting of non-infested trees. The timber value of cutting a healthy tree is € 60 (Appendix, Table S3.7 and Methods S3.4.4). We assumed that the infested trees that have been logged and chipped have no value as timber. The timber value for the whole pine forest when no PWN occurs was about € 240 million.

3.5.7.2 Effectiveness

The net reproductive number (R) is the yearly multiplication factor of infested units, and was used as an indicator of effectiveness. It indicates whether the epidemic can be stopped by the eradication strategy in the long term (Heesterbeek 2002). R_{cases} was the indicator used to evaluate the yearly spread of PWN among host trees and R_{vector} was used to estimate the rate of annual spread of PWN among beetles that vector PWN. The epidemic can be stopped if R_{cases} is below one. Specifically, we define R_{cases} as follows:

$$R_{cases} = \frac{T_{inf,t=1}}{T_{inf,t=0}} \qquad (3.1)$$

where $T_{inf,t=1}$ is the number of PWN infested trees with eggs at the start of growing season of the second year and $T_{inf,t=0}$ is the number of initially PWN infested trees with eggs at the start of the growing season of the first year. R_{vector} is defined as:

$$R_{vector} = \frac{B_{t=1}}{B_{t=0}} \qquad (3.2)$$

where $B_{t=1}$ is the number of adult beetles emerging from PWN infested trees and carrying PWN at the start of the second year. These adult beetles emerged from eggs laid by initial emerging adult beetles carrying PWN, and from eggs of native patrolling beetles that laid eggs on infested trees. $B_{t=0}$ is the number of initial adult beetles with PWN at the beginning of the first year. We estimated the number of adult patrolling beetles on PWN-infested trees by multiplying the native patrolling beetle density by the number of PWN-infested trees. Based on field observations, the number of native patrolling beetles emerging per tree (of ca 1 m^3) in Southwestern France is about 1,000. The number of initially PWN-infested trees from which adult beetles emerged is constant at 1 in our model (Appendix, Methods S3.3). We also calculated the aforementioned metrics assuming no native patrolling beetles are present, thus adult beetles emerging from PWN-infested trees and carrying PWN at the second year are divided by the initial emerging adult beetles with PWN. The results of effectiveness with no native patrolling beetles involved can be found in Appendix, Figs. S3.4 and S3.5.

The sensitivity of the eradication strategy (Eq. 3.3) specifies which proportion of infested trees are cut relative to the total number of infested trees. The specificity indicates how many healthy trees are preserved relative to the total number of healthy trees (Eq. 3.4).

$$Sensitivity = \frac{Cut\ infested\ trees}{Total\ infested\ trees} \qquad (3.3)$$

$$Specificity = \frac{Preserved\ healthy\ trees}{Total\ healthy\ trees} \qquad (3.4)$$

3.5.8 Model scenarios

We compared the two eradication strategies in combination with intensity-varying surveillance methods based on visual ground surveillance, visual ground surveillance combined with trapping networks and aerial surveillance. We used the number of sampled roads as measure of visual ground surveillance intensity, and aerial efficiency and air flight numbers for aerial surveillance. For the visual ground surveillance and visual ground surveillance combined with trapping networks, we tested a range of sampled roads from 10 to 40 (for each direction), with an increment of 10. For aerial surveillance, we tested an efficiency of 0.51, 0.71 to 0.91 per air flight (1, 2, and 3 air flights for each efficiency) to take into account the variation of aerial performance in practice.

We considered three starting scenarios regarding the number of initial emerging beetles. We applied these combinations when 100%, 80%, 60%, 40%, and 20% of the infested trees were symptomatic, resulting in 510 different scenarios. Specifically, we explored scenarios with the near-perfect condition, i.e. 4 and 5 air flights at 0.91 detection efficiency per air flight, and 100% of infested trees were symptomatic under the most likely scenario of PWN introduction (1-100 initial emerging beetles) for two strategies (Figs. 3.1 and 3.2, A and F). This investigation resulted in the formulation of four additional scenarios. We also calculated another extreme condition in which no native patrolling beetles are present, meaning there is no contribution of native patrolling beetles to R_{cases} and R_{vector} (Appendix*,* Figs. S3.4 and S3.5), resulting in 340 additional scenarios.

Code availability

Data and R scripts are available at: https://zenodo.org/records/10370415.

Acknowledgments and funding sources

This work was funded by the European Union's Horizon 2020 Program for Research and Innovation under grant agreement "HOMED" (European Union; grant number: 7771271), and China Scholarship Council (China; grant number: 201906350034). M.B. is support by national funds of the FCT (Portuguese Foundation for Science and Technology) under the projects Forest Research Centre (CEF) (UIDB/00239/2020), and the Laboratory for Sustainable Land Use and Ecosystem Services—TERRA (LA/P/0092/2020).

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Chapter 4

Comparing inward and outward strategies for delimiting non-native plant pest outbreaks

Hongyu Sun [1], Jacob C. Douma [1], Martijn F. Schenk [2], Wopke van der Werf [1]

[1] Wageningen University and Research, Centre for Crop Systems Analysis, P.O. Box 430, 6700 AK Wageningen, The Netherlands

[2] Netherlands Food and Consumer Product Safety Authority (NVWA), P.O. Box 43006, 3540 AA Utrecht, The Netherlands

Abstract

This chapter addresses the problem of delimiting an outbreak of a non-native plant pest. Currently, outbreaks are delimited by sampling around the initial finding, moving outward as long as infestations are found (outward strategy). It has been suggested that it might be more effective to start delimitation with an initial estimate of the infested zone, and then sample inward from this initially estimated frontier until infestations are found or outward until no new infestations are found (inward strategy). We used individual-based modelling to compare the effectiveness and sampling effort of such outward and inward strategies. Both strategies successfully delimited a high proportion of infested plants within the infested zone, 0.9982 for the inward strategy and 0.9977 for the outward strategy. However, both strategies had a low probability of enclosing all of the infested plants (*viz.* 0.15 vs 0.12). In those cases (44% of the simulations) that the two strategies delimited equal proportions of infested plants, the outward strategy usually (76% of cases) outperformed by using fewer samples. The costs of the inward strategy depended greatly on the size of the initially hypothesized infested zone (used as a starting point of the inward strategy). Sampling costs of this strategy could be very high if the initial estimate of the size of the infested zone was far greater than the true spatial extent of the outbreak. The modeling results indicated that both strategies are prone to error, particularly in delimiting outbreaks caused by pests with fat-tailed dispersal. Theoretically, a high rate of correct delimitations requires very high sampling effort, ensuring high detection probability at low prevalence. Best performance of the inward strategy is obtained if the initial estimate of the infested zone is close to the true value. Whether the inward or outward strategy is more effective depends on the certainty of knowledge about the true position of the leading front of the outbreak. Possibilities are discussed to further improve the cost-effectiveness of sampling for delimitation. For instance, a safety factor could be used to the delimited zone to enclose all infested plants depending on the relative proportion of long distance jumps.

Keywords Delimitation, infested zone, invasive plant pests, risk management, survey

4.1 Introduction

Non-native plant pests can be introduced into new areas with plants or plant products via trade (Smith et al. 2007; Hulme 2009; Chapman et al. 2017). When phytosanitary measures fail to prevent entry, pests may transfer to a suitable host and establish if environmental conditions are favorable (Box 4.1). FAO (2023) defines an outbreak of a non-native plant pest as “a recently detected pest population, including an incursion”, while an incursion is defined as “an isolated population of a pest recently detected in an area, not known to be established, but expected to survive for the immediate future”. To facilitate eradication of outbreaks, it is important to determine the spatial extent of the population (FAO 2023). The process of establishing the boundaries of an outbreak is called delimitation (ISPM 5, FAO, 2023). Once the delimitation is completed, this typically results in the establishment of so-called demarcated areas in which phytosanitary measures are imposed to achieve eradication of the pest and prevent further spread (European Union 2019). Delimitation is usually used to describe the infested zone, whereas demarcation typically refers to a demarcated area that includes an infested zone and a buffer zone (European Union, 2019).

Typically, the demarcated area consists of an infested zone and a buffer zone (European Union 2019). The infested zone is infested by the specified organism, while the buffer zone surrounds the infested zone and is established to minimize the probability of spread of the pest out of the infested zone. Whenever the pest is subsequently detected in the buffer zone, this should trigger enlargement of the infested zone (FAO 2019). Both the infested zone and buffer zone are usually subject to specific phytosanitary measures (European Union 2012, 2015). Typical measures for the infested zone are destruction of infested plants or host plants and a ban on transport of host plants (European Union 2015, 2020; European Commission 2018), whereas surveillance is a typical measure in the buffer zone (EPPO 2021a). Given that measures are zone-specific, it is very important to accurately delimit the infested zone. When the infested zone is too small, undetected infested plants may serve as a source for further spread, thus jeopardizing the success of eradication or containment (EFSA 2012a). When the infested zone is too big, more plants than needed are subject to destructive measures (Yemshanov et al. 2019). Both types of errors can be costly and undesirable.

Currently, there is no consensus on how to delimit the infested zone most accurately (EPPO 2021a). An intuitive procedure for delimitation would be to initiate the surveys in close vicinity to the first finding by examining host plants that are within the spread distance of the involved pest and then gradually move outward, until no further detections are made (hereafter called outward strategy). As an alternative, one may aim to start surveying ahead of an unknown, presumed disease front, further away from the first finding, and move inward until detections are made (EFSA, 2020a, b). This strategy might be efficient if a good estimate of the leading front of the outbreak can be made. The outward strategy is standing practice (EPPO 2021b), and the inward strategy is, to the best of our knowledge not used in practice, but was recently proposed by the European Food Safety Authority (EFSA) (EFSA, 2020a, b). Both strategies for delimitation of the infested zone, which we hereafter will refer to as outward and inward, are envisioned as an iterative process, in which the survey area may be divided into survey bands that are subject to a survey procedure in which host plants are selected at random, and additional bands are surveyed depending on whether the pest is found in previously surveyed bands.

The advantage of the outward strategy would be that the area with the highest probability of finding infested plants is surveyed first, thus allowing a rapid initiation of the eradication measures on infested plants. It avoids the risk that resources are spent on surveillance of distant host plants while the outbreak could still be limited in size. On the other hand, the advantage of the inward strategy is that it opts for a precautionary approach by enclosing more potentially infested plants. However, if the starting point for the surveys is too far away from the actual disease front, a large survey effort is required to reach the disease front, consuming time and resources. Finally, the shape of the dispersal kernel could influence where offspring are deposited (Fletcher and Westcott 2013), and this might affect the relative efficacy of the inward and outward strategies.

The two strategies are likely to differ in terms of the number of \`false negatives\`(infested host plants that are not enclosed in the delimited zone), the area of \`false positives\` (the area with non-infested host plants that are included in the delimited zone), the frequency of correctly delimited outbreaks with all infested plants in the infested zone, and the survey effort (the number of surveyed host plants). Using a modelling approach we examine which of the two strategies (inward or outward) is better in delimiting outbreaks and how the error rates such as the probabilities of false negatives and false positives trade off with sampling effort. We further ask how this comparison is affected by the parameters that are used to design the delimiting survey and the shape of the dispersal kernel of the pest.

Box 4.1: Glossary of terms, taken from FAO (2023)

Terminology	Definition
Entry	Movement of a pest into an area where it is not yet present, or present but not widely distributed and being officially controlled
Establishment	Perpetuation, for the foreseeable future, of a pest within an area after entry
Introduction	The entry of a pest resulting in its establishment
Incursion	An isolated population of a pest recently detected in an area, not known to be established, but expected to survive for the immediate future
Outbreak	A recently detected pest population, including an incursion, or a sudden significant increase of an established pest population in an area
Delimitation survey	Survey conducted to establish the boundaries of an area considered to be infested by or free from a pest

4.2 Methods

4.2.1 General outline

To evaluate the performance of the two delimitation strategies, we first simulated 500 outbreaks (i.e. simulation replicates) using a spatially explicit spread model incorporating population growth and dispersal of an invasive pest (Section 4.2.2). Three different dispersal kernels (Gaussian kernel, negative exponential kernel and 2Dt kernel) were used to explore the effect of long distance dispersal on the effectiveness and effort of the outward and inward strategy. The Gaussian kernel has a thin tail, resulting in low frequency of long distance dispersal events, while the exponential kernel represents a fatter tail, and the 2Dt kernel can have very fat tails with a tendency to strongly favour long distance dispersal events. For each of the 3 × 500 outbreaks, the outward and inward strategies were tested, that is, the exact same simulations were used for testing the outward and inward strategies (Section 4.2.3). Both strategies were implemented by using survey bands. For the outward strategy, these were subsequently laid out radiating out from the initial finding of the pest, until no more infestations were found; for the inward strategy these were laid out radiating inward from a presumed outbreak frontier until the first findings were made or, in case the presumed outbreak frontier is smaller than the actual one, radiating outward from the presumed outbreak frontier until no more findings were made. Comparisons of the performance of the two strategies were made while varying the survey design parameters, in the case of the inward strategy the initial estimate for the size of the infested zone, and for both strategies the size of the survey band, and the confidence level and design prevalence that were used to calculate the number of samples within each survey band. We compared the performance of the two strategies in two ways: by calculating the proportion of replicates in which one strategy performed better than the other, and by comparing average characteristics of the simulation replicates, such as the average proportion of infested plants inside the delimited zone (Section 4.2.4). In the case of average characteristics for a strategy, we calculated the mean performance and also the standard error of the mean to be able to assess whether the comparison resulted in a significant difference using paired t-tests. To tie the model parameters to reality and make sure these are biologically plausible, we used an example organism, *Xylella fastidiosa,* when choosing the biological model parameters. Below, we describe each step in detail.

4.2.2 Growth and spread model

To model the outbreak of host plants infested by the pest, a spatially explicit spread model consisting of population growth and a dispersal kernel of the pest was built. We simulated the outbreak over an area for several years. We assumed a geometric population growth as we assumed no density dependence when the outbreak is first detected, i.e. the population is still far from the carrying capacity:

$$N_k = \lambda^k * N_0 \qquad (4.1)$$

where λ represents a yearly multiplication factor (Table 4.1), N_0 is the number of initially infested plants in the year of first establishment (Table 4.1), and N_k is the number of infested plants after k years (Table 4.1).

To explore how dispersal affects the performance of the two strategies, we considered three two-dimensional (2D) cross-section kernels (Fig. 4.1a): Gaussian, negative exponential, and 2Dt (Nathan et al. 2012). These kernels differ in the fatness of the tail, which represents occasional long distance dispersal events. Assuming long distance jumps is reasonable when the pest can be transported by human-mediated activities such as hitchhiking, trade or propagation materials, or by wind or water currents (Kot et al. 1996; Gippet et al. 2019; Mukherjee et al. 2021).

Dispersal kernels are 2D probability distributions that can be obtained by rotating a symmetric 1D probability distribution around its axis of symmetry. This applies, for instance, to the normal and t-distributions, which are bell shaped. Another symmetric distribution is the exponential distribution of the absolute value of a variable x, defined from minus to plus infinity: $f(|x|) = \frac{\alpha}{2}\exp\left(\frac{|x|}{\alpha}\right)$. This is also called the Laplace distribution. Intuitively, the dispersal distributions are best understood by analysing a cross section through the 2D distribution. This is called the cross-section kernel. When using the distribution to draw dispersal distances r in 2D space, the marginal distribution (integrated over angles θ from 0 to 2π) needs to be used (Fig. 4.1c). This marginal distribution has the same functional form as the cross-section kernel, but multiplied by $2\pi r$ and with an appropriate integration constant so the total probability over 2D space equals one. Here we present the marginal kernels, which are derived by rotating and integrating the cross-section kernels (within square brackets in Eqs. 4.2, 4.3, 4.4) over angles from 0 to 2π.

Marginal kernel derived from the Gaussian cross-section kernel:

$$k_M(r) \ = \ 2\pi r\left[\frac{1}{\pi(a_1)^2}\exp\left(-\frac{r^2}{(a_1)^2}\right)\right] \qquad (4.2)$$

$$\text{where } a_1 = \frac{2D}{\sqrt{\pi}}$$

Marginal kernel derived from the negative exponential cross-section kernel:

$$k_M(r) \ = \ 2\pi r\left[\frac{1}{2\pi(a_2)^2}\exp\left(-\frac{r}{a_2}\right)\right] \qquad (4.3)$$

$$\text{where } a_2 = \frac{D}{2}$$

Marginal kernel derived from the 2Dt cross-section kernel:

$$k_M(r) \ = \ 2\pi r\left[\frac{b-1}{\pi(a_3)^2}\left(1+\frac{r^2}{(a_3)^2}\right)^{-b}\right] \qquad (4.4)$$

$$\text{where } a_3 = \frac{2*D*\Gamma(b-1)}{\sqrt{\pi}*\Gamma(b-1.5)},\ b = 3$$

where $k_M(r)$ represents the probability density for a marginal kernel, with the distance from the source represented by r. a_1, a_2 and a_3 are scale parameters for the three cross-section kernels, and b is the shape parameter (degrees of freedom) for the 2Dt cross-section kernel, Γ is the Gamma function. We assumed a very small value for b, setting it to 3, to create a fat-tailed distribution. D is the mean dispersal distance for the marginal kernel (Table 4.1). We calculated the parameters of the three cross-section kernels (a_1, a_2, and a_3) by keeping the mean dispersal distance (D) equal across the three kernels.

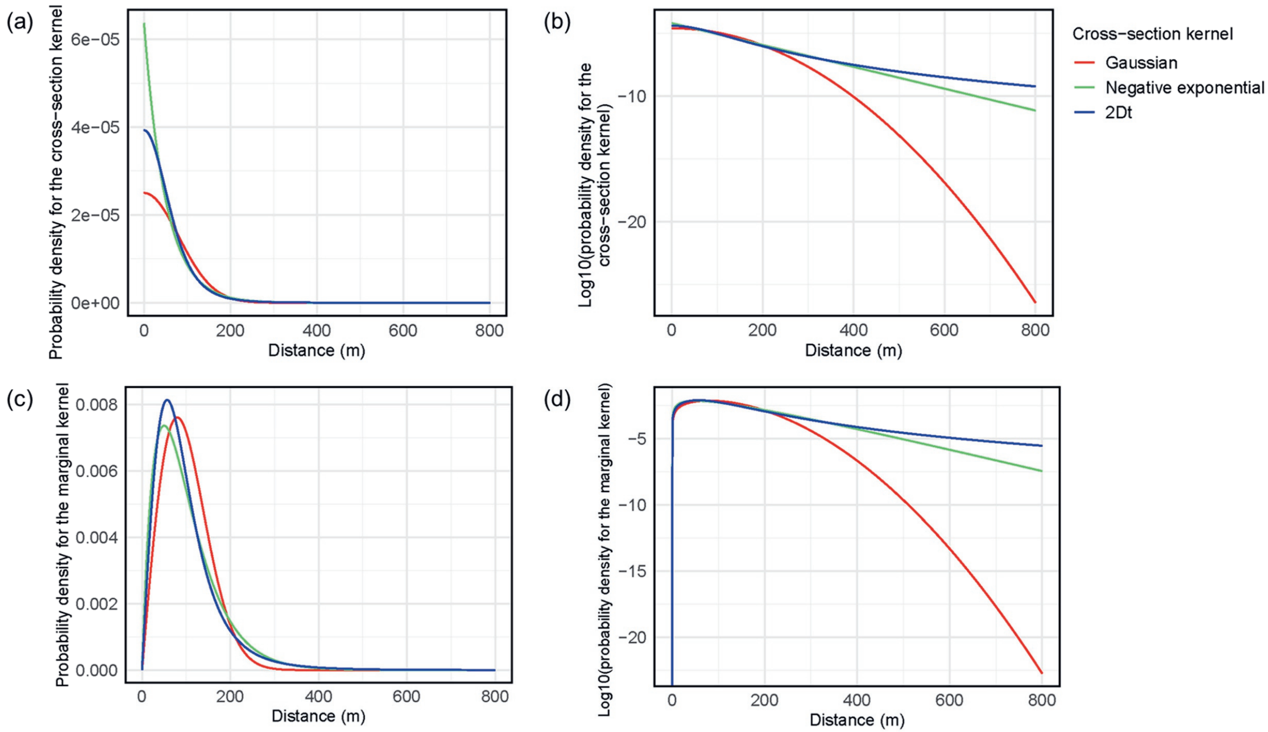


Fig. 4.1 Illustration of the three probability distribution models for dispersal used in this study. Panel (a) shows the three cross-section kernels, while panel (b) shows the same kernels on a log scale to highlight the differences in fatness of the tail. For comparison with the marginal kernels, they are shown from the origin to infinity, and not from -infinity to infinity. Panel (c) shows the marginal kernels, which represent the true distribution of dispersal distances used in simulations. Marginal kernels are obtained by rotating the cross section kernel around 0, and then integrating the resulting 2D kernels over the angles from 0 to 2π. Contrary to the cross-section kernels in panel (a), the marginal kernels in (c) integrate to one (see text). Panel (d) shows the marginal kernels on a log scale. *Red lines* represent the results for the Gaussian cross-section kernel, *green lines* represent the results for the negative exponential cross-section kernel, and *blue lines* indicate the results for the 2Dt cross-section kernel. The mean dispersal distance parameter (100 m) is the same for the three marginal kernels

4.2.3 Delimiting survey

Based on the described population growth model and chosen dispersal kernels, we generated 3 × 500 outbreaks with an age of *k* years, and assumed that the first detection was made in year *k* (t_d in Table 4.1). For each simulated outbreak, we randomly selected a single infested plant as the first detection. This first detection was subsequently used as the centroid in the delimiting process for both the outward and inward strategy. For the outward strategy, a survey band with a radius R_s (s for survey) was established around the first detection and additional survey bands with a width R_s were established around the previous bands until a band was reached in which no detections were made. The finally delimited zone then includes all bands that were found to be infested, but not the last band without findings. For the inward strategy, a potentially infested zone (initial estimate) with radius R_{inward} was first established. In the first step, a survey band was added around this potentially infested zone. In case the pest was detected, additional survey bands would be added on the outside until no detection was made in a newly added survey band, as in the outward strategy. However, if the pest was not detected in the first step, the survey proceeded inward by adding a new band within the initial estimate of the infested zone. The process then continued until arriving at a band in which the pest was detected. Then this band, and all the area inside of it would be considered infested. The two delimitation strategies are illustrated at https://zenodo.org/uploads/11525473.

Table 4.1 Parameters in the spatially explicit spread model and delimiting survey taking *X. fastidiosa* with a negative exponential cross-section kernel as an example

Parameter	Symbol	Value	Units	References
Outbreak				
Number of initial infested plants	N_0	1	-	-
Yearly multiplication factor	λ	19	Offspring/parent/year	(White et al. 2020)
Mean dispersal distance in a year for marginal kernels	D	100	m	(White et al. 2017)
Years of spread in outbreak simulation	k	3	year	-
Delimiting survey				
Average position of the frontier	R_F	784	m	Model testing
Width of a survey band (one eighth of R_F)	R_s	98	m	Model testing
Radius of the potentially infested zone (from one fourth of R_F to four times R_F)	R_{inward}	[196, 392, 784, 1,568, 2,352, 3,136]	m	Model testing
Assumed age of outbreak at the time of first detection	t_d	3	year	-
Confidence level	CL[1]	95%	-	(EFSA, 2020b)
Design prevalence	DP[1]	0.1%	-	(EFSA, 2020b)
Method sensitivity	$MeSe$[1]	0.55	-	(EFSA, 2020b)
Number of trees per square meter	TD	0.2	Number per m^2	https://www.agromillora.com/shd-olive-crops/

1 Some terminology follows notation by EFSA (2020b)

Sampling procedure

The sample size *n* in each survey band represents the number of units (usually plants) inspected and/or sampled. This number is calculated so that sampling reaches a certain confidence level *CL*[1] that the pest prevalence would be below a certain design prevalence *DP*[1] (prevalence being defined as a proportion of infested plants), when a sampling method is used with probability *MeSe*[1] (method sensitivity) that the pest is detected when an infested plant is inspected and/or tested (EFSA 2012b, 2020b; Milanzi et al. 2015). We used both the binomial distribution (infinite population) and hypergeometric distribution (finite population) to estimate the sample size in each survey band in line with EFSA (2020b). We defined that the population is infinite when $\frac{n}{N} < 0.1$, i.e. when less than 10% of the population was sampled, in which the binomial distribution was used. Otherwise, it is finite and the hypergeometric distribution was used.

When the population size is infinite, the relationship between confidence level, design prevalence and method sensitivity is:

$$CL = 1 - (1 - MeSe * DP)^n \qquad (4.5) \quad \text{(EFSA 2020b)}$$

Based on Eq. 4.5, the sample size per survey band is:

$$n = \frac{\log(1-CL)}{\log(1-MeSe*DP)} \qquad (4.6)$$

When the population size is finite, the relationship between confidence level, design prevalence and method sensitivity is adjusted using the hypergeometric distribution as:

$$CL = 1 - (1 - \frac{n*MeSe}{N-0.5*(N*DP*MeSe-1)})^{N*DP} \qquad (4.7) \quad \text{(EFSA 2020b)}$$

$$n = \frac{\left(1-(1-CL)^{\frac{1}{N*DP}}\right)*(N-\frac{1}{2}*(N*DP*MeSe-1))}{MeSe} \qquad (4.8) \quad \text{(EFSA 2020b)}$$

N is the total population size of host plants in the survey area, which we calculated by multiplying the host density (*TD* in Table 4.1) by the area size of the survey band.

Then, sample collection was simulated by applying a Bernoulli distribution to the infested plants to determine whether sampling an infested plant would result in detection.

[1] Terminology follows notation by EFSA (2020b)

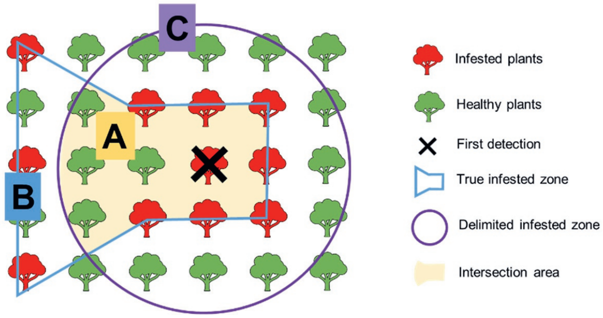
4.2.4 Metrics for assessing effectiveness and sampling effort

Effectiveness for each simulated outbreak was quantified using three metrics: i) the proportion of the infested plants enclosed within the delimited zone, ii) the proportion of the area of the true infested zone within the boundaries of the delimited zone (sensitivity, $\frac{A}{B}$, Fig. 4.2), and iii) the proportion of the area of the delimited zone that overlapped with the true infested zone (specificity, $\frac{A}{C}$, Fig. 4.2). The sensitivity is indicative for the ability of the strategy to enclose as much of the infested area as possible, whereas specificity is indicative for the ability of the strategy to avoid delimitation of non-infested areas. These metrics were each averaged over the 500 simulation replicates for each kernel and delimitation strategy to characterize the average effectiveness, its variation across replicates (SD) and the standard error of the calculated average (SE).

Furthermore, we calculated across all 500 simulation replicates for each kernel and delimitation strategy: i) the proportion of cases in which all infested plants were enclosed, ii) the proportion of cases in which no infested zone was delimited (i.e. no detections were made in any survey band) a situation referred to as "stop-too-early", and iii) the proportion of cases in which (a) the two strategies performed equally well in terms of the proportion of delimited infested plants, (b) the inward strategy performed better than the outward strategy, and (c) the outward strategy performed better than the inward strategy.

Effort was defined using two metrics for each individual outbreak: i) the actual sample size, i.e. the number of host plants inspected and/or sampled to delimit the infested zone, and ii) the number of bands that were surveyed during the delimitation. Again, the metrics were averaged across the 500 simulation replicates, and the SD and SE were also quantified.

In the case of the inward strategy, we calculated for each simulated outbreak for each metric the average performance over the range of values for R_{inward} tested. Then we calculated an overall average performance by linearly interpolating for each simulated outbreak the metric values between the obtained simulation results for different R_{inward}, integrating under the thus constructed piecewise linear function over the range of values used for R_{inward}, and finally dividing by the width of the range. The resulting average metric value across the evaluated range of R_{inward} gives insight in the average effectiveness and effort of the inward strategy when there is uncertainty about the position of the frontier. Since the two strategies are based on the same 500 outbreak cases, we used paired t-tests to analyze where the simulation analysis indicates a significant difference between the two strategies.



Ch. 4

Fig. 4.2 Graphical representation of sensitivity ($\frac{A}{B}$) and specificity ($\frac{A}{C}$). A is the intersection between the delimited zone (C: *purple circle*) and the true infested zone (B: *blue*) which surrounds all infested plants (*red trees*)

4.3 Parameterizing the model taking *Xylella fastidiosa* as an example

We used *Xylella fastidiosa* as an example organism to derive parameter values to be used in simulations for comparing the performance of the inward and outward strategies. *X. fastidiosa* is an emerging plant pathogen of global importance causing, for instance, Pierce's disease in the Western USA, olive quick decline syndrome in Italy and Spain, and almond leaf scorch disease in Spain (Sicard et al. 2018; Trkulja et al. 2022). *X. fastidiosa* is a major threat to olive production in Europe (Schneider et al. 2020).

4.3.1 Growth and spread model parameters

In our spread model, we assumed that the number of initial infested plants was 1 (N_0 in Table 4.1), and the yearly multiplication factor was 19 (λ in Table 4.1). This large value is broadly in line with results of White et al. (2020) though we used here a simpler model than White et al. (2020) did. Like White et al. (2017), we assumed a mean dispersal distance of 100 m per year (D in Table 4.1) based on the spread capacity of the vector of *X. fastidiosa*. To achieve a mean dispersal distance of 100 m, we used a parameter of a_1 = 113 m for the Gaussian kernel, a_2 = 50 m for the negative exponential cross-section kernel and a_3 = 127 m for the 2Dt cross-section kernel when taking a shape parameter of 3. For the simulations, we assumed that the pathogen was first detected after 3 years of spread (t_d in Table 4.1).

4.3.2 Survey design parameters

In the case of the inward strategy, the radius of the potentially infested zone needs to be estimated (R_{inward} in Table 4.1). We used a range of values for this initial estimate, based on the average position of the frontier (the distance of the furthest individual to the source, R_{F} in Table 4.1) across 500 outbreak simulations for each kernel. R_{F} was approximately 584 (s.e. ± 2) m for the Gaussian cross-section kernel, 784 ± 3.8 m for the negative exponential cross-section kernel, and 6,176 ± 84.5 m for the 2Dt cross-section kernel. We then chose six values for the size of the potentially infested zone (R_{inward}): $\frac{R_{\text{F}}}{4}, \frac{R_{\text{F}}}{2}, R_{\text{F}}, 2R_{\text{F}}, 3R_{\text{F}}$ and $4R_{\text{F}}$. To ensure that the delimited zones for the two strategies may stop at the same position, we used the size of the survey band as a proportion of the average position of the frontier for both strategies. We chose the width of the survey band, R_{s}, to be one eighth of R_{F}. For example, the sizes of the potentially infested zone for the negative exponential cross-section kernel that were tested were 196, 392, 784, 1,568, 2,352, and 3,136 m, and the size of survey band was 98 m (Table 4.1).

In line with practices recommended by EFSA (2020b), we set the confidence level to 0.95 and the design prevalence to 0.001 for all three cross-section kernels. We set the method sensitivity at 0.55 (*MeSe* in Table 4.1) (EFSA, 2020b). Based on those parameter values, the required sample size for ensuring pest freedom in a survey band is 5,445 when the population size is considered infinite (based on a binomial distribution). This is the maximum number of plants that will be sampled in a survey band to declare it is pest free with a confidence of 0.95 when no infested trees are detected. The actual sample size in a band can be much smaller because in practice sampling in a band will be terminated as soon as the first infestation is found during delimiting survey.

To assess how confidence level, design prevalence, and the width of the survey band affect the effectiveness and effort of the inward and outward strategies, we conducted further tests for each cross-section kernel (Appendix, Figs. S4.5-S4.12). Specifically, we explored confidence levels of 0.9 and 0.99, as well as the design prevalence of 0.0001 and 0.01, altering only one parameter at a time. Additionally, we examined a scenario that combines a confidence level of 0.99 with a design prevalence of 0.0001 thus aiming to achieve very strong evidence for pest freedom in the survey bands. We changed the width of the survey band from one eighth of R_{F} to one fourth of R_{F}. These simulations answer the question how well outbreak delimitation can work (i.e. how low error rates may get) when resources would not be a limiting factor.

4.4 Results

4.4.1 Effects of long distance dispersal on the performance of the strategy

The fatness of the tail of the dispersal kernel (Gaussian < negative exponential < 2Dt; Fig. 4.1) had a large effect on the proportion of cases in which all infested plants were enclosed (Fig. 4.3a). When the inward strategy is used, the average proportion of outbreak cases in which all infested plants were enclosed was 0.15 (s.e. ± 0.003) for the Gaussian cross-section kernel, compared to 0.07 ± 0.003 for the negative exponential cross-section kernel, and 0.0002 ± 0.0001 for the 2Dt cross-section kernel (Fig. 4.3a). For the outward strategy, these proportions of cases in which all infested plants were enclosed was even lower: 0.12 ± 0.015 for the Gaussian cross-section kernel, compared to 0.04 ± 0.009 for the negative exponential cross-section kernel, and zero for the 2Dt cross-section kernel. The probability of enclosing all infested plants increased with the size of the potentially infested zone for the Gaussian cross-section kernel, but was never higher than 0.20 (Appendix, Fig. S4.1). Despite both strategies performing poorly in enclosing all infested plants, the inward strategy was slightly better across the three different kernels examined (Fig. 4.3a).

Additionally, in some cases the outward strategy did not delimit any zone (i.e. “stop-too-early”). This happened when the first detection was made far from the epicenter of the infestation. In these cases, the infestation was confined to a single plant, and the conclusion was drawn that the organism had not yet spread. This “stop-too-early” problem did not occur with the inward strategy (Fig. 4.3b). It only occurred for the 2Dt cross-section kernel for the outward strategy, with a proportion of 0.008 ± 0.004 of the cases (Fig. 4.3b).

In approximately half of the outbreak cases, the inward and outward strategies performed equally well in terms of the proportion of delimited infested plants (Fig. 4.4). For the Gaussian cross-section kernel, the average proportion of cases in which the two strategies performed equally well was 0.50 ± 0.002, compared with 0.44 ± 0.003 for the negative exponential cross-section kernel, and 0.62 ± 0.002 for the 2Dt cross-section kernel (Fig. 4.4). The inward strategy had a larger proportion of cases in which it performed better when the size of the potentially infested zone was larger than the size of the average position of the frontier (0.291 vs 0.338) (Appendix, Fig. S4.3). However, this came at the cost of a large number of samples (Appendix, Fig. S4.2).

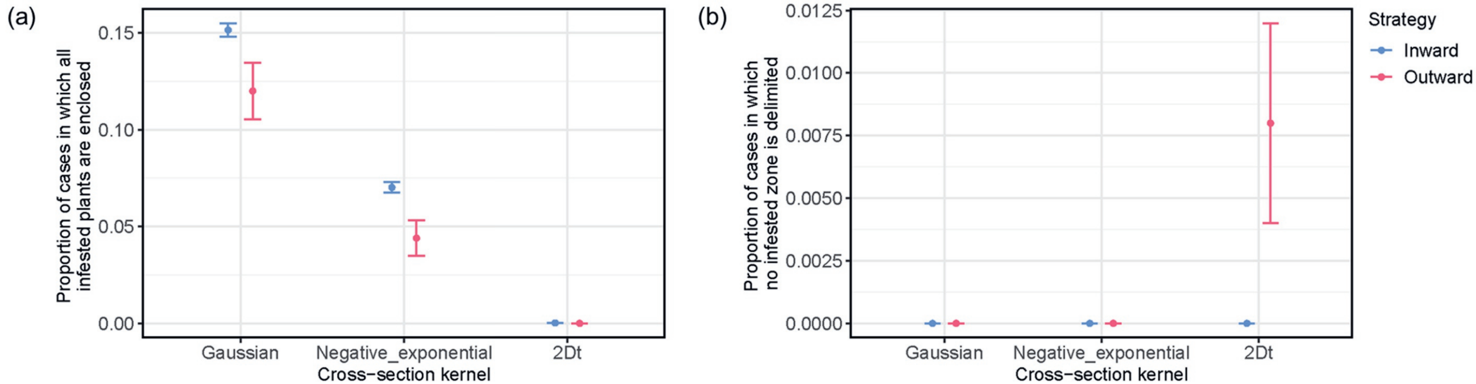


Fig. 4.3 Proportion of cases in which all infested plants are enclosed (a), and proportion of cases in which no infested zone is delimited (b), as a function of the cross-section kernel (x-axis). *Blue circle* data points and error bars represent the average ± standard error for the inward strategy averaged across all sizes of the potentially infested zone. *Red circle* data points and error bars represent the average ± standard error for the outward strategy

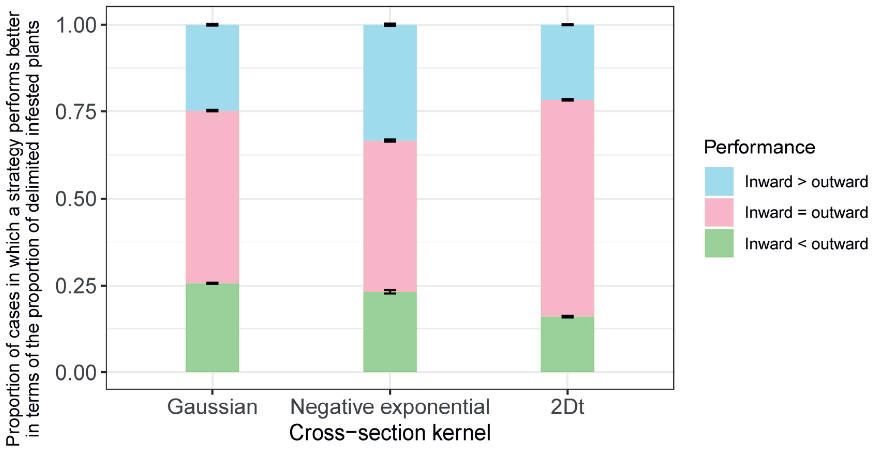


Fig. 4.4 Proportion of 500 outbreak simulation replicates in which a strategy performs better than the other strategy in terms of the proportion of delimited infested plants (y-axis), as a function of the dispersal kernel (x-axis). *Blue (pink, green)* areas represent the proportion of cases in which the inward strategy performs better (equally good, worse) than the outward strategy averaged across all sizes of the potentially infested zone. *Black* points and error bars represent the average ± standard error

4.4.2 Comparing metrics between two strategies, taking the negative exponential kernel as an example

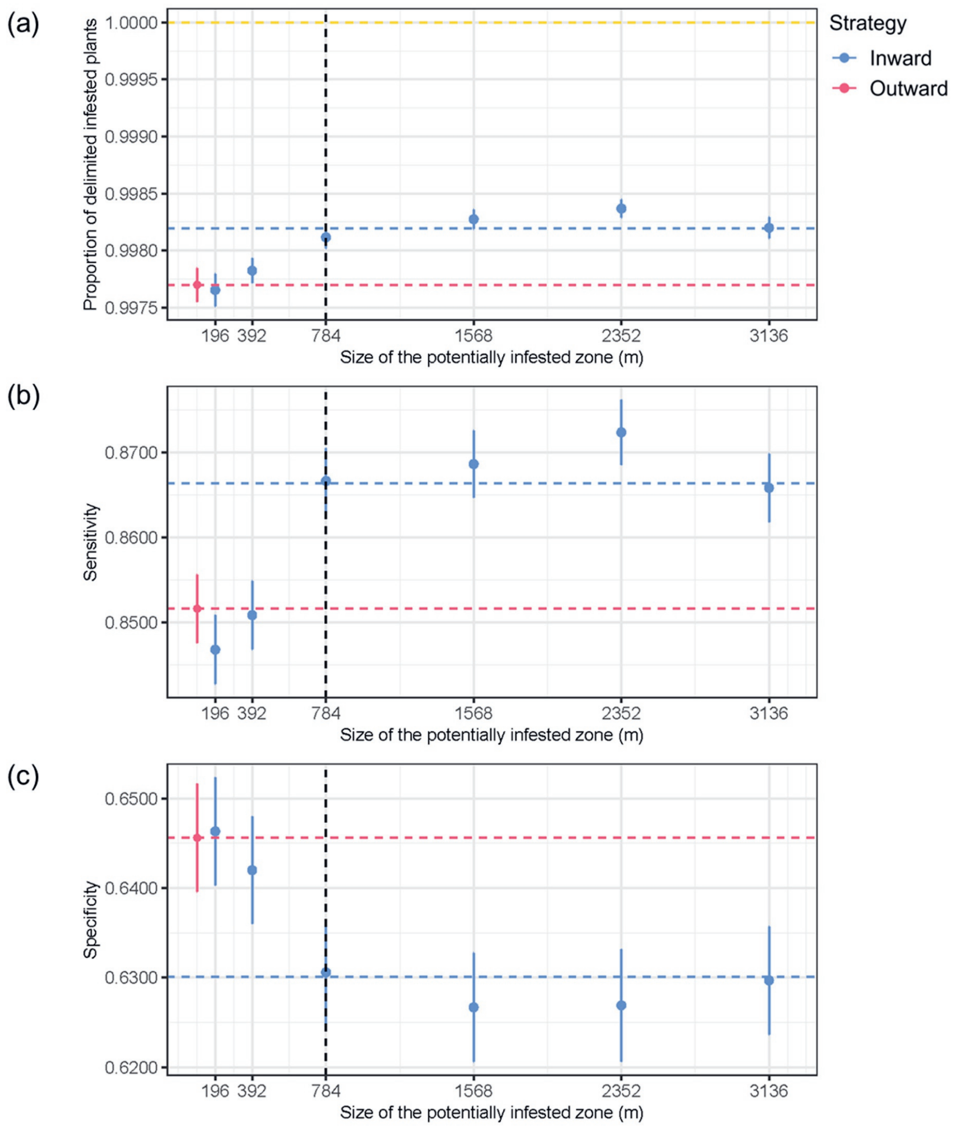
We now zoom in on the performance of the two strategies (inward and outward) taking the negative exponential kernel as an example. Results for the Gaussian and 2Dt cross-section kernels are presented in Appendix S4.1, S4.2, S4.5-S4.13, and showed a similar trend to the negative exponential kernel as described below.

While both strategies failed to delimit all infested plants in the majority of the simulations, they both enclosed a high proportion of infested plants. However, the inward strategy performed marginally better than the outward strategy in terms of the proportion of delimited infested plants (Fig. 4.5a). The inward strategy had an average proportion of inclusion in the infested zone of infested plants of 0.9982 ± 0.00003, compared with 0.9977 ± 0.0001 for the outward strategy ($p \leq 0.001$, n = 500) (Fig. 4.5a). This means that the average number of infested plants that were not enclosed was 14.4 for the inward strategy and 18.4 for the outward strategy.

Neither strategy achieved a high sensitivity (i.e. proportion of the area of the true infested zone that is in the delimited zone), but the inward strategy performed marginally better than the outward strategy (Fig. 4.5b). The inward strategy had an average sensitivity of 0.87 ± 0.003, and the outward strategy had an average sensitivity of 0.85 ± 0.004 ($p \leq 0.05$, n = 500) (Fig. 4.5b). The inward strategy had a marginally lower specificity (i.e. proportion of the area of the delimited zone that is within the true infested zone) than the outward strategy, averaging 0.63 ± 0.001 for the inward strategy compared with 0.65 ± 0.006 for the outward strategy ($p \leq 0.05$, n = 500) (Fig. 4.5c).

The results show that the performance of the two strategies is highly similar, though not identical (Fig. 4.5). The proportion of delimited infested plants and area-based sensitivity are traded off against specificity, whereby the inward strategy scores marginally better on sensitivity and the outward strategy marginally better on specificity. Even if the differences in effectiveness between the two strategies are significant, we would interpret them as so small to be not relevant in practice.

The inward strategy used on average seven times as many samples as the outward strategy (respectively 62,508 ± 180 and 8,866 ± 107) (Fig. 4.6a). The inward strategy used on average 12.5 ± 0.03 survey bands compared with 8.3 ± 0.05 for the outward strategy (Fig. 4.6b). The difference in sampling effort between the two strategies became larger when the size of the potentially infested zone was increased beyond the average position of the frontier (Fig. 4.6). On average, the inward strategy had a marginally lower number of samples than the outward strategy when the infested zone was smaller than the average position of the frontier, which was also reflected in a lower number of bands needed for delimitation.



Ch. 4

Fig. 4.5 Metrics for the effectiveness (y-axis), *viz*. the proportion of delimited infested plants (a), the sensitivity (b), and the specificity (c), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars represent the mean ± standard error of 500 simulations for the inward strategy for six different sizes of the potentially infested zone. The *red* data point and error bar represent the mean ± standard error of 500 simulations for the outward strategy, which is independent of the size of the potentially infested zone. The *blue dashed line* represents the average of the averages of 500 simulations for the inward strategy. The *red dashed line* represents the mean of 500 simulations for the outward strategy. The *vertical black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

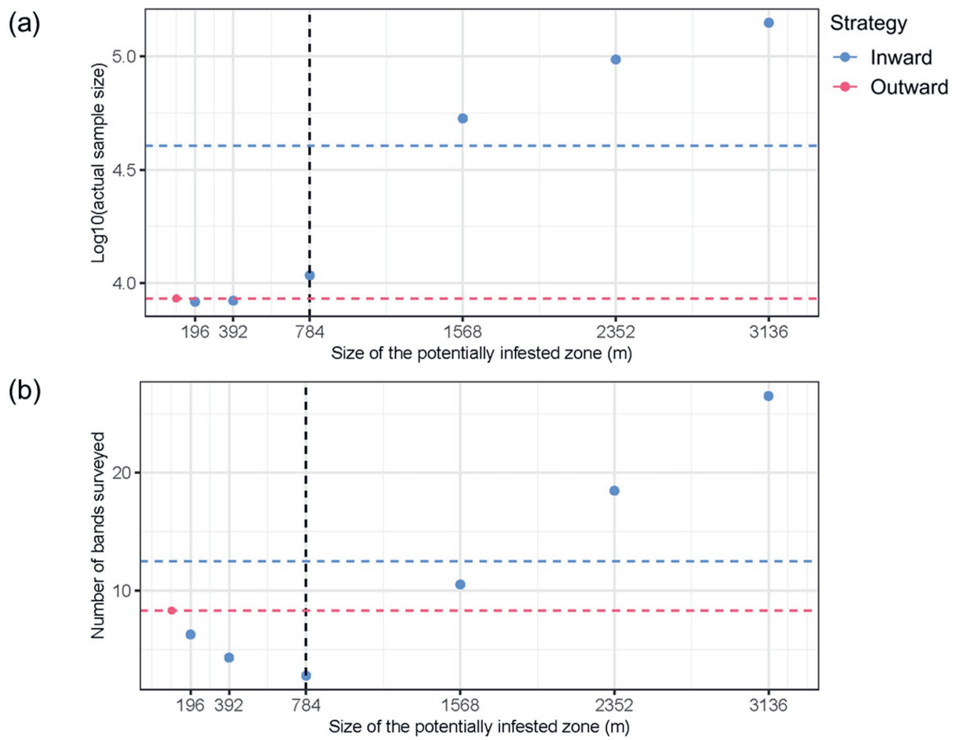


Fig. 4.6 Metrics for sampling effort (y-axis) including actual sample size on a log10 scale (a), and number of bands surveyed (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars represent the mean ± standard error of 500 simulations for the inward strategy for six different sizes of the potentially infested zone. The *red* data point and error bar represent the mean ± standard error of 500 simulations for the outward strategy. The standard error is too small to be visible in the figure. The *blue dashed line* represents the average of the averages of 500 simulations for the inward strategy. The *red dashed line* represents the mean of 500 simulations for the outward strategy (independent of the size of the potentially infested zone). The *vertical black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

On average, the inward strategy delimited a slightly larger infested zone (732 ± 4 m) than the outward strategy (715 ± 50 m) (Fig. 4.7). Neither strategy delimited an infested zone larger than the average position of the frontier (784 m, Fig. 4.7).

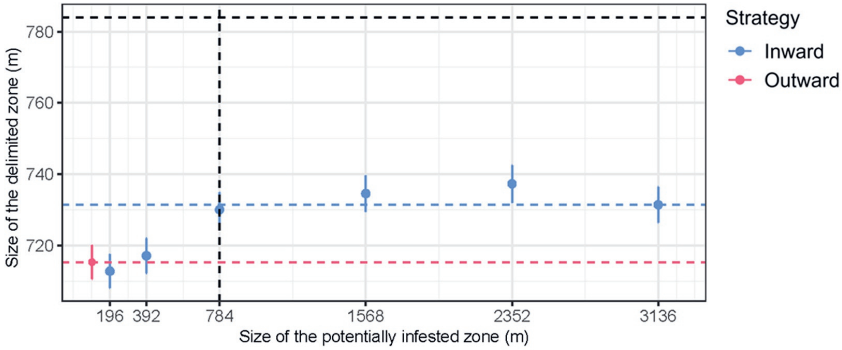


Fig. 4.7 Size of the delimited zone (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars represent the mean ± standard error of 500 simulations for the inward strategy for six different sizes of the potentially infested zone. The *red* data point and error bar represent the mean ± standard error of 500 simulations for the outward strategy, which is independent of the size of the potentially infested zone. The *blue dashed line* represents the average of the averages of 500 simulations for the inward strategy. The *red dashed line* represents the mean of 500 simulations for the outward strategy (independent of the size of the potentially infested zone). The *black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

Confidence level, design prevalence and the width of survey band had an effect on the effectiveness and effort but did not change the qualitative differences between two strategies. Increasing the confidence level and decreasing the design prevalence increased the proportion of delimited infested plants (Fig. 4.8a) but at a large cost of additional sampling (Fig. 4.8b). For example, for the inward strategy, increasing the confidence level from 0.95 to 0.99 and lowering the design prevalence from 0.001 to 0.0001 increased the number of samples required by a factor 12 (Fig. 4.8b). Increasing the size of the survey band from 98 m to 196 m decreased the proportion of delimited infested plants and the sample size (Appendix, Fig. S4.11).

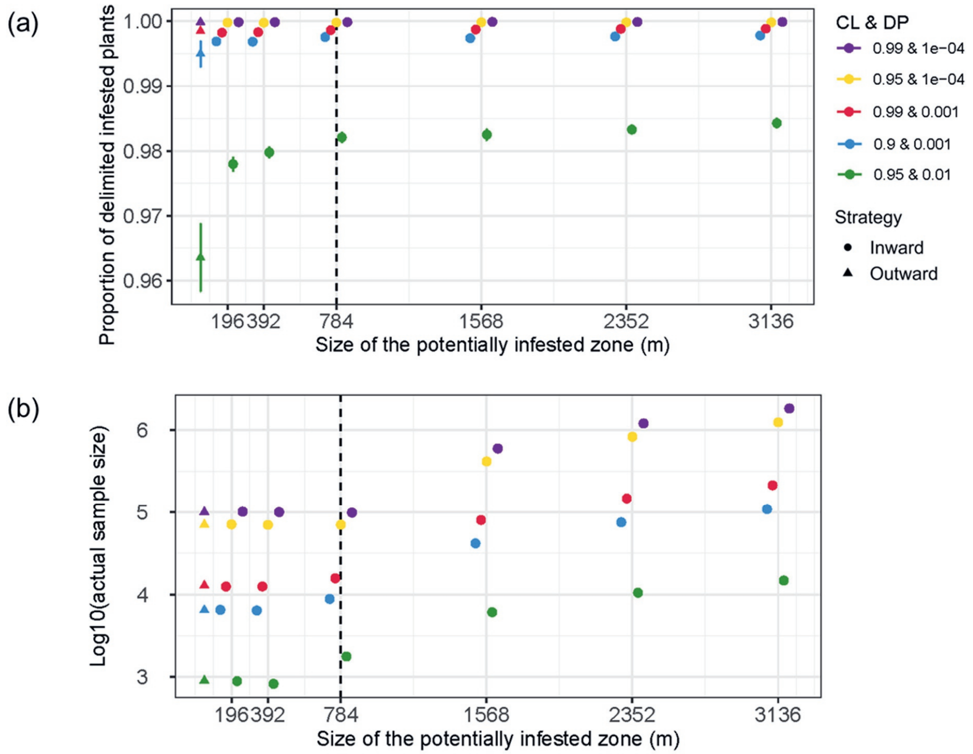


Fig. 4.8 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in case of the inward strategy. Data points and error bars represent the average ± standard error of 500 simulations for the inward strategy (*circle points*) and the outward strategy (*triangle points*). The standard error is too small to be visible in the figure. CL & DP indicates respectively the value of confidence level and design prevalence. The *vertical black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

4.5 Discussion

The aim of this study was to compare two strategies to delimit outbreaks of plant pests. We tested both outward and inward strategies and explored the effects of survey design parameters and the shape of the dispersal kernel of the organism on the performance of the delimitation strategies. We found that neither strategy was effective at enclosing all infested plants and the proportion of infested plants not included in the delimited zone increased with the likelihood of long distance dispersal events, as characterized by the fatness of the tail of the dispersal kernel. In the majority of the simulated outbreaks, the two strategies performed equally well in terms of the proportion of delimited infested plants, but the outward strategy required on average fewer samples to achieve this.

Both inward and outward strategies for delimiting an outbreak had a lower than 20% chance of enclosing all infested plants. This finding is striking because the purpose of a delimiting survey is to find all infested plants. This implies that the inward strategy based on the guidelines from EFSA (2019, 2020a, b) is not efficient in enclosing all infested plants. In a way, this failure to delimit all infested plants is built in the design parameters of the protocols, because a confidence level of 0.95 and design prevalence of 0.001 imply that at a prevalence of one infested plant in a thousand the probability of detection is 0.95, i.e. less than one. At lower design prevalence than 0.001, the change of detecting will naturally be higher. It is very difficult, though, to increase sampling effort because sampling resources are constrained by time and capacity of competent authorities, such as national plant protection agencies. In practice, a buffer zone is therefore established around the delimited zone to ensure the pest does not spread beyond it or find the missed infested plants. Hence, missing a few infested plants in delimitation of the infested zone is perhaps not a critical problem. Including this buffer zone in assessments of the effectiveness and costs of both strategies could further improve the usefulness of the results of such assessments.

Both strategies delimited a large proportion of infested plants. For the negative exponential cross-section kernel, the inward strategy had an average proportion of inclusion in the infested zone of infested plants of 0.9982, compared with 0.9977 for the outward strategy (Fig. 4.5a). Likewise, the inward strategy captured a larger proportion of the area of the true infested zone than the outward strategy. However, this came at the cost of also enclosing a larger area that does not contain infested plants (i.e. lower specificity). As the inward strategy had a lower specificity, the measures applied in the infested zone will be applied to a larger area that is not infested. This is costly if the host plants are of high economic or esthetic value. If the delimiting process is conducted in an urban area, the inward strategy will involve a greater residential area being included in an infested zone. This may result in measures, e.g. clear-cutting, being implemented over a wider area, which may invoke resistance of residents and stakeholders. National plant protection agencies are cognizant of this and try to avoid unduly delimiting non-infested areas. For example, when an outbreak of *Anoplophora glabripennis* was detected in the Netherlands, the size of the infested zone subjected to clear-cutting of all host plants was reduced from 100 m in Almere to 50 m in Winterswijk, as the outbreak in Winterswijk occurred in a residential area where the public would have been more affected (EPPO 2010, 2012). While the differences between the two strategies in sensitivity were significant, the difference in sampling resource required may be more practically relevant for national plant protection agencies. The inward strategy used on average seven times as many samples as the outward strategy (respectively 62,508 and 8,866) and the inward strategy used on average 12.5 survey bands compared with 8.3 for the outward strategy. Ultimately, the choice of the delimitation strategy needs to balance efficacy and costs, and competent authorities need to weigh the pros and cons.

When the size of the potentially infested zone is smaller than the true position of the frontier, the inward strategy performs better, achieving similar effectiveness to the outward strategy but with fewer samples used (Figs. 4.5, 4.6, and Appendix, Figs. S4.2, S4.3). This is because the first bands are skipped, thus saving samples (Fig. 4.6 and Appendix, Fig. S4.4). However, if the size of the potentially infested zone is larger than the position of the frontier, the outward strategy is superior in terms of sample size. In these cases the first bands assessed by the inward strategy contain no or only a few infested plants, requiring a very large number of samples before the band is declared pest free (Fig. 4.6b). Therefore, to effectively delimit the infested zone with the inward strategy, it is necessary to know as accurately as possible the position of the frontier. Competent authorities may wish to avoid the inward strategy if there is high uncertainty on the likely position of the frontier, e.g. because the age of the new outbreak is uncertain. And if there is uncertainty, it is less costly to err on the low side (i.e. estimate the outbreak is still small) than err on the high side (i.e. make a high initial estimate of the infested zone).

Knowing the position of the frontier of a recently detected outbreak is very difficult. This position can e.g. be estimated using information on the pest's natural spread distance and the number of years since the last survey (EFSA 2019, 2020a, b). Natural spread is influenced by factors such as population growth and natural dispersal distance (Liebhold and Tobin 2008; White et al. 2017). Although natural spread rates can be estimated from the yearly multiplication factor and natural dispersal distance, they are fraught with uncertainty (EPPO 2014, 2021a; Lázaro et al. 2021; Fang et al. 2022). In addition, uncertainty can arise from lack of knowledge about the time elapsed since the pest was first introduced (Wallner 1987; Boyd et al. 2013; Almeida and Nunney 2015; Urquhart et al. 2017). In our model, we assumed that the estimated age of the outbreak was in line with the actual generated outbreak. In reality, this would be the greatest uncertainty. Consequently, expert judgement on the position of the frontier and thus the size of the potentially infested zone is easily over or underestimated. Experts may set an upper bound on the timing of introduction by examining previous surveys in the area and a lower bound by considering factors such as population density on the infested trees or the age of bore holes. However, these estimates could be off by years. Such uncertainty is particularly likely during the initial establishment phase of pests, impacting the effectiveness and effort of the delimiting process (Koch et al. 2009; Yemshanov et al. 2010; Boulanger et al. 2016; Occhibove et al. 2020).

The inward and outward strategies showed differences in robustness in dealing with these uncertainties. When the size of the potentially infested zone was overestimated (e.g. due to overestimating the yearly multiplication factor, the mean dispersal distance, or the age of the outbreak), the outward strategy tended to be more effective, achieving a marginally lower effectiveness than the inward strategy (0.9977 vs 0.9983, $p \leq 0.001$, n = 500), but with much fewer samples (~ 86% less samples compared to the inward strategy). For example, if the dispersal distance is overestimated by a factor four, which is a level of uncertainty that is quite common in expert judgement - sometimes even spanning orders of magnitudes - sample size in the inward strategy needs ~ 16 times more samples compared to the outward strategy. Conversely, if the size of the potentially infested zone is underestimated, the inward strategy had lower sample size than the outward strategy.

Only if the frontier can be accurately estimated, it is most efficient to start surveying at the frontier regardless of the dispersal kernel, confidence level, design prevalence, and width of the survey band (Figs. 4.5, 4.6, and Appendix, Figs. S4.2, S4.3, S4.5-S4.13). When using the inward strategy, it may be advantageous to use as initial estimate for the size of the outbreak an estimate that is at the low end of the plausible range. A potential drawback of the outward strategy that happens in around of 1% of the cases when the dispersal has a fat tail is that if the detection occurs far from the infestation center, the strategy may terminate prematurely.

The simulations done in this study do not cover all possible survey designs that could be tested and implemented, and there are likely ways in which the performance of both strategies can be further improved, e.g. by fine-tuning the width of survey bands, and using results obtained during survey in the choice of the subsequent steps of the survey. Here we did not explore all possibilities. For instance, in our model, we assumed that the size of the survey band was independent of the size of the potentially infested zone. This resulted in a high number of samples when the size of the potentially infested zone is large, as a higher number of bands were surveyed (Fig. 4.6). Another option could be to assume that the width of the survey band is scaled to the size of the potentially infested zone (e.g. using the annual spread rate by dividing the size of the potentially infested zone by the number of years of spread). This would likely reduce the average sample size of the inward strategy, but because the delimitation uses coarse steps, further refinements might be needed to try and find a precise estimate for the true extent of the outbreak, e.g. by reducing the width of survey bands. We did not include such scenarios here, but it would be interesting to explore them. It would also be interesting to explore the effectiveness and effort of any options that involve fine-tuning the size of the survey band based on detection results. The results of sampling in previous bands (particularly for the outward approach) could be used to predict the size of the outbreak and plan the width of subsequent survey bands accordingly. For example, the survey band could be kept constant if very few detections are made in the last survey band but it might be increased if many infestations are found. It would even be imaginable to make “satellite samples” far outside the estimated frontier, to explore fat tailed distributions. If the aim is to enclose all infested plants in the delimited zone, a possible way out is to apply a safety factor to the delimited zone by the survey procedure (Appendix, Figs. S4.14 and S4.15) to ensure that there is at least a 0.95 chance of enclosing all infested plants. For both the inward and outward strategies, in the cases of the Gaussian and negative exponential cross-section kernels, the infested zone had to be made 1.5 times larger than the infested zone that was delimited by sampling. In the case of the 2Dt cross-section kernel, the delimited zones needed to be increased by a safety factor of nine (Appendix, Figs. S4.14 and S4.15). However, increasing the size of delimited zone comes at the cost of specificity, i.e. it means that more non-infested territory is also included in the delimited zone.

4.6 Conclusion

Overall, both strategies delimited a high proportion of the infested plants but both had a low probability of enclosing all infested plants. Failing to delimit all infested plants jeopardizes the objectives of the subsequent demarcation, which is eradication or containment. The comparison between the two strategies suggests that the inward strategy works best if the position of the frontier can be determined with sufficient certainty. In case of uncertainty the inward strategy becomes very sampling intensive if the size of the potentially infested zone is overestimated. We argue that uncertainty is very common in the delimitation phase because of uncertainty on the spread rate of the pest and timing of introduction, and consequently, the size of the outbreak. Therefore, for this strategy, it is more cost-effective to choose an initial estimate of the infested zone that is near the lower end of the plausible range than a high estimate. Although high sampling costs may also be addressed by choosing a survey band width that depends on the initial estimate of the infested zone. The inward strategy furthermore provides some protection against poor delimitation if the initial finding of a disease is far from the true center of the outbreak as may happen in case of long distance dispersal events. Altogether, the results of this work suggest that delimitation of pest outbreaks is difficult, laborious, and prone to error. While the inward strategy achieves a marginally greater effectiveness than the outward strategy, it comes on average with substantially increased cost of sampling compared to the outward strategy. The outward strategy is more robust to uncertainty about the size of the infested zone. This analysis can provide a basis for designing more effective sampling design, such as applying a variable bandwidth or a safety factor to the delimited zone to maximize the probability that all infested plants are enclosed.

Contributions

MS proposed the idea. HS, JCD and WW developed the methodology. HS developed the model, analysed data and wrote the manuscript. MS shared his insight in how delimitation of the infested zone is done in practice. All authors contributed to modifying the final manuscript.

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Chapter 5

General discussion

This thesis addresses three scientific issues in the management of outbreaks of non-native plant pests. In Chapter 2, I reviewed outbreak reports of zoning strategies for plant pests in the European Union (EU) to describe how zoning strategies are implemented in practice, thereby identifying gaps in zoning strategies for further scientific investigation. In Chapter 3, I used an individual-based model of the spread of the pine wood nematode (PWN) by its insect vector to compare the costs and effectiveness of a novel strategy, tree-by-tree selective cutting, with that of the current standard strategy of a 500-m-radius clear-cutting zone around infested plants as prescribed in the EU regulation (Chapter 3). In Chapter 4, I developed a general individual-based model to evaluate the effectiveness and sampling requirements of delimiting the infested zone of a non-native pest outbreak using two different protocols, one based on sampling radially outward from the first identified infested plants (outward strategy), and another (inward strategy) based on starting the sampling near the expected location of the outbreak frontier.

In Section 5.1, I state the main findings of this thesis. In Section 5.2, I discuss the thesis from a broader perspective across the three research chapters. In Section 5.3, I provide implications for the management of non-native plant pest outbreaks in both regulation and practice. In Section 5.4, I list key limitations and future research directions. Finally, this chapter ends with concluding remarks in Section 5.5.

5.1 Main findings of this thesis

All three research chapters concern the management of outbreaks of non-native plant pests. Chapter 2 is the first review ever conducted in the domain of the management of outbreaks of non-native plant pests. Chapters 3 and 4 used the same modeling approach, individual-based modelling, to explore and compare the costs and effectiveness of alternative strategies. The main findings of the three research chapters are described below.

5.1.1 How are outbreaks of plant pests managed in the European Union?

In Chapter 2, I reviewed 121 outbreak cases caused by 25 non-native species (10 insect species, 13 pathogen species, and 2 nematode species) in the EU between 1975 and 2020. I found that infested zones, buffer zones, and clear-cutting zones are commonly used to aid management of outbreaks, with the combination of the infested zone and buffer zone being the most frequently applied. Measures are different within different zones to minimize the impact of measures.

An infested zone is defined as an area where the presence of the specified organism has been confirmed, and which includes all known infested plants caused by the specified organism or, alternatively, all plants belonging to the same lot at the time of planting. In the infested zone, destruction of infested plants and host plants is frequently applied. A clear-cutting zone is a zone with a specific radius around individual infested plants or around the infested zone where all hosts are removed. Finally, a buffer zone is a zone with a specific radius beyond the boundary of the infested zone, in which several measures are applied to minimize spread of the target pest out of the infested zone. The buffer zone contains no known infested plants, surveillance is conducted and other phytosanitary measures may be taken, e.g. public awareness campaigns may be organized.

The terminology used for describing zones in outbreak management reports is in many cases ambiguous. I found that synonyms and homonyms are sometimes used. Such ambiguity hampers effective communication about zoning strategies. The sizes of the zones specified in regulations often correspond to the largest size of the zones used before regulations were issued.

5.1.2 Which strategy is the most cost-effective to eradicate the pine wood nematode (PWN): clear-cutting or tree-by-tree selective cutting?

In Chapter 3, I compared the costs and effectiveness of clear-cutting and tree-by-tree selective cutting. For this, I developed an individual-based model that combines the dispersal of the vector, the transmission of PWN, and the interactions between the nematode transmission and host plants to model the spread of PWN in a large forested area. Visual ground surveillance, visual ground surveillance combined with trapping networks, and aerial surveillance in combination with clear-cutting and tree-by-tree selective cutting were modelled. I calculated the costs associated with surveillance, wood sampling, tree removal, and revenue loss to determine which strategy is the most cost-effective in eradicating PWN.

I found that both strategies could eradicate PWN if intensive aerial surveillance was conducted when almost all infested plants were symptomatic. In this case, tree-by-tree selective cutting was 200-fold cheaper than clear-cutting. However, it is unlikely that all infested plants are symptomatic at the time when surveillance is conducted. If some infested plants did not show symptoms at the time of surveillance, neither tree-by-tree selective cutting nor clear-cutting could eradicate PWN. Yet, clear-cutting was more effective than tree-by-tree selective cutting when the surveillance intensity was the same, as clear-cutting removed surrounding trees that were infested but did not show symptoms or were not detected. When no less than 60% of the infested trees showed symptoms, tree-by-tree selective cutting with aerial surveillance could achieve the same level of effectiveness as the standing practice of clear-cutting with visual surveillance but at lower costs (on average by a factor of 88) by avoiding the cutting of healthy trees. However, there is a limit to the effectiveness of tree-by-tree selective cutting because the infested trees need to show symptoms before detection is possible, while under clear-cutting non-detected infested trees can be removed as well.

5.1.3 Which strategy is the most effective to delimit an infested zone: inward or outward?

In Chapter 4, I compared two delimitation strategies in terms of the effectiveness of enclosing infested plants and sampling effort. I developed a general individual-based model that includes pest spread to compare the inward and outward survey for delimiting an infested zone. To explore the effectiveness of these two strategies and the effort involved in their implementation, I did a number of scenario studies. First, I explored the effect of long-distance dispersal on the costs and effectiveness of these two strategies by using a Gaussian, negative exponential, or 2Dt cross-section kernel to describe the probability distribution of dispersal distances. Additionally, comparisons were made using different survey design parameters, such as the size of the initially hypothesized infested zone for the inward strategy, and the size of the survey band, the confidence level and design parameters for both strategies.

I found that both the inward and outward strategies often fail to enclose all infested plants, especially if the invasive organism has fat-tailed dispersal. Yet, both strategies manage to enclose a high proportion of infested plants. On average, the inward strategy had a marginally higher proportion of delimited infested plants than the outward strategy, at the cost of requiring more samples. The choice between the two strategies depends on how accurately the position of the frontier can be estimated. The inward strategy is the most cost-effective of the two when the initial estimate of the infested zone is accurate. If the position of the frontier is not known accurately due to, for example, uncertainty about the age of the outbreak or the dispersal distance of the pest, the outward strategy is on average a more cost-effective choice. It achieves marginally smaller effectiveness than the inward strategy but requires on average seven times less samples.

5.2 Comparison to other work

5.2.1 Difficulty of eradication for diseases with a long incubation period

My modelling work in Chapter 3 indicated that eradication would be possible if all infested plants would be symptomatic at the time of surveillance; however, this is difficult to achieve because the incubation period is long while surveillance should be conducted before the emergence of a new vector generation in the next year (European Commission 2012). Due to the long incubation period, a minority of infested trees are still asymptomatic at the time of survey between October and the following May (Chapter 3). Long incubation period may contribute to the explanation to the failure of the eradication of PWN in Portugal (Økland et al. 2010; De la Fuente and Beck 2018; Robinet et al. 2024) as well as for other plant pest outbreaks, as missing already two infested plants will lead to a failure of eradication (assuming disease spread from one initially infested plant).

Similar to PWN, clear-cutting of host plants (100 m) was applied to *X. fastidiosa* but it failed to eradicate this pest in Puglia, Italy (Chapters 2). One explanation for this failure could be the long incubation period of approximately 1.2 years for infested trees affected by *X. fastidiosa*, which resulted in a large infested area at the time of survey (White et al. 2020; Morelli et al. 2021; Trkulja et al. 2022). Eradication may be achievable if the infested plants have a relatively short incubation period, making all infested plants symptomatic at the time of survey, before new generations of vectors begin transmitting the disease. Previous meta-analyses have not paid attention to the impact of the incubation period on the success of eradication efforts (Pluess et al. 2012; Tobin et al. 2014; Branco et al. 2023).

5.2.2 Importance of science in outbreak management

Exploring cost-effective strategies considering their effectiveness and societal acceptance

Current outbreak management practices are not always effective (Carrasco et al. 2010; Robinet et al. 2020), or encounter resistance from society (Yokomizo et al. 2014). For example, farmers in Puglia, Italy, protested against measures such as 100-m-radius clear-cutting applied to the host plants around the infested olive trees by *X. fastidiosa*, and the use of pesticides to kill the vectors of the bacterium (Burdeau 2018). They believe that the measures are heavy-handed and not necessary. Likewise, the 500-m-radius clear-cutting, while having big impact, was not large enough to eradicate PWN in Portugal (Robinet et al. 2020). Tree-by-tree selective cutting is currently being tested in Portugal, but its efficacy in slowing the development of the epidemics remains unclear (Robinet et al. 2020). Practitioners are eager to know the costs and effectiveness of this tree-by-tree selective cutting strategy compared to the conventional clear-cutting strategy. Therefore, there is a need for science to seek alternative cost-effective methods to balance the trade-offs between feasibility and effectiveness in practice. The results from Chapter 3 showed that clear-cutting cannot eradicate PWN, which is in line with previous modeling work (de la Fuente et al. 2018; Robinet et al. 2020) and the practical implementation in Portugal, but my modelling provides a scientific support that alternatives exist which are more cost-effective.

Added value of science to practice in managing outbreaks considering uncertainty

Scientists can provide a service to the society by investigating the effectiveness of current practices and exploring alternative management strategies, taking into account uncertainties in knowledge and budget constraints. Chapter 4 showed that the EFSA-recommended inward strategy is, on average, not as cost-effective as the standing outward strategy. Our modelling indicated, however, that the inward strategy is advantageous when the initial estimate of the infested zone is close to the actual frontier (Chapter 4). However, practitioners face high uncertainty in the estimation of the location of the frontier. EFSA (2020) proposes using the spread distance of the pest since its introduction as the size of the initial estimate of the infested zone. In practice, the frontier of the infestation is difficult to estimate (Baxter and Possingham 2011; Moore et al. 2011; Yemshanov et al. 2019) because the dispersal distance, which underlies the spread distance (Harrison 1981; Xu and Ridout 1998; Luo et al. 2012), the first introduction, and the years since introduction are very difficult to assess (Chapter 4). The inward strategy may require a large budget for surveillance to identify the extent of the outbreak (Chapter 4), which may use up funds that could alternatively be used for eradication measures such as host removal (Yokomizo et al. 2014). However, investing in survey-only strategies is never as effective as investing in surveys along with eradication measures (Rout et al. 2014). This is because host removal in high-risk areas would effectively prevent the pest from spreading to unaffected regions (Yemshanov et al. 2019). Considering the difficulty in estimating the position of the frontier and the inward strategy being very sensitive to the initial estimate of the frontier, the standing outward strategy is a more cost-effective choice than the EFSA-recommended inward strategy. Previous studies have emphasized the importance of including such uncertainties in modeling to select effective outbreak management strategies (Yokomizo et al. 2014; Yemshanov et al. 2017, 2019; Jafari et al. 2018). Therefore, our modelling provides a robust cost-effectiveness analysis of different strategies taking into account the uncertainties in outbreak management in practice.

A need to connect science and practice

Currently, connections between scientific researchers and practitioners are not sufficient. Modelers have the knowledge to develop bioeconomic models to evaluate the effectiveness of different strategies, but they may not know how these strategies are implemented in practice or on what principles these strategies are based. This lack of information makes it difficult for modelers to develop pest spread models in combination with strategies to compare their costs and effectiveness. In contrast, people from EFSA, EPPO, and NPPOs may have a good knowledge of practical zoning strategies but may lack the expertise or resources to conceptualize and model these strategies in combination with pest spread (Soliman et al. 2015). Once an NPPO starts managing an outbreak, usually an outbreak management team or Technical Advice Team (TAT) or Incident Management Team (IMT) is formed in the NPPO that will manage the actions to be taken. In the Netherlands, this team would in general consist of a decision-maker, a pest risk analyst, a team manager of field inspectors, an EU officer, and a sector manager. Outbreaks are managed by this team, who do not have an explicit decision scheme on the table but rather one in their heads, balancing all kinds of needs and resources (source: interviews with NPPO practitioners in the Netherlands). Enhancing the connections between scientific researchers and practitioners can help bridge the gap between science and practice. By doing so, models can be developed and fine-tuned based on practical experience, current practices can be evaluated, and those results can be translated into practice to manage outbreaks of plant pests in a evidence-based and cost-effective way.

5.2.3 Role of the EU to balance the trade-offs between the benefits of different stakeholders

Zoning strategies should consider the trade-offs between the benefits to stakeholders in the infested area and their counterparts outside of it. In Europe, PWN was first detected in Portugal in 1999 (Vicente et al. 2012). In 2018, the outbreak of PWN covered more than 30% of mainland Portugal due to the failure of eradication efforts (de la Fuente et al., 2018). Currently, the pest is spreading towards other European countries such as Spain and France, posing a great threat to them in terms of both products with market value and ecosystem services (de la Fuente et al. 2018; De la Fuente and Beck 2018). While our results indicated that tree-by-tree selective cutting is more cost-effective locally (Chapter 3), an extreme case could be that clear-cutting of host plants in the invaded forest of Portugal might potentially save the rest of Europe. The effectiveness could be measured by the prevention of economic loss due to the spread of PWN to other countries, while the cost could be the economic loss of clear-cutting in Portugal. When considering the geographical scope of all of Europe and assuming that PWN in Portugal is the source of introduction to other countries, clear-cutting might be more cost-effective because the large non-infested areas greatly benefit from clear-cutting in the infested areas. Nevertheless, this approach might not be accepted by society in Portugal, whereas other member states might support it. Therefore, outbreak management should be structured as an intergovernmental project within the EU, not just in a regulatory way of how to delimit zones in response to an outbreak, but also financially. The current situation is that the EU and member states financially co-support the official phytosanitary measures applied to plant pests (European Union 2021). This means that the EU provides funding on the condition that the member states also contribute to compensating the owners affected by the official phytosanitary measures. However, the determination on funding such actions differs across countries. The governments in Spain and Portugal provide financial compensation for the loss due to official phytosanitary measures, whereas the Dutch government rarely does (source: interviews with NPPO practitioners in Spain and the Netherlands). A possible solution to balance the trade-offs between different stakeholders inside and outside the infested area is for the EU to take charge of allocating compensation to owners for the losses incurred from the measures applied to their plants, independent of the member states. Additionally, planting tolerant plant species funded by the EU should be considered to mitigate the long-term losses caused by clear-cutting of host plants in the pest invaded areas.

5.2.4 How much detail is needed for an individual-based model?

Individual-based models, both case-specific and general (as Chapters 3 and 4), provide insight into the dynamics of complex systems. Thereby, case-specific individual-based models offer a higher degree of realism by tailoring to specific conditions (Grimm 1999). Nevertheless, they are constrained by the need to make many assumptions, which can lead to bias in the model outcomes. In contrast, general individual-based models (such as the model used in Chapter 4), trade accuracy for broader applicability, simplifying assumptions to cater to a wider range of situations but at the cost of reduced accuracy, especially when managing specific outbreaks. The general model in Chapter 4 made a simple assumption by simulating the spread of infested plants, rather than simulating the relationship between the dispersal of vectors and the transmission of the pest that results in the distribution of infested plants, and it did not take landscape heterogeneity into account. This approach allows for broad applicability of the model but at the cost of lower accuracy, as outbreak management differs from case to case (Chapter 2). Therefore, in the context of the specific research question, the design and application of individual-based models need to carefully balance realism, accuracy and applicability to optimize the assessment of outbreak management strategies. A judicious selection of parameters is needed to ensure that models provide relevant outcomes for decision-makers in fields that require outbreak management strategies tailored to specific epidemiological contexts (Beaudouin et al. 2008; Elevitch and Johnson 2020).

5.3 Implications for policy and practice

In this thesis, I used individual-based models to generate outcomes that may inform practical management of outbreaks, and ultimately even regulations of such management. Several modeling studies have indicated that EU regulations regarding the sizes of zones, which are derived from the practices of EU member states, are not effective (Carrasco et al. 2010; White et al. 2017; Robinet et al. 2020; Cendoya et al. 2022). Thus, implementing these sizes in regulations to guide the management of outbreaks in new locations, based solely on experience, is risky, even if it may be a result of a compromise between feasibility in practice and the effectiveness of the strategy.

Following the detection of an outbreak, the priority is to accurately delimit the boundaries of the infestation. Surveys could start at the presumed outbreak frontier if practitioners have high certainty that this presumed frontier is close to the actual one; otherwise, sampling radiating out from the initial finding is more cost-effective (Chapter 4). These general guidelines for the delimitation of the infested zone taking into account uncertainty in outbreak extent are not provided in the EFSA guidelines. Including such general guidelines in the EFSA guidelines could show how to delimit zones cost-effectively depending on available biological information of the pest.

At the same time, NPPOs should enhance the collaboration with researchers to develop case-specific models and conduct bioeconomic analysis, like the one in Chapter 3, to compare the cost and effectiveness of proposed eradication measures, e.g. clear-cutting or intensive tree-by-tree selective cutting. This can help provide recommendations on the most cost-effective eradication strategies.

Results of Chapter 4 confirm the necessity of including a buffer zone adjacent to an infested zone in practice (Chapter 2). Similar to the infested zone, the size of the buffer zone should take into account the fatness of the tail of the dispersal kernel. For example, as mentioned in Chapter 4, the average size of the infested zone was 732 meters using the inward strategy when *X. fastidiosa* had spread for three years with a negative exponential cross-section kernel. The distance from the furthest infested plant to the first detection was 1,437 meters. Therefore, to increase the probability of enclosing all infested plants, a buffer zone of similar size to the infested zone could enclose potentially infested plants outside the delimited area. However, when the dispersal has a fat tail as 2Dt cross-section kernel, the size of the buffer zone should be nine times as large as the size of the infested zone. Therefore, it is clear that using the mean spread distance, calculated by multiplying the mean dispersal distance per year by the number of years of spread (300 m, derived from 100 m per year over three years for *X. fastidiosa*), as the indicator for the size of a buffer zone is insufficient to enclose the remaining infested plants that are not yet enclosed by the infested zone. Thus, the mean spread distance cannot serve as a general rule for the size of the buffer zone because it should also take into account the distribution of the dispersal distances (EPPO 2021), especially the fatness of the dispersal tail.

5.4 Limitations and future research directions

How to best combine different zones needs to be further explored. Effectiveness and costs of delimiting only one zone (either clear-cutting zone or infested zone) were evaluated in Chapters 3 and 4, respectively. However, the infested zone, clear-cutting zone, and buffer zone have been combined in seven different ways in practical outbreak management in Europe (Chapter 2). Bioeconomic analysis on different combinations of zones could provide insight into the most cost-effective combination of zones and their optimal size. For example, when combining a clear-cutting zone and a buffer zone, increasing sampling effort in the buffer zone could allow for a decrease in the size of the clear-cutting zone, but the cost of increased sampling might be higher or lower than the benefits of reducing the size of the clear-cutting zone. Likewise, when combining an infested zone and a buffer zone, increasing the size of the infested zone may reduce the size of the buffer zone. However, this may also enclose more non-infested plants, subjecting them to destructive measures. Alternatively, more intensive sampling can improve the delimitation of the infested zone, minimizing the inclusion of non-infested individuals and avoiding unnecessary destruction. Chapter 2 found that the clear-cutting zone can be delimited either around the infested plants within an infested zone or around the infested zone itself. Modeling the two methods of delimitation of a clear-cutting zone could provide insight into how to most cost-effectively delimit the clear-cutting zone in space.

5.5 Conclusions

In an effort to review outbreak management cases in the EU, I summarized how outbreaks of plant pests are managed in practice and identified the knowledge gaps in zoning strategies for plant pest management. Modeling was used to compare the costs and effectiveness of the standing clear-cutting strategy, and an alternative tree-by-tree selective cutting strategy when aiming at eradicating PWN. I further explored the effectiveness of enclosing infested plants and the costs of sampling between the standing outward strategy and an EFSA-proposed inward strategy when delimiting an infested zone. This thesis bridges the gap between outbreak management in practice and scientific work, based on modelling to better indicate how to conduct the management of outbreaks of plant pests in practice. The main conclusions of this thesis are:

- When an outbreak of plant pests is detected, the infested zone, buffer zone and clear-cutting zone are three main zones that are used (Chapter 2).
- Most often the combination of an infested zone is used with a buffer zone; this is an appropriate option to enclose undetected infested plants (Chapters 2 and 3).
- Zoning strategies become less diverse after a pest is regulated (Chapter 2).
- Neither clear-cutting nor tree-by-tree selective cutting could eradicate PWN under realistic conditions (Chapter 3).
- Under the goal of containment, clear-cutting could be replaced by tree-by-tree selective cutting with aerial surveillance as it can achieve a given level of effectiveness at lower costs compared to the current practice of clear-cutting with visual surveillance when a large proportion (≥ 60%) of infested trees are symptomatic (Chapter 3).
- Remote sensing is the future of pest surveillance (Chapter 3).
- Both the inward and outward strategies are prone to error in delimiting all infested plants, particularly in delimiting outbreaks of pests with fat-tailed dispersal patterns (Chapter 4).
- The standing practice of outward sampling for outbreak demarcation is recommended considering the uncertainty about the position of the frontier (Chapter 4).
- Enhancing connections between scientific researchers and practitioners could improve the management of outbreaks of non-native plant pests (Chapters 2, 3, 4).

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Supplementary Information for Chapter 3

Pine wood nematode control without clear-cutting:

a scenario analysis

Supplementary methods

Supplementary results

Fig. S3.7 The distribution of PWN-infested symptomatic trees (*red points*) and asymptomatic trees (*blue points*)

Table S3.8 Number of cut trees, and cut infested trees (average value ± standard error) by visual ground surveillance

Table S3.9 Number of cut trees, and cut infested trees (average value ± standard error) by visual ground surveillance combined with trapping networks

Table S3.10 Number of cut trees, and cut infested trees (average value ± standard error) by aerial surveillance

Table S3.11 Cost components for visual surveillance from the ground in 100,000 Euro for 1-100 initial emerging beetles

Table S3.12 Cost components for visual surveillance from the ground combined with trapping networks in 100,000 Euro for 1-100 initial emerging beetles

Table S3.13 Cost components for aerial surveillance in 100,000 Euro for 1-100 initial emerging beetles

Table S3.14 Cost components for visual surveillance from the ground in 100,000 Euro for 10-60 initial emerging beetles

Table S3.15 Cost components for visual surveillance from the ground combined with trapping networks in 100,000 Euro for 10-60 initial emerging beetles

Table S3.16 Cost components for aerial surveillance in 100,000 Euro for 10-60 initial emerging beetles

Table S3.17 Cost components for visual surveillance from the ground in 100,000 Euro for 1,000 initial emerging beetles

Table S3.18 Cost components for visual surveillance from the ground combined with trapping networks in 100,000 Euro for 1,000 initial emerging beetles

Table S3.19 Cost components for aerial surveillance in 100,000 Euro for 1,000 initial emerging beetles

Materials and Methods

The following texts provide details on the used methodology. The first three supplements describe respectively details on the host plants (Methods S3.1), vector dispersal and PWN transmission (Methods S3.2), and three entry scenarios of PWN (Methods S3.3). The fourth supplement describes the three surveillance methods and the cost calculations in detail (Methods S3.4).

Methods S3.1 Host

Maritime pines, *Pinus pinaster*, were the host plants of interest in our study as this species is susceptible to PWN. In Southwestern France, if trees are infested by the end of July, the disease develops fast due to a rapid increase of the nematode population associated with the warm climate. In our model, we did not take into account the effect of temperature on speed with which symptoms developed after infection by PWN. However, pine trees commonly die about 30 days after becoming inoculated by PWN (University of California 2023). In our model, we thus assumed that incubation time was 30 days (parameter L in Table S3.1). As a result, most PWN-infested trees will show symptoms in October.

Methods S3.2 Vector dispersal and PWN transmission

Adult beetles transport the nematodes within their tracheae from infested trees where they emerged to healthy trees nearby during their flight season (May-October). There are two principal pathways of transmitting the nematode to healthy trees: via feeding wounds on the pine shoots and twigs by adult beetles during maturation feeding, and via oviposition wounds made by females on the tree trunk (Schröder et al. 2009). The first pathway of infection is by far the most important. Transmission of the PWN from tree to tree via the roots is negligible (Mamiya and Shoji 1989). In Portugal and France, most *M. galloprovincialis* take one year to complete their life cycle (Schenk et al. 2020). Successful overwintering eggs laid on the PWN-infested trees could become an infection source of the next year.

We simulated the dispersal of *M. galloprovincialis* and PWN transmission during the vector's adult life span (120 days, parameter I in Table S3.1). We built on an individual-based model that was developed by Robinet et al. (2019). Beetles emerge from trees at the beginning of May and emergence peaks in the mid of July (Naves et al. 2008). In our simulations, we assumed that the emergence of beetles followed a Gaussian distribution (mean = 83 days, sd = 15 days) (Julian day starting on May 1^{st}) from a single PWN-infested log (depending on the initial entry scenario, see Methods S3.3). In our model, we assumed that 91% of the initial emerging beetles will carry PWN (Naves et al. 2006).

Once beetles emerge from the trees, they disperse for maturation feeding. We assumed that at each insect stop, the insect could find a host tree. Here, we assumed that the host trees were the destination for each dispersal event (i.e. the daily stop of beetles resulting from the stochastic dispersal model was "rounded" to the location of the closest tree). Usually, beetles use living trees for feeding and stay on it for one day before the move to another tree (Robinet et al. 2020). Transmission via feeding occurs during the first 77 days after emergence for both mature and reproductively immature adult beetles (Naves et al. 2007), although dispersal lasts until October. We assumed that the trees subject to feeding of PWN-carrying beetles during this transmission period always became infested by PWN. We took this assumption as the relationship between transmission of the disease and feeding of PWN-carrying beetles because the nematode load is not well understood. In our model, we assumed that beetles stayed on the tree for one day if it was used for feeding (parameter β in Table S3.1).

We assumed further that female beetles began to oviposit from 20 days to 53 days after emerging (following Naves et al. (2007); Robinet et al. (2020)). Female beetles prefer weakened or dead trees for oviposition (Schröder et al. 2009) and it takes about five days after egg laying before they fly again (B. Luis pers. com.). In our model, we assumed that females selected declining trees nearby the endpoint of their flight (infested with PWN or affected by other factors) to oviposit and stayed on the oviposited trees for five day before the next flight (parameter π in Table S3.1). However, if there were no declining trees were found nearby, females laid eggs on healthy trees with a probability of 0.01 (parameter p_{oh} in Table S3.1). We considered that the probability of nematode transmission was 0.37 via egg-laying (parameter PO in Table S3.1 (Naves et al. 2007)). In our model, we assumed that overwintering eggs have a survival rate of 0.53 (Naves et al. 2008). All parameters, their values and references used to simulate the dispersal of vector beetle and transmission of PWN are listed in Table S3.1.

Table S3.1 Parameters used in the model to vector dispersal and PWN transmission

Parameter	Definition	Values	References
r	Sex ratio (proportion females)	0.5	(Robinet et al. 2020)
p_{fm}	Daily probability of flying for mature beetles	0.61	(David et al. 2014)
p_{fi}	Daily probability of flying for immature beetles	0.45	(David et al. 2015)
n	Number of emerging adult insects that may carry PWN from the initial infested tree	1-100, 10-60 or 1,000	Preliminary simulations and realistic assumption
Pc	Proportion of initial emerging beetles that carry PWN	91%	(Naves et al. 2006)
I	Adult longevity (in days)	120	(Robinet et al. 2019, 2020)
α	Mean daily dispersal distance (in meters)	2,000	(Robinet et al. 2019, 2020)
β	Number of resting days between two flights for beetles who did feeding at the last flight (in days)	1	(Robinet et al. 2020)
π	Number of resting days between two flights for beetles who laid eggs at the last flight (in days)	5	B. Luis pers. com.
NE	Number of eggs laid per female each day during the oviposition period	2	(Robinet et al. 2020)
PO	Probability to transmit PWN when egg laying	0.37	(Naves et al. 2007)
L	Period between PWN inoculation and appearance of symptoms (in days)	30	Field observation in southwestern France
p_{oh}	Probability that a female lays eggs on healthy trees	0.01	B. Luis pers. com.
M	Survival rate of eggs during overwintering	0.53	(Naves et al. 2008)

Methods S3.3 Three entry scenarios

We considered three different entry scenarios as it may be uncertain how PWN arrives into a new area, and to evaluate the robustness of the results against the choice of the entry scenario. In the first scenario, we assumed that beetles (1-100) were introduced by a log that originated from an area where PWN was present in the previous year, and from which they escaped in spring in the study area and released PWN, so called “1-100 initial emerging beetles”. We assumed a uniform distribution for each value from 1 to 100 initial emerging beetles. In the second scenario, we assumed that a mated and infested female beetle entered the study area (for example by hitchhiking on a log or truck) at the end of the growing season and that laid eggs on a healthy tree. Its offspring emerged in spring from this tree and are the source of the infection. In this scenario, patrolling beetles from the endemic population have not laid eggs on the PWN-infested tree. We simulated 10, 20, 30, 40, 50, and 60 emerging beetles to escape from a single PWN-infested tree, so called “10-60 initial emerging beetles” with respective probabilities of 0.56, 0.25, 0.11, 0.05, 0.02, and 0.01 for each number (results shown of this entry scenario are shown in Fig. S3.2). These probabilities were obtained from model pilot runs and analyzing the number of emerging beetles from an infested tree. In the third scenario, we expanded on the second scenario by assuming that endemic patrolling beetles could lay eggs on the PWN-infested trees form the hitchhiking beetle, leading to approximately 1,000 initial emerging infested beetles in spring (H. Jactel pers. com.) (results shown of this entry scenario are shown in Fig. S3.3).

The three entry scenarios results in qualitatively the same conclusions. In particular Fig. 3.1 and Fig. S3.2 were very comparable. The third entry scenario resulted in a very high number of infested trees which covered almost the entire landscape. The outcomes of this scenario deviated from the previous two in that clear-cutting in combination with aerial surveillance could eradicate PWN when at least 80% of infested trees were symptomatic (Fig. S3.3). However, this approach would lead to the destruction of almost the entire forest, which is not acceptable to stakeholders.

Methods S3.4 Surveillance

Methods S3.4.1 Visual surveillance from the ground

The road density (including roads that can be accessed by a four-wheel drive) is roughly 3.8 km/km^2 in the forest of Southwestern France (Parc naturel régional des Landes de Gascogne). For convenience we implemented a grid pattern of 40 roads running north-south and 40 roads running east-west, each road at 0.5 km distance from the nearest parallel road. Field data has indicated that the maximum sighting distance of declining trees was 39.8 m (Samalens et al. 2007). In accordance with this, we assumed that declining trees were detected if they were located within 40 m to the sampled road (parameter P_r in Table S3.2).

Methods S3.4.2 Visual surveillance from the ground combined with trapping networks

Pheromone trapping is commonly done for surveillance and early detection. However, such networks could also be used to locate the origin of emerging beetles based on the location of the traps which caught PWN-carrying beetles (Nunes et al. 2021). The fewer traps used to locate the origin, the better. This is because a great number of traps could reduce the population of native beetles which is not a desirable situation for stakeholders and a smaller number of traps could reduce the resource cost to locate the emerging tree. A trap density of 1 trap per 16 km^2 is a compromise between the likelihood of detection and practicality for field implementation. Thus, we assumed that 25 traps were homogenously distributed in the forest (parameter T_d in Table S3.2). When modeling the dispersal of each beetle, we simulated trap capture with a probability of 0.01 when the insect crossed the 100 m attraction radius of a trap (parameters λ and D_t in Table S3.2).

Methods S3.4.3 Aerial surveillance

The detection probability from remote sensing images is 0.91 (Qin et al. 2021), which is the ratio of the number of detected declining trees over the number of all declining trees. In our model, we tested a range of aerial efficiencies 0.51, 0.71 and 0.91 per flight, with 1, 2 and 3 flights for each efficiency (parameter P_a in Table S3.2) and additionally tested 4 or 5 flights for the near-perfect condition.

Table S3.2 Model parameters for simulating surveillance and management

Parameter	Definition	Values	References
P_r	Detection distance of the declining tree to the road (in meters)	40	(Samalens et al. 2007)
N	Number of sampled roads in each direction (/40)	10 - 40	Model testing
P_a	Probability that a declining tree is detected by aircraft	0.51, 0.71 and 0.91	(HOMED 2018)
Nf	Number of flights	1 - 5	Preliminary simulations
T_d	Trap number on the 20 km × 20 km study area	25	Realistic assumption
D_t	Attraction distance of the trap (in meters)	100	(Jactel et al. 2019)
λ	Trap efficiency (rate)	0.01	(Jactel et al. 2019; Robinet et al. 2019)
R	Radius of the clear-cutting zone (in meters)	500	(European Commission 2006, 2012, 2018)

Methods S3.4.4 Costs of surveillance, wood sampling, eradication and revenue loss

Costs included in the analysis are surveillance costs, wood sampling costs (field sampling and laboratory testing), eradication costs (logging and chipping) and revenue loss of the timber value due to cutting healthy trees.

Costs per surveillance method

The costs of visual surveillance (***CVS***) accounted for the operational costs consisting of vehicle, labour and daily allowance costs (Table S3.3) and the number of roads sampled can be calculated as:

$$CVS_{Nrs} = (Nr_s * Lr_s) * (Veh_{km} + \frac{1}{Sp} * Labor_h) + \frac{Nr_s * Lr_s}{Dist_d} * Allow_d$$

Table S3.3 Input parameters visual surveillance costs calculation

Parameter description	Variable	Value	Unit
Vehicle cost per kilometer (fuel cost, maintenance cost)	Veh_{km}	0.4	€/km
Daily allowance (ex: meal expenses of field workers)	$Allow_d$	17	€/day
Labor cost per hour	$Labor_h$	64	€/hour
Speed of surveillance	Sp	20	km/hour
Max distance traveled per day	$Dist_d$	160	km/day
Number of roads sampled	Nr_s	[10 - 40]	--
Length of a single road	Lr_s	20	km

Estimated by experts Forest Health Department – INRAE

Depending on the number of roads sampled, the costs ranged from € 1,491 for sampling 10 roads to € 5,930 for sampling 40 roads on an area of 20 km × 20 km.

The costs of aerial surveillance (***CAS***) covered the flight costs over the 20 km × 20 km area and the costs for the analysis and storage of the images that have been taken. Based on Table S3.4 these surveillance costs corresponded to a total amount of € 80,000 per flight, irrespective of the PWN spread.

Table S3.4 Input parameters aerial surveillance costs calculation

Parameter description	Cost (€)
Flight over 20 km × 20 km ~ 10 days timespan per flight	25,000
Images analysis for 20 km × 20 km (8 km²/day/flight)	50,000
Data storage in the cloud per flight	5,000

Estimated by experts Forest Health Department – INRAE

SI. 3

The costs of trapping surveillance (***CTS***) included the costs of the traps, the labour and equipment costs related to trap installation and checking, and the costs of analysing the collected samples in the lab. Based on the input of Table S3.5, the investment costs in 25 traps and the necessary required pheromone lures were estimated at:

$$Ntrap * (PhT + Ch * PhL) = € \, 5{,}125 \, .$$

The labour costs for installation were equal to:

$$\frac{Ntrap}{Nin} * h * Labor_h + \frac{Ntrap}{Nin} * Allow_d = € \, 1{,}331.$$

The labour costs for checking the traps were set equal to:

$$Ch * \left(\frac{Ntrap}{Nch} * h * Labor_h + \frac{Ntrap}{Nch} * Allow_d \right) = € \, 3{,}549.$$

The costs for the analyses of the samples were estimated at a value of

$$Ch * Ntrap * (Ss + LabT) = € \, 6{,}500.$$

Summation of the various cost components resulted in total costs of trapping surveillance (*CTS*) equaled to € 16,505.

Table S3.5 Input parameters trapping surveillance costs calculation

Parameter description	Variable	Value	Unit
Price Pheromone trap *Monochamus*	*PhT*	45	€/trap
Costs pheromone lures (Dispenser Galloprotect Pack)	*PhL*	40	€/dispenser /check
Number of traps installed	*Ntrap*	25	--
Number of checks during flight season	*Ch*	4	--
Number of traps installed per day	*Nin*	10	/day
Number of traps checked per day	*Nch*	15	/day
Number of working hours per day	*h*	8	hours/day
Daily allowance	$Allow_d$	17	€/day
Labor costs per hour	$Labor_h$	64	€/hour
Costs to send samples to the lab	*Ss*	30	€/trap
Costs PWN identification per trap	*LabT*	35	€/trap

Estimated by experts Forest Health Department – INRAE

Wood sampling costs

After the detection of declining trees by visual or aerial surveillance, a separate management team was sent out to sample these trees for confirmation tests in the laboratory. Costs related to these wood sampling and confirmation tests (***CWs***) were calculated, given the input of Table S3.6, as follow:

$$CW_s = NW * (Wst + LabWs)$$

Table S3.6 Input parameters wood sampling costs calculation

Parameter description	Variable	Value	Unit
Costs wood sampling declining tree	*Wst*	23 [a]	€/sample
Costs DNA confirmation test wood sample	*LabWs*	34 [a]	€/sample
Number of wood samples	*NW*	Model output	--

[a)] Estimated by experts Forest Health Department - INRAE

Table S3.6 indicates a lump sum value of sampling and confirmation tests costs: it included labour and equipment costs. Based on these values, the total costs for sampling and testing equaled € 57 per wood sample.

Costs per eradication strategy

SI. 3

As the costs calculation of the eradication strategies (***CCS***) only varied by the number of trees cut, the costs of both eradication strategies depended on the costs of logging and chipping a tree (Table S3.7):

$$CCS = Ntc * (Lo + Gr)$$

Table S3.7 Input parameters eradication costs calculation

Parameter	Variable	Value	Unit
Logging costs per tree	*Lo*	10	€/tree
Chipping costs per tree	*Gr*	12	€/tree
Total number of trees cut	*Ntc*	Model output	--
Total number of non-infested trees cut	*Nni*	Model output	--
Timber value per tree/standing stock (ready to be harvested)	*Tim*	60	€/tree

Estimated by experts Forest Health Department – INRAE

Table S3.7 indicates lump sum value on logging and chipping, which included an estimation of labour and equipment costs. Based on these values, the total costs for cutting a tree equaled € 22.

Revenue loss

The opportunity value of the non-PWN infested trees that were cut as part of the clear-cutting was aligned with the estimated standing value of a ‘ready-to-be-harvest‘ tree. Revenue loss (RL) was the losses (revenues foregone) due to the cutting of non-PWN infested trees (Table S3.7):

$$RL = Nni * Tim$$

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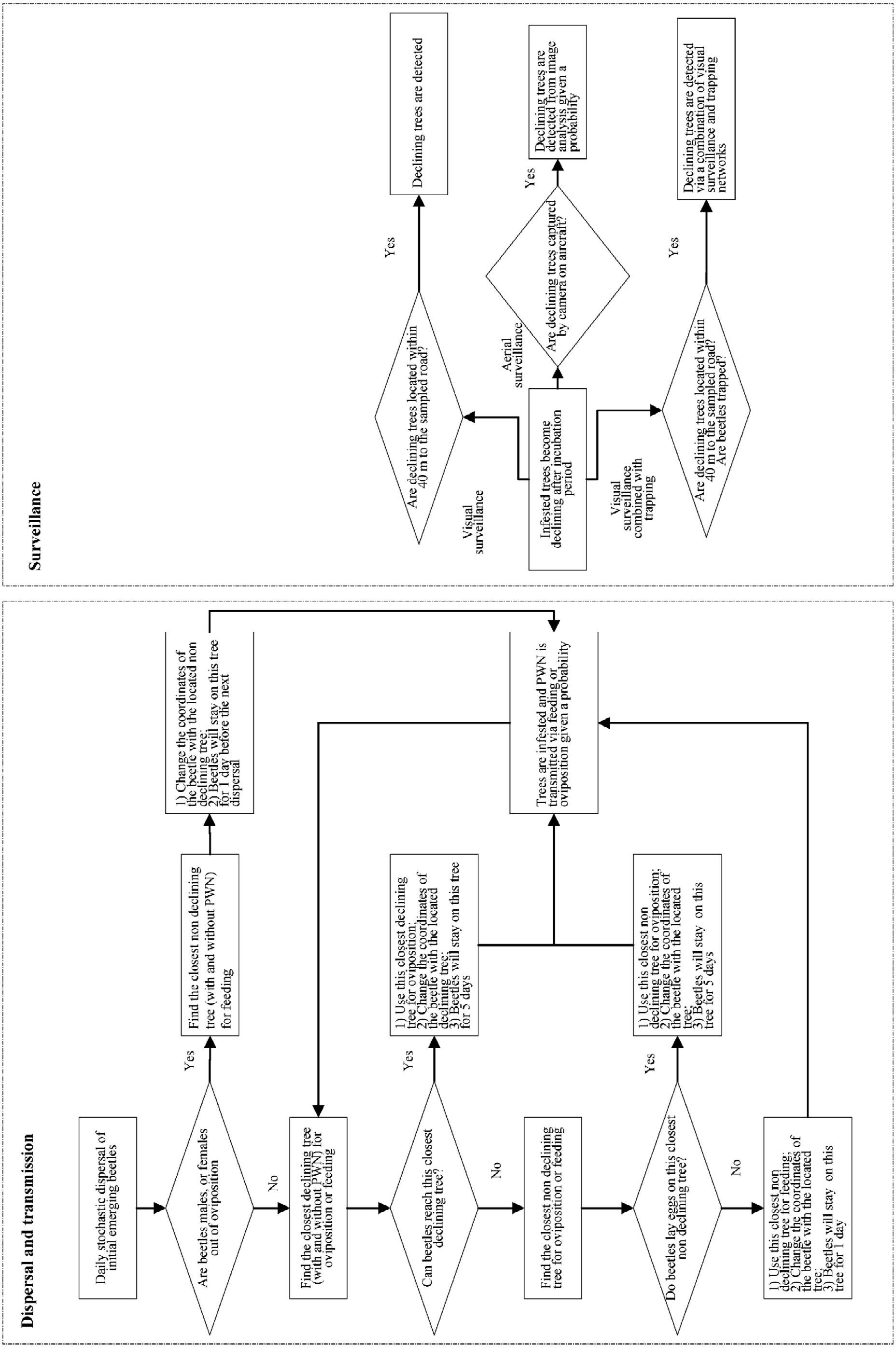
Dispersal and transmission
Daily stochastic dispersal of initial emerging beetles
Are beetles males, or females out of oviposition
Yes
No
Find the closest non declining tree (with and without PWN) for feeding
1) Change the coordinates of the beetle with the located non declining tree;
2) Beetles will stay on this tree for 1 day before the next dispersal
Find the closest declining tree (with and without PWN) for oviposition or feeding
Can beetles reach this closest declining tree?
1) Use this closest declining tree for oviposition;
2) Change the coordinates of the beetle with the located declining tree;
3) Beetles will stay on this tree for 5 days
Find the closest non declining tree for oviposition or feeding
Do beetles lay eggs on this closest non declining tree?
1) Use this closest non declining tree for oviposition;
2) Change the coordinates of the beetle with the located tree;
3) Beetles will stay on this tree for 5 days
1) Use this closest non declining tree for feeding;
2) Change the coordinates of the beetle with the located tree;
3) Beetles will stay on this tree for 1 day
Trees are infested and PWN is transmitted via feeding or oviposition given a probability
Surveillance
Infested trees become declining after incubation period
Visual surveillance
Are declining trees located within 40 m to the sampled road?
Declining trees are detected
Aerial surveillance
Are declining trees captured by camera on aircraft?
Declining trees are detected from image analysis given a probability
Visual surveillance combined with trapping
Are declining trees located within 40 m to the sampled road? Are beetles trapped?
Declining trees are detected via a combination of visual surveillance and trapping networks

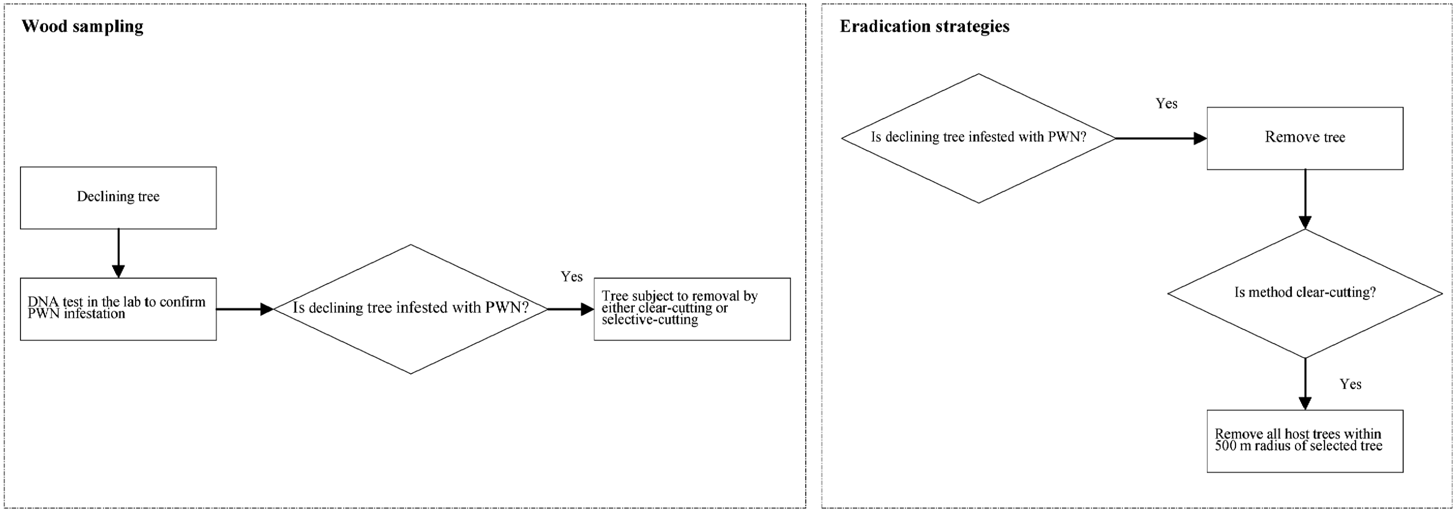

Fig. S3.1 Conceptual framework of modelling approach. The framework consists of four modules (*dotted line*): vector dispersal and PWN transmission, surveillance of declining trees, wood sampling, and eradication strategies. *Rectangles* and *diamonds* indicate the components of the four modules. *Arrows* indicate a causal relationship: starting from the cause pointing into the effect

SI. 3

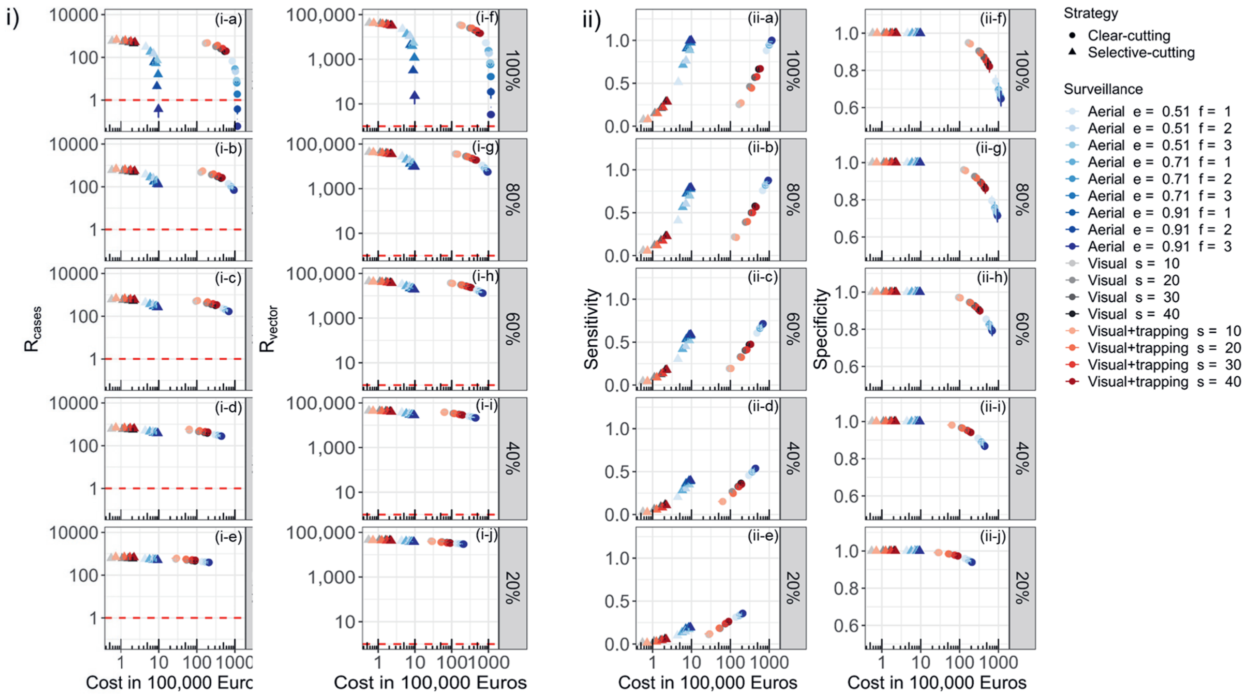

Fig. S3.2 Relationships between costs (x-axis) and the four performance metrics R_{cases}, R_{vector}, sensitivity and specificity (y-axis) of the evaluated eradication strategies based on clear-cutting and tree-by-tree selective cutting at the entry scenario of 10-60 initial emerging beetles in the presence of patrolling beetles. Three methods for surveillance are considered: (1) aerial surveillance, (2) visual ground surveillance and (3) a combination of visual ground surveillance and trapping networks with pheromone traps to locate the first diseased tree. Surveillance is carried out when 100%, 80%, 60%, 40% and 20% (right side of each panel) of the infested trees are symptomatic. Costs are presented on a log10 logarithmic axis. *Circles* represent clear-cutting, and *triangles* indicate tree-by-tree selective cutting. *Blue colors* represent aerial surveillance with aerial detection efficiency *e* per flight and *f* numbers of flights, *grey colors* represent visual ground surveillance with *s* roads sampled, and *red colors* indicate visual ground surveillance combined with trapping networks *s* roads sampled. *Bars* represent confidence intervals of the mean for 50 simulations. *Horizontal dashed red lines* represent R_{cases} and R_{vector} values of 1

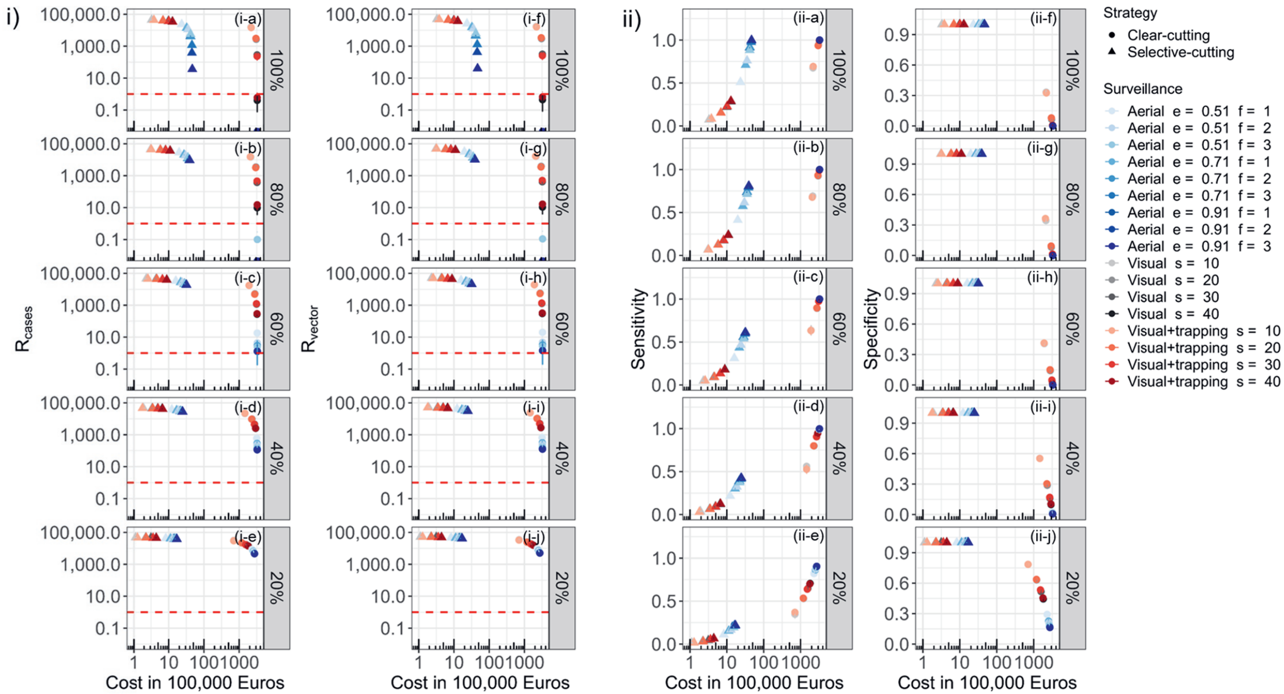

Fig. S3.3 Relationships between costs (x-axis) and the four performance metrics R_{cases}, R_{vector}, sensitivity and specificity (y-axis) of the evaluated eradication strategies based on clear-cutting and tree-by-tree selective cutting at the entry scenario of 1,000 initial emerging beetles in the presence of patrolling beetles. Three methods for surveillance are considered: (1) aerial surveillance, (2) visual ground surveillance and (3) a combination of visual ground surveillance and trapping networks with pheromone traps to locate the first diseased tree. Surveillance is carried out when 100%, 80%, 60%, 40% and 20% (right side of each panel) of the infested trees are symptomatic. Costs are presented on a log10 logarithmic axis. *Circles* represent clear-cutting, and *triangles* indicate tree-by-tree selective cutting. *Blue colors* represent aerial surveillance with aerial detection efficiency *e* per flight and *f* numbers of flights, *grey colors* represent visual ground surveillance with *s* roads sampled, and *red colors* indicate visual ground surveillance combined with trapping networks *s* roads sampled. *Bars* represent confidence intervals of the mean for 50 simulations. *Horizontal dashed red lines* represent R_{cases} and R_{vector} values of 1

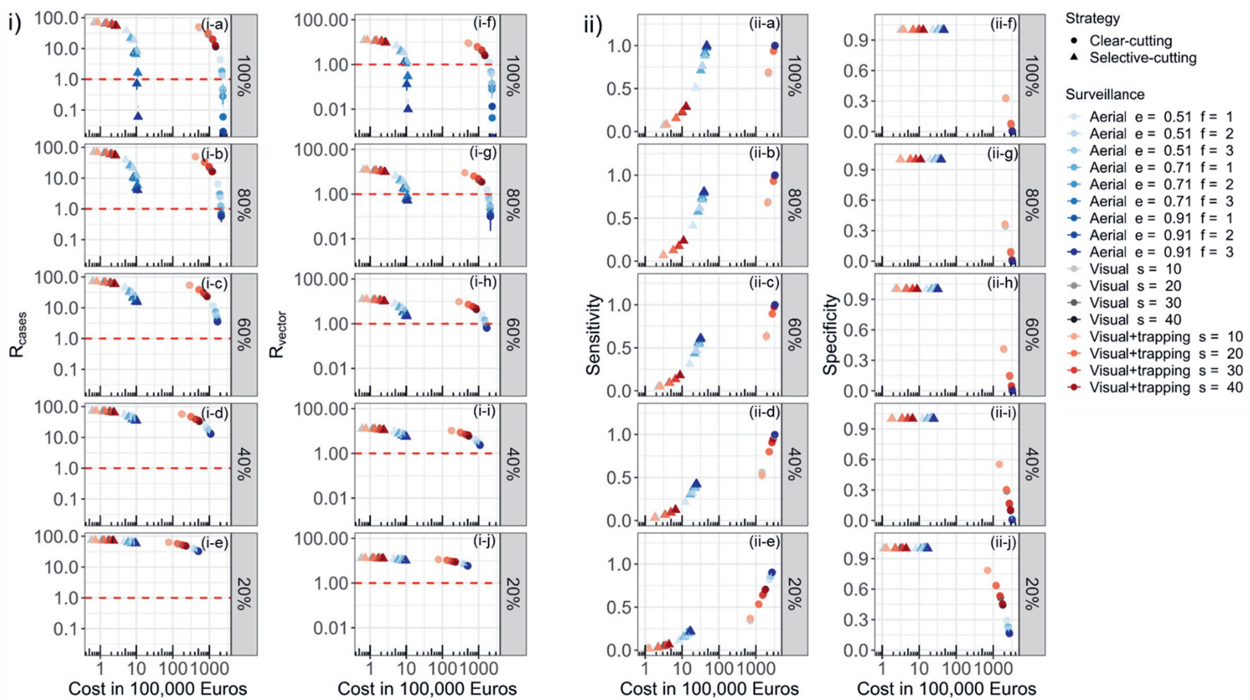

Fig. S3.4 Relationships between costs (x-axis) and the four performance metrics R_{cases}, R_{vector}, sensitivity and specificity (y-axis) of the evaluated eradication strategies based on clear-cutting and tree-by-tree selective cutting at the entry scenario of 1-100 initial emerging beetles without patrolling beetles present. Three methods for surveillance are considered: (1) aerial surveillance, (2) visual ground surveillance and (3) a combination of visual ground surveillance and trapping networks with pheromone traps to locate the first diseased tree. Surveillance is carried out when 100%, 80%, 60%, 40% and 20% (right side of each panel) of the infested trees are symptomatic. Costs are presented on a log10 logarithmic axis. *Circles* represent clear-cutting, and *triangles* indicate tree-by-tree selective cutting. *Blue colors* represent aerial surveillance with aerial detection efficiency *e* per flight and *f* numbers of flights, *grey colors* represent visual ground surveillance with *s* roads sampled, and *red colors* indicate visual ground surveillance combined with trapping networks *s* roads sampled. *Bars* represent confidence intervals of the mean for 50 simulations. *Horizontal dashed red lines* represent R_{cases} and R_{vector} values of 1

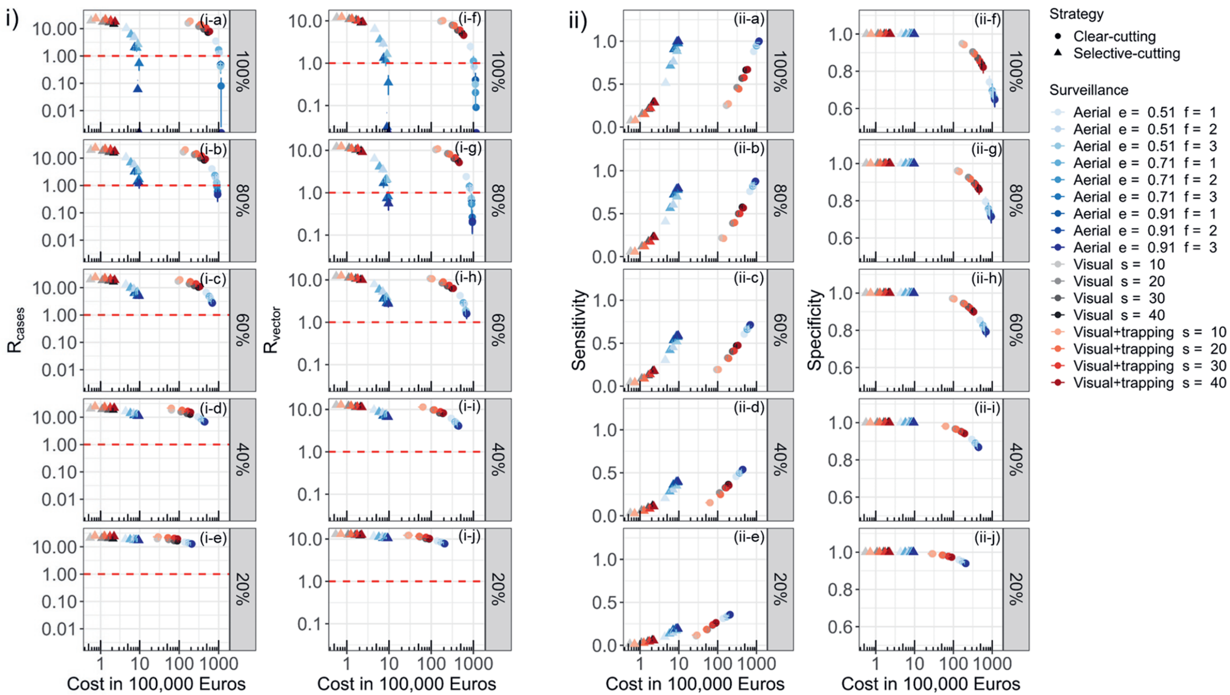

Fig. S3.5 Relationships between costs (x-axis) and the four performance metrics R_{cases}, R_{vector}, sensitivity and specificity (y-axis) of the evaluated eradication strategies based on clear-cutting and tree-by-tree selective cutting at the entry scenario of 10-60 initial emerging beetles without patrolling beetles present. Three methods for surveillance are considered: (1) aerial surveillance, (2) visual ground surveillance and (3) a combination of visual ground surveillance and trapping networks with pheromone traps to locate the first diseased tree. Surveillance is carried out when 100%, 80%, 60%, 40% and 20% (right side of each panel) of the infested trees are symptomatic. Costs are presented on a log10 logarithmic axis. *Circles* represent clear-cutting, and *triangles* indicate tree-by-tree selective cutting. *Blue colors* represent aerial surveillance with aerial detection efficiency *e* per flight and *f* numbers of flights, *grey colors* represent visual ground surveillance with *s* roads sampled, and *red colors* indicate visual ground surveillance combined with trapping networks *s* roads sampled. *Bars* represent confidence intervals of the mean for 50 simulations. *Horizontal dashed red lines* represent R_{cases} and R_{vector} values of 1

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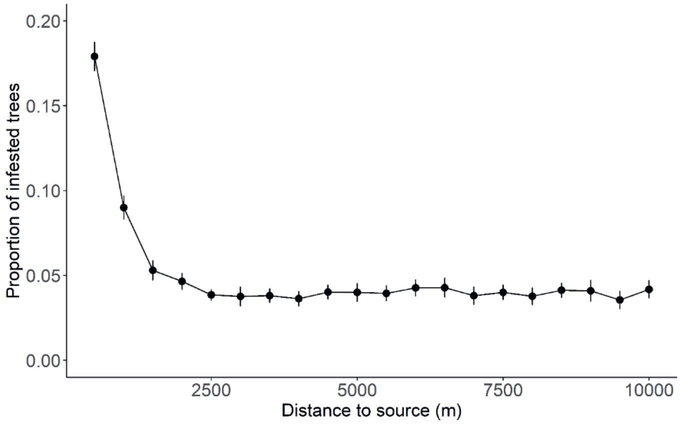

Fig. S3.6 The proportion of infested trees in relation to their distance (m) to the first infested tree. *Points* indicate mean proportion infested trees within bins of 500-meter and *bars* represent their 95% confidence interval of the mean based on 50 simulations

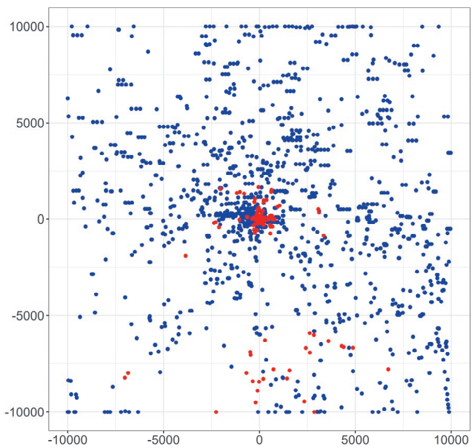

Fig. S3.7 The distribution of PWN-infested symptomatic trees (*red points*) and asymptomatic trees (*blue points*) in case of 36 initial emerging beetles at the end of the growing season, as an example. The study area is a 20 km × 20 km landscape of pure pine plantations, representative of the Landes Forest (the largest artificial forest in Europe, located in Southwestern France)

Table S3.8 Number of cut trees, and cut infested trees (average value ± standard error) by **visual ground surveillance** under clear-cutting or tree-by-tree selective cutting at 100%, 80%, 60%, 40% and 20% of symptomatic trees per entry scenario. The number of infested trees resulting from 1-100, 10-60 and 1,000 initial emerging beetles are 2,416 ± 189, 631 ± 54, and 48,160 ± 123, respectively

		1-100				10-60				1,000			
Proportion of symptomatic trees	Number of sampled roads	Cut trees		Cut infested trees		Cut trees		Cut infested trees		Cut trees		Cut infested trees	
		Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	660,626 ± 46,200	191 ± 16	1,003 ± 97	191 ± 16	204,970 ± 16,362	47 ± 4	175 ± 22	47 ± 4	2,671,549 ± 31,972	3,542 ± 173	32,528 ± 869	3,542 ± 173
	20	1,146,606 ± 75,825	366 ± 29	1,546 ± 140	366 ± 29	383,919 ± 29,991	94 ± 8	310 ± 34	94 ± 8	3,749,341 ± 11,214	7,448 ± 167	45,468 ± 175	7,448 ± 167
	30	1,523,658 ± 97,815	540 ± 44	1,861 ± 163	540 ± 44	515,281 ± 37,259	133 ± 12	377 ± 38	133 ± 12	3,974,168 ± 4,860	10,577 ± 210	47,872 ± 131	10,577 ± 210
	40	1,820,203 ± 111,418	694 ± 54	2,056 ± 177	694 ± 54	652,558 ± 47,959	180 ± 16	441 ± 45	180 ± 16	4,003,909 ± 47	13,806 ± 169	48,160 ± 123	13,806 ± 169
80%	10	506,107 ± 35,332	157 ± 17	880 ± 89	157 ± 17	155,106 ± 12,540	36 ± 3	154 ± 20	36 ± 3	2,627,320 ± 37,487	3,274 ± 223	33,295 ± 1,081	3,274 ± 223
	20	902,243 ± 62,554	284 ± 24	1,336 ± 123	284 ± 24	298,183 ± 23,047	75 ± 7	264 ± 28	75 ± 7	3,676,961 ± 17,367	6,058 ± 267	44,650 ± 401	6,058 ± 267
	30	1,233,153 ± 77,266	422 ± 33	1,660 ± 148	422 ± 33	421,102 ± 32,619	111 ± 10	335 ± 36	111 ± 10	3,957,992 ± 4,363	8,437 ± 167	47,786 ± 129	8,437 ± 167
	40	1,483,329 ± 93,570	568 ± 45	1,855 ± 164	568 ± 45	524,926 ± 37,768	145 ± 13	381 ± 38	145 ± 13	4,001,168 ± 766	11,516 ± 148	48,151 ± 121	11,516 ± 148
60%	10	343,960 ± 26,100	107 ± 11	727 ± 79	107 ± 11	114,782 ± 10,379	27 ± 3	133 ± 17	27 ± 3	2,375,524 ± 29,434	2,284 ± 216	30,630 ± 1,359	2,284 ± 216
	20	639,032 ± 44,865	223 ± 20	1,167 ± 108	223 ± 20	220,192 ± 15,782	58 ± 6	224 ± 24	58 ± 6	3,436,351 ± 20,458	4,327 ± 227	42,999 ± 210	4,327 ± 227
	30	872,966 ± 60,755	311 ± 27	1,392 ± 129	311 ± 27	292,391 ± 22,912	79 ± 7	273 ± 29	79 ± 7	3,830,283 ± 12,211	6,562 ± 190	46,995 ± 179	6,562 ± 190
	40	1,053,297 ± 70,434	410 ± 33	1,542 ± 139	410 ± 33	372,620 ± 26,473	110 ± 10	313 ± 32	110 ± 10	3,950,289 ± 5,399	8,763 ± 135	47,889 ± 126	8,763 ± 135
40%	10	222,527 ± 17,006	81 ± 8	637 ± 65	81 ± 8	77,265 ± 6,665	21 ± 3	111 ± 17	21 ± 3	1,795,168 ± 23,778	1,796 ± 191	27,003 ± 734	1,796 ± 191
	20	393,026 ± 26,786	161 ± 15	950 ± 86	161 ± 15	135,028 ± 10,191	38 ± 4	175 ± 19	38 ± 4	2,854,342 ± 23,870	3,056 ± 204	38,483 ± 344	3,056 ± 204
	30	530,074 ± 35,302	221 ± 18	1,097 ± 99	221 ± 18	190,478 ± 13,832	57 ± 5	220 ± 23	57 ± 5	3,366,761 ± 20,039	4,320 ± 226	43,608 ± 139	4,320 ± 226
	40	647,319 ± 43,123	282 ± 23	1,214 ± 110	282 ± 23	228,036 ± 17,303	74 ± 7	245 ± 26	74 ± 7	3,614,269 ± 15,860	5,858 ± 52	45,650 ± 167	5,858 ± 52
20%	10	93,463 ± 7,497	51 ± 8	462 ± 53	51 ± 8	33,593 ± 3,121	9 ± 1	70 ± 10	9 ± 1	871,049 ± 19,870	775 ± 112	16,774 ± 1,128	775 ± 112
	20	174,712 ± 12,483	80 ± 9	688 ± 64	80 ± 9	64,780 ± 5,908	18 ± 2	124 ± 17	18 ± 2	1,479,428 ± 27,473	1,543 ± 133	25,596 ± 405	1,543 ± 133
	30	231,337 ± 16,666	115 ± 11	804 ± 72	115 ± 11	88,917 ± 6,404	26 ± 2	155 ± 15	26 ± 2	1,943,340 ± 37,319	2,139 ± 77	31,170 ± 378	2,139 ± 77
	40	277,192 ± 20,323	144 ± 12	865 ± 77	144 ± 12	106,792 ± 8,882	39 ± 4	175 ± 19	39 ± 4	2,232,450 ± 32,656	3,181 ± 81	34,014 ± 346	3,181 ± 81

SI. 3

Table S3.9 Number of cut trees, and cut infested trees (average value ± standard error) by **visual ground surveillance combined with trapping networks** under clear-cutting or tree-by-tree selective cutting at 100%, 80%, 60%, 40% and 20% of symptomatic trees per entry scenario. The number of infested trees resulting from 1-100, 10-60 and 1,000 initial emerging beetles are 2,416 ± 189, 631 ± 54, and 48,160 ± 123, respectively

		1-100				10-60				1,000			
		Cut trees		Cut infested trees		Cut trees		Cut infested trees		Cut trees		Cut infested trees	
Proportion of symptomatic trees	Number of sampled roads	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	623,019 ± 45,158	164 ± 14	872 ± 87	164 ± 14	229,862 ± 24,551	58 ± 7	235 ± 39	58 ± 7	2,703,377 ± 22,679	3,955 ± 308	32,752 ± 977	3,955 ± 308
	20	1,120,786 ± 76,580	355 ± 30	1,498 ± 138	355 ± 30	426,782 ± 42,889	105 ± 12	351 ± 50	105 ± 12	3,686,333 ± 22,274	7,271 ± 227	44,234 ± 328	7,271 ± 227
	30	1,493,857 ± 97,300	510 ± 42	1,799 ± 161	510 ± 42	583,708 ± 58,185	161 ± 20	454 ± 66	161 ± 20	3,978,149 ± 5,157	10,798 ± 240	47,073 ± 211	10,798 ± 240
	40	1,785,333 ± 109,428	684 ± 56	1,993 ± 173	684 ± 56	715,128 ± 65,086	204 ± 24	516 ± 72	204 ± 24	4,003,798 ± 78	13,760 ± 193	47,305 ± 193	13,760 ± 193
80%	10	504,908 ± 35,294	140 ± 13	808 ± 85	140 ± 13	173,053 ± 16,579	38 ± 4	166 ± 26	38 ± 4	2,549,811 ± 36,272	3,190 ± 241	32,074 ± 912	3,190 ± 241
	20	898,367 ± 62,457	286 ± 24	1,341 ± 123	286 ± 24	333,484 ± 33,955	85 ± 11	318 ± 49	85 ± 11	3,632,925 ± 17,505	5,951 ± 190	44,106 ± 205	5,951 ± 190
	30	1,197,295 ± 80,872	420 ± 35	1,609 ± 147	420 ± 35	452,845 ± 43,663	123 ± 15	394 ± 58	123 ± 15	3,948,179 ± 6,700	8,358 ± 186	46,847 ± 203	8,358 ± 186
	40	1,450,133 ± 93,342	543 ± 44	1,790 ± 159	543 ± 44	559,167 ± 53,729	165 ± 21	445 ± 64	165 ± 21	3,998,927 ± 1,040	11,225 ± 190	47,291 ± 193	11,225 ± 190
60%	10	355,634 ± 25,509	113 ± 12	717 ± 81	113 ± 12	126,292 ± 14,607	35 ± 6	175 ± 33	35 ± 6	2,351,456 ± 23,654	2,406 ± 243	29,972 ± 1,141	2,406 ± 243
	20	631,916 ± 46,470	209 ± 18	1,143 ± 110	209 ± 18	233,043 ± 22,445	61 ± 7	253 ± 38	61 ± 7	3,404,524 ± 13,421	4,380 ± 139	42,428 ± 308	4,380 ± 139
	30	841,078 ± 59,023	309 ± 26	1,337 ± 125	309 ± 26	323,319 ± 31,913	97 ± 12	328 ± 50	97 ± 12	3,811,379 ± 12,322	6,397 ± 206	46,065 ± 167	6,397 ± 206
	40	1,033,040 ± 70,825	406 ± 34	1,497 ± 139	406 ± 34	404,707 ± 40,418	128 ± 16	373 ± 55	128 ± 16	3,947,414 ± 4,328	8,457 ± 117	47,013 ± 203	8,457 ± 117
40%	10	213,335 ± 17,103	74 ± 8	615 ± 65	74 ± 8	76,464 ± 8,900	20 ± 3	128 ± 24	20 ± 3	1,796,536 ± 22,828	1,420 ± 144	24,937 ± 1,183	1,420 ± 144
	20	382,006 ± 27,578	159 ± 14	929 ± 88	159 ± 14	142,977 ± 14,897	44 ± 7	213 ± 36	44 ± 7	2,795,557 ± 13,835	3,028 ± 189	37,821 ± 395	3,028 ± 189
	30	514,367 ± 35,975	218 ± 19	1,075 ± 101	218 ± 19	200,872 ± 20,487	60 ± 9	260 ± 39	60 ± 9	3,329,386 ± 12,630	4,308 ± 213	42,810 ± 235	4,308 ± 213
	40	627,962 ± 43,176	284 ± 24	1,177 ± 109	284 ± 24	235,524 ± 23,246	79 ± 10	281 ± 43	79 ± 10	3,588,700 ± 14,981	5,923 ± 98	44,739 ± 195	5,923 ± 98
20%	10	95,010 ± 6,827	35 ± 4	467 ± 52	35 ± 4	34,934 ± 4,629	10 ± 2	97 ± 19	10 ± 2	868,010 ± 37,051	786 ± 51	17,482 ± 545	786 ± 51
	20	161,575 ± 12,464	71 ± 7	661 ± 64	71 ± 7	62,170 ± 6,488	21 ± 4	157 ± 26	21 ± 4	1,462,213 ± 20,313	1,427 ± 120	25,299 ± 496	1,427 ± 120
	30	220,694 ± 15,979	99 ± 9	777 ± 71	99 ± 9	90,154 ± 9,273	32 ± 4	193 ± 29	32 ± 4	1,874,902 ± 29,253	2,530 ± 80	30,235 ± 331	2,530 ± 80
	40	272,819 ± 18,725	141 ± 12	841 ± 77	141 ± 12	108,115 ± 10,657	41 ± 5	208 ± 31	41 ± 5	2,192,990 ± 27,666	3,039 ± 69	33,141 ± 343	3,039 ± 69

Table S3.10 Number of cut trees, and cut infested trees (average value ± standard error) by **aerial surveillance** under clear-cutting or tree-by-tree selective cutting at 100%, 80%, 60%, 40% and 20% of symptomatic trees per entry scenario. The number of infested trees resulting from 1-100, 10-60 and 1,000 initial emerging beetles are 2,416 ± 189, 631 ± 54, and 48,160 ± 123, respectively

			1-100				**10-60**				**1,000**			
Proportion of symptomatic trees	**Aerial efficiency**	**Flight number**	**Cut trees**		**Cut infested trees**		**Cut trees**		**Cut infested trees**		**Cut trees**		**Cut infested trees**	
			Clear-cutting	**Selective-cutting**	**Clear-cutting**	**Selective-cutting**	**Clear-cutting**	**Selective-cutting**	**Clear-cutting**	**Selective-cutting**	**Clear-cutting**	**Selective-cutting**	**Clear-cutting**	**Selective-cutting**
100%	0.51	1	2,437,177 ± 126,713	1,233 ± 96	2,324 ± 188	1,233 ± 96	1,032,141 ± 65,309	325 ± 28	565 ± 52	325 ± 28	4,004,001 ± 0	24,545 ± 69	48,160 ± 123	24,545 ± 69
		2	2,728,653 ± 130,241	1,836 ± 144	2,393 ± 189	1,836 ± 144	1,254,629 ± 73,908	481 ± 41	609 ± 54	481 ± 41	4,004,001 ± 0	36,640 ± 93	48,160 ± 123	36,640 ± 93
		3	2,821,440 ± 130,005	2,133 ± 167	2,407 ± 189	2,133 ± 167	1,345,410 ± 76,838	558 ± 48	623 ± 54	558 ± 48	4,004,001 ± 0	42,516 ± 109	48,160 ± 123	42,516 ± 109
	0.71	1	2,682,407 ± 130,389	1,721 ± 135	2,384 ± 189	1,721 ± 135	1,216,370 ± 72,452	449 ± 38	602 ± 54	449 ± 38	4,004,001 ± 0	34,193 ± 113	48,160 ± 123	34,193 ± 113
		2	2,846,569 ± 129,770	2,210 ± 173	2,411 ± 189	2,210 ± 173	1,361,085 ± 78,387	578 ± 50	625 ± 54	578 ± 50	4,004,001 ± 0	44,117 ± 126	48,160 ± 123	44,117 ± 126
		3	2,883,141 ± 129,328	2,357 ± 184	2,415 ± 189	2,357 ± 184	1,397,552 ± 79,088	615 ± 53	629 ± 55	615 ± 53	4,004,001 ± 0	46,983 ± 122	48,160 ± 123	46,983 ± 122
	0.91	1	2,839,469 ± 130,635	2,200 ± 173	2,409 ± 189	2,200 ± 173	1,357,105 ± 77,804	572 ± 49	624 ± 54	572 ± 49	4,004,001 ± 0	43,870 ± 109	48,160 ± 123	43,870 ± 109
		2	2,889,915 ± 129,582	2,397 ± 188	2,416 ± 189	2,397 ± 188	1,408,599 ± 79,301	627 ± 54	631 ± 55	627 ± 54	4,004,001 ± 0	47,776 ± 120	48,160 ± 123	47,776 ± 120
		3	2,894,209 ± 129,568	2,414 ± 189	2,416 ± 189	2,414 ± 189	1,411,681 ± 79,420	631 ± 55	631 ± 55	631 ± 55	4,004,001 ± 0	48,124 ± 122	48,160 ± 123	48,124 ± 122
80%	0.51	1	2,078,326 ± 116,569	991 ± 78	2,167 ± 182	991 ± 78	819,533 ± 53,496	258 ± 22	492 ± 47	258 ± 22	4,003,844 ± 95	19,894 ± 64	48,160 ± 123	19,894 ± 64
		2	2,385,614 ± 123,781	1,474 ± 116	2,275 ± 187	1,474 ± 116	1,004,675 ± 64,305	382 ± 34	536 ± 50	382 ± 34	4,003,977 ± 24	29,690 ± 92	48,160 ± 123	29,690 ± 92
		3	2,491,524 ± 125,793	1,715 ± 135	2,304 ± 188	1,715 ± 135	1,076,804 ± 66,949	443 ± 39	550 ± 50	443 ± 39	4,003,968 ± 33	34,443 ± 99	48,160 ± 123	34,443 ± 99
	0.71	1	2,342,389 ± 122,304	1,373 ± 108	2,261 ± 186	1,373 ± 108	972,618 ± 62,576	358 ± 31	530 ± 50	358 ± 31	4,003,929 ± 72	27,679 ± 79	48,160 ± 123	27,679 ± 79
		2	2,516,267 ± 125,950	1,777 ± 140	2,310 ± 188	1,777 ± 140	1,098,721 ± 67,923	459 ± 41	554 ± 51	459 ± 41	4,003,978 ± 16	35,738 ± 118	48,160 ± 123	35,738 ± 118

SI. 3

Table S3.10 (continued) Number of cut trees, and cut infested trees (average value ± standard error) by **aerial surveillance** under clear-cutting or tree-by-tree selective cutting at 100%, 80%, 60%, 40% and 20% of symptomatic trees per entry scenario. The number of infested trees resulting from 1-100, 10-60 and 1,000 initial emerging beetles are 2,416 ± 189, 631 ± 54, and 48,160 ± 123, respectively

		3	2,561,293 ± 126,112	1,894 ± 149	2,319 ± 188	1,894 ± 149	1,131,422 ± 69,370	491 ± 43	560 ± 51	491 ± 43	4,003,992 ± 9	38,074 ± 122	48,160 ± 123	38,074 ± 122
	0.91	1	2,510,137 ± 125,480	1,766 ± 139	2,307 ± 188	1,766 ± 139	1,093,252 ± 67,553	457 ± 40	554 ± 51	457 ± 40	4,003,978 ± 16	35,493 ± 114	48,160 ± 123	35,493 ± 114
		2	2,569,386 ± 126,225	1,924 ± 152	2,322 ± 188	1,924 ± 152	1,140,856 ± 69,824	499 ± 44	561 ± 51	499 ± 44	4,003,992 ± 9	38,699 ± 120	48,160 ± 123	38,699 ± 120
		3	2,574,908 ± 126,166	1,939 ± 153	2,323 ± 188	1,939 ± 153	1,143,156 ± 69,934	503 ± 44	562 ± 51	503 ± 44	4,003,992 ± 9	38,990 ± 121	48,160 ± 123	38,990 ± 121
60%	0.51	1	1,540,269 ± 94,949	737 ± 59	1,860 ± 164	737 ± 59	584,421 ± 40,325	194 ± 18	400 ± 40	194 ± 18	3,998,569 ± 1,435	15,050 ± 64	48,142 ± 123	15,050 ± 64
		2	1,840,884 ± 106,850	1,101 ± 87	2,010 ± 174	1,101 ± 87	730,179 ± 47,942	287 ± 25	441 ± 43	287 ± 25	4,002,411 ± 939	22,397 ± 89	48,156 ± 123	22,397 ± 89
		3	1,949,535 ± 110,385	1,278 ± 101	2,054 ± 177	1,278 ± 101	788,124 ± 50,807	331 ± 30	455 ± 44	331 ± 30	4,003,128 ± 350	26,024 ± 119	48,158 ± 123	26,024 ± 119
	0.71	1	1,797,746 ± 105,572	1,028 ± 82	1,987 ± 173	1,028 ± 82	696,966 ± 46,307	266 ± 24	432 ± 42	266 ± 24	4,002,423 ± 648	20,921 ± 91	48,157 ± 123	20,921 ± 91
		2	1,974,601 ± 111,387	1,326 ± 105	2,063 ± 178	1,326 ± 105	800,084 ± 51,287	344 ± 30	458 ± 44	344 ± 30	4,002,870 ± 504	27,011 ± 130	48,157 ± 123	27,011 ± 130
		3	2,017,732 ± 112,416	1,411 ± 112	2,079 ± 179	1,411 ± 112	823,948 ± 52,534	365 ± 33	462 ± 44	365 ± 33	4,003,415 ± 320	28,774 ± 135	48,159 ± 123	28,774 ± 135
	0.91	1	1,969,614 ± 111,456	1,316 ± 105	2,060 ± 178	1,316 ± 105	796,377 ± 51,323	340 ± 30	457 ± 44	340 ± 30	4,003,397 ± 329	26,835 ± 125	48,159 ± 123	26,835 ± 125
		2	2,029,748 ± 113,160	1,436 ± 114	2,084 ± 179	1,436 ± 114	830,829 ± 52,881	372 ± 33	464 ± 44	372 ± 33	4,003,417 ± 320	29,242 ± 139	48,159 ± 123	29,242 ± 139
		3	2,034,818 ± 113,227	1,446 ± 115	2,086 ± 179	1,446 ± 115	833,952 ± 53,013	374 ± 33	465 ± 44	374 ± 33	4,003,417 ± 320	29,462 ± 138	48,159 ± 123	29,462 ± 138
40%	0.51	1	964,758 ± 62,535	505 ± 41	1,461 ± 132	505 ± 41	359,533 ± 24,906	130 ± 12	301 ± 30	130 ± 12	3,894,662 ± 8,167	10,436 ± 81	47,564 ± 131	10,436 ± 81
		2	1,177,271 ± 75,446	753 ± 61	1,596 ± 144	753 ± 61	456,605 ± 31,767	195 ± 18	334 ± 34	195 ± 18	3,958,901 ± 4,741	15,546 ± 116	47,925 ± 117	15,546 ± 116
		3	1,257,977 ± 78,866	878 ± 71	1,638 ± 147	878 ± 71	497,047 ± 33,017	224 ± 20	345 ± 34	224 ± 20	3,971,635 ± 4,249	18,020 ± 135	48,004 ± 123	18,020 ± 135

Table S3.10 (continued) Number of cut trees, and cut infested trees (average value ± standard error) by **aerial surveillance** under clear-cutting or tree-by-tree selective cutting at 100%, 80%, 60%, 40% and 20% of symptomatic trees per entry scenario. The number of infested trees resulting from 1-100, 10-60 and 1,000 initial emerging beetles are 2,416 ± 189, 631 ± 54, and 48,160 ± 123, respectively

	0.71	1	1,133,582 ± 71,953	704 ± 57	1,570 ± 141	704 ± 57	441,082 ± 29,366	180 ± 17	327 ± 32	180 ± 17	3,948,931 ± 7,176	14,558 ± 107	47,871 ± 117	14,558 ± 107
		2	1,278,809 ± 79,877	909 ± 74	1,651 ± 148	909 ± 74	506,847 ± 33,997	233 ± 22	348 ± 35	233 ± 22	3,974,634 ± 3,836	18,739 ± 141	48,016 ± 120	18,739 ± 141
		3	1,314,091 ± 81,564	970 ± 79	1,671 ± 150	970 ± 79	525,104 ± 34,945	247 ± 23	353 ± 35	247 ± 23	3,978,300 ± 3,426	19,956 ± 141	48,038 ± 121	19,956 ± 141
	0.91	1	1,275,885 ± 79,494	903 ± 73	1,650 ± 148	903 ± 73	506,389 ± 33,562	232 ± 21	348 ± 35	232 ± 21	3,973,983 ± 3,637	18,609 ± 127	48,014 ± 120	18,609 ± 127
		2	1,323,156 ± 82,008	986 ± 80	1,675 ± 150	986 ± 80	528,932 ± 35,278	252 ± 23	353 ± 35	252 ± 23	3,979,421 ± 3,202	20,299 ± 150	48,043 ± 121	20,299 ± 150
		3	1,326,984 ± 82,315	994 ± 81	1,677 ± 151	994 ± 81	531,154 ± 35,452	254 ± 23	354 ± 35	254 ± 23	3,979,982 ± 3,203	20,448 ± 148	48,046 ± 121	20,448 ± 148
20%	0.51	1	425,350 ± 30,024	260 ± 22	1,015 ± 92	260 ± 22	163,842 ± 11,895	63 ± 6	207 ± 21	63 ± 6	2,840,243 ± 36,684	5,391 ± 63	39,517 ± 329	5,391 ± 63
		2	522,576 ± 36,386	387 ± 33	1,095 ± 99	387 ± 33	205,305 ± 15,481	94 ± 9	226 ± 24	94 ± 9	3,161,177 ± 39,464	8,002 ± 94	42,068 ± 344	8,002 ± 94
		3	568,543 ± 39,599	449 ± 38	1,130 ± 102	449 ± 38	228,593 ± 16,830	111 ± 11	232 ± 24	111 ± 11	3,267,059 ± 31,284	9,318 ± 106	42,946 ± 280	9,318 ± 106
	0.71	1	506,950 ± 35,855	362 ± 31	1,081 ± 98	362 ± 31	203,063 ± 15,747	88 ± 9	223 ± 23	88 ± 9	3,099,535 ± 31,749	7,474 ± 88	41,570 ± 272	7,474 ± 88
		2	578,711 ± 40,283	466 ± 39	1,136 ± 103	466 ± 39	230,304 ± 17,141	114 ± 11	233 ± 24	114 ± 11	3,288,110 ± 33,047	9,653 ± 110	43,099 ± 296	9,653 ± 110
		3	595,872 ± 41,172	497 ± 42	1,150 ± 104	497 ± 42	240,342 ± 17,861	122 ± 12	236 ± 25	122 ± 12	3,335,255 ± 33,508	10,285 ± 115	43,449 ± 289	10,285 ± 115
	0.91	1	572,300 ± 39,778	464 ± 39	1,134 ± 103	464 ± 39	232,279 ± 16,901	114 ± 11	234 ± 24	114 ± 11	3,284,655 ± 35,114	9,584 ± 106	43,087 ± 313	9,584 ± 106
		2	599,508 ± 41,489	505 ± 43	1,153 ± 104	505 ± 43	243,061 ± 17,974	124 ± 12	237 ± 25	124 ± 12	3,346,977 ± 33,061	10,457 ± 117	43,530 ± 298	10,457 ± 117
		3	601,524 ± 41,517	509 ± 43	1,154 ± 104	509 ± 43	243,765 ± 18,031	125 ± 12	237 ± 25	125 ± 12	3,351,126 ± 32,530	10,530 ± 117	43,567 ± 288	10,530 ± 117

SI. 3

Table S3.11 Cost components for **visual surveillance from the ground** in 100,000 Euro for 1-100 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Number of sampled roads	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
						Logging cost		Chipping cost			
				Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	0.015*	0.64 ± 0.01	395.77 ± 27.66	0	66.06 ± 4.62	0.02 ± 0.00	79.28 ± 5.54	0.02 ± 0.00	541.76 ± 37.84	0.69 ± 0.01
	20	0.03*	1.23 ± 0.02	687.04 ± 45.41	0	114.66 ± 7.58	0.037 ± 0.003	137.59 ± 9.1	0.044 ± 0.004	940.55 ± 62.11	1.34 ± 0.02
	30	0.045*	1.83 ± 0.03	913.08 ± 58.59	0	152.37 ± 9.78	0.054 ± 0.004	182.84 ± 11.74	0.065 ± 0.005	1,250.16 ± 80.14	2 ± 0.04
	40	0.059*	2.38 ± 0.03	1090.89 ± 66.75	0	182.02 ± 11.14	0.069 ± 0.005	218.42 ± 13.37	0.083 ± 0.007	1,493.77 ± 91.29	2.59 ± 0.04
80%	10	0.015*	0.62 ± 0.01	303.14 ± 21.15	0	50.61 ± 3.53	0.016 ± 0.002	60.73 ± 4.24	0.019 ± 0.002	415.11 ± 28.93	0.67 ± 0.01
	20	0.03*	1.2 ± 0.01	540.54 ± 37.46	0	90.22 ± 6.26	0.028 ± 0.002	108.27 ± 7.51	0.034 ± 0.003	740.26 ± 51.24	1.29 ± 0.02
	30	0.045*	1.76 ± 0.02	738.9 ± 46.27	0	123.32 ± 7.73	0.042 ± 0.003	147.98 ± 9.27	0.051 ± 0.004	1,011.99 ± 63.29	1.9 ± 0.03
	40	0.059*	2.3 ± 0.03	888.88 ± 56.05	0	148.33 ± 9.36	0.057 ± 0.005	178 ± 11.23	0.068 ± 0.005	1,217.58 ± 76.66	2.48 ± 0.04
60%	10	0.015*	0.58 ± 0.01	205.94 ± 15.62	0	34.4 ± 2.61	0.011 ± 0.001	41.28 ± 3.13	0.013 ± 0.001	282.21 ± 21.36	0.62 ± 0.01
	20	0.03*	1.16 ± 0.01	382.72 ± 26.86	0	63.9 ± 4.49	0.022 ± 0.002	76.68 ± 5.38	0.027 ± 0.002	524.49 ± 36.74	1.24 ± 0.02
	30	0.045*	1.69 ± 0.02	522.94 ± 36.38	0	87.3 ± 6.08	0.031 ± 0.003	104.76 ± 7.29	0.037 ± 0.003	716.74 ± 49.76	1.81 ± 0.02
	40	0.059*	2.2 ± 0.02	631.05 ± 42.18	0	105.33 ± 7.04	0.041 ± 0.003	126.4 ± 8.45	0.049 ± 0.004	865.04 ± 57.69	2.35 ± 0.03
40%	10	0.015*	0.57 ± 0.01	133.13 ± 10.17	0	22.25 ± 1.7	0.008 ± 0.001	26.7 ± 2.04	0.01 ± 0.001	182.68 ± 13.91	0.6 ± 0.01
	20	0.03*	1.12 ± 0.01	235.25 ± 16.02	0	39.3 ± 2.68	0.016 ± 0.001	47.16 ± 3.21	0.019 ± 0.002	322.86 ± 21.92	1.18 ± 0.01
	30	0.045*	1.66 ± 0.01	317.39 ± 21.12	0	53.01 ± 3.53	0.022 ± 0.002	63.61 ± 4.24	0.027 ± 0.002	435.7 ± 28.9	1.75 ± 0.01
	40	0.059*	2.14 ± 0.02	387.66 ± 25.81	0	64.73 ± 4.31	0.028 ± 0.002	77.68 ± 5.17	0.034 ± 0.003	532.28 ± 35.31	2.27 ± 0.02
20%	10	0.015*	0.55 ± 0.01	55.8 ± 4.47	0	9.35 ± 0.75	0.005 ± 0.001	11.22 ± 0.9	0.006 ± 0.001	76.93 ± 6.13	0.58 ± 0.01
	20	0.03*	1.08 ± 0.01	104.41 ± 7.46	0	17.47 ± 1.25	0.008 ± 0.001	20.97 ± 1.5	0.01 ± 0.001	143.96 ± 10.2	1.13 ± 0.01
	30	0.045*	1.58 ± 0.01	138.32 ± 9.96	0	23.13 ± 1.67	0.012 ± 0.001	27.76 ± 2	0.014 ± 0.001	190.84 ± 13.63	1.65 ± 0.01
	40	0.059*	2.06 ± 0.01	165.8 ± 12.15	0	27.72 ± 2.03	0.014 ± 0.001	33.26 ± 2.44	0.017 ± 0.001	228.9 ± 16.63	2.15 ± 0.01

* indicates the mean values are constant

Table S3.12 Cost components for **visual surveillance from the ground combined with trapping networks** in 100,000 Euro for 1-100 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Number of sampled roads	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
						Logging cost		Chipping cost			
				Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	0.18*	0.62 ± 0.01	373.29 ± 27.05	0	62.3 ± 4.52	0.016 ± 0.001	74.76 ± 5.42	0.02 ± 0.002	511.15 ± 36.99	0.84 ± 0.01
	20	0.195*	1.23 ± 0.02	671.57 ± 45.87	0	112.08 ± 7.66	0.036 ± 0.003	134.49 ± 9.19	0.043 ± 0.004	919.57 ± 62.73	1.5 ± 0.03
	30	0.21*	1.8 ± 0.03	895.24 ± 58.29	0	149.39 ± 9.73	0.051 ± 0.004	179.26 ± 11.68	0.061 ± 0.005	1,225.9 ± 79.72	2.12 ± 0.03
	40	0.224*	2.37 ± 0.03	1070 ± 65.56	0	178.53 ± 10.94	0.068 ± 0.006	214.24 ± 13.13	0.082 ± 0.007	1,465.38 ± 89.66	2.75 ± 0.04
80%	10	0.18*	0.61 ± 0.01	302.46 ± 21.13	0	50.49 ± 3.53	0.014 ± 0.001	60.59 ± 4.24	0.017 ± 0.002	414.33 ± 28.9	0.82 ± 0.01
	20	0.195*	1.2 ± 0.01	538.22 ± 37.4	0	89.84 ± 6.25	0.029 ± 0.002	107.8 ± 7.49	0.034 ± 0.003	737.25 ± 51.16	1.46 ± 0.02
	30	0.21*	1.76 ± 0.02	717.41 ± 48.44	0	119.73 ± 8.09	0.042 ± 0.004	143.68 ± 9.7	0.05 ± 0.004	982.78 ± 66.25	2.06 ± 0.03
	40	0.224*	2.28 ± 0.02	869.01 ± 55.91	0	145.01 ± 9.33	0.054 ± 0.004	174.02 ± 11.2	0.065 ± 0.005	1,190.54 ± 76.47	2.63 ± 0.03
60%	10	0.18*	0.59 ± 0.01	212.95 ± 15.26	0	35.56 ± 2.55	0.011 ± 0.001	42.68 ± 3.06	0.014 ± 0.001	291.96 ± 20.88	0.8 ± 0.01
	20	0.195*	1.14 ± 0.01	378.46 ± 27.82	0	63.19 ± 4.65	0.021 ± 0.002	75.83 ± 5.58	0.025 ± 0.002	518.82 ± 38.05	1.38 ± 0.01
	30	0.21*	1.69 ± 0.02	503.84 ± 35.34	0	84.11 ± 5.9	0.031 ± 0.003	100.93 ± 7.08	0.037 ± 0.003	690.78 ± 48.34	1.97 ± 0.02
	40	0.224*	2.21 ± 0.02	618.93 ± 42.41	0	103.3 ± 7.08	0.041 ± 0.003	123.96 ± 8.5	0.049 ± 0.004	848.63 ± 58.01	2.52 ± 0.03
40%	10	0.18*	0.56 ± 0.01	127.63 ± 10.23	0	21.33 ± 1.71	0.007 ± 0.001	25.6 ± 2.05	0.009 ± 0.001	175.31 ± 13.99	0.76 ± 0.01
	20	0.195*	1.12 ± 0.01	228.65 ± 16.5	0	38.2 ± 2.76	0.016 ± 0.001	45.84 ± 3.31	0.019 ± 0.002	314 ± 22.57	1.35 ± 0.01
	30	0.21*	1.65 ± 0.01	307.97 ± 21.53	0	51.44 ± 3.6	0.022 ± 0.002	61.72 ± 4.32	0.026 ± 0.002	422.99 ± 29.45	1.9 ± 0.01
	40	0.224*	2.13 ± 0.02	376.07 ± 25.84	0	62.8 ± 4.32	0.028 ± 0.002	75.36 ± 5.18	0.034 ± 0.003	516.58 ± 35.35	2.42 ± 0.02
20%	10	0.18*	0.55 ± 0	56.73 ± 4.07	0	9.5 ± 0.68	0.003 ± 0	11.4 ± 0.82	0.004 ± 0	78.35 ± 5.58	0.73 ± 0
	20	0.195*	1.06 ± 0.01	96.55 ± 7.44	0	16.16 ± 1.25	0.007 ± 0.001	19.39 ± 1.5	0.009 ± 0.001	133.35 ± 10.19	1.27 ± 0.01
	30	0.21*	1.57 ± 0.01	131.95 ± 9.55	0	22.07 ± 1.6	0.01 ± 0.001	26.48 ± 1.92	0.012 ± 0.001	182.28 ± 13.07	1.8 ± 0.01
	40	0.224*	2.06 ± 0.01	163.19 ± 11.19	0	27.28 ± 1.87	0.014 ± 0.001	32.74 ± 2.25	0.017 ± 0.001	225.49 ± 15.32	2.32 ± 0.01

* indicates the mean values are constant

SI. 3

Table S3.13 Cost components for **aerial surveillance** in 100,000 Euro for 1-100 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Aerial efficiency	Flight number	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
							Logging cost		Chipping cost			
					Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	0.51	1	0.83*	4.17 ± 0.05	1,460.91 ± 75.92	0	243.72 ± 12.67	0.123 ± 0.01	292.46 ± 15.21	0.148 ± 0.012	2,002.09 ± 103.85	5.27 ± 0.07
		2	1.66*	6.22 ± 0.08	1,635.76 ± 78.04	0	272.87 ± 13.02	0.184 ± 0.014	327.44 ± 15.63	0.22 ± 0.017	2,243.94 ± 106.77	8.28 ± 0.11
		3	2.49*	7.22 ± 0.09	1,691.42 ± 77.9	0	282.14 ± 13	0.213 ± 0.017	338.57 ± 15.6	0.256 ± 0.02	2,321.85 ± 106.58	10.18 ± 0.13
	0.71	1	0.83*	5.81 ± 0.07	1,608.01 ± 78.13	0	268.24 ± 13.04	0.172 ± 0.013	321.89 ± 15.65	0.207 ± 0.016	2,204.78 ± 106.88	7.02 ± 0.1
		2	1.66*	7.49 ± 0.1	1,706.5 ± 77.76	0	284.66 ± 12.98	0.221 ± 0.017	341.59 ± 15.57	0.265 ± 0.021	2,341.89 ± 106.39	9.64 ± 0.13
		3	2.49*	7.98 ± 0.1	1,728.44 ± 77.49	0	288.31 ± 12.93	0.236 ± 0.018	345.98 ± 15.52	0.283 ± 0.022	2,373.2 ± 106.04	10.99 ± 0.14
	0.91	1	0.83*	7.45 ± 0.1	1,702.24 ± 78.28	0	283.95 ± 13.06	0.22 ± 0.017	340.74 ± 15.68	0.264 ± 0.021	2,335.2 ± 107.1	8.76 ± 0.13
		2	1.66*	8.12 ± 0.1	1,732.5 ± 77.64	0	288.99 ± 12.96	0.24 ± 0.019	346.79 ± 15.55	0.288 ± 0.023	2,378.06 ± 106.25	10.31 ± 0.15
		3	2.49*	8.18 ± 0.1	1,735.08 ± 77.64	0	289.42 ± 12.96	0.241 ± 0.019	347.31 ± 15.55	0.29 ± 0.023	2,382.47 ± 106.24	11.2 ± 0.15
80%	0.51	1	0.83*	4.04 ± 0.04	1,245.7 ± 69.84	0	207.83 ± 11.66	0.099 ± 0.008	249.4 ± 13.99	0.119 ± 0.009	1,707.79 ± 95.52	5.08 ± 0.06
		2	1.66*	6.02 ± 0.06	1,430 ± 74.16	0	238.56 ± 12.38	0.147 ± 0.012	286.27 ± 14.85	0.177 ± 0.014	1,962.51 ± 101.45	8 ± 0.09
		3	2.49*	6.98 ± 0.08	1,493.53 ± 75.37	0	249.15 ± 12.58	0.172 ± 0.014	298.98 ± 15.1	0.206 ± 0.016	2,051.14 ± 103.11	9.85 ± 0.11
	0.71	1	0.83*	5.62 ± 0.06	1,404.08 ± 73.27	0	234.24 ± 12.23	0.137 ± 0.011	281.09 ± 14.68	0.165 ± 0.013	1,925.85 ± 100.24	6.75 ± 0.08
		2	1.66*	7.25 ± 0.08	1,508.37 ± 75.46	0	251.63 ± 12.6	0.178 ± 0.014	301.95 ± 15.11	0.213 ± 0.017	2,070.86 ± 103.25	9.3 ± 0.11
		3	2.49*	7.72 ± 0.08	1,535.38 ± 75.56	0	256.13 ± 12.61	0.189 ± 0.015	307.36 ± 15.13	0.227 ± 0.018	2,109.08 ± 103.38	10.63 ± 0.11
	0.91	1	0.83*	7.19 ± 0.08	1,504.7 ± 75.18	0	251.01 ± 12.55	0.177 ± 0.014	301.22 ± 15.06	0.212 ± 0.017	2,064.95 ± 102.86	8.41 ± 0.11
		2	1.66*	7.85 ± 0.08	1,540.24 ± 75.63	0	256.94 ± 12.62	0.192 ± 0.015	308.33 ± 15.15	0.231 ± 0.018	2,115.01 ± 103.48	9.93 ± 0.12
		3	2.49*	7.91 ± 0.08	1,543.55 ± 75.59	0	257.49 ± 12.62	0.194 ± 0.015	308.99 ± 15.14	0.233 ± 0.018	2,120.43 ± 103.43	10.82 ± 0.12
60%	0.51	1	0.83*	3.89 ± 0.03	923.05 ± 56.87	0	154.03 ± 9.49	0.074 ± 0.006	184.83 ± 11.39	0.088 ± 0.007	1,266.63 ± 77.79	4.89 ± 0.04
		2	1.66*	5.8 ± 0.05	1,103.32 ± 64.01	0	184.09 ± 10.69	0.11 ± 0.009	220.91 ± 12.82	0.132 ± 0.01	1,515.78 ± 87.56	7.7 ± 0.07
		3	2.49*	6.74 ± 0.06	1,168.49 ± 66.13	0	194.95 ± 11.04	0.128 ± 0.01	233.94 ± 13.25	0.153 ± 0.012	1,606.61 ± 90.47	9.51 ± 0.08
	0.71	1	0.83*	5.42 ± 0.04	1,077.46 ± 63.24	0	179.77 ± 10.56	0.103 ± 0.008	215.73 ± 12.67	0.123 ± 0.01	1,479.21 ± 86.51	6.48 ± 0.06
		2	1.66*	6.99 ± 0.06	1,183.52 ± 66.73	0	197.46 ± 11.14	0.133 ± 0.011	236.95 ± 13.37	0.159 ± 0.013	1,626.59 ± 91.29	8.94 ± 0.08
		3	2.49*	7.45 ± 0.06	1,209.39 ± 67.35	0	201.77 ± 11.24	0.141 ± 0.011	242.13 ± 13.49	0.169 ± 0.013	1,663.23 ± 92.14	10.25 ± 0.09
	0.91	1	0.83*	6.94 ± 0.06	1,180.53 ± 66.77	0	196.96 ± 11.15	0.132 ± 0.01	236.35 ± 13.37	0.158 ± 0.013	1,621.62 ± 91.35	8.06 ± 0.08
		2	1.66*	7.57 ± 0.06	1,216.6 ± 67.79	0	202.97 ± 11.32	0.144 ± 0.011	243.57 ± 13.58	0.172 ± 0.014	1,672.37 ± 92.75	9.55 ± 0.09
		3	2.49*	7.63 ± 0.06	1,219.64 ± 67.83	0	203.48 ± 11.32	0.145 ± 0.011	244.18 ± 13.59	0.174 ± 0.014	1,677.42 ± 92.8	10.43 ± 0.09

Table S3.13 (continued) Cost components for **aerial surveillance** in 100,000 Euro for 1-100 initial emerging beetles. The number represents average value ± standard error

40%	0.51	1	0.83*	3.76 ± 0.02	577.98 ± 37.44	0	96.48 ± 6.25	0.051 ± 0.004	115.77 ± 7.5	0.061 ± 0.005	794.81 ± 51.22	4.7 ± 0.03
		2	1.66*	5.6 ± 0.03	705.41 ± 45.18	0	117.73 ± 7.54	0.075 ± 0.006	141.27 ± 9.05	0.09 ± 0.007	971.66 ± 61.81	7.42 ± 0.05
		3	2.49*	6.51 ± 0.04	753.8 ± 47.23	0	125.8 ± 7.89	0.088 ± 0.007	150.96 ± 9.46	0.105 ± 0.009	1,039.55 ± 64.62	9.19 ± 0.05
	0.71	1	0.83*	5.24 ± 0.03	679.21 ± 43.09	0	113.36 ± 7.2	0.07 ± 0.006	136.03 ± 8.63	0.085 ± 0.007	934.66 ± 58.95	6.22 ± 0.04
		2	1.66*	6.75 ± 0.04	766.3 ± 47.84	0	127.88 ± 7.99	0.091 ± 0.007	153.46 ± 9.59	0.109 ± 0.009	1,056.04 ± 65.45	8.61 ± 0.06
		3	2.49*	7.19 ± 0.04	787.45 ± 48.85	0	131.41 ± 8.16	0.097 ± 0.008	157.69 ± 9.79	0.116 ± 0.009	1,086.24 ± 66.84	9.9 ± 0.06
	0.91	1	0.83*	6.72 ± 0.04	764.54 ± 47.61	0	127.59 ± 7.95	0.09 ± 0.007	153.11 ± 9.54	0.108 ± 0.009	1,052.78 ± 65.14	7.75 ± 0.05
		2	1.66*	7.31 ± 0.04	792.89 ± 49.12	0	132.32 ± 8.2	0.099 ± 0.008	158.78 ± 9.84	0.118 ± 0.01	1,092.96 ± 67.2	9.19 ± 0.06
		3	2.49*	7.37 ± 0.04	795.18 ± 49.3	0	132.7 ± 8.23	0.099 ± 0.008	159.24 ± 9.88	0.119 ± 0.01	1,096.98 ± 67.45	10.08 ± 0.06
20%	0.51	1	0.83*	3.63 ± 0.01	254.6 ± 17.96	0	42.53 ± 3	0.026 ± 0.002	51.04 ± 3.6	0.031 ± 0.003	352.63 ± 24.58	4.51 ± 0.02
		2	1.66*	5.39 ± 0.02	312.89 ± 21.78	0	52.26 ± 3.64	0.039 ± 0.003	62.71 ± 4.37	0.046 ± 0.004	434.91 ± 29.8	7.14 ± 0.02
		3	2.49*	6.26 ± 0.02	340.45 ± 23.7	0	56.85 ± 3.96	0.045 ± 0.004	68.23 ± 4.75	0.054 ± 0.005	474.28 ± 32.43	8.85 ± 0.03
	0.71	1	0.83*	5.04 ± 0.02	303.52 ± 21.46	0	50.7 ± 3.59	0.036 ± 0.003	60.83 ± 4.3	0.043 ± 0.004	420.92 ± 29.36	5.95 ± 0.02
		2	1.66*	6.5 ± 0.02	346.55 ± 24.11	0	57.87 ± 4.03	0.047 ± 0.004	69.45 ± 4.83	0.056 ± 0.005	482.02 ± 32.99	8.26 ± 0.03
		3	2.49*	6.92 ± 0.02	356.83 ± 24.64	0	59.59 ± 4.12	0.05 ± 0.004	71.5 ± 4.94	0.06 ± 0.005	497.34 ± 33.72	9.52 ± 0.03
	0.91	1	0.83*	6.46 ± 0.02	342.7 ± 23.81	0	57.23 ± 3.98	0.046 ± 0.004	68.68 ± 4.77	0.056 ± 0.005	475.9 ± 32.58	7.39 ± 0.03
		2	1.66*	7.04 ± 0.02	359.01 ± 24.83	0	59.95 ± 4.15	0.05 ± 0.004	71.94 ± 4.98	0.061 ± 0.005	499.6 ± 33.98	8.81 ± 0.03
		3	2.49*	7.09 ± 0.02	360.22 ± 24.85	0	60.15 ± 4.15	0.051 ± 0.004	72.18 ± 4.98	0.061 ± 0.005	502.14 ± 34.01	9.69 ± 0.03

* indicates the mean values are constant

SI. 3

Table S3.14 Cost components for **visual surveillance from the ground** in 100,000 Euro for 10-60 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Number of sampled roads	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
						Logging cost		Chipping cost			
				Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	0.015*	0.55 ± 0	122.88 ± 9.81	0	20.5 ± 1.64	0.005 ± 0	24.6 ± 1.96	0.006 ± 0.001	168.54 ± 13.41	0.58 ± 0.004
	20	0.03*	1.1 ± 0.01	230.17 ± 17.97	0	38.39 ± 3	0.009 ± 0.001	46.07 ± 3.6	0.011 ± 0.001	315.75 ± 24.58	1.15 ± 0.008
	30	0.045*	1.59 ± 0.01	308.94 ± 22.33	0	51.53 ± 3.73	0.013 ± 0.001	61.83 ± 4.47	0.016 ± 0.001	423.94 ± 30.54	1.67 ± 0.012
	40	0.059*	2.09 ± 0.01	391.27 ± 28.75	0	65.26 ± 4.8	0.018 ± 0.002	78.31 ± 5.76	0.022 ± 0.002	536.98 ± 39.31	2.19 ± 0.014
80%	10	0.015*	0.55 ± 0	92.97 ± 7.51	0	15.51 ± 1.25	0.004 ± 0	18.61 ± 1.5	0.004 ± 0	127.66 ± 10.27	0.57 ± 0.004
	20	0.03*	1.09 ± 0.01	178.75 ± 13.81	0	29.82 ± 2.3	0.008 ± 0.001	35.78 ± 2.77	0.009 ± 0.001	245.47 ± 18.89	1.13 ± 0.008
	30	0.045*	1.58 ± 0.01	252.46 ± 19.55	0	42.11 ± 3.26	0.011 ± 0.001	50.53 ± 3.91	0.013 ± 0.001	346.73 ± 26.73	1.65 ± 0.011
	40	0.059*	2.08 ± 0.01	314.73 ± 22.64	0	52.49 ± 3.78	0.014 ± 0.001	62.99 ± 4.53	0.017 ± 0.002	432.35 ± 30.96	2.17 ± 0.013
60%	10	0.015*	0.54 ± 0	68.79 ± 6.22	0	11.48 ± 1.04	0.003 ± 0	13.77 ± 1.25	0.003 ± 0	94.6 ± 8.5	0.56 ± 0.004
	20	0.03*	1.07 ± 0	131.98 ± 9.46	0	22.02 ± 1.58	0.006 ± 0.001	26.42 ± 1.89	0.007 ± 0.001	181.52 ± 12.93	1.11 ± 0.006
	30	0.045*	1.57 ± 0.01	175.27 ± 13.73	0	29.24 ± 2.29	0.008 ± 0.001	35.09 ± 2.75	0.01 ± 0.001	241.21 ± 18.77	1.63 ± 0.008
	40	0.059*	2.05 ± 0.01	223.38 ± 15.86	0	37.26 ± 2.65	0.011 ± 0.001	44.71 ± 3.18	0.013 ± 0.001	307.47 ± 21.69	2.13 ± 0.011
40%	10	0.015*	0.54 ± 0	46.29 ± 3.99	0	7.73 ± 0.67	0.002 ± 0	9.27 ± 0.8	0.002 ± 0	63.85 ± 5.46	0.56 ± 0.003
	20	0.03*	1.06 ± 0	80.91 ± 6.1	0	13.5 ± 1.02	0.004 ± 0	16.2 ± 1.22	0.005 ± 0	111.71 ± 8.35	1.1 ± 0.005
	30	0.045*	1.56 ± 0.01	114.15 ± 8.29	0	19.05 ± 1.38	0.006 ± 0.001	22.86 ± 1.66	0.007 ± 0.001	157.67 ± 11.33	1.62 ± 0.008
	40	0.059*	2.03 ± 0.01	136.68 ± 10.37	0	22.8 ± 1.73	0.007 ± 0.001	27.36 ± 2.08	0.009 ± 0.001	188.93 ± 14.18	2.1 ± 0.011
20%	10	0.015*	0.53 ± 0	20.11 ± 1.87	0	3.36 ± 0.31	0.001 ± 0	4.03 ± 0.37	0.001 ± 0	28.05 ± 2.56	0.55 ± 0.003
	20	0.03*	1.05 ± 0	38.79 ± 3.54	0	6.48 ± 0.59	0.002 ± 0	7.77 ± 0.71	0.002 ± 0	54.12 ± 4.84	1.08 ± 0.005
	30	0.045*	1.54 ± 0.01	53.26 ± 3.83	0	8.89 ± 0.64	0.003 ± 0	10.67 ± 0.77	0.003 ± 0	74.4 ± 5.24	1.59 ± 0.006
	40	0.059*	2.01 ± 0.01	63.97 ± 5.32	0	10.68 ± 0.89	0.004 ± 0	12.82 ± 1.07	0.005 ± 0.001	89.53 ± 7.28	2.07 ± 0.009

* indicates the mean values are constant

Table S3.15 Cost components for **visual surveillance from the ground combined with trapping networks** in 100,000 Euro for 10-60 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Number of sampled roads	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
						Logging cost		Chipping cost			
				Clear-cutting	Selective -cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	0.18*	0.56 ± 0.01	137.78 ± 14.71	0	22.99 ± 2.46	0.006 ± 0.001	27.58 ± 2.95	0.007 ± 0.001	189.09 ± 20.11	0.76 ± 0.007
	20	0.195*	1.1 ± 0.01	255.86 ± 25.7	0	42.68 ± 4.29	0.011 ± 0.001	51.21 ± 5.15	0.013 ± 0.001	351.05 ± 35.15	1.32 ± 0.011
	30	0.21*	1.61 ± 0.01	349.95 ± 34.87	0	58.37 ± 5.82	0.016 ± 0.002	70.04 ± 6.98	0.019 ± 0.002	480.18 ± 47.68	1.85 ± 0.017
	40	0.224*	2.1 ± 0.02	428.77 ± 39.01	0	71.51 ± 6.51	0.02 ± 0.002	85.82 ± 7.81	0.024 ± 0.003	588.42 ± 53.34	2.37 ± 0.02
80%	10	0.18*	0.55 ± 0	103.73 ± 9.93	0	17.31 ± 1.66	0.004 ± 0	20.77 ± 1.99	0.005 ± 0.001	142.53 ± 13.58	0.74 ± 0.005
	20	0.195*	1.09 ± 0.01	199.9 ± 20.34	0	33.35 ± 3.4	0.008 ± 0.001	40.02 ± 4.07	0.01 ± 0.001	274.55 ± 27.82	1.3 ± 0.01
	30	0.21*	1.58 ± 0.01	271.47 ± 26.16	0	45.28 ± 4.37	0.012 ± 0.002	54.34 ± 5.24	0.015 ± 0.002	372.89 ± 35.78	1.82 ± 0.013
	40	0.224*	2.07 ± 0.01	335.23 ± 32.2	0	55.92 ± 5.37	0.016 ± 0.002	67.1 ± 6.45	0.02 ± 0.003	460.55 ± 44.03	2.33 ± 0.018
60%	10	0.18*	0.55 ± 0	75.67 ± 8.75	0	12.63 ± 1.46	0.004 ± 0.001	15.16 ± 1.75	0.004 ± 0.001	104.18 ± 11.96	0.74 ± 0.006
	20	0.195*	1.07 ± 0.01	139.67 ± 13.45	0	23.3 ± 2.24	0.006 ± 0.001	27.97 ± 2.69	0.007 ± 0.001	192.21 ± 18.39	1.28 ± 0.006
	30	0.21*	1.58 ± 0.01	193.79 ± 19.12	0	32.33 ± 3.19	0.01 ± 0.001	38.8 ± 3.83	0.012 ± 0.001	266.71 ± 26.15	1.81 ± 0.011
	40	0.224*	2.06 ± 0.01	242.6 ± 24.22	0	40.47 ± 4.04	0.013 ± 0.002	48.56 ± 4.85	0.015 ± 0.002	333.92 ± 33.12	2.31 ± 0.014
40%	10	0.18*	0.54 ± 0	45.8 ± 5.33	0	7.65 ± 0.89	0.002 ± 0	9.18 ± 1.07	0.002 ± 0	63.34 ± 7.29	0.73 ± 0.004
	20	0.195*	1.06 ± 0.01	85.66 ± 8.92	0	14.3 ± 1.49	0.004 ± 0.001	17.16 ± 1.79	0.005 ± 0.001	118.37 ± 12.2	1.26 ± 0.007
	30	0.21*	1.55 ± 0.01	120.37 ± 12.27	0	20.09 ± 2.05	0.006 ± 0.001	24.1 ± 2.46	0.007 ± 0.001	166.32 ± 16.78	1.78 ± 0.009
	40	0.224*	2.02 ± 0.01	141.15 ± 13.92	0	23.55 ± 2.32	0.008 ± 0.001	28.26 ± 2.79	0.009 ± 0.001	195.21 ± 19.04	2.26 ± 0.012
20%	10	0.18*	0.54 ± 0	20.9 ± 2.77	0	3.49 ± 0.46	0.001 ± 0	4.19 ± 0.56	0.001 ± 0	29.31 ± 3.79	0.72 ± 0.004
	20	0.195*	1.05 ± 0	37.21 ± 3.88	0	6.22 ± 0.65	0.002 ± 0	7.46 ± 0.78	0.003 ± 0	52.13 ± 5.31	1.25 ± 0.005
	30	0.21*	1.53 ± 0.01	53.98 ± 5.55	0	9.02 ± 0.93	0.003 ± 0	10.82 ± 1.11	0.004 ± 0.001	75.55 ± 7.59	1.74 ± 0.008
	40	0.224*	2 ± 0.01	64.74 ± 6.38	0	10.81 ± 1.07	0.004 ± 0.001	12.97 ± 1.28	0.005 ± 0.001	90.76 ± 8.73	2.24 ± 0.01

* indicates the mean values are constant

SI. 3

Table S3.16 Cost components for **aerial surveillance** in 100,000 Euro for 10-60 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Aerial efficiency	Flight number	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
							Logging cost		Chipping cost			
					Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	0.51	1	0.83*	3.68 ± 0.02	618.95 ± 39.15	0	103.21 ± 6.53	0.032 ± 0.003	123.86 ± 7.84	0.039 ± 0.003	850.52 ± 53.54	4.58 ± 0.022
		2	1.66*	5.47 ± 0.02	752.41 ± 44.31	0	125.46 ± 7.39	0.048 ± 0.004	150.56 ± 8.87	0.058 ± 0.005	1,035.56 ± 60.6	7.24 ± 0.032
		3	2.49*	6.34 ± 0.03	806.87 ± 46.07	0	134.54 ± 7.68	0.056 ± 0.005	161.45 ± 9.22	0.067 ± 0.006	1,111.7 ± 63	8.96 ± 0.037
	0.71	1	0.83*	5.12 ± 0.02	729.46 ± 43.44	0	121.64 ± 7.25	0.045 ± 0.004	145.96 ± 8.69	0.054 ± 0.005	1,003.01 ± 59.4	6.04 ± 0.03
		2	1.66*	6.59 ± 0.03	816.28 ± 47	0	136.11 ± 7.84	0.058 ± 0.005	163.33 ± 9.41	0.069 ± 0.006	1,123.97 ± 64.27	8.38 ± 0.039
		3	2.49*	7.02 ± 0.03	838.15 ± 47.42	0	139.76 ± 7.91	0.062 ± 0.005	167.71 ± 9.49	0.074 ± 0.006	1,155.12 ± 64.85	9.64 ± 0.041
	0.91	1	0.83*	6.55 ± 0.03	813.89 ± 46.65	0	135.71 ± 7.78	0.057 ± 0.005	162.85 ± 9.34	0.069 ± 0.006	1,119.83 ± 63.79	7.5 ± 0.038
		2	1.66*	7.14 ± 0.03	844.78 ± 47.55	0	140.86 ± 7.93	0.063 ± 0.005	169.03 ± 9.52	0.075 ± 0.006	1,163.47 ± 65.02	8.94 ± 0.042
		3	2.49*	7.19 ± 0.03	846.63 ± 47.62	0	141.17 ± 7.94	0.063 ± 0.005	169.4 ± 9.53	0.076 ± 0.007	1,166.88 ± 65.12	9.82 ± 0.042
80%	0.51	1	0.83*	3.63 ± 0.01	491.42 ± 32.07	0	81.95 ± 5.35	0.026 ± 0.002	98.34 ± 6.42	0.031 ± 0.003	676.18 ± 43.85	4.51 ± 0.017
		2	1.66*	5.41 ± 0.02	602.48 ± 38.55	0	100.47 ± 6.43	0.038 ± 0.003	120.56 ± 7.72	0.046 ± 0.004	830.59 ± 52.72	7.16 ± 0.026
		3	2.49*	6.28 ± 0.02	645.75 ± 40.14	0	107.68 ± 6.69	0.044 ± 0.004	129.22 ± 8.03	0.053 ± 0.005	891.42 ± 54.89	8.87 ± 0.03
	0.71	1	0.83*	5.05 ± 0.02	583.25 ± 37.52	0	97.26 ± 6.26	0.036 ± 0.003	116.71 ± 7.51	0.043 ± 0.004	803.11 ± 51.3	5.96 ± 0.025
		2	1.66*	6.52 ± 0.02	658.9 ± 40.72	0	109.87 ± 6.79	0.046 ± 0.004	131.85 ± 8.15	0.055 ± 0.005	908.8 ± 55.69	8.28 ± 0.031
		3	2.49*	6.95 ± 0.02	678.52 ± 41.59	0	113.14 ± 6.94	0.049 ± 0.004	135.77 ± 8.32	0.059 ± 0.005	936.87 ± 56.88	9.55 ± 0.033
	0.91	1	0.83*	6.48 ± 0.02	655.62 ± 40.5	0	109.33 ± 6.76	0.046 ± 0.004	131.19 ± 8.11	0.055 ± 0.005	903.45 ± 55.38	7.41 ± 0.03
		2	1.66*	7.07 ± 0.02	684.18 ± 41.86	0	114.09 ± 6.98	0.05 ± 0.004	136.9 ± 8.38	0.06 ± 0.005	943.89 ± 57.25	8.83 ± 0.034
		3	2.49*	7.12 ± 0.02	685.56 ± 41.93	0	114.32 ± 6.99	0.05 ± 0.004	137.18 ± 8.39	0.06 ± 0.005	946.66 ± 57.34	9.72 ± 0.034
60%	0.51	1	0.83*	3.59 ± 0.01	350.41 ± 24.17	0	58.44 ± 4.03	0.019 ± 0.002	70.13 ± 4.84	0.023 ± 0.002	483.41 ± 33.05	4.47 ± 0.015
		2	1.66*	5.36 ± 0.01	437.84 ± 28.74	0	73.02 ± 4.79	0.029 ± 0.003	87.62 ± 5.75	0.034 ± 0.003	605.5 ± 39.3	7.08 ± 0.02
		3	2.49*	6.22 ± 0.02	472.6 ± 30.46	0	78.81 ± 5.08	0.033 ± 0.003	94.57 ± 6.1	0.04 ± 0.004	654.7 ± 41.65	8.78 ± 0.022

Table S3.16 (continued) Cost components for **aerial surveillance** in 100,000 Euro for 10-60 initial emerging beetles. The number represents average value ± standard error

	0.71	1	0.83*	5 ± 0.01	417.92 ± 27.76	0	69.7 ± 4.63	0.027 ± 0.002	83.64 ± 5.56	0.032 ± 0.003	577.08 ± 37.96	5.89 ± 0.019
		2	1.66*	6.45 ± 0.02	479.78 ± 30.75	0	80.01 ± 5.13	0.034 ± 0.003	96.01 ± 6.15	0.041 ± 0.004	663.91 ± 42.05	8.19 ± 0.024
		3	2.49*	6.88 ± 0.02	494.09 ± 31.49	0	82.39 ± 5.25	0.036 ± 0.003	98.87 ± 6.3	0.044 ± 0.004	684.73 ± 43.07	9.45 ± 0.025
	0.91	1	0.83*	6.41 ± 0.02	477.55 ± 30.77	0	79.64 ± 5.13	0.034 ± 0.003	95.57 ± 6.16	0.041 ± 0.004	660 ± 42.07	7.32 ± 0.023
		2	1.66*	6.99 ± 0.02	498.22 ± 31.7	0	83.08 ± 5.29	0.037 ± 0.003	99.7 ± 6.35	0.045 ± 0.004	689.65 ± 43.35	8.73 ± 0.025
		3	2.49*	7.04 ± 0.02	500.09 ± 31.78	0	83.4 ± 5.3	0.037 ± 0.003	100.07 ± 6.36	0.045 ± 0.004	693.1 ± 43.46	9.62 ± 0.025
40%	0.51	1	0.83*	3.56 ± 0.01	215.54 ± 14.93	0	35.95 ± 2.49	0.013 ± 0.001	43.14 ± 2.99	0.016 ± 0.001	299.02 ± 20.41	4.41 ± 0.009
		2	1.66*	5.31 ± 0.01	273.76 ± 19.04	0	45.66 ± 3.18	0.02 ± 0.002	54.79 ± 3.81	0.023 ± 0.002	381.18 ± 26.04	7.01 ± 0.013
		3	2.49*	6.15 ± 0.01	298.02 ± 19.79	0	49.7 ± 3.3	0.022 ± 0.002	59.65 ± 3.96	0.027 ± 0.002	416.02 ± 27.06	8.69 ± 0.015
	0.71	1	0.83*	4.96 ± 0.01	264.45 ± 17.6	0	44.11 ± 2.94	0.018 ± 0.002	52.93 ± 3.52	0.022 ± 0.002	367.28 ± 24.07	5.83 ± 0.013
		2	1.66*	6.39 ± 0.01	303.9 ± 20.38	0	50.68 ± 3.4	0.023 ± 0.002	60.82 ± 4.08	0.028 ± 0.003	423.46 ± 27.87	8.1 ± 0.016
		3	2.49*	6.81 ± 0.01	314.85 ± 20.95	0	52.51 ± 3.49	0.025 ± 0.002	63.01 ± 4.19	0.03 ± 0.003	439.67 ± 28.65	9.35 ± 0.017
	0.91	1	0.83*	6.35 ± 0.01	303.62 ± 20.12	0	50.64 ± 3.36	0.023 ± 0.002	60.77 ± 4.03	0.028 ± 0.003	422.21 ± 27.51	7.23 ± 0.016
		2	1.66*	6.92 ± 0.01	317.15 ± 21.15	0	52.89 ± 3.53	0.025 ± 0.002	63.47 ± 4.23	0.03 ± 0.003	442.1 ± 28.92	8.64 ± 0.017
		3	2.49*	6.97 ± 0.01	318.48 ± 21.25	0	53.12 ± 3.55	0.025 ± 0.002	63.74 ± 4.25	0.03 ± 0.003	444.8 ± 29.06	9.52 ± 0.017

SI. 3

Table S3.16 (continued) Cost components for **aerial surveillance** in 100,000 Euro for 10-60 initial emerging beetles. The number represents average value ± standard error

20%	0.51	1	0.83*	3.51 ± 0	98.18 ± 7.13	0	16.38 ± 1.19	0.006 ± 0.001	19.66 ± 1.43	0.008 ± 0.001	138.57 ± 9.75	4.36 ± 0.006
		2	1.66*	5.25 ± 0.01	123.05 ± 9.28	0	20.53 ± 1.55	0.009 ± 0.001	24.64 ± 1.86	0.011 ± 0.001	175.12 ± 12.69	6.93 ± 0.008
		3	2.49*	6.1 ± 0.01	137.02 ± 10.09	0	22.86 ± 1.68	0.011 ± 0.001	27.43 ± 2.02	0.013 ± 0.001	195.9 ± 13.79	8.61 ± 0.008
	0.71	1	0.83*	4.9 ± 0.01	121.7 ± 9.44	0	20.31 ± 1.57	0.009 ± 0.001	24.37 ± 1.89	0.011 ± 0.001	172.11 ± 12.9	5.75 ± 0.009
		2	1.66*	6.32 ± 0.01	138.04 ± 10.27	0	23.03 ± 1.71	0.011 ± 0.001	27.64 ± 2.06	0.014 ± 0.001	196.69 ± 14.05	8.01 ± 0.008
		3	2.49*	6.74 ± 0.01	144.06 ± 10.7	0	24.03 ± 1.79	0.012 ± 0.001	28.84 ± 2.14	0.015 ± 0.001	206.17 ± 14.64	9.26 ± 0.008
	0.91	1	0.83*	6.29 ± 0.01	139.23 ± 10.13	0	23.23 ± 1.69	0.011 ± 0.001	27.87 ± 2.03	0.014 ± 0.001	197.45 ± 13.85	7.14 ± 0.008
		2	1.66*	6.85 ± 0.01	145.69 ± 10.77	0	24.31 ± 1.8	0.012 ± 0.001	29.17 ± 2.16	0.015 ± 0.001	207.68 ± 14.73	8.54 ± 0.009
		3	2.49*	6.9 ± 0.01	146.12 ± 10.81	0	24.38 ± 1.8	0.013 ± 0.001	29.25 ± 2.16	0.015 ± 0.001	209.14 ± 14.78	9.42 ± 0.009

* indicates the mean values are constant

Table S3.17 Cost components for **visual surveillance** from the ground in 100,000 Euro for 1,000 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Number of sampled roads	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
						Logging cost		Chipping cost			
				Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	0.015*	2.49 ± 0.1	1,583.41 ± 19.11	0	267.15 ± 3.2	0.354 ± 0.017	320.59 ± 3.84	0.425 ± 0.021	2,173.66 ± 26.11	3.29 ± 0.138
	20	0.03*	5.22 ± 0.1	2,222.32 ± 6.69	0	374.93 ± 1.12	0.745 ± 0.017	449.92 ± 1.35	0.894 ± 0.02	3,052.43 ± 9.15	6.89 ± 0.132
	30	0.045*	7.43 ± 0.12	2,355.78 ± 2.91	0	397.42 ± 0.49	1.058 ± 0.021	476.9 ± 0.58	1.269 ± 0.025	3,237.57 ± 3.98	9.8 ± 0.171
	40	0.059*	9.68 ± 0.11	2,373.45 ± 0.09	0	400.39 ± 0	1.381 ± 0.017	480.47 ± 0.01	1.657 ± 0.02	3,264.05 ± 0.12	12.78 ± 0.152
80%	10	0.015*	2.34 ± 0.13	1,556.42 ± 22.3	0	262.73 ± 3.75	0.327 ± 0.022	315.28 ± 4.5	0.393 ± 0.027	2,136.78 ± 30.56	3.08 ± 0.175
	20	0.03*	4.41 ± 0.15	2,179.39 ± 10.25	0	367.7 ± 1.74	0.606 ± 0.027	441.24 ± 2.08	0.727 ± 0.032	2,992.76 ± 14.08	5.77 ± 0.213
	30	0.045*	6.21 ± 0.11	2,346.12 ± 2.6	0	395.8 ± 0.44	0.844 ± 0.017	474.96 ± 0.52	1.012 ± 0.02	3,223.13 ± 3.57	8.11 ± 0.144
	40	0.059*	8.4 ± 0.08	2,371.81 ± 0.52	0	400.12 ± 0.08	1.152 ± 0.015	480.14 ± 0.09	1.382 ± 0.018	3,260.52 ± 0.69	10.99 ± 0.115
60%	10	0.015*	1.79 ± 0.12	1,406.94 ± 17.28	0	237.55 ± 2.94	0.228 ± 0.022	285.06 ± 3.53	0.274 ± 0.026	1,931.36 ± 23.76	2.31 ± 0.17
	20	0.03*	3.43 ± 0.13	2,036.01 ± 12.22	0	343.64 ± 2.05	0.433 ± 0.023	412.36 ± 2.45	0.519 ± 0.027	2,795.46 ± 16.68	4.41 ± 0.176
	30	0.045*	5.14 ± 0.11	2,269.97 ± 7.25	0	383.03 ± 1.22	0.656 ± 0.019	459.63 ± 1.47	0.787 ± 0.023	3,117.82 ± 9.9	6.63 ± 0.156
	40	0.059*	6.82 ± 0.09	2,341.44 ± 3.23	0	395.03 ± 0.54	0.876 ± 0.013	474.03 ± 0.65	1.052 ± 0.016	3,217.38 ± 4.4	8.81 ± 0.115
40%	10	0.015*	1.5 ± 0.11	1,060.9 ± 14.38	0	179.52 ± 2.38	0.18 ± 0.019	215.42 ± 2.85	0.216 ± 0.023	1,457.36 ± 19.56	1.91 ± 0.148
	20	0.03*	2.7 ± 0.11	1,689.52 ± 14.33	0	285.43 ± 2.39	0.306 ± 0.02	342.52 ± 2.86	0.367 ± 0.024	2,320.2 ± 19.52	3.4 ± 0.159
	30	0.045*	3.87 ± 0.13	1,993.89 ± 11.99	0	336.68 ± 2	0.432 ± 0.023	404.01 ± 2.4	0.518 ± 0.027	2,738.5 ± 16.42	4.87 ± 0.177
	40	0.059*	5.18 ± 0.03	2,141.17 ± 9.46	0	361.43 ± 1.59	0.586 ± 0.005	433.71 ± 1.9	0.703 ± 0.006	2,941.55 ± 12.94	6.53 ± 0.039
20%	10	0.015*	0.93 ± 0.06	512.57 ± 11.42	0	87.1 ± 1.99	0.077 ± 0.011	104.53 ± 2.38	0.093 ± 0.013	705.14 ± 15.83	1.12 ± 0.089
	20	0.03*	1.86 ± 0.08	872.3 ± 16.42	0	147.94 ± 2.75	0.154 ± 0.013	177.53 ± 3.3	0.185 ± 0.016	1,199.66 ± 22.44	2.23 ± 0.104
	30	0.045*	2.63 ± 0.06	1,147.3 ± 22.17	0	194.33 ± 3.73	0.214 ± 0.008	233.2 ± 4.48	0.257 ± 0.009	1,577.51 ± 30.4	3.14 ± 0.072
	40	0.059*	3.65 ± 0.05	1,319.06 ± 19.4	0	223.25 ± 3.27	0.318 ± 0.008	267.89 ± 3.92	0.382 ± 0.01	1,813.91 ± 26.6	4.41 ± 0.066

* indicates the mean values are constant

SI. 3

Table S3.18 Cost components for **visual surveillance from the ground combined with trapping networks** in 100,000 Euro for 1,000 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Number of sampled roads	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
						Logging cost		Chipping cost			
				Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	10	0.18*	2.75 ± 0.18	1,602.37 ± 13.36	0	270.34 ± 2.27	0.395 ± 0.031	324.41 ± 2.72	0.475 ± 0.037	2,200.05 ± 18.38	3.8 ± 0.243
	20	0.195*	5.1 ± 0.13	2,185.26 ± 13.28	0	368.63 ± 2.23	0.727 ± 0.023	442.36 ± 2.67	0.873 ± 0.027	3,001.54 ± 18.16	6.89 ± 0.18
	30	0.21*	7.56 ± 0.14	2,358.65 ± 3.07	0	397.81 ± 0.52	1.08 ± 0.024	477.38 ± 0.62	1.296 ± 0.029	3,241.6 ± 4.2	10.14 ± 0.191
	40	0.224*	9.66 ± 0.12	2,373.9 ± 0.13	0	400.38 ± 0.01	1.376 ± 0.019	480.46 ± 0.01	1.651 ± 0.023	3,264.61 ± 0.21	12.91 ± 0.164
80%	10	0.18*	2.3 ± 0.14	1,510.64 ± 21.63	0	254.98 ± 3.63	0.319 ± 0.024	305.98 ± 4.35	0.383 ± 0.029	2,074.08 ± 29.61	3.18 ± 0.19
	20	0.195*	4.33 ± 0.11	2,153.29 ± 10.43	0	363.29 ± 1.75	0.595 ± 0.019	435.95 ± 2.1	0.714 ± 0.023	2,957.06 ± 14.34	5.84 ± 0.148
	30	0.21*	6.19 ± 0.11	2,340.8 ± 4.02	0	394.82 ± 0.67	0.836 ± 0.019	473.78 ± 0.8	1.003 ± 0.022	3,215.8 ± 5.46	8.24 ± 0.151
	40	0.224*	8.22 ± 0.12	2,370.98 ± 0.67	0	399.89 ± 0.1	1.122 ± 0.019	479.87 ± 0.12	1.347 ± 0.023	3,259.19 ± 0.91	10.91 ± 0.163
60%	10	0.18*	1.86 ± 0.14	1,392.89 ± 13.92	0	235.15 ± 2.37	0.241 ± 0.024	282.17 ± 2.84	0.289 ± 0.029	1,912.25 ± 19.14	2.57 ± 0.191
	20	0.195*	3.45 ± 0.08	2,017.26 ± 7.94	0	340.45 ± 1.34	0.438 ± 0.014	408.54 ± 1.61	0.526 ± 0.017	2,769.9 ± 10.86	4.61 ± 0.11
	30	0.21*	5.04 ± 0.12	2,259.19 ± 7.42	0	381.14 ± 1.23	0.64 ± 0.021	457.37 ± 1.48	0.768 ± 0.025	3,102.94 ± 10.11	6.66 ± 0.165
	40	0.224*	6.66 ± 0.07	2,340.24 ± 2.56	0	394.74 ± 0.43	0.846 ± 0.012	473.69 ± 0.52	1.015 ± 0.014	3,215.56 ± 3.54	8.75 ± 0.094
40%	10	0.18*	1.31 ± 0.08	1,062.96 ± 13.23	0	179.65 ± 2.28	0.142 ± 0.014	215.58 ± 2.74	0.17 ± 0.017	1,459.68 ± 18.29	1.8 ± 0.116
	20	0.195*	2.66 ± 0.11	1,654.64 ± 8.23	0	279.56 ± 1.38	0.303 ± 0.019	335.47 ± 1.66	0.363 ± 0.023	2,272.52 ± 11.27	3.52 ± 0.147
	30	0.21*	3.85 ± 0.13	1,971.95 ± 7.5	0	332.94 ± 1.26	0.431 ± 0.021	399.53 ± 1.52	0.517 ± 0.026	2,708.47 ± 10.34	5.01 ± 0.172
	40	0.224*	5.19 ± 0.07	2,126.38 ± 8.98	0	358.87 ± 1.5	0.592 ± 0.01	430.64 ± 1.8	0.711 ± 0.012	2,921.31 ± 12.28	6.72 ± 0.092
20%	10	0.18*	0.94 ± 0.03	510.32 ± 22.02	0	86.8 ± 3.71	0.079 ± 0.005	104.16 ± 4.45	0.094 ± 0.006	702.39 ± 30.18	1.29 ± 0.042
	20	0.195*	1.78 ± 0.06	862.15 ± 12.13	0	146.22 ± 2.03	0.143 ± 0.012	175.47 ± 2.44	0.171 ± 0.014	1,185.81 ± 16.6	2.29 ± 0.091
	30	0.21*	2.83 ± 0.05	1,106.8 ± 17.4	0	187.49 ± 2.93	0.253 ± 0.008	224.99 ± 3.51	0.304 ± 0.01	1,522.32 ± 23.88	3.59 ± 0.07
	40	0.224*	3.57 ± 0.05	1,295.91 ± 16.46	0	219.3 ± 2.77	0.304 ± 0.007	263.16 ± 3.32	0.365 ± 0.008	1,782.16 ± 22.59	4.46 ± 0.067

* indicates the mean values are constant

Table S3.19 Cost components for **aerial surveillance** in 100,000 Euro for 1,000 initial emerging beetles. The number represents average value ± standard error

Proportion of symptomatic trees	Aerial efficiency	Flight number	Surveillance cost	Wood sampling cost	Revenue loss		Eradication cost				Total cost	
							Logging cost		Chipping cost			
					Clear-cutting	Selective -cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting	Clear-cutting	Selective-cutting
100%	0.51	1	0.83*	17.19 ± 0.03	2,373.5 ± 0.07	0	400.4 ± 0	2.454 ± 0.007	480.48 ± 0	2.945 ± 0.008	3,272.41 ± 0.04	23.42 ± 0.048
		2	1.66*	25.65 ± 0.06	2,373.5 ± 0.07	0	400.4 ± 0	3.664 ± 0.009	480.48 ± 0	4.397 ± 0.011	3,281.69 ± 0.03	35.37 ± 0.077
		3	2.49*	29.77 ± 0.07	2,373.5 ± 0.07	0	400.4 ± 0	4.252 ± 0.011	480.48 ± 0	5.102 ± 0.013	3,286.65 ± 0.02	41.62 ± 0.089
	0.71	1	0.83*	23.96 ± 0.07	2,373.5 ± 0.07	0	400.4 ± 0	3.419 ± 0.011	480.48 ± 0	4.103 ± 0.014	3,279.17 ± 0.03	32.31 ± 0.097
		2	1.66*	30.9 ± 0.07	2,373.5 ± 0.07	0	400.4 ± 0	4.412 ± 0.013	480.48 ± 0	5.294 ± 0.015	3,286.94 ± 0.01	42.27 ± 0.101
		3	2.49*	32.91 ± 0.07	2,373.5 ± 0.07	0	400.4 ± 0	4.698 ± 0.012	480.48 ± 0	5.638 ± 0.015	3,289.79 ± 0.01	45.74 ± 0.097
	0.91	1	0.83*	30.71 ± 0.06	2,373.5 ± 0.07	0	400.4 ± 0	4.387 ± 0.011	480.48 ± 0	5.264 ± 0.013	3,285.93 ± 0.02	41.19 ± 0.086
		2	1.66*	33.46 ± 0.07	2,373.5 ± 0.07	0	400.4 ± 0	4.778 ± 0.012	480.48 ± 0	5.733 ± 0.014	3,289.51 ± 0.01	45.63 ± 0.095
		3	2.49*	33.71 ± 0.07	2,373.5 ± 0.07	0	400.4 ± 0	4.812 ± 0.012	480.48 ± 0	5.775 ± 0.015	3,290.58 ± 0.01	46.78 ± 0.096
80%	0.51	1	0.83*	14.56 ± 0.04	2,373.41 ± 0.1	0	400.38 ± 0.01	1.989 ± 0.006	480.46 ± 0.01	2.387 ± 0.008	3,269.65 ± 0.1	19.77 ± 0.05
		2	1.66*	21.71 ± 0.05	2,373.49 ± 0.08	0	400.4 ± 0	2.969 ± 0.009	480.48 ± 0	3.563 ± 0.011	3,277.73 ± 0.05	29.9 ± 0.07
		3	2.49*	25.17 ± 0.06	2,373.49 ± 0.08	0	400.4 ± 0	3.444 ± 0.01	480.48 ± 0	4.133 ± 0.012	3,282.02 ± 0.06	35.24 ± 0.079
	0.71	1	0.83*	20.23 ± 0.05	2,373.46 ± 0.09	0	400.39 ± 0.01	2.768 ± 0.008	480.47 ± 0.01	3.321 ± 0.009	3,275.39 ± 0.08	27.15 ± 0.063
		2	1.66*	26.12 ± 0.07	2,373.49 ± 0.07	0	400.4 ± 0	3.574 ± 0.012	480.48 ± 0	4.289 ± 0.014	3,282.14 ± 0.04	35.64 ± 0.093
		3	2.49*	27.83 ± 0.07	2,373.5 ± 0.08	0	400.4 ± 0	3.807 ± 0.012	480.48 ± 0	4.569 ± 0.015	3,284.69 ± 0.04	38.69 ± 0.096
	0.91	1	0.83*	25.95 ± 0.07	2,373.49 ± 0.07	0	400.4 ± 0	3.549 ± 0.011	480.48 ± 0	4.259 ± 0.014	3,281.14 ± 0.04	34.58 ± 0.09
		2	1.66*	28.29 ± 0.07	2,373.5 ± 0.08	0	400.4 ± 0	3.87 ± 0.012	480.48 ± 0	4.644 ± 0.014	3,284.33 ± 0.04	38.46 ± 0.094
		3	2.49*	28.5 ± 0.07	2,373.5 ± 0.08	0	400.4 ± 0	3.899 ± 0.012	480.48 ± 0	4.679 ± 0.015	3,285.37 ± 0.04	39.57 ± 0.095
60%	0.51	1	0.83*	11.79 ± 0.03	2,370.26 ± 0.87	0	399.86 ± 0.14	1.505 ± 0.006	479.83 ± 0.17	1.806 ± 0.008	3,262.56 ± 1.19	15.93 ± 0.046
		2	1.66*	17.53 ± 0.05	2,372.55 ± 0.58	0	400.24 ± 0.09	2.24 ± 0.009	480.29 ± 0.11	2.688 ± 0.011	3,272.28 ± 0.79	24.12 ± 0.07
		3	2.49*	20.39 ± 0.07	2,372.98 ± 0.24	0	400.31 ± 0.04	2.602 ± 0.012	480.38 ± 0.04	3.123 ± 0.014	3,276.55 ± 0.31	28.6 ± 0.094
	0.71	1	0.83*	16.38 ± 0.05	2,372.56 ± 0.42	0	400.24 ± 0.06	2.092 ± 0.009	480.29 ± 0.08	2.511 ± 0.011	3,270.3 ± 0.55	21.81 ± 0.072
		2	1.66*	21.15 ± 0.08	2,372.83 ± 0.32	0	400.29 ± 0.05	2.701 ± 0.013	480.34 ± 0.06	3.241 ± 0.016	3,276.27 ± 0.44	28.75 ± 0.106
		3	2.49*	22.53 ± 0.08	2,373.15 ± 0.22	0	400.34 ± 0.03	2.877 ± 0.014	480.41 ± 0.04	3.453 ± 0.016	3,278.92 ± 0.28	31.35 ± 0.108
	0.91	1	0.83*	21.01 ± 0.07	2,373.14 ± 0.23	0	400.34 ± 0.03	2.684 ± 0.012	480.41 ± 0.04	3.22 ± 0.015	3,275.73 ± 0.29	27.74 ± 0.099
		2	1.66*	22.9 ± 0.08	2,373.16 ± 0.22	0	400.34 ± 0.03	2.924 ± 0.014	480.41 ± 0.04	3.509 ± 0.017	3,278.46 ± 0.28	30.99 ± 0.11
		3	2.49*	23.07 ± 0.08	2,373.16 ± 0.22	0	400.34 ± 0.03	2.946 ± 0.014	480.41 ± 0.04	3.535 ± 0.017	3,279.47 ± 0.28	32.04 ± 0.109

SI. 3

Table S3.19 (continued) Cost components for **aerial surveillance** in 100,000 Euro for 1,000 initial emerging beetles. The number represents average value ± standard error

40%	0.51	1	0.83*	9.15 ± 0.05	2,308.26 ± 4.88	0	389.47 ± 0.82	1.044 ± 0.008	467.36 ± 0.98	1.252 ± 0.01	3,175.06 ± 6.69	12.27 ± 0.066
		2	1.66*	13.64 ± 0.07	2,346.59 ± 2.85	0	395.89 ± 0.47	1.555 ± 0.012	475.07 ± 0.57	1.865 ± 0.014	3,232.85 ± 3.9	18.72 ± 0.093
		3	2.49*	15.82 ± 0.08	2,354.18 ± 2.54	0	397.16 ± 0.42	1.802 ± 0.014	476.6 ± 0.51	2.162 ± 0.016	3,246.25 ± 3.49	22.27 ± 0.108
	0.71	1	0.83*	12.74 ± 0.06	2,340.64 ± 4.3	0	394.89 ± 0.72	1.456 ± 0.011	473.87 ± 0.86	1.747 ± 0.013	3,222.97 ± 5.88	16.77 ± 0.081
		2	1.66*	16.43 ± 0.08	2,355.97 ± 2.3	0	397.46 ± 0.38	1.874 ± 0.014	476.96 ± 0.46	2.249 ± 0.017	3,248.48 ± 3.15	22.21 ± 0.112
		3	2.49*	17.5 ± 0.08	2,358.16 ± 2.06	0	397.83 ± 0.34	1.996 ± 0.014	477.4 ± 0.41	2.395 ± 0.017	3,253.38 ± 2.82	24.39 ± 0.112
	0.91	1	0.83*	16.34 ± 0.07	2,355.58 ± 2.19	0	397.4 ± 0.36	1.861 ± 0.013	476.88 ± 0.44	2.233 ± 0.015	3,247.02 ± 3	21.26 ± 0.1
		2	1.66*	17.8 ± 0.09	2,358.83 ± 1.92	0	397.94 ± 0.32	2.03 ± 0.015	477.53 ± 0.38	2.436 ± 0.018	3,253.76 ± 2.64	23.93 ± 0.119
		3	2.49*	17.93 ± 0.09	2,359.16 ± 1.93	0	398 ± 0.32	2.045 ± 0.015	477.6 ± 0.38	2.454 ± 0.018	3,255.18 ± 2.64	24.92 ± 0.118
20%	0.51	1	0.83*	6.27 ± 0.04	1,680.44 ± 21.83	0	284.02 ± 3.67	0.539 ± 0.006	340.83 ± 4.4	0.647 ± 0.008	2,312.39 ± 29.92	8.29 ± 0.052
		2	1.66*	9.33 ± 0.05	1,871.47 ± 23.49	0	316.12 ± 3.95	0.8 ± 0.009	379.34 ± 4.74	0.96 ± 0.011	2,577.92 ± 32.2	12.75 ± 0.074
		3	2.49*	10.85 ± 0.06	1,934.47 ± 18.63	0	326.71 ± 3.13	0.932 ± 0.011	392.05 ± 3.75	1.118 ± 0.013	2,666.56 ± 25.54	15.39 ± 0.083
	0.71	1	0.83*	8.72 ± 0.05	1,834.78 ± 18.92	0	309.95 ± 3.17	0.747 ± 0.009	371.94 ± 3.81	0.897 ± 0.011	2,526.23 ± 25.91	11.19 ± 0.07
		2	1.66*	11.25 ± 0.06	1,947.01 ± 19.68	0	328.81 ± 3.3	0.965 ± 0.011	394.57 ± 3.97	1.158 ± 0.013	2,683.3 ± 26.98	15.04 ± 0.084
		3	2.49*	11.99 ± 0.06	1,975.08 ± 19.96	0	333.53 ± 3.35	1.028 ± 0.012	400.23 ± 4.02	1.234 ± 0.014	2,723.32 ± 27.36	16.74 ± 0.09
	0.91	1	0.83*	11.17 ± 0.06	1,944.94 ± 20.91	0	328.47 ± 3.51	0.958 ± 0.011	394.16 ± 4.21	1.15 ± 0.013	2,679.57 ± 28.66	14.11 ± 0.08
		2	1.66*	12.19 ± 0.07	1,982.07 ± 19.69	0	334.7 ± 3.31	1.046 ± 0.012	401.64 ± 3.97	1.255 ± 0.014	2,732.25 ± 26.99	16.15 ± 0.092
		3	2.49*	12.28 ± 0.07	1,984.54 ± 19.38	0	335.11 ± 3.25	1.053 ± 0.012	402.14 ± 3.9	1.264 ± 0.014	2,736.55 ± 26.56	17.08 ± 0.092

* indicates the mean values are constant

Supplementary Information for Chapter 4

Comparing inward and outward strategies for delimiting non-native plant pest outbreaks

Supplementary results

Fig. S4.1 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, presented on a log10 x-axis) in the case of the inward strategy

Fig. S4.2 Proportion of delimited infested plants (a), and actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, presented on a log10 logarithmic x-axis) in the case of the inward strategy

Fig. S4.3 Proportion of cases in which a strategy performs better in terms of the proportion of delimited infested plants (y-axis) as a function of the size of the potentially infested plants (R_{inward}, x-axis) in the case of the inward strategy for the negative exponential cross-section kernel

Fig. S4.4 Proportion of cases in which the inward strategy goes inside (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy

Fig. S4.5 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian (a), negative exponential (b) and 2Dt (c) cross-section kernel for different combinations of the confidence level and design prevalence

Fig. S4.6 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian cross-section kernel for different combinations of the confidence level and design prevalence

Fig. S4.7 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the 2Dt cross-section kernel for different combinations of the confidence level and design prevalence

Fig. S4.8 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian cross-section kernel when increasing the size of the survey band

Fig. S4.9 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian cross-section kernel when increasing the size of the survey band

Fig. S4.10 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the negative exponential cross-section kernel when increasing the size of the survey band

Fig. S4.11 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the negative exponential cross-section kernel when increasing the size of the survey band

Fig. S4.12 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the 2Dt cross-section kernel when increasing the size of the survey band

Fig. S4.13 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the 2Dt cross-section kernel when increasing the size of the survey band

Fig. S4.14 Frequency distribution of the size of theoretical infested zones for the Gaussian (a), negative exponential (b) and 2Dt cross-section kernel (c) based on 500 outbreaks for each kernel

Fig. S4.15 Frequency of the difference in sizes between theoretical (i.e. true position of the frontier) and delimited infested zones for the Gaussian (a), negative exponential (b) and 2Dt cross-section kernel (c)

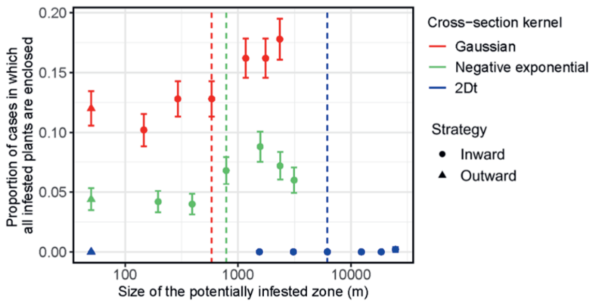

Fig. S4.1 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, presented on a log10 x-axis) in the case of the inward strategy. *Red color* represents the results for the Gaussian cross-section kernel, *green color* represents the results for the negative exponential cross-section kernel, and *blue color* indicates the results for the 2Dt cross-section kernel. *Circle* data points and error bars represent the average ± standard error of 500 simulations for the inward strategy, and the *triangle* data point and error bar represent the average ± standard error of 500 simulations for the outward strategy. *Dashed lines* represent the average position of the frontier

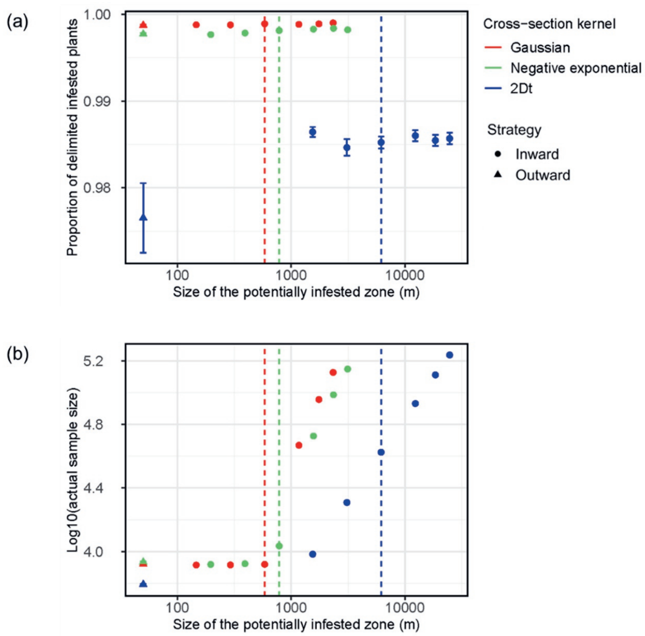

Fig. S4.2 Proportion of delimited infested plants (a), and actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, presented on a log10 logarithmic x-axis) in the case of the inward strategy. *Red color* represents the results for the Gaussian cross-section kernel, *green color* represents the results for the negative exponential cross-section kernel, and *blue color* indicates the results for the 2Dt cross-section kernel. *Circle* data points and error bars represent the average ± standard error of 500 simulations for the inward strategy, and the *triangle* data point and error bar represent the average ± standard error of 500 simulations for the outward strategy. The standard error is too small to be visible in the Fig. (b). *Dashed lines* represent the average position of the frontier

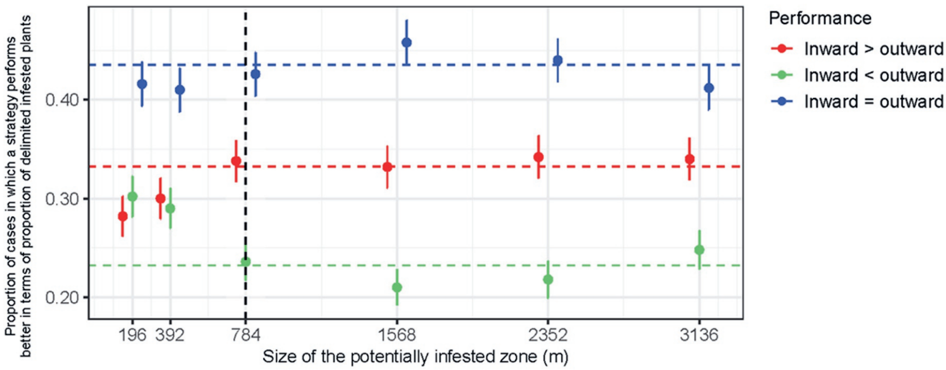

Fig. S4.3 Proportion of cases in which a strategy performs better in terms of the proportion of delimited infested plants (y-axis) as a function of the size of the potentially infested plants (R_{inward}, x-axis) in the case of the inward strategy for the negative exponential cross-section kernel. *Red circle* data points represent the average ± standard error proportion of cases where the inward strategy performs better than the outward strategy in terms of the proportion of delimited infested plants. *Green circle points* represent the average ± standard error proportion of cases where the inward strategy performs worse than the outward strategy in terms of the proportion of delimited infested plants. *Blue circle points* represent the average ± standard error proportion of cases where the inward strategy performs equally to the outward strategy in terms of delimiting infested plants. *Dashed lines* represent average performance averaged across all sizes of the potentially infested zone. The *black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

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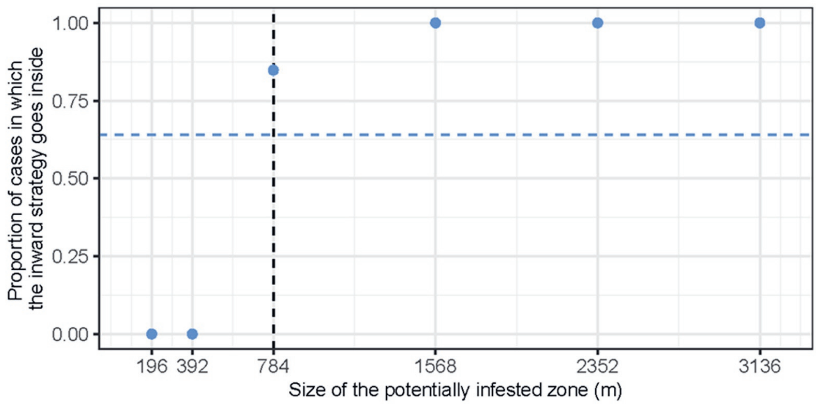

Fig. S4.4 Proportion of cases in which the inward strategy goes inside (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars represent the average ± standard error of 500 simulations for the inward strategy. The standard error is too small to be visible in the figure. The *blue dashed line* represents the average proportion of cases in which the inward strategy goes inside averaged across all sizes of the potentially infested zone. The *black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

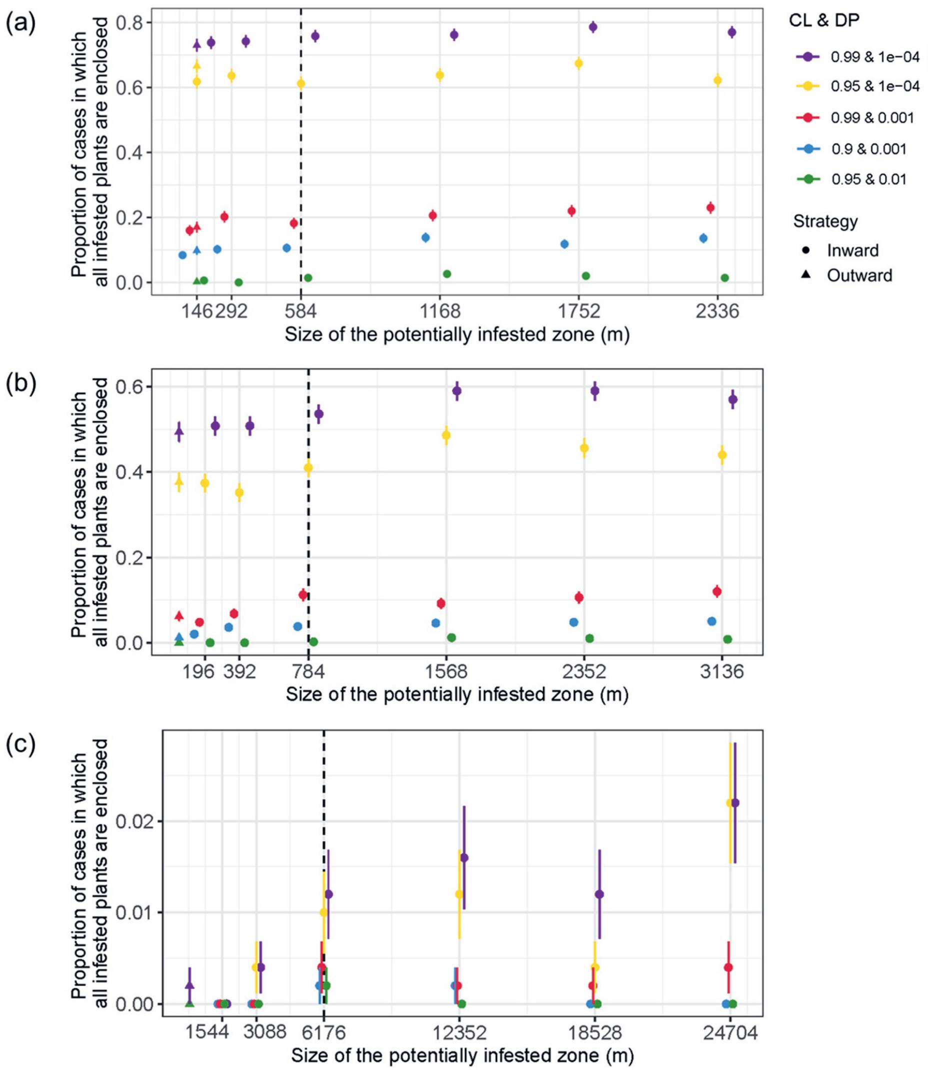

Fig. S4.5 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian (a), negative exponential (b) and 2Dt (c) cross-section kernel. Data points and error bars represent the average ± standard error of 500 simulations for the inward strategy (*circle points*) and the outward strategy (*triangle points*). CL & DP indicates the value of confidence level and design prevalence

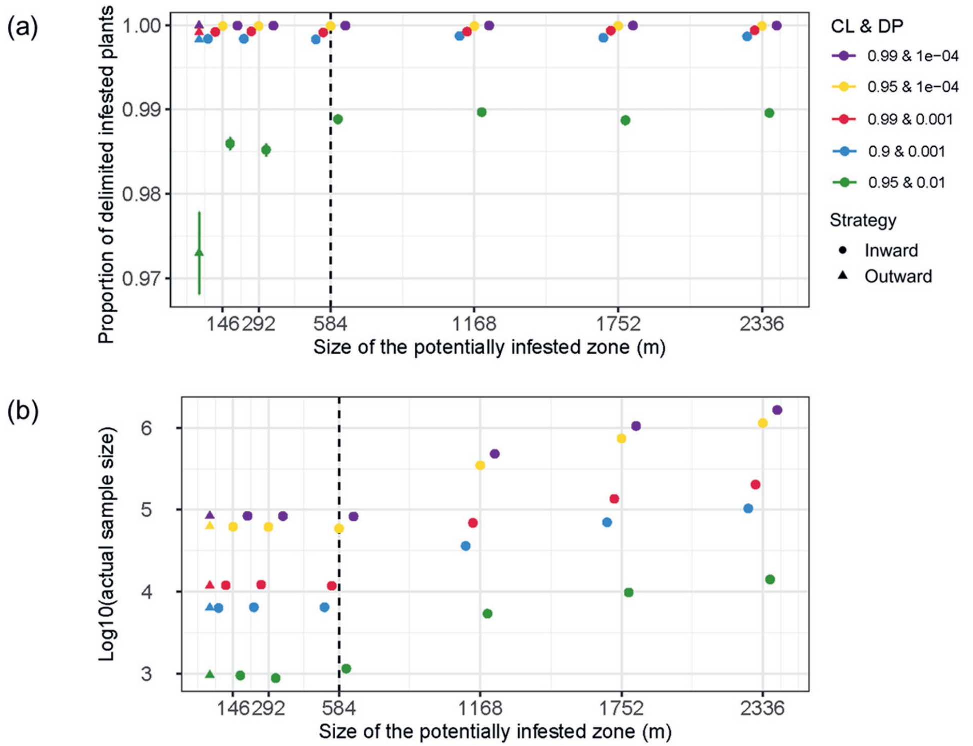

Fig. S4.6 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian cross-section kernel. Data points and error bars represent the average ± standard error of 500 simulations for the inward strategy (*circle points*) and the outward strategy (*triangle points*). The standard error is too small to be visible in the figure. CL & DP indicates the value of confidence level and design prevalence. The *black dashed line* denotes the average position of the frontier (584 m based on the spread model)

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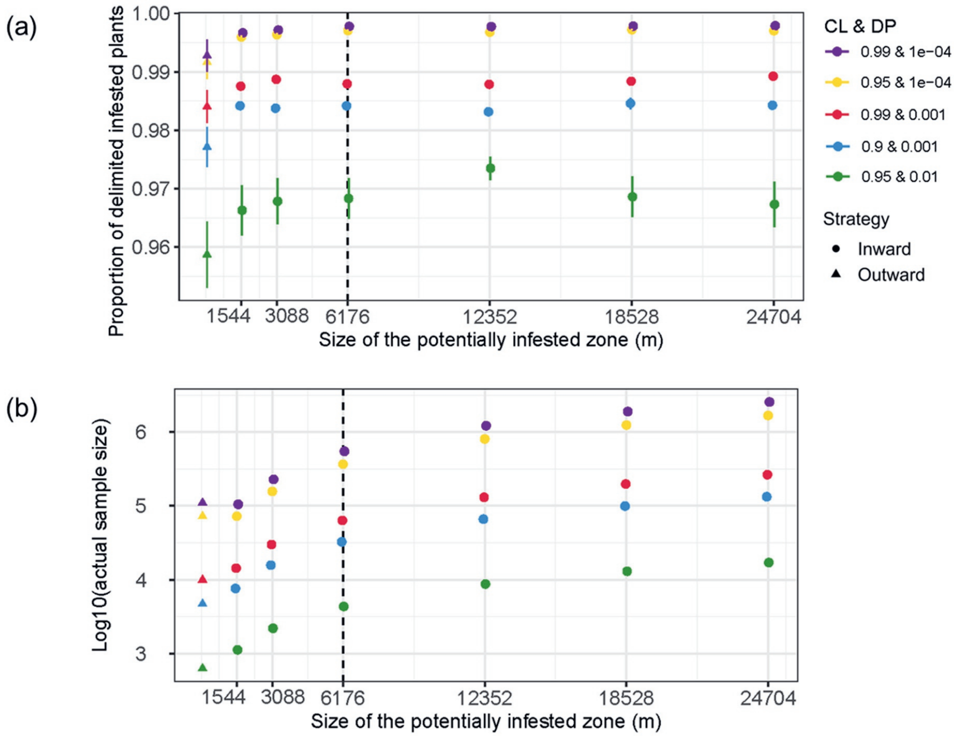

Fig. S4.7 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the 2Dt cross-section kernel. Data points and error bars represent the average ± standard error of 500 simulations for the inward strategy (*circle points*) and the outward strategy (*triangle points*). The standard error is too small to be visible in the figure. CL & DP indicates the value of confidence level and design prevalence. The *black dashed line* denotes the average position of the front (6,176 m based on the spread model)

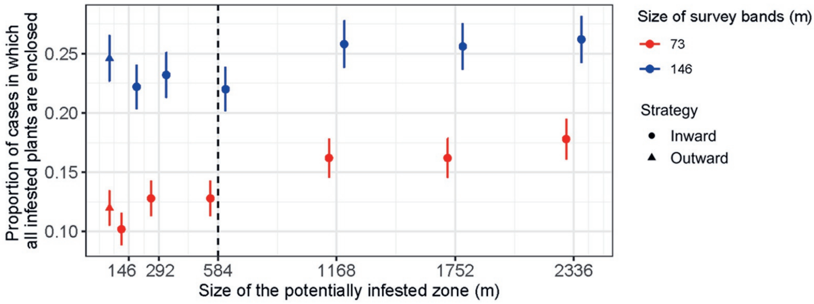

Fig. S4.8 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian cross-section kernel. *Red* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 73 m, *blue* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 146 m. *Circle points* denote the result for the inward strategy and *triangle points* represent the result for the outward strategy (584 m based on the spread model)

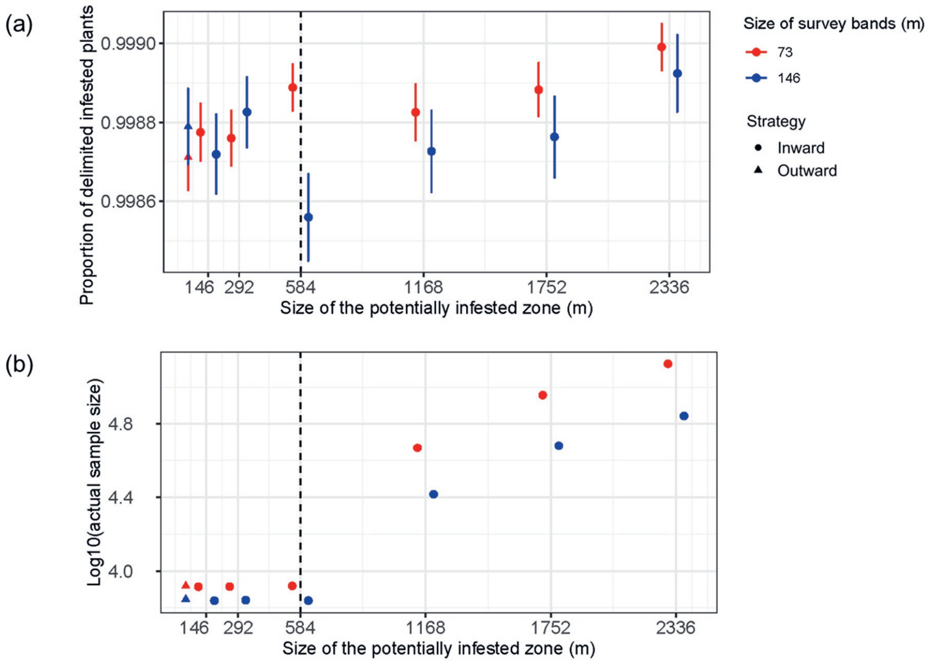

Fig. S4.9 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the Gaussian cross-section kernel. *Red* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 73 m, *blue* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 146 m. *Circle points* denote the result for the inward strategy and *triangle points* represent the result for the outward strategy. The standard error is too small to be visible in the Fig. (b). The *black dashed line* denotes the average position of the frontier (584 m based on the spread model)

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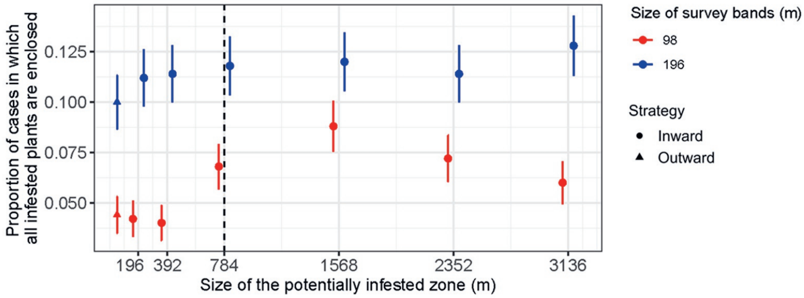

Fig. S4.10 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the negative exponential cross-section kernel. *Red* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 98 m, *blue* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 196 m. *Circle points* denote the result for the inward strategy and *triangle points* represent the result for the outward strategy. The *black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

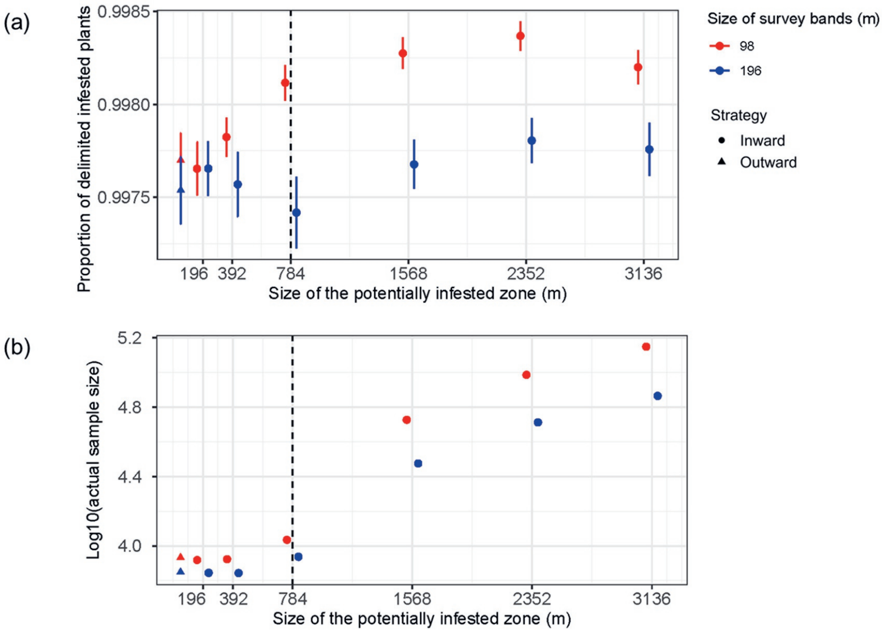

Fig. S4.11 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the negative exponential cross-section kernel. *Red* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 98 m, *blue* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 196 m. *Circle points* denote the result for the inward strategy and *triangle points* represent the result for the outward strategy. The standard error is too small to be visible in the Fig. (b). The *black dashed line* denotes the average position of the frontier (784 m based on the spread model in Table 4.1)

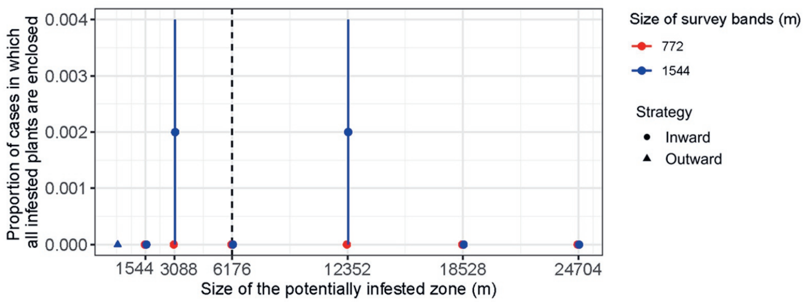

Fig. S4.12 Proportion of cases in which all infested plants are enclosed (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the 2Dt cross-section kernel. *Red* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 772 m, *blue* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 1,544 m. *Circle points* denote the result for the inward strategy and *triangle points* represent the result for the outward strategy. The *black dashed line* denotes the average position of the frontier (6,176 m based on the spread model)

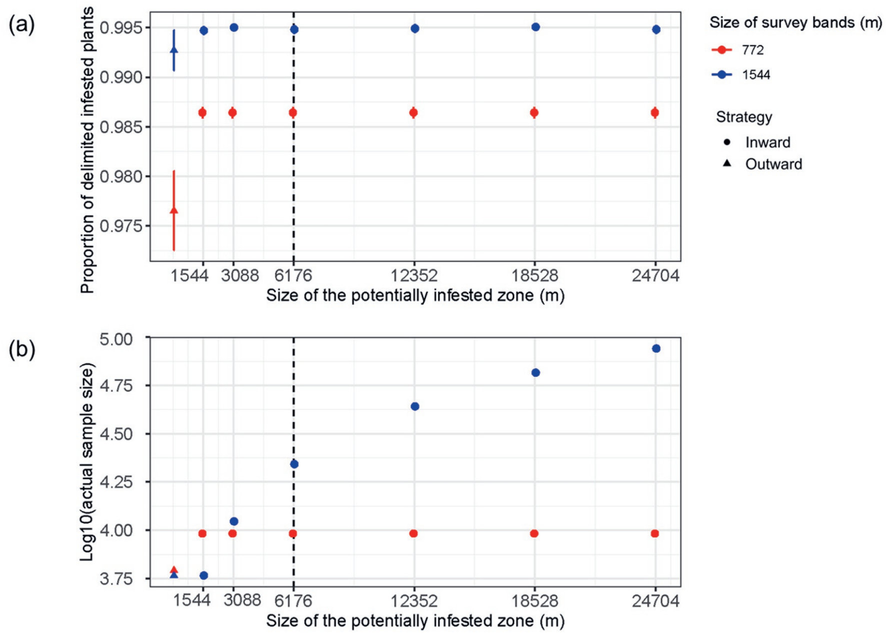

Fig. S4.13 Metrics for effectiveness, *viz*, the proportion of delimited infested plants (a), and sampling effort, *viz*, actual sample size on a log10 scale (b), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy for the 2Dt cross-section kernel. *Red* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 772 m, *blue* data points and error bars represent the average ± standard error of 500 simulations for the width of survey band of 1,544 m. *Circle points* denote the result for the inward strategy and *triangle points* represent the result for the outward strategy. The standard error is too small to be visible in the Fig. (b). The *black dashed line* denotes the average position of the frontier (6,176 m based on the spread model)

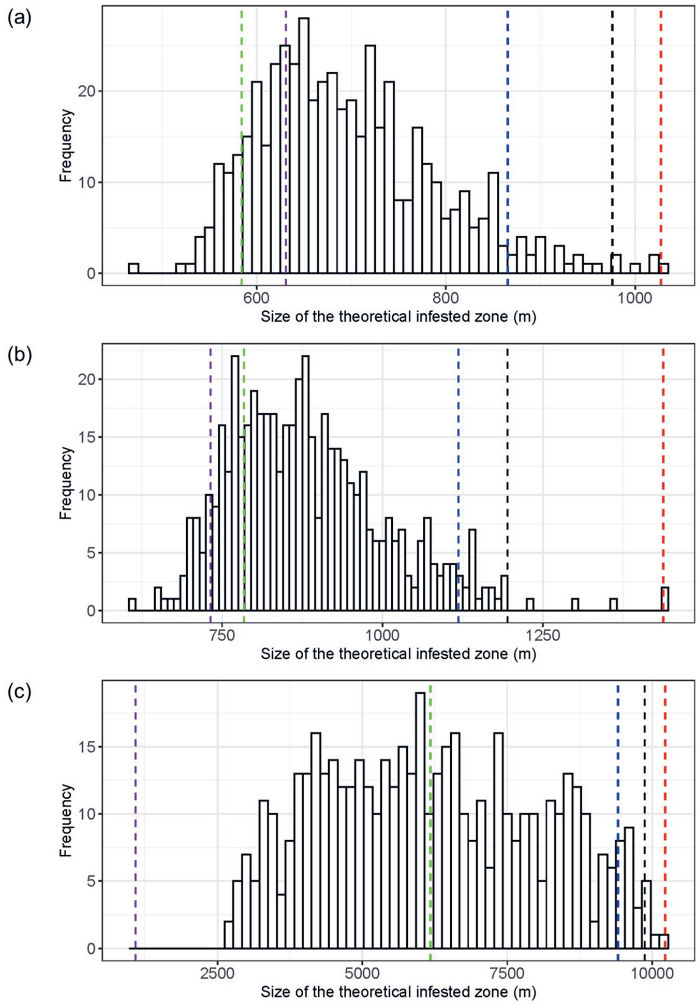

Fig. S4.14 Frequency distribution of the size of theoretical infested zones for the Gaussian (a), negative exponential (b) and 2Dt cross-section kernel (c) based on 500 outbreaks for each kernel. The *green dotted line* repesents the average positon of the frontier. The *purple dotted line* represents the average size of the delimited infested zone. The *blue and black dotted lines* represent the 95 and 99 percentiles of the infested zone distribution while the *red dotted line* represents the maximum value observed in simulations

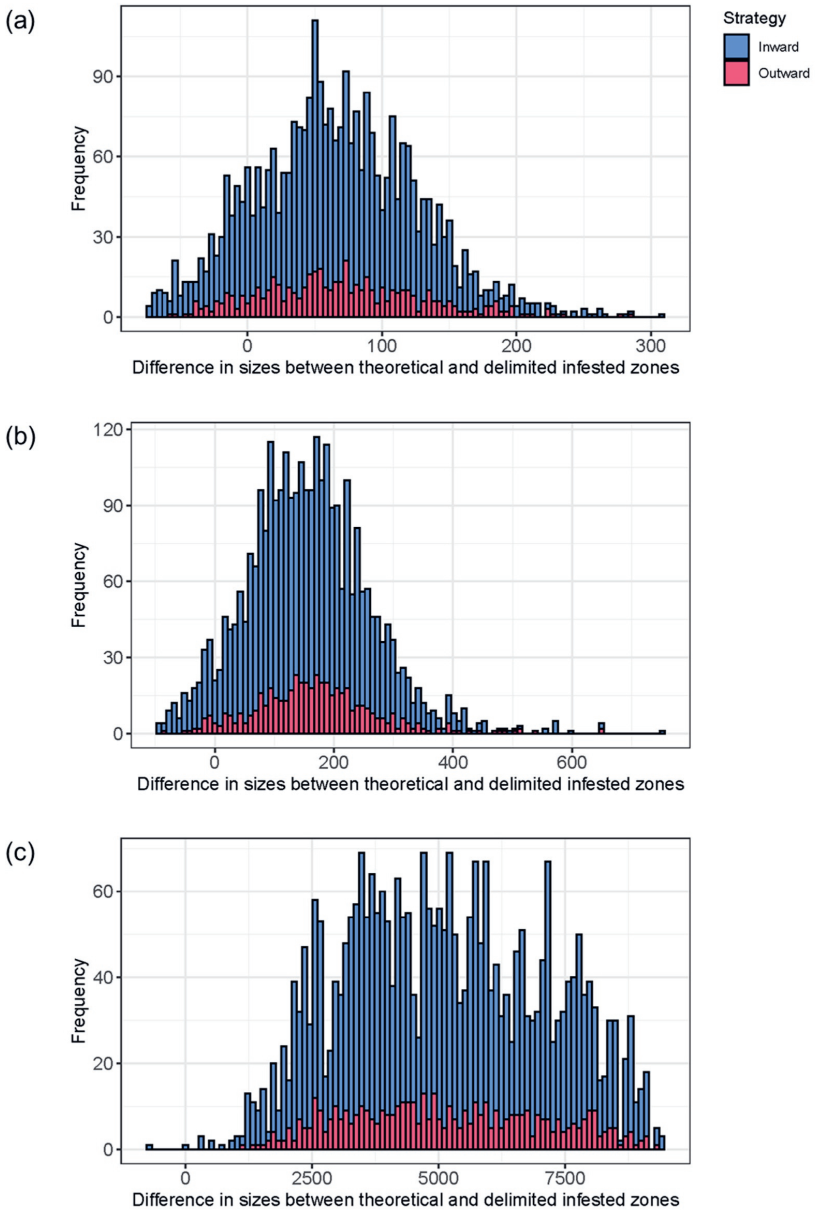

Fig. S4.15 Frequency of the difference in sizes between theoretical (i.e. true position of the frontier) and delimited infested zones for the Gaussian (a), negative exponential (b) and 2Dt cross-section kernel (c). *Blue bars* represent the frequency for the inward stategy for all sizes of the potentially infested zone (3,000 simulations), and *red bars* represent the frequency for the outward strategy (500 simulations, independent of the potentially infested zone). Differences in height between the two strategies are purely driven by the difference in number of simulations

Summary

Agriculture and natural environments in Europe are threatened by invasion of non-native plant pests, including both pathogens and insect herbivores. Preventive measures cannot always stop the entry of non-native plant pests, which may lead to their establishment and outbreaks in the invaded areas. Following an outbreak, effective management is critical, including delimitation of different zones and eradication measures within those zones. When an outbreak is detected, sampling is needed to determine where it has already spread and which area is still pest free. It is important to determine sampling strategies for new pest outbreaks that are effective in delimiting the boundaries of the outbreak but that nevertheless do not require too many sampling resources. In this thesis I study how outbreaks are delimited and managed in practice and how this delimitation and management might be improved.

To describe outbreak delimitation in practice, I review past outbreak records in Europe, in particular how outbreaks are spatially delimited. Next, in a simulation study, I compare the cost-effectiveness of two different strategies for managing outbreaks of the pine wood nematode: individual felling of infested trees on a tree-by-tree basis to the regulatory standard, clear-cutting trees around the infested tree. In a second simulation study, I evaluate different strategies for delimiting the infested zone of an outbreak.

In Chapter 2, I reviewed 121 outbreak cases caused by 10 non-native insect species, 13 pathogen species, and 2 nematode species in the European Union between 1975 and 2020 to figure out how outbreaks of non-native plant pests are managed. I found that the infested zone, buffer zone, and clear-cutting zone are commonly used, with the combination of the infested zone and buffer zone being the most frequently delimited. In the infested zone, destruction of infested plants and host plants is most often applied. In the buffer zone, surveillance is always applied. In the clear-cutting zone, removal of all host plants is conducted. I also found that the sizes of the zones in regulations often match the largest size recorded before the regulations were issued. Synonyms and homonyms in naming zones hamper the assessment of the effectiveness of zoning strategies. The diversity of results in Chapter 2 highlights that it would be beneficial to assess the effectiveness of different zoning strategies by modelling. Guidelines for designing cost-effective zoning strategies could be explored by modelling pest spread, spatial allocation of measures and costs.

In Chapter 3, I developed an individual-based model for the spread of the pine wood nematode to compare the costs and effectiveness of clear-cutting and tree-by-tree selective cutting. The model incorporates the dispersal of vector and the transmission of the nematode, two eradication strategies (clear-cutting and tree-by-tree selective cutting), and three methods for

disease surveillance: visual ground surveillance, visual ground surveillance combined with trapping networks, and aerial surveillance. To compare the costs and effectiveness of the two strategies, I calculated net reproductive numbers of infested plants and of beetles carrying the pine wood nematode as measures of effectiveness, and calculated the surveillance costs, wood sampling costs, eradication costs, and revenue loss for each surveillance method in combination with each eradication strategy as proxies for the costs of each management. I found that both clear-cutting and tree-by-tree selective cutting cannot eradicate the pine wood nematode as a minority of infested trees are still asymptomatic at the time of survey. Under a strategy aiming at containment, when no less than 60% of the infested trees showed symptoms, tree-by-tree selective cutting with intensive surveillance allowed an average 88-fold reduction in costs compared to the standing practice of clear-cutting with visual ground surveillance, mainly by preserving healthy trees. Additionally, it reduced unquantified environmental and societal costs. The results indicated that tree-by-tree selective cutting is more cost-effective than clear-cutting. The model can act as a case study exemplifying other pest-vector-plant or pest-plant systems, allowing for further exploration of alternative control strategies rather than clear-cutting.

In Chapter 4, I evaluated the costs and effectiveness of two contrasting strategies, inward and outward, to delimit an infested zone, by employing an individual-based model for spread of a disease in combination with the two surveillance strategies. In the outward strategy, which is standing practice, sampling is done radiating out from the initial finding. In the inward strategy, sampling starts at a presumed frontier of the outbreak and either works inward or outward to map out the true frontier of the invasion. I quantified for each strategy how effective they are in enclosing infested plants and at which sampling costs. To explore the effect of long-distance dispersal on the comparison between the two strategies, I considered Gaussian, negative exponential, and 2Dt cross-section kernels representing the probability distribution of dispersal distance. Comparisons were made under different survey design parameters, such as the size of the initial estimate of the infested zone for the inward strategy, the size of the survey band, the confidence level, and design prevalence for the two strategies. I found that both the inward and outward strategies were prone to error in enclosing all infested plants, particularly in the case of fat-tailed dispersal. However, both strategies delimited high proportions of infested plants. On average, the inward strategy achieved a marginally higher effectiveness, at the cost of substantially more samples than the outward strategy. The choice between the two strategies depends on the uncertainty of the frontier. The inward strategy outperforms the outward strategy when the initial guess of the infested zone is close to the actual one. If the position of the frontier is highly uncertain, the outward strategy is more cost-effective because it requires much fewer samples than the inward strategy while reaching similar effectiveness. This topic indicated that to better delimit an infested zone, a safety factor to the delimited infested zone, or a buffer zone around the delimited infested zone, should be used to enclose all infested plants.

Main conclusions

- When an outbreak of plant pests is detected, the infested zone, buffer zone and clear-cutting zone are three main zones that are used (Chapter 2).
- Most often the combination of an infested zone is used with a buffer zone; this is an appropriate option to enclose undetected infested plants (Chapters 2 and 3).
- Zoning strategies become less diverse after a pest is regulated (Chapter 2).
- Neither clear-cutting nor tree-by-tree selective cutting could eradicate PWN under realistic conditions (Chapter 3).
- Under the goal of containment, clear-cutting could be replaced by tree-by-tree selective cutting with aerial surveillance as it can achieve a given level of effectiveness at lower costs compared to the current practice of clear-cutting with visual surveillance when a large proportion ($\geq$ 60%) of infested trees are symptomatic (Chapter 3).
- Remote sensing is the future of pest surveillance (Chapter 3).
- Both the inward and outward strategies are prone to error in delimiting all infested plants, particularly in delimiting outbreaks of pests with fat-tailed dispersal patterns (Chapter 4).
- The standing practice of outward sampling for outbreak demarcation is recommended considering the uncertainty about the position of the frontier (Chapter 4).

Implications for practice and policy

- Regulations should not be based solely on previous practices but should be grounded in scientific outcomes (Chapters 2, 3, 4).
- Case-specific models should be used to evaluate the costs and effectiveness of different measures (Chapters 2, 3).
- Which strategy is used for delimiting surveys should take into account the uncertainty of the position of the frontier and the budget (Chapter 4).

- The European Union should take the responsibility to balance the trade-offs between the benefits of stakeholders in the infested area and their counterparts outside of it (Chapters 2, 3, 4).
- Enhancing connections between scientific researchers and practitioners can improve the management of outbreaks of non-native plant pests (Chapters 2, 3, 4).

Acknowledgements

First, I would like to express my gratitude to my promotor, **Wopke van der Werf**. You taught me invaluable lessons on how to think critically and logically, which have formed the foundation of my PhD journey. You introduced me to many ecological courses at the beginning of my PhD, which deepened my theoretical knowledge of ecology, pest management, and modeling. You helped me connect with experts in the field of pest management and offered support when I faced challenges in life, especially during the COVID pandemic. You encouraged me to take vacations to clear my mind when I felt stuck. I will always remember our wonderful conversations and your invaluable guidance.

Second, I would like to express my sincere gratitude to my co-promotor, **Bob Douma**. I still remember the first day we met—you picked me up at the entrance of Radix, and we had a wonderful conversation. Your kind and patient guidance has been like a beam of light, illuminating my path in scientific research. Before our meetings, we would always take around five minutes to chat, and I was always glad to share my life experiences with you. Whenever I encountered problems, whether in research or in life, you listened carefully and provided thoughtful advice.

I would also like to thank **Martijn F. Schenk**, **Roel P. J. Potting**, **Donato Boscia**, **Antonio Vicent**, and **Alan MacLeod**. Through our interviews, you provided me with a comprehensive understanding of how plant pest outbreaks are managed in practice and what key concerns are involved. I gained valuable insights into outbreak management across different countries during our discussions. Whenever I had questions, you always responded promptly and with detailed answers.

I would like to thank **Christelle Robinet**, **Hervé Jactel**, **Monique Mourits**, and **Manuela Branco** for providing me with valuable insights into the world of pine wood nematode. **Christelle**, you were my mentor in developing the individual-based model, and I learned a great deal about modeling during my visit to your institution. Your considerate, warm, and efficient approach made working with you a pleasure. **Hervé** and **Manuela**, you provided me with extensive knowledge on how pine wood nematode is managed in practice, which laid the foundation for my model development. **Monique**, you offered a thorough explanation of economic analysis. We had several meetings throughout this project to discuss how to conduct cost-effectiveness analysis using the surveyed data and modeling outcomes.

I would also like to thank the CSA secretaries, **Petra** and **Nicole**. You both have been incredibly helpful, whether with work-related matters or personal issues. **Petra**, I am very grateful for your assistance with my PhD extension application and conference reimbursements. **Nicole**, thank you so much for introducing the thesis guidelines to me and for reviewing the reading version of my thesis.

I am grateful to all my CSA PhD fellows. Thank you, **Zishen**, **Bei**, **Jin**, **Phuong**, **Zhuo**, **Zhan**, **Robbert**, **Zohralyn**, **Mengxiao**, **Jian**, **Xiaorui**, **Shuangshuang**, **Zhenxiang**, **Jie**, **Ana**, **Kostas**, **Tinko**, **Qian**, **Yanjie**, **Tao**, **David**, **Yujuan**, and many others. I would also like to extend my thanks to my officemates—**Haozheng**, **Jiahui**, **Hao**, **Cyprian**, and **Viriato**—for creating such a supportive environment.

I would like to thank my friends: **Qi**, **Danni**, **Xiaohan**, **Wenjing**, **Alejandro**, **Jiali**, **Pulv**, **Darrell**, **Lei**, **Huifang**, **Yu**, **Weiwei**, **Shanshan**, **Yujun**, **Weixin**, **Chenyu**, **Zhengyuan**, **Yifan**, **Nana**, **Xiangyu**, **Yue**, **Hao**, **Zulin** and many others. **Qi**, I am so glad I met you. We have shared so many great memories together—hanging out during the COVID pandemic, enjoying delicious meals, having late-night talks, and going hiking. I love our debates; even when we do not agree, we respect our differences, and it is in those discussions that the most interesting ideas emerge. **Danni**, I consider you my soul friend. You were my light during my time in Bennekom. I still remember our first hotpot, where we both became emotional talking about our families and the deeper aspects of life. Thank you so much for taking care of Chacha—you are a wonderful godmother! **Pulv**, I wish I had met you earlier. I enjoy every moment we spend together—chatting, bouldering, walking... I hope we can continue to meet often after I leave the Netherlands. We could explore more things together, like skiing! **Jiali**, my dear beer friend. I really enjoy talking with you over a beer. We have shared our journeys and supported each other through difficult times. Finally, I want to say that we deserve a happy ending to our PhDs, and I wish you a bright and successful future. **Xiaohan**, I am so glad to have you as my friend, and I want to thank you for attending my defense. Even though we do not chat often, I always value your friendship. **Darrell**, master of mushroom. You are the first person who ever got me interested in mushrooms. Thank you for giving me advice on my future career development while I was feeling perplexed. **Alejandro**, our friendship started when you first invited me to work out together. We really put together a detailed and well-planned schedule. I hope we can stick with fitness for the rest of our lives because it is so much fun! To all my dear friends, we have shared countless stories that I cannot recount here, but they will forever remain in my heart.

I would like to thank my bachelor and master supervisor, **Zhihong**. Your guidance and support have ignited my passion for working in academia. I also want to express my gratitude to **Zihua** for your kind and encouraging words, which helped me through a tough time. **Yue**, thank you for providing valuable information about the career landscape and for your suggestions on my career development.

Chacha (Avocado, as named in his passport**)**, my dear baby, you have been the greatest surprise during my PhD. Your presence fills my life with joy and pleasure. Sometimes, I think people could learn a lot from your independence and your peaceful state of mind. You are the best and bravest kitty!

Junjie, my dear boyfriend, you are my companion, my friend, and my sunshine. I truly believe that a good relationship helps us both grow and become the best versions of ourselves. We have shared so many wonderful moments—chasing the aurora, camping to watch the sunrise and sunset, capturing beautiful memories with our cameras, exercising together, and savoring delicious food. You inspire me and lift me up when I am facing challenges. You respect and support my decisions. Together, we have witnessed every important milestone in our journey. I love you, and I want to explore the future with you.

Finally, I manage to say thank you to my family—**爸爸**，**妈妈**，**姥姥**，**姥爷**，**爷爷**和**奶奶**。亲爱的爸爸妈妈，我非常感谢你们在我攻读博士的过程中给予的支持，无论是精神上还是经济上的。你们从不拿我和别人比较，只希望我能够开心快乐。我喜欢和你们一起聊天、打麻将、健身，还有一起去看风景。妈妈，我真的很喜欢你的性格，你坚韧、包容，能够接受这个世界的各种样貌。爸爸，虽然你不善于用言语表达对我的爱，但你的行动已经告诉了我一切。你永远站在我身后支持我，告诉我无论发生什么，你们都会是我的坚强后盾。我爱你们。

About the author

Hongyu was born in January 1993 in Heilongjiang, China. She completed her bachelor study in plant protection at China Agricultural University. The topic of her bachelor thesis was Potential geographical distribution of *Drosophila suzukii* based on MaxEnt. After that, she went to Inner Mongolia for a one-year teaching project.

During her master's project, she continued to work on invasive ecology at China Agricultural University. The topic was potential Economic Loss of *Zeugodacus cucurbitae* to China's Bitter Melon Industry using @RISK. She discovered her deep enthusiasm for science during her master's program.

In 2019, Hongyu moved to the Netherlands and started her PhD project under the supervision of Dr. Wopke van der Werf and Dr. Jacob C. Douma at the Centre for Crop Systems Analysis, Wageningen University. From 2019 to 2024, she worked on the management of outbreaks of non-native plant pests in the European Union. She conducted a review on how outbreaks of non-native plant pests are managed in practice, and completed two modeling projects on outbreak management strategies and the delimitation of outbreaks. One of her PhD topics was part of the European Union's Horizon 2020 Program for Research and Innovation under grant agreement "HOMED". The outcomes of his project have been presented in this thesis.

List of publications

Sun, H., Douma, J.C., Schenk, M. F., Potting, R. P., Boscia, D., Vicent, A., ... & Van der Werf, W. (2023). Zoning strategies for managing outbreaks of alien plant pests in the European Union: a review. Journal of Pest Science, 1-17.

Sun Hongyu, Christelle Robinet, Hervé Jactel, Monique Mourits, Manuela Branco, Wopke van der Werf, Jacob C. Douma. Pine wood nematode control without clear-cutting: a scenario analysis. To be submitted.

Sun, H., Douma, J.C., Schenk, M. F., & Van der Werf, W. Comparing inward and outward strategies for delimiting plant pest outbreaks. Under review in Journal of Pest Science.

Sun Hongyu, Qin Yujia, Fang Yan, Zhao Zhonghua, Pan Xubin, Zhao Shouqi, ... & Li Zhihong. (2018). Evaluation of Potential Economic Loss of *Zeugodacus cucurbitae* to China's Bitter Melon Industry Based on @RISK. Phytosanitary, 32 (6), 64-69.

Sun Hongyu, Li Zhihong, Yang Puyun, Wu Jiajiao, Xiao Chun, Li Ping, ... & Zhao Zihua. (2016). Study on the fitness of Spotted wing drosophila based on the maximum entropy model. Plant Quarantine, (12), 66-73.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 30 ECTS (= 20 weeks of activities)

Review/project proposal (4.5 ECTS)
- Alien plant pest invasions; data analysis, modelling and mitigation

Post-graduate courses (4.8 ECTS)
- Forest Management and Biodiversity across Europe, PE&RC (2021)
- Statistics for Data Science, WIAS/PE&RC (2022)
- Meta-Analysis, PE&RC (2023)

Deficiency, refresh, brush-up courses (24 ECTS)
- Advanced Statistics, WUR (2019)
- Systems Analysis, Simulation and Systems Management, PPS (2019)
- Population and Systems Ecology, CSA (2020)
- Ecological Modeling and Data Analysis in R, CSA (2020)

Laboratory training and working visits (0.9 ECTS)
- Individual-based modelling, INRAE (2022)

Competence, skills and career-oriented activities (3.4 ECTS)
- Project and Time Management, WGS (2020)
- Critical Thinking and Argumentation, WGS (2021)
- Scientific Publishing, WGS (2021)
- Efficient Writing Strategies, WGS (2021)

Scientific Integrity/Ethics in science activities (0.6 ECTS)
- Scientific Integrity, WGS (2020)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.5 ECTS)
- PE&RC First year weekend (2020)
- PE&RC Last year weekend (2023)

National scientific meetings, local seminars, and discussion groups (5.6 ECTS)
- *Xylella* additional Seminar (2019-2022)
- EFSA workshop (2020-2021)
- CSA journal club (2021-2023)
- Annual Meeting of the International Pest Risk Research Group (2024)

International symposia, workshops and conferences (6 ECTS)
- IUFRO International Symposium on Pine Wilt Disease, Lisbon (2022)
- HOMED final meeting, Lisbon (2022)
- IUFRO International Symposium on Pine Wilt Disease, Nanjing (2023)

Societally relevant exposure (0.4 ECTS)
- Guardian newspaper interview (2023)

Lecturing/supervision of practicals/tutorials (1.5 ECTS)
- Integrated Pest Management (2023)

The research described in this thesis was financially supported by the China Scholarship Council (grant agreement no. 201906350034) and the European Union's Horizon 2020 Program for Research and Innovation under grant agreement "HOMED" (grant agreement no. 771271). Financial support from Wageningen University & Research for printing this thesis is gratefully acknowledged.

Cover design by Hongyu Sun, with the assistance of Midjourney, ChatGPT 4, Procreate and Photoshop
Layout by Hongyu Sun and Junjie Zhang
Printed by ProefschriftMaken.nl