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RESEARCH ARTICLE

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Early detection strategies for invading tree pests: Targeted surveillance and stakeholder perspectives

Vasthi Alonso Chávez[1] | Nathan Brown[1,2] | Frank van den Bosch[3] | Stephen Parnell[4] | Alison Dyke[5] | Clare Hall[2] | Berglind Karlsdottir[2] | Mariella Marzano[6] | Joanne Morris[5] | Liz O'Brien[2] | David Williams[2] | Alice E. Milne[1]

[1]Net Zero and Resilient Farming, Rothamsted Research, Harpenden, UK; [2]Forest Research, Alice Holt Lodge, Farnham, Surrey, UK; [3]Quantitative Biology & Epidemiology Group, Plant Pathology Department, University of California, Davis, California, USA; [4]School of Life Sciences, The University of Warwick, Coventry, UK; [5]Stockholm Environment Institute, University of York, York, UK and [6]Forest Research, Northern Research Station, Roslin, UK

Correspondence
Alice E. Milne
Email: alice.milne@rothamsted.ac.uk

Vasthi Alonso Chávez
Email: vasthi.alonso-chavez@rothamsted.ac.uk

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Abstract

1. Trees are at an increasing risk from pests and diseases as global trade of trees and their products increases. One of the most destructive pests found outside its native range is the emerald ash borer (*Agrilus planipennis* Fairmaire), responsible for the death of millions of ash trees in the United States, Canada, Russia and Eastern Europe. Its early detection in countries where it is not yet present is essential for effective control.
2. One of the most likely introduction pathways for emerald ash borer into Great Britain (GB) is through firewood imports from Eastern Europe, with potential spread from ports, firewood depots and households using wood-burning fires. We developed a novel modelling framework accounting for the likely invasion pathways of emerald ash borer, its population dynamics, spread and detection sensitivities to determine sampling locations that maximise the probability of detection within 2, 4 and 8 years. To provide a sociological perspective, we interviewed firewood stakeholders to understand biosecurity implications of importing and moving firewood and used scenario workshops to explore landowners' willingness to adopt early detection methods for the emerald ash borer.
3. Optimised sampling strategies significantly improve detection compared with ranked entry points (REPS) if detection resources are plentiful and optimisation targets detection within 8 years of emerald ash borer arrival. For detection within less than 4–6 years or fewer than 70 detection devices REPS are almost as effective as optimised strategies. The methods' detection sensitivity and knowledge of likely entry pathways influence the optimal spatial sampling design.

Vasthi Alonso Chávez and Nathan Brown contributed equally to this work.

4. Firewood imports are actively inspected, and samples taken to ensure biosecurity measures are followed, but compliance at source remains uncertain. Landowners with many ash trees were more open to tree girdling, which may lead to increased detection.
5. *Synthesis and applications*: We provide the first surveillance map for emerald ash borer incursions in GB with potential for deployment by government agencies and stakeholders concerned with biosecurity. Our framework establishes optimal surveillance locations depending on factors, including detection within different timeframes, knowledge certainty of entry pathways and sensitivity of detection methods. This methodological framework is applicable to other invasive threats.

KEYWORDS
biosecurity, emerald ash borer, eradication, invasive pest species, modelling, scenario workshops, stakeholder interviews, tree pests and diseases

1 | INTRODUCTION

The growing volume of trade and travel across continents has accelerated the movement and introduction of pests and pathogens into regions outside their native range. Recent reviews have highlighted the unprecedented ecological and economic impact of these biological invasions (Brasier, 2008; Epanchin-Niell, 2017; Hill et al., 2019; Liebhold et al., 2012). A clear example of the impact of invasive pests is the introduction of the emerald ash borer (*Agrilus planipennis* Fairmaire) which, following major incursions in Canada, the United States and Russia, has become the most significant pest for all ash (*Fraxinus* spp.) species; responsible for the destruction of hundreds of millions of trees with economic impacts of well over $25 billion in the United States alone (Epanchin-Niell, 2017). Therefore, effective biosecurity and surveillance measures, including early detection and rapid response strategies, are essential to mitigate these threats.

The emerald ash borer is a beetle belonging to the Buprestidae family, native to East Asia where it primarily infests stressed ash trees (*Fraxinus* spp.) and causes minimal damage to healthy ones, as its population is controlled by host resistance, parasitoids and predators. This high relative resistance, attributed to targeted defences being selected via coevolution with emerald ash borer, is lacking in North American ash species where all trees have been shown to be susceptible to emerald ash borer to varying degrees (Herms & McCullough, 2014). Additionally, the absence of species-specific natural enemies leads to increasing beetle populations (Evans et al., 2020).

First detected in the United States and Canada in 2002 (Cappaert et al., 2005) and in Moscow, Russia in 2003 (Volkovitsh et al., 2021), by late 2020, the emerald ash borer had been reported in five provinces of Canada, 35 states of the United States (EAB Network—Home, n.d.), 18 provinces of Russia, and one province of Ukraine (Orlova-Bienkowskaja et al., 2020; Volkovitsh et al., 2021). However, the true extent of its spread is likely to be wider.

The widespread devastation caused by the emerald ash borer in North America is a warning for Europe and offers valuable insights for prevention and management of potential incursions (Evans et al., 2020; Marzano et al., 2020). In both the European Union (EU) and GB the emerald ash borer is classified as a quarantine pest, leading to the development of contingency plans to reduce the likelihood of its introduction and establishment, raise awareness of the pest and ensure that outbreaks are tackled swiftly (Inward & Straw, 2021; Schans et al., 2020; Schrader et al., 2020).

The introduction of this beetle into North America is thought to have been through infested ash material, such as crating, pallets or dunnage (Cappaert et al., 2005), while subsequent spread was greatly enhanced by human movement of affected material, including nursery stock and logs (Mercader et al., 2012). The widespread practice of taking firewood on camping trips contributed to notable jumps in the geographical spread across the United States (Diss-Torrance et al., 2018). Additionally, adult beetles are also known to hitchhike on vehicles (Evans et al., 2020; Short et al., 2020).

The main pathways identified for the potential introduction of emerald ash borer into Europe are timber trade, solid wood packing material and live ash for planting (Evans et al., 2020), but firewood trade is considered the most likely entry pathway (Inward & Straw, 2021; Schans et al., 2020).

Effective surveillance is crucial for the detection and management of potential new invasive pests. Some of the most common emerald ash borer detection methods include visual inspection, under-bark sampling, tree girdling and trapping. Each varies in terms of sensitivity, effort to deploy and acceptability (Evans et al., 2020; Mercader et al., 2013; Schans et al., 2020; Schrader et al., 2020). When implementing surveillance strategies, considering land managers' views on the acceptability of each approach in terms of effort, cost and immediate impacts on trees is crucial.

As well as considering the best method for early detection, it is necessary to determine where to focus effort. While a pragmatic approach is to deploy surveillance at the most likely entry points, which we refer to as Ranked Entry Points (REPS), this approach does not account for host density or pest dynamics and so may underperform (Mastin et al., 2020). Risk-based strategies account for variability between potentially invaded locations due to factors, such as host availability, likely entry points, environmental suitability, threat spread characteristics, detection method sensitivity, etc. (Koch et al., 2020). Nonetheless, risk-based sampling may lead to redundancy in some surveillance locations, that is if risk-based surveillance identifies two locations close to one another, the benefit of deploying detection devices in these two locations may be small. There might be greater benefit in moving one to a new location. Optimising sampling based on the detection probability solves this issue. Mastin et al. (2020) explored how to combine the population dynamics of the citrus disease Huanglongbing with a statistical model of detection and an optimisation routine to maximise the probability of disease detection. They showed that accounting for patterns of pathogen entry and spread outperformed focusing solely on the highest-risk locations. This highlights the importance of spreading resource allocation throughout the landscape to cover all areas of risk instead of targeting only a small number of high-risk areas (Yemshanov et al., 2020).

We present a surveillance deployment approach that explicitly incorporates the population dynamics and spatial spread of the emerald ash borer. Firstly, we determined its most likely entry points. We then used a distribution map of ash in GB (Brown et al., 2023) and modelled the beetles' population dynamics and spread for 10,000 stochastic simulations. The simulation outputs of the model were used in an optimisation algorithm to determine a set of surveillance locations that maximise the probability of detection. Focusing on early detection, we considered three surveillance methods (traps, tree girdling and under-bark assessments) at varying sampling intensities. We used this approach to better understand where to target surveillance deployment in GB to maximise the probability of detection within a specified timeframe of the beetles' arrival. We focused on the following questions:

1. To what extent does a model-based optimisation strategy improve on a strategy based on the ranking of the emerald ash borer most likely entry points (REPS), and how is this affected by the timeframe over which detection is optimised?
2. How does improved identification of potential entry points affect optimal surveillance strategies and how do current processes and practices affect firewood biosecurity?
3. Which method of surveillance improves the detection ability and how does knowledge of efficacy affect the likely engagement of key stakeholders with surveillance?

2 | MATERIALS AND METHODS

2.1 | Ash host map

A map of ash tree density across GB (Brown et al., 2023) (hectares of ash per 1 km × 1 km cell) was used to set up our model. Ash density was converted into numbers of trees per cell using an estimate of 889 trees per ha (Brewer & Ditchburn, 2013). The map was produced using various GB land-use layers, including UKCEH Land Cover Map (Morton et al., 2020), National Forest Inventory (NFI) woodland cover map (NFI, 2020), NFI ash estimates in British woodland (Brewer & Ditchburn, 2013), UKCEH Distribution of Ash trees (*F. excelsior*) in Countryside Survey data, (Maskell et al., 2013), iTree surveys (Monteiro et al., 2020) and Small woody features (Langanke, 2019).

2.2 | EAB population dynamics model

To simulate the spread of emerald ash borer across GB we built a spatially explicit population dynamics model and parametrised the beetle life cycle from data available in the literature (see Appendix S2, Table 1). Its lifecycle was modelled using annual timesteps and two distinct populations: univoltine and semivoltine. Eggs are laid on ash trees in early summer and spring, developing into larvae with survival assumed to be density-dependent due to starvation, cannibalism and tree defence mechanisms (Duan et al., 2013). Larvae pupate before emerging as adults the following spring (univoltine) or the one after (semivoltine) (see Figure S1.1 in Supporting Information). The number of adults (per m^2 phloem) emerging from trees that have been infested for more than 1 year $a^{(2)}$ in cell (i,j) is:

$$a^{(2)}_{t+1}(i,j) = \frac{(1-\theta)\kappa\beta\frac{A_t(i,j)}{\phi I_t(i,j)} + \beta L_t(i,j)}{1+\gamma\kappa\frac{A_t(i,j)}{\phi I_t(i,j)} + \gamma L_t(i,j)} \tag{1}$$

This includes adults from both univoltine and semivoltine populations. Here $A_t(i,j)$ represents the total number of adults in cell (i,j) at time t after dispersal, $L_t(i,j)$ represents the total number of semivoltine larvae in cell (i,j) at time t, $I_t(i,j)$ is the number of infested trees in cell (i,j), ϕ is phloem per tree, θ is the proportion of semivoltine larvae, $\kappa = (1-\sigma)k$ where k is the number of viable eggs per adult and $(1-\sigma)$ is the mating success, β is the rate of larval death per year and γ is a density-dependent death rate parameter which captures the mechanism of starvation and cannibalism (see Appedix S2).

The number of larvae from the semivoltine population is:

$$L_{t+1}(i,j) = \theta\frac{\kappa\beta\frac{A_t(i,j)}{\phi I_t(i,j)}}{1+\gamma\kappa\frac{A_t(i,j)}{\phi I_t(i,j)} + \gamma L_t(i,j)} \tag{2}$$

The number of larvae from the univoltine population is:

TABLE 1 Model parameters.

Name	Interpretation	Value	Reference
θ	Proportion of semivoltine larvae. Early infection is approximately 0.25. This varies with host's condition and environment	$\text{Prop}_{(t)} = 0.194\ln\left(\frac{\text{Larvae}}{\text{Prop}_{(t-1)}}\right) + 0.9862$	Mercader et al. (2011a, 2011b)
σ	Probability of adults dying before reproduction	0.6105	Duan et al. (2015) and Mercader et al. (2011b)
κ	Larvae offspring per adult. Fifty-three viable eggs per female, then assume a 50:50 sex ratio	26.5	Jennings et al. (2015), Rutledge & Keena, 2012 and Van Driesche and Reardon (2015)
α	Daily cannibalism death rate	$0.011 / T$	Mercader et al. (2011b)
ω	Daily starvation/other death rate	$0.2 / T$	Duan et al. (2013)
T	Larval development time	56 days	Duan et al. (2013)
β	Compound death rate parameter (starvation/other)	$\exp(-\omega T)$	
γ	Compound death rate parameter (cannibalism and starvation/other)	$\frac{\alpha}{\omega}\exp(-\omega T)$	
μ	Probability of laying an egg on an uninfested tree	0.00001 (0.0005–0.00004)	Siegert et al. (2010)
ϕ	Phloem per tree. A mean diameter of 17.65 cm was used to calculate phloem area per tree as 4.54 m^2	$0.024\text{DBH}^2 - 0.307 \cdot \text{DBH} + 2.63\,(4.54)$	Brewer and Ditchburn (2013) and Siegert et al. (2010)
N	Average number of trees per hectare in GB	889	Brewer and Ditchburn (2013)
	Rate of annual ash mortality per emergence hole per m^2	0.014	Steiner et al. (2019)
c_X	Detection efficacy of girdled trees, traps and under-bark samples, respectively	$c_G = 0.5096$ $c_T = 0.052$ $c_B = 0.026$	Mercader et al. (2012, 2013) and Siegert et al. (2010)
P_{jump}	Probability that EAB is dispersed anthropogenically	0.0002	Siegert et al. (2014)

$$U_t(i,j) = (1-\theta)\frac{\kappa\beta\frac{A_t(i,j)}{\phi I_t(i,j)}}{1+\gamma\kappa\frac{A_t(i,j)}{\phi I_t(i,j)} + \gamma L_t(i,j)} \quad (3)$$

Adults per m^2 phloem in a tree previously uninfested $a^{(1)}$ are:

$$a^{(1)}_{t+1}(i,j) = (1-\theta)\frac{\kappa\beta\frac{A_t(i,j)}{\phi I_t(i,j)}}{1+\gamma\kappa\frac{A_t(i,j)}{\phi I_t(i,j)}} \quad (4)$$

The number of susceptible trees remaining in cell (i,j) in year $t+1$ is:

$$S_{t+1}(i,j) = S_t(i,j)\, e^{-\psi A_t(i,j)} \quad (5)$$

where $\psi = \mu\rho$ where μ is the probability of infesting a new tree, and ρ is the proportion of adults landing on an uninfested tree. It follows that the number of infested trees in year $t+1$ is:

$$I_{t+1}(i,j) = I_t(i,j) + S_t(i,j)\left(1 - e^{-\psi A_t(i,j)}\right) \quad (6)$$

The total number of adults emerging from cell (i,j) is:

$$E_{t+1}(i,j) = \phi\left[\left(I_{t+1}(i,j) - I_t(i,j)\right)a^{(1)}_{t+1}(i,j) + I_t\, a^{(2)}_{t+1}(i,j)\right] \quad (7)$$

2.3 | EAB dispersal

After adults emerge some remain in their original cell while others disperse beyond the cell. The dispersal is modelled stochastically through natural short-range dispersal and longer-range human-mediated dispersal. The dispersal was parameterised using data from Russia and the United States. This a conservative assumption, where *F. excelsior* is as susceptible to emerald ash borer infestation as *F. pennsylvanica* (Showalter et al., 2020).

Natural dispersal is modelled by

$$\hat{E}_t(k,l) = \sum_{i=1}^{n_i}\sum_{j=1}^{n_j} D_{ij}(k,l)E_t(i,j) \quad (8)$$

$D_{ij}(k,l)$ is the proportion of adults starting in cell (i,j) and landing in cell (k,l), and $\hat{E}_t(k,l)$ is the number of adults in cell (k,l) after natural dispersal (Milne et al., 2020). We modelled this dispersal by fitting a Cauchy dispersal kernel to intensively sampled data from (Mercader et al., 2009) (Cauchy $\lambda = 0.0414$ km). We chose this distribution as it is relatively fat-tailed and fits the observed data better than an exponential distribution (Milne et al., 2020). The function defines the probability $p_{ij}(k,l)$ of an adult starting in cell (i,j)

and landing in cell (k, l). We calculate the number of adults staying in their original cell by sampling from a binomial distribution with parameters defined by $p_{ij}(k, l)$. We then move to the cell south of the source cell and repeat the process, adjusting the remaining probabilities so that they sum to one. In this way working around and outwards, we simulate natural dispersal (Mercader et al., 2009).

To simulate the long-distance dispersal of the emerald ash borer we assume that in any year, the number of beetles travelling through human-mediated dispersal, N_{HM}, from a given location (i, j) is generated by sampling from a Poisson distribution with mean $P_{jump}E_{t+1}(i, j)$, where $E_{t+1}(i, j)$ denotes the total emerging adults from location (i, j). The distance travelled by any individual is sampled from an exponential distribution with a half-life of 47 km (Orlova-Bienkowskaja & Bieńkowski, 2018; Ward et al., 2020; Webb et al., 2021).

2.4 | Entry point probability

Given that GB is isolated from the rest of Europe by the sea and the limited natural dispersal of the emerald ash borer, invasion is assumed to occur only through human-mediated means. In the EU and GB, all wood packaging material must adhere to the International Standards for Phytosanitary Measures No. 15, requiring debarking, heat treatment or fumigation and stamping. Firewood import controls are tree species-specific and vary by country of origin and wood or product type (Plant Health Forestry—Forestry Commission, 2021). However, there is imperfect drying, and import notifications are often through self-reporting, although regulations have been tightened recently (Selling wood for domestic use in England—GOV.UK, n.d.). Therefore, high-risk pathways are associated with wood imports from continental Europe (Figure 1), predominantly ash firewood. Based on this, our model of entry point probability comprises ports that receive firewood from European sources, depots that receive firewood from these ports (Figure 1) and the predicted distribution of wood-burning fires.

Data on firewood imports (including country of origin, port location, container quantities of ash wood, shipment arrival dates and phytosanitary measures) were provided by the Forestry Commission. The data also included approximate locations of the depots receiving firewood from the ports.

To estimate the distribution of firewood use, we calculated the number of households with the potential to burn firewood in each 1 km × 1 km cell. Using 2011 Census data (Nomis—Official Census and Labour Market Statistics, 2011), we excluded property types unlikely to have wood fires, such as apartments. We then regionally scaled this number to match regional firewood use data (DECC, 2016).

The probability of the first entry point being at location (i, j) is given by:

$$R_{Total}(i,j) = \omega_P g\left(R_{Port}(i,j), R_{Depot}(i,j)\right) + \omega_F R_{Fire}(i,j) \tag{9}$$

where ω_P and ω_F are weights given to each source of risk and $g(:,:)$ is a function combining the probability of arrival and escape at ports and depots receiving ash wood. We assume that the probability is proportional to the wood volume arriving at each port or depot, with a 50% chance of beetles emerging at the port if the wood arrives between June and September; otherwise, they emerge at depots. Furthermore, we assume the constraint that the sum over GB for $g(:,:)$ equals one, and similarly for $R_{Fire}(i, j)$. It was not feasible to quantify these weights; thus, we explore a range of scenarios, ranging from a situation where we are 70% confident that invasions would come through known pathways (Figure S1.2) (personal communication van den Bosch, F. & Parnell, S.) to a less optimistic scenario with only 30% confidence (see Table 2). REPS were ranked according to $R_{Total}(i, j)$, going from the highest probability to the lowest probability where the number of locations depends on the number of devices available.

2.5 | Detection

We optimised the probability of emerald ash borer detection in GB considering the deployment of one of three methods: (i) traps (T), (ii) tree girdling (G) and (iii) under-bark tree assessment (B). Traps attract adult beetles by using visual and olfactory attraction cues and their deployment is relatively straightforward (Evans et al., 2020). Girdled trees produce tree-stress volatiles that are highly attractive to adult beetles. These trees are prepared in early spring by girdling the trunk and adding sticky bands or traps for capturing adults or checking for under-bark larval establishment later in the year (Schrader et al., 2020); however, this stresses the tree and leads to its death over time. Under-bark sampling is better than visual detection, but it is labour-intensive with low accuracy if no external symptoms are present (Mercader et al., 2012; Siegert et al., 2010).

The probability of detection during one sampling round is given by

$$P = 1 - \exp\left(-c_i N_i \Upsilon\right) \tag{10}$$

where N_i denotes either the number of traps, girdled trees or under-bark assessment per unit area for $i = T, G, B$, respectively, c_i relates to the efficacy of the surveillance method (see Table 1) and Υ is either larvae or adult density across all trees in the 1 km square, depending on which life stage the surveillance method targets (see Appendix S3).

2.6 | Scenarios and optimisation

Our objective was to develop a strategy that maximises the probability of detecting beetles within T years of first entry to GB. For this, we set up an objective function given by the average probability to detect over R realisations of the simulation. That is:

$$\Omega = \frac{1}{R}\sum_{k=1}^{R}\left\{1 - \prod_{j=1}^{n}\prod_{t=1}^{T}\exp\left(-c_i N_i \Upsilon_t(j,k)\right)\right\} \tag{11}$$

where $\Upsilon_t(j, k)$ is the number of beetles at trap location j for year t and realisation k, and n is the number of traps. Considering ten thousand

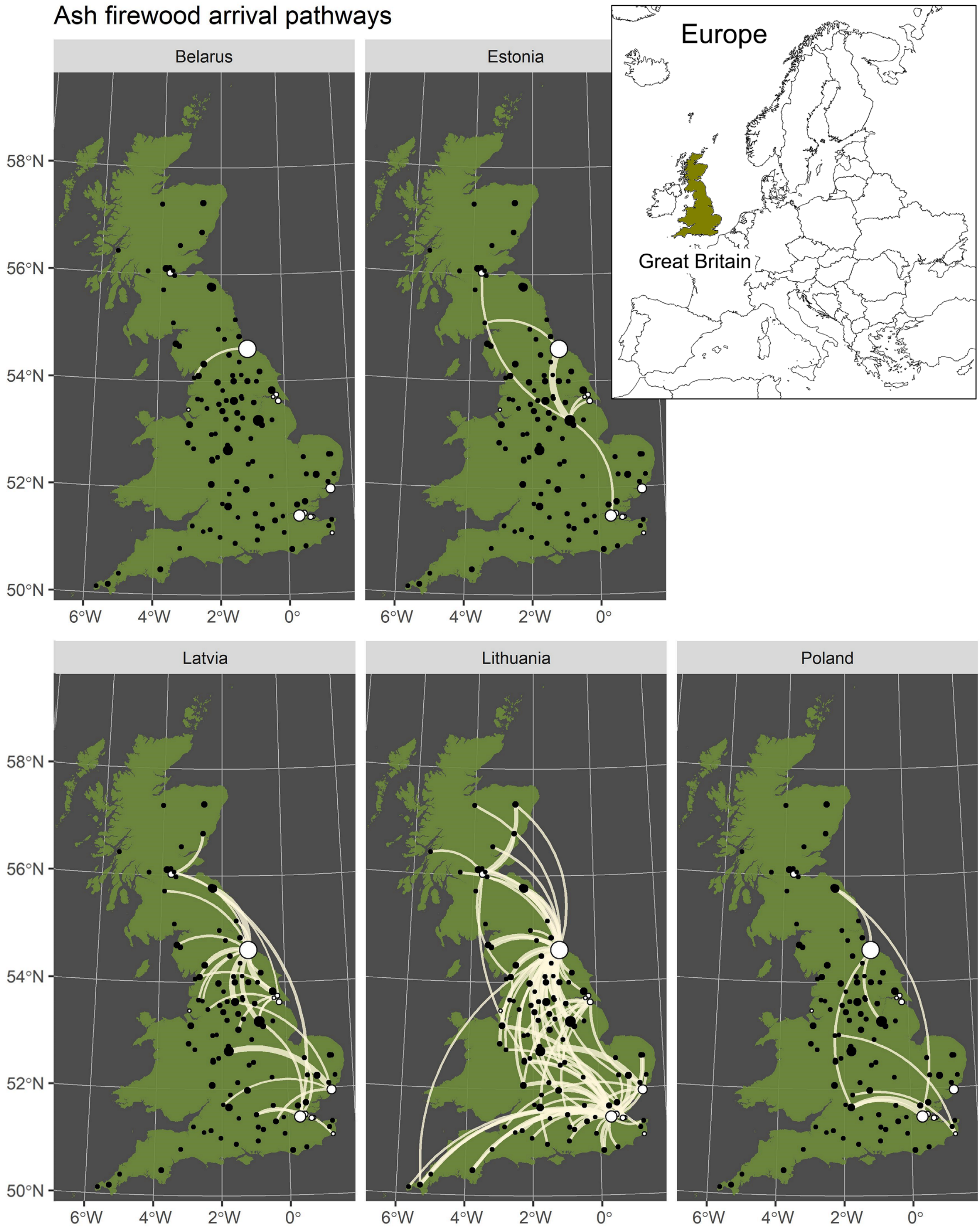

FIGURE 1 White discs show the ports where imported wood arrives and white paths the onward destinations. The black dots are approximate locations of the distribution depots. The insert in the top-right corner shows GB in relation to Europe.

TABLE 2 Factors explored in the scenario analysis and associated levels.

Factors	Levels				
Entry point certainty at ports (ω_P %)	30	50	70		
Detection method	Traps (T)	Girdled trees (G)	Under-bark sampling (B)		
Probability of EAB escaping from ports	0.25	0.50	0.75		
Sampling location numbers	50	100	200	400	500

realisations of the simulation we sampled an entry point per realisation based on the probability maps described in §2.4 and ran the model for T years.

Initially, we considered $T = 8$ as (Siegert et al., 2014) estimated that the emerald ash borer had been established at least 7 years before it was first identified in the United States. We then considered shorter timeframes of 2 and 4 years. Early surveillance for emerald ash borer conducted by the Forestry Commission in 2021 used only 20 trapping locations due to perceived low risk and financial constraints (pers. comm. K. Parker). In our optimisation, we explore $n = 50$, 100, 200, 400 and 500. To optimise the objective function, we used a simulated annealing algorithm (Mastin et al., 2020).

We set up a range of scenarios based on detection method, number of trap locations and confidence that invasions would come through a known route (Table 2), and compared optimised surveillance with REPS. For the model code, please see Milne et al. (2024).

2.7 | Firewood stakeholders' in-depth interviews and scenario workshops with tree managers

Stakeholder perspectives play a crucial role in firewood importation and surveillance efforts and help us understand the context in which the surveillance model's outputs may be used. Two activities were conducted to address these points: semi-structured interviews and scenario workshops.

All research activities with participants received a favourable ethics review from the Environment and Geography Ethics Committee at the University of York. Written free prior informed consent was obtained. Interviewees were sent a participant information sheet and then signed a consent form prior to participating in the interview. Scenario workshop participants were provided with a project information sheet and asked to consent by completing an online consent form using the Menti polling tool at the beginning of the workshop.

We conducted five semi-structured interviews with key informants (individuals with first-hand knowledge about the topic of interest) in the GB firewood sector. Questions focussed on whether and how they value ash, experiences with ash dieback, importation practices with a focus on firewood and attitudes towards biosecurity. Interviews were held online and recorded. Intelligent verbatim transcripts were produced and thematically coded to unpack current practices.

Three scenario workshops were held, involving a total of 20 participants, including stakeholders who manage or advise on ash trees for local councils, small and large private or third-sector farms or estates, and transport and utilities companies with large tracts of land. Participants discussed their current surveillance practices and how they might change after receiving information on the effectiveness of surveillance methods, including tree girdling and trapping and depending on whether there was support available. The workshops were held online, recorded and analysed for the factors guiding their surveillance practices.

3 | RESULTS

3.1 | Optimising surveillance to maximise the detection probability within 8 years of emerald ash borer invasion in GB

Out of the surveillance methods considered, girdled trees are the most sensitive and under-bark sampling is the least. However, the advantage of using girdled trees decreases as the certainty of predicting likely entry location increases (Figure 2). Comparing the scenarios for five hundred traps, if sampling is based on REP, the probability of detection increases by 0.305 when the confidence of entry pathways increases from 30% to 70% (Figure 2a,c). However, with optimised sampling the benefit is smaller: for the same scenarios, the difference is 0.247. In general, the benefit of optimised surveillance strategies over REPS is more significant when entry point certainty is low. For REPS, we see a substantial decrease in detection probability (0.27–0.32) when comparing a scenario with 70% entry point certainty versus one with 30% certainty. For optimised strategies, the decrease is more conservative (0.19–0.27) but still substantial.

The optimised values give a ceiling for the detection probability for a given number of sample locations (Figure 2). There are clear diminishing returns with number of sample locations. These are most acute when the knowledge of the most likely entry points is more certain (Figure 2a).

In our simulations, we varied the likelihood that emerald ash borer would escape at the ports as opposed to depots. This made negligible difference to the results (see vertical bars in Figure 2) because in all strategies surveillance resources were allocated at both ports and depots where the beetle is likely to be found.

The more sensitive the detection method, the more the optimisation algorithm spreads the surveillance devices across the landscape (Figure 3, see also Appendix S5 for quantification). Additionally, optimised locations are more spread than those derived by REP because

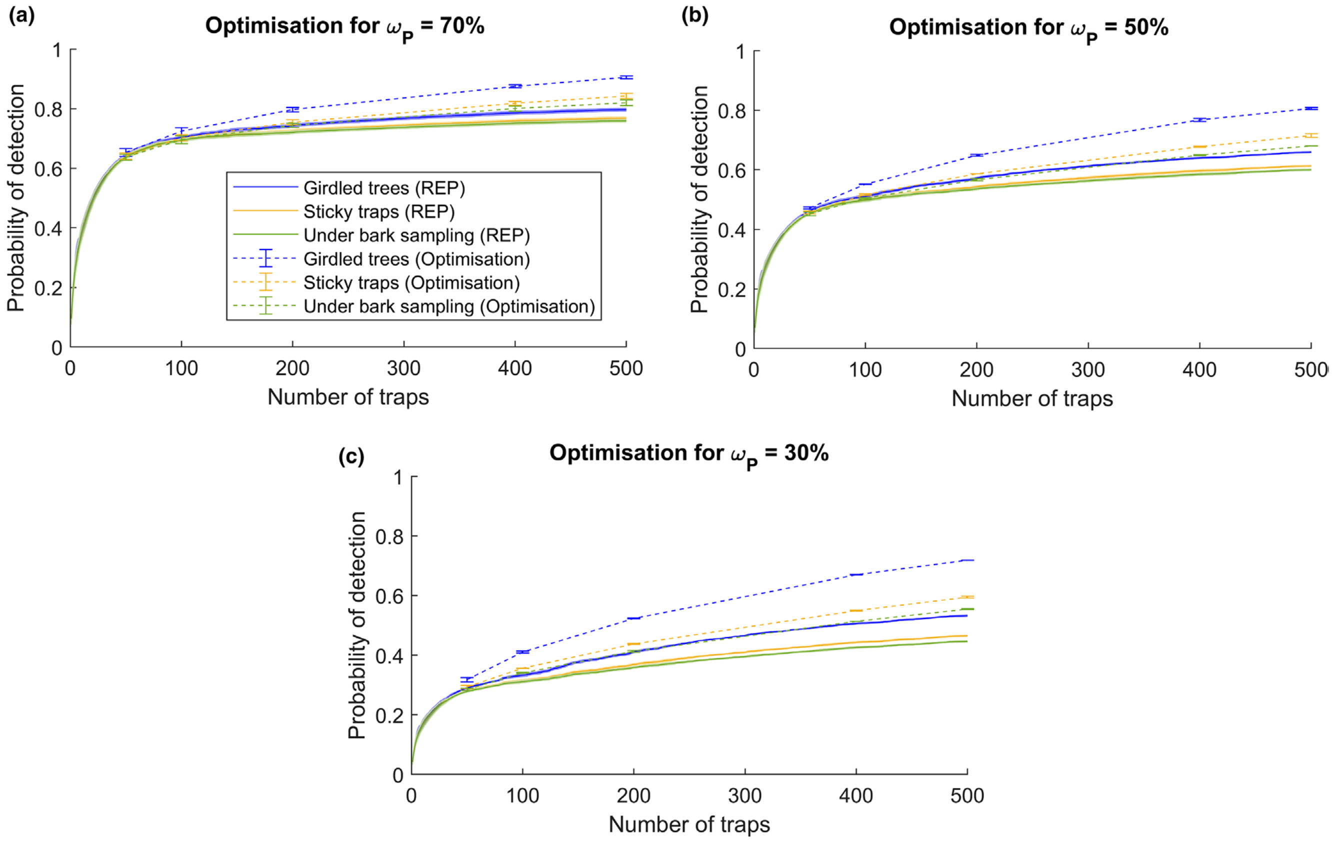

FIGURE 2 Probability of EAB detection within 8 years of arrival plotted against trap number for scenarios with (a) 70% (b) 50% (c) 30% certainty that EAB will arrive through known firewood import pathways. The solid lines show REPS results while symbols show the results for optimised sampling, with upper and lower bounds indicating a 0.75 and 0.25 probability, respectively, of EAB escape at ports.

the optimised design negates the redundancies associated with close-lying locations.

Improved knowledge of likely entry points increases the probability of detection. For example, while only 50 girdled trees are necessary to reach a probability of detection of approximately 0.65 with a 70% certainty that emerald ash borer will enter through known pathways, 200 girdled trees are needed to reach approximately the same probability when certainty decreases to 50%.

Table 3 provides a guideline for the number of devices needed for the different surveillance strategies to reach a desired detection probability. The same type of calculation can be done for a different timeframe.

3.2 | Comparing surveillance optimisation to maximise the probability of detection within different timeframes

We compared surveillance strategies using REP with those optimised to detect emerald ash borer within 2, 4 and 8 years (Figure 4a,b). For each sampling design, we then calculated the probability of detection within 1, 2, ... 8 years. The sampling scheme optimised for 2 years does better than the other schemes for 2 years, the scheme optimised for 4 years does best for 4 years and so on.

We found that optimising for detection within 8 years is a poor strategy for detecting the beetle within less than 6 years, likely because it accounts for a potentially greater pest spread. Optimising for 4 years provides a better balance, performing reasonably well across all timeframes (Figure 4a,b).

Figure 4c depicts surveillance deployment schemes for girdled trees and traps optimised to detect within 2, 4 and 8 years and for REPS. The 2-year optimised scheme is more widespread across the GB compared with those optimised for longer periods where sample locations cluster around sites associated with more ash trees.

3.3 | Reconciling firewood stakeholders' interviews with surveillance strategies

Our key informants included a mixture of businesses, two primarily used locally sourced firewood, while others mostly imported from Eastern Europe and the Baltic states. One business was already approved to deal with infected ash trees and once kiln-dried, shifted the ash quickly onto the market. All interviewees highlighted that they received and/or processed firewood at distribution centres although importers also provide firewood directly to customers. Some preferred to keep their markets more local, while others were more focussed on UK distribution.

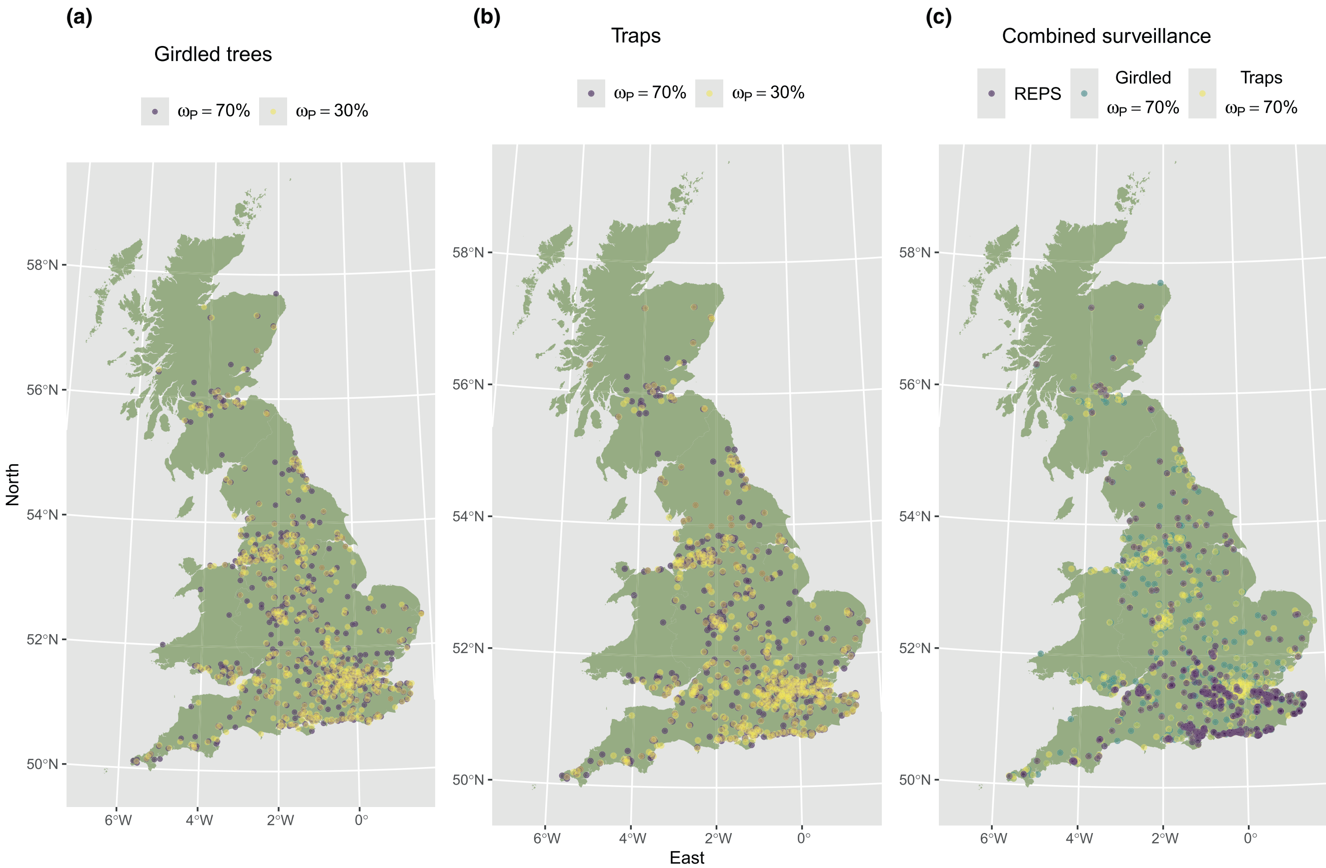

FIGURE 3 Optimised location of (a) girdled trees, (b) traps where EAB entry pathway certainty is 70% and 30%, respectively. Strategies based on REPS and optimised girdled, and traps are compared in (c). For all scenarios, there is a probability of 0.5 that EAB arriving at ports escape.

The quality of the firewood product was intricately linked to biosecurity measures. All interviewees indicated that logs were kiln-dried to ensure low moisture content (regulated at 20% in England). The heating process was expected to kill any potential pests, and this was considered the ultimate biosecurity practice by all interviewees. Some expressed suspicions about the quality of imported firewood with one interviewee emphasising the challenges in ensuring overseas partners' regulations compliance. Another outlined their personal quality control processes at their distribution centres, primarily involving checking moisture content. Interviewees also emphasised the stringent inspection procedures at ports of entry and distribution centres.

3.4 | Reconciling woodland managers' views with surveillance strategies

All scenario workshop participants reported using standard health and safety inspections as their main surveillance method, some combining this with other visual methods. These inspections identify trees showing visual signs of ill health but would not be effective for emerald ash borer early detection.

After learning about the effectiveness, cost and time commitment associated with under-bark sampling, traps and girdling, only larger land managers with high numbers of ash trees considered adding these more effective surveillance options. Participants mentioned that girdling sounded like a more attractive option due to the lower cost of losing one tree among many for more effective monitoring.

Resource constraints were the chief reason for participants' reluctance to engage in additional surveillance unless additional financial and technical support was available. Both large and small organisations were concerned about the low chance of spotting EAB early enough to eradicate it:

> it's basically firefighting really where we have trees neighbouring on residential gardens, for instance.
>
> (small urban woodland, third-sector run, North Wales workshop, discussion comment)

> …if there's nothing much we can do as a result of knowing we've got it, apart from watch the tree die, there seems to be less need to actively monitor it, […] but if one could effectively save the tree somehow, I'd be keener on monitoring.
>
> (Small woodland, National workshop, discussion comment)

TABLE 3 Number of devices needed to achieve a desired detection probability dependent on the knowledge of entry pathway (70%, 50% and 30%), sampling strategy (REPS or optimisation) and the type of detection method (G, T and U). G, T and U represent tree girdling, traps and under-bark sampling, respectively.

Probability of detection	70% entry point certainty at ports						50% entry point certainty at ports						30% entry point certainty at ports					
	REP			Optimised			REP			Optimised			REP			Optimised		
No. of devices	G	T	U	G	T	U	G	T	U	G	T	U	G	T	U	G	T	U
50	0.64	0.64	0.64	0.65	0.64	0.64	0.46	0.45	0.45	0.47	0.46	0.43	0.29	0.28	0.28	0.32	0.29	0.29
100	0.70	0.70	0.69	0.72	0.70	0.70	0.51	0.50	0.49	0.55	0.52	0.48	0.33	0.32	0.31	0.41	0.36	0.34
200	0.74	0.73	0.72	0.80	0.75	0.74	0.57	0.54	0.53	0.65	0.59	0.55	0.41	0.37	0.36	0.52	0.44	0.41
400	0.79	0.76	0.75	0.88	0.82	0.80	0.64	0.59	0.58	0.77	0.68	0.62	0.51	0.44	0.42	0.67	0.55	0.51
500	0.80	0.77	0.76	0.91	0.84	0.82	0.66	0.61	0.59	0.81	0.68	0.65	0.53	0.46	0.44	0.72	0.60	0.55

Particularly in Kent, where many trees have already been lost to ash dieback, participants had a more fatalistic view:

> I've pretty much given up on ash other than keeping a few ones that are showing resistance for the future trees
>
> (small private woodland manager 2, Kent workshop, discussion comment)

All participants follow authorities' guidance (e.g. Forest Research or APHA). However, they also asked for more information about the cost and effectiveness of trapping and girdling, and guidance on identifying emerald ash borer and targeting surveillance.

4 | DISCUSSION

4.1 | To what extent does using a model-based optimisation strategy improve on a purely ranked entry points sampling, and how is this affected by the timeframe over which detection is optimised?

Our results show that model-based optimised sampling improves on REPS, enhancing detection probability by considering the pests' epidemiology and removing redundancies associated with deploying traps close to one another. This accords with the findings of Mastin et al. (2020) and aligns with Yemshanov et al. (2020) who discovered that to minimise the impact of failed detections, it is better to survey more sites with high host densities at farther distances where new arrivals may cause significant damage. The optimised sampling schemes were more spatially spread than the REPS (see Appendix S5), which were clustered around firewood use and entry-associated areas. What is less intuitive is that as the sensitivity of trap type increases so does the spatial spread of the traps. This is because these surveillance methods can detect the pest at lower levels and so more locations become candidates for detection of emerald ash borer. This accords with Mastin et al. (2020), who evaluated the optimal distribution of surveillance resources for the detection of the citrus disease huanglongbing and found that diagnostics with greater sensitivity should be spread more throughout the landscape.

We found that optimised sampling substantially improves detection probability when the objective function is formulated to maximise the probability of detection within 8 years (see Figure 2). However, advantages of optimised strategies over REPS diminish as the timeframe for optimising detection is reduced, (Figure 4a,b) because emerald ash borer's natural dispersal is relatively limited early in the invasion and the probability of human-mediated spread is assumed to be small, so dispersal away from the entry points in the first few years is not extensive. This highlights the importance of understanding pest biology and potential dispersal mechanisms. If it is known that the pest spreads slowly, risk-based surveillance can be considered as effective as an optimised strategy.

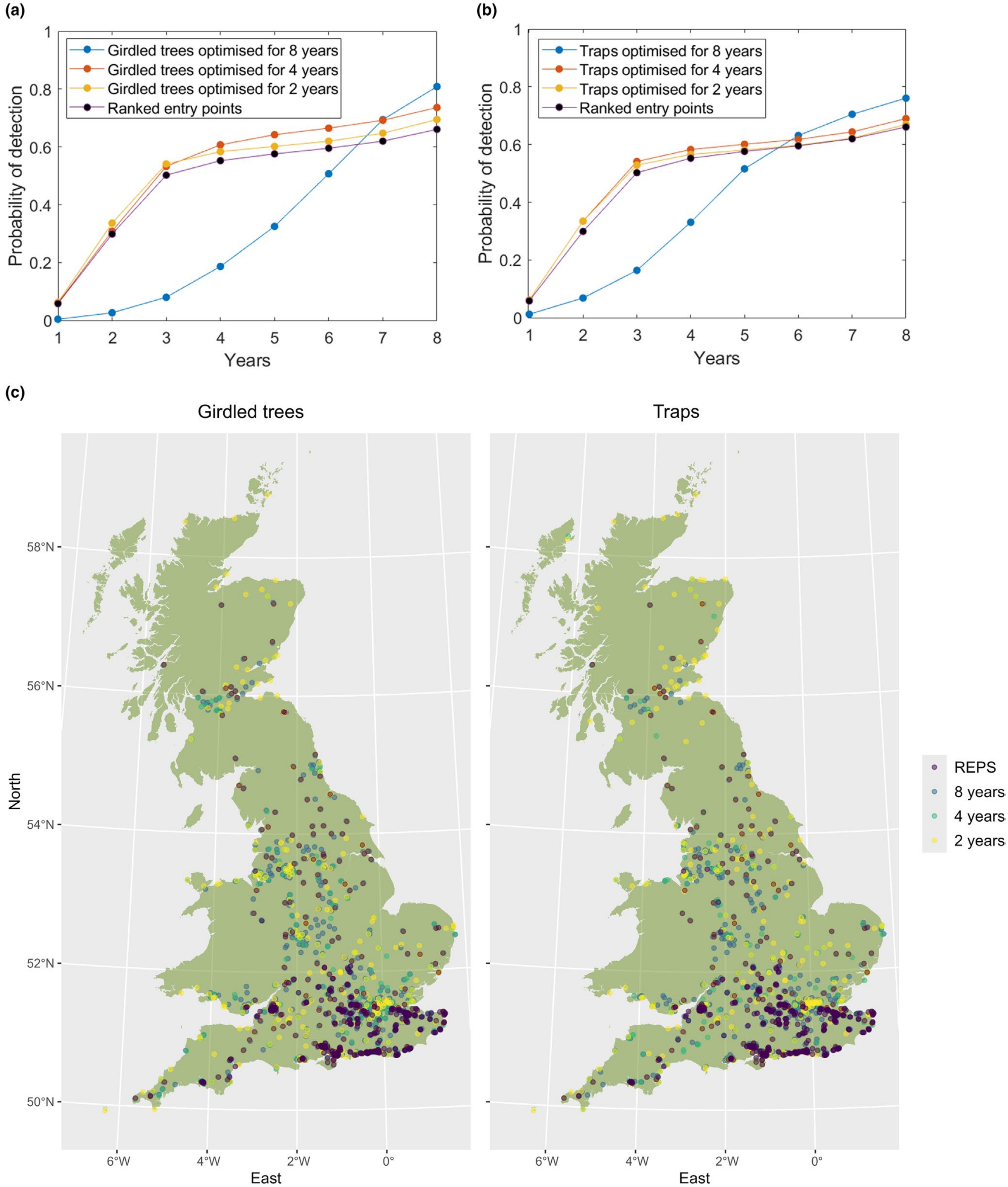

FIGURE 4 Detection probability over time for REP and surveillance schemes optimised for detection within 2, 4 and 8 years of EAB arrival using (a) girdled trees and (b) traps with 50% certainty of entry points. Corresponding deployment schemes are shown in (c).

To further understand how the population dynamics of the pest would affect the detection probability, we considered the sensitivity of our results to dispersal rate and voltinism (see Appendix S7). In line with our previous results, we found that as the insect population becomes more established in the environment (in this case due to more rapid development or increased natural dispersal) the probability of detection increases and at the same time the relative value of an optimised surveillance strategy over REPS increases.

In our analysis, optimising surveillance for detection within 8 years performed poorly compared with strategies considered for detecting the pest within 1–6 years and 1–5 years after arrival for girdled trees and traps, respectively (Figure 4a,b). This is because the 8-year strategy is more influenced by the pest population dynamics (interaction with host) and spread than the other two, as it accounts for a timeframe when the pest has become more established (Figure 4c). It is worth noting that (Siegert et al., 2014) estimated that emerald ash borer had been established at least 7 years before it was first detected in the United States, and this is the timeframe where we see the clear effect of the pest–host dynamics in our optimised strategies (Figure 4a,b).

Our results on the impact of timeframe show how important it is to both capture the pest–host dynamics as precisely as possible and clearly frame the question of interest. Here, we aimed to optimise surveillance within a given timeframe, but (as discussed above) this did lead to strategies that were substantially suboptimal for detecting early in the invasion. Optimising for detection within an 8-year timeframe may increase the detection probability, but by then, the beetle may be well established. Optimising for detection within shorter timeframes can result in smaller detection probabilities. However, prioritising early detection increases the chances of eradication (Mbah & Gilligan, 2010; Yemshanov et al., 2020).

4.2 | How does improved identification of potential entry points affect optimal surveillance strategies and how do current processes and practices affect firewood biosecurity?

We found that higher certainty of the emerald ash borer entry points increases the detection probability for all surveillance methods (§3.1). This underlines the importance of reducing the risks associated with unpredictable pathways through, for example, raised sector awareness of biosecurity measures.

Our research highlights that firewood importers were acutely aware of current and increasing biosecurity and environmental legislation related to firewood, testifying that appropriate and stringent moisture checks were conducted. However, they noted that overseas biosecurity practices' variability poses some risks. This suggests that although these pathways are still arguably the most likely source of emerald ash borer, this hazard is actively being minimised through regulation and inspections.

4.3 | Which method of surveillance improves the detection ability and how does knowledge of efficacy affect engagement of stakeholders with surveillance?

We compared the sensitivity of the different surveillance strategies investigated in our analysis. Our analysis provides a useful tool for determining the number of devices needed to achieve a specific desired detection outcome and can be further used to inform cost–benefit analyses whereby costs of surveillance can be weighted-up against probability of detection (Table 3).

Girdling trees and setting traps are considered the most appropriate tools for early detection. However, only one workshop participant currently uses these methods, aligning with findings from a broader survey ($n=368$) (unpublished data, Hall, C.). In that study, traps were favoured and seen as more acceptable than tree girdling. This contrasts with our workshops results in which girdling was seen as a favourable approach by managers responsible for large areas of ash. A key difference in the approaches used was that in the workshops we revealed information about trap efficacy and costs, allowing participants to make informed decisions. This highlights the importance of disseminating clear and quantifiable guidance to land managers. Moreover, including them and other stakeholders in surveillance is an important approach to increase detection of unexpected invasions.

For early detection strategies to be practical, they must be both, cost-effective and feasible within existing resource limitations (e.g. see Mastin et al., 2019; Mbah & Gilligan, 2010; Yemshanov et al., 2020). Tree girdling while effective, is labour-intensive, making it generally time-consuming and expensive. Deploying traps offers a more financially viable surveillance option, though the costs and practicality can still be difficult to assess given the trade-offs between different trapping methods with no clear consensus among experts (Santoiemma et al., 2024; Williams et al., 2023). Therefore, studies looking at optimising sampling strategies comparing different detection methods, such as the one presented here, can help plant health inspectors and policymakers compare the efficacy of different sampling strategies given budgetary constraints and support more informed decisions.

4.4 | Model assumptions and limitations

We present a predictive model to support decisions on where to target surveillance. It is not possible to fully validate the model as emerald ash borer is not present in GB; however, the background model of its population dynamics and spread is grounded on extensive data and components of the model are validated (see Appendix S7).

We used data from the United States (Duan et al., 2013; Lyons, 2015; Mercader et al., 2011a, 2011b) to approximate the proportion of univoltine to semivoltine larvae and the dispersal parameters were fitted to data from Russia and United States (Mercader et al., 2009; Orlova-Bienkowskaja & Bieńkowski, 2018; Ward et al., 2020; Webb et al., 2021). Our tree death rates were based on data for green (*Fraxinus pennsylvanica* Marsh.) black (*F. nigra*) and white ash (*F. americana* L.) (Siegert et al., 2021; Steiner et al., 2019). However, the proportion of univoltine to semivoltine larvae greatly depends on tree susceptibility to emerald ash borer, temperature and environmental conditions, while dispersal depends on the ability of the beetle to reproduce and establish. Green and white ash are known to be among the most susceptible species to emerald ash borer (Lyons, 2015; Steiner et al., 2019). Thus, the data used to parametrise our model represents a conservative scenario with a relatively large proportion of univoltine larvae and where *F.*

excelsior may be as susceptible to them as *F. pennsylvanica* (Showalter et al., 2020). As more data become available, these parameters can be adjusted to better reflect the conditions in GB.

4.5 | Practical outcomes

Our analysis provides the first surveillance map for emerald ash borer incursions in GB with great potential for deployment by government agencies and interested stakeholders. In practical terms, if trapping is to be implemented, woodland managers are likely to need significant incentives to engage. This work can be improved and informed by other methods of surveillance, such as volunteer work and stakeholder passive surveillance considering the costs, acceptability and sensitivity of each surveillance approach. Whilst our findings are specific to this pest, the model and methodology can be adapted to other pest and disease species, such as the Bronze Birch Borer (*Agrilus anxius*) to inform surveillance in practice and where investment should be targeted. Of particular importance is the relative value of knowledge of likely entry path given a species rate of dispersal and host availability.

AUTHOR CONTRIBUTIONS

Vasthi Alonso Chávez, Nathan Brown, Alice E. Milne and Frank van den Bosch conceived the ideas and designed the methodology. Vasthi Alonso Chávez, Nathan Brown, Alice E. Milne, Stephen Parnell and Frank van den Bosch collected the model data. Mariella Marzano, Berglind Karlsdottir, Alison Dyke and Joanne Morris collected the social-science data. Vasthi Alonso Chávez, Nathan Brown and Alice E. Milne analysed the model data. Mariella Marzano and Berglind Karlsdottir analysed the interviews data. Alison Dyke and Joanne Morris analysed the workshops data. Vasthi Alonso Chávez, Nathan Brown and Alice E. Milne led the writing of the manuscript. Vasthi Alonso Chávez, Nathan Brown, Frank van den Bosch, Stephen Parnell, Alison Dyke, Clare Hall, Berglind Karlsdottir, Mariella Marzano, Joanne Morris, Liz O'Brien, David Williams and Alice E. Milne contributed critically to the original and revised drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The host map data are available from the Rothamsted Research repository (Brown et al., 2023), https://doi.org/10.23637/rothamsted.98y37. The code for the model analyses and results can be found at https://doi.org/10.5281/zenodo.10610811 (Milne et al., 2024).

ORCID

Vasthi Alonso Chávez https://orcid.org/0000-0003-3506-7603
Frank van den Bosch https://orcid.org/0000-0002-9225-7828
Liz O'Brien https://orcid.org/0000-0001-7976-9987

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SUPPORTING INFORMATION

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

Appendix S1. Supplementary figures.

Appendix S2. Population dynamics of EAB model.

Appendix S3. Detection probabilities for different devices.

Appendix S4. Optimisation algorithm.

Appendix S5. Quantification of sample location spread.

Appendix S6. Model validation of the invasion and spread of the Emerald Ash Borer in Great Britain (EAB; Agrilus Planipennis).

Appendix S7. Simulations with higher dispersal rates and bigger proportions of semivoltine larvae.

Data S1. Scenario workshops questions.

Data S2. Interviews.

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