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

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Abstract
The delimitation of outbreaks is an essential step in the containment and eradication of non-native plant pests. Outbreaks are habitually delimited by sampling around the initial finding, moving away from this locus in several directions as long as infestations are found (outward strategy). An alternative, inward, strategy would entail starting delimitation with an initial estimate of the location of the frontier and then sampling inward until the first infestations are found or outward until no more infestations are found. We used individual-based modelling to compare the effectiveness and sampling effort of the two strategies. Both successfully contained > 99% of infested plants within the delimited zone. Yet, both had a low probability (< 15%) of containing all the infested plants within the delimited zone. The number of samples of the inward strategy depended greatly on the size of the initially hypothesized infested zone. Best performance of this strategy was obtained with an accurate initial estimate of the infested zone width, while sample size increased strongly when the estimated frontier was far beyond the true location of the frontier. Consequently, the outward strategy uses fewer samples on average than the inward strategy when the position of the frontier is uncertain. Both strategies were prone to error when delimiting outbreaks caused by pests with fat-tailed dispersal. Whether the inward or outward strategy is more effective depends on the certainty about the true position of the leading frontier of the outbreak. Possibilities are discussed for maximizing the cost-effectiveness of sampling for outbreak delimitation.

Keywords Delimitation · Infested zone · Invasive pests · Pest management · Survey

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). A non-native plant pest is defined as "any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products" introduced to new areas (FAO 2023). When phytosanitary measures fail to prevent entry into the new area, pests may transfer to a suitable host and establish if environmental conditions are favourable (Table 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 (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 2016).

Typically, the demarcated area consists of an infested zone, surrounded by a buffer zone (European Union 2016). The infested zone is infested by the pest of concern, while the buffer zone is established to minimize the probability of spread of the pest out of the infested zone. Whenever the

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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, 2018, 2020), whereas surveillance is a typical measure in the buffer zone (EPPO 2021a; FAO 2023). 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 of the pest, 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 the most accurate strategy to delimit the infested zone (EPPO 2021a). An intuitive procedure for delimitation would be to initiate the surveillance in close vicinity to the first finding by examining host plants that are within the spread distance of the 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 at or ahead of a presumed disease frontier, 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 frontier 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 is 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. If the starting point is close to true frontier of the disease, this saves both time and resources. However, if the starting point for the surveys is too far away from the actual disease frontier, a large sampling effort is required to reach the disease frontier, consuming time and resources. Finally, at which distance offspring is deposited from the source, and whether some offspring disperses far from the source might affect the relative efficacy of the inward and outward strategies (Fletcher and Westcott 2013).

The two strategies are likely to differ in terms of the number of infested host plants that are not enclosed in the delimited zone, 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 sampling 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.

Methods

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 "Growth and spread model"). Dispersal of offspring is described by so-called dispersal kernels, which are distributions that describe the dispersal distances that the offspring will travel with their associated probability densities. Three dispersal kernels with different fatness of the tail (Gaussian kernel, negative exponential kernel and 2Dt kernel; see Fig. 1a for a visual illustration) were used to explore the effect of long-distance dispersal on the effectiveness and effort of the outward and inward strategy. For each of the 3×500 outbreaks, the outward and inward strategies were tested, using the exact same simulations (section "Delimiting survey"). 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. The size of this presumed outbreak frontier is estimated based on the spread characteristics of the pest (section "Survey design parameters").

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

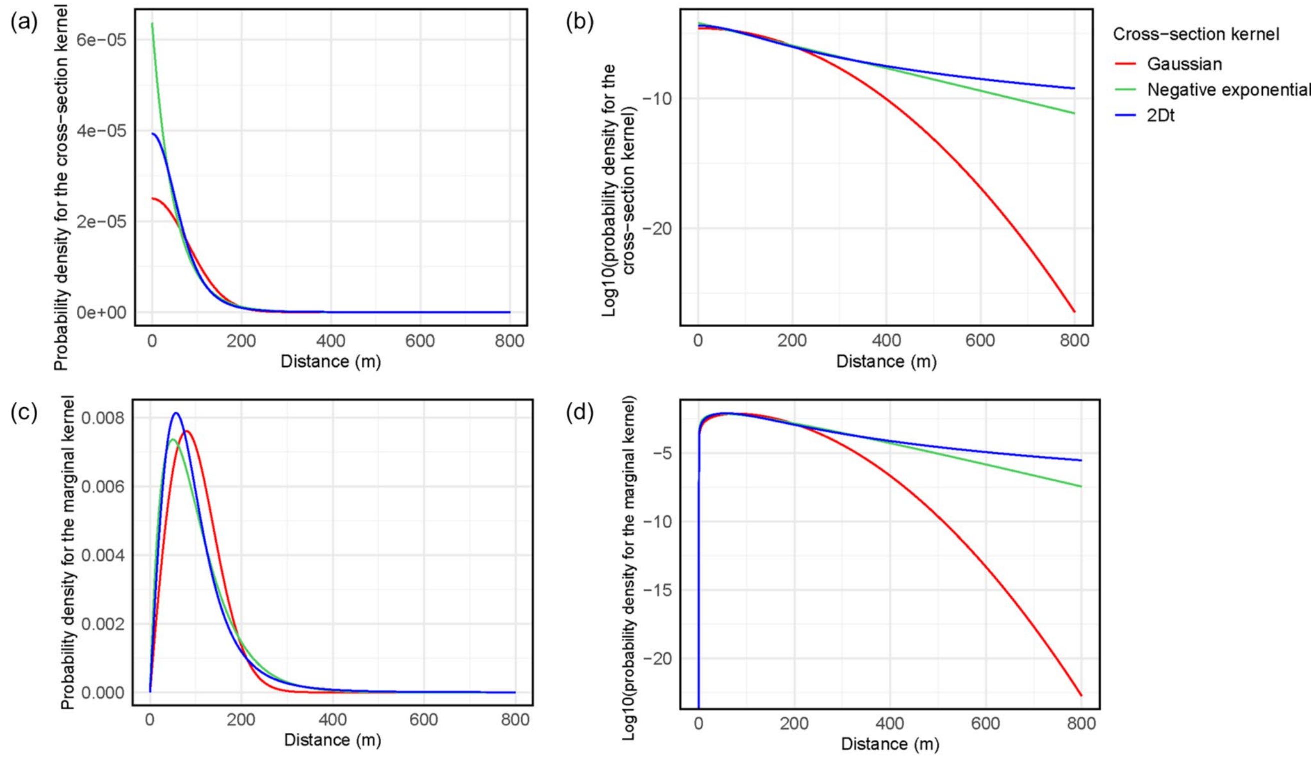

Fig. 1 Illustration of the three probability distribution models for dispersal used in this study. Panel **a** shows the three cross-section kernels, while panel **b** shows the same kernels on a log scale to highlight the differences in fatness of the tail. For comparison with the marginal kernels, 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 all three marginal kernels

Table 1 Glossary of terms, taken from FAO (2023)

Terminology	Definition
Plant pest	Any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products. Pests can be categorized as native or non-native plant pests
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
Delimiting survey	Survey conducted to establish the boundaries of an area considered to be infested by or free from a pest

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 simulation replicates in which one strategy outperformed the other, and by comparing average characteristics of the replicates, such as the average proportion of infested plants inside the delimited zone (section "Metrics for assessing effectiveness and sampling effort"). 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 ensure that the model parameters are biologically plausible, we used *Xylella fastidiosa* as an example to choose the biological model parameters. Below, we describe each step in detail.

Growth and spread model

To model the outbreak of host plants infested by the pest, a spatially explicit spread model consisting of population growth (in terms of the number of infested plants) and a dispersal kernel of the pest was built. We simulated the outbreak over an area for several years. We used a geometric population growth, assuming that there was no density dependence at the time of the first detection, i.e. the population is still far from the carrying capacity:

$$N_k = \lambda^k * N_0 \quad (1)$$

where λ represents a yearly multiplication factor (Table 2), N_0 is the number of initially infested plants in the year of first establishment (Table 2) and N_k is the number of infested plants after k years (Table 2).

To explore how dispersal affects the performance of the two strategies, we considered three two-dimensional (2D) cross-section kernels (Fig. 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. 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. Long-distance jumps may occur 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. 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. 2, 3, 4) over angles from 0 to 2π.

Marginal kernel is derived from the Gaussian cross-section kernel:

Table 2 Parameters in the spatially explicit spread model and delimiting survey procedure. Biological parameters from *Xylella fastidiosa* with a negative exponential cross-section kernel were used as an example

Parameter	Symbol	Value	Units	References
Outbreak				
Number of plants initially infested	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 host plants per square metre	TD	0.2	Number per m^2	https://www.agromillora.com/shd-olive-crops/

[1] Some terminology follows notation by EFSA (2020b)

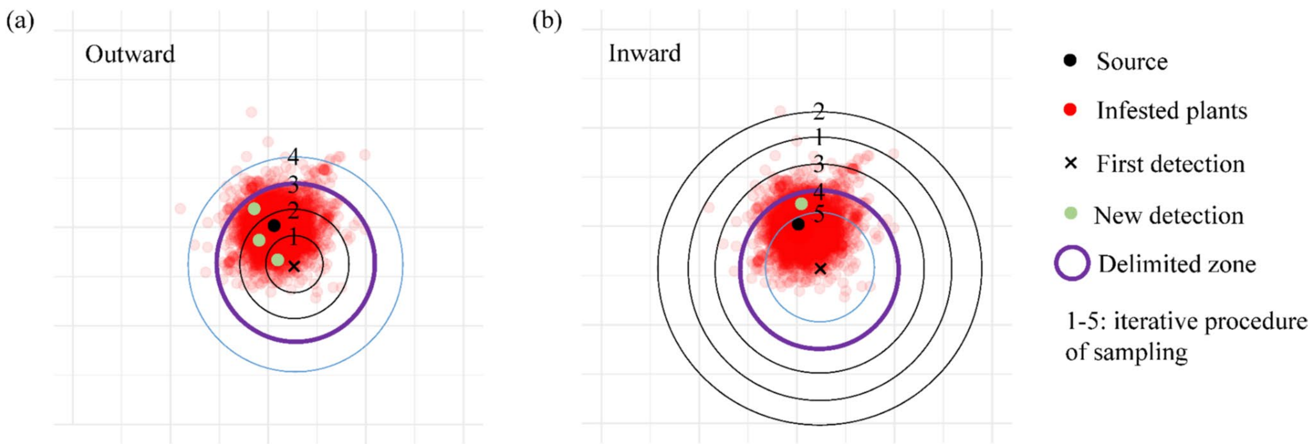

Fig. 2 Illustration of the outward and inward strategies. For the **outward strategy a**, a survey band with a radius R_s (s for survey) was established around the first detection and additional survey bands with a width R_s were established around the previous bands until a band was reached in which no detections were made. Thus, delimitation is considered to be complete once disease freedom outside of an infested band has been substantiated. The finally delimited zone then includes all bands that were found to be infested. For the **inward strategy b**, a potentially infested zone (initial estimate) with a radius R_{inward} was first established. In the first step, a survey band with a radius R_s was added around this potentially infested zone. If the pest was not detected in the first step, the survey proceeded inward by adding a new band within the potentially 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. However, if the pest was detected in the first survey band, additional survey bands with a radius R_s would be added on the outside until no detection was made in a newly added survey band, as in the outward strategy

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

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

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

$$k_M(r) = 2\pi r\left[\frac{1}{2\pi(a_2)^2}\exp\left(-\frac{r}{a_2}\right)\right] \tag{3}$$

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

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

$$k_M(r) = 2\pi r\left[\frac{b-1}{\pi(a_3)^2}\left(1+\frac{r^2}{(a_3)^2}\right)^{-b}\right] \tag{4}$$

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 marginal kernels, b is the shape parameter (degrees of freedom) for the 2Dt kernel, and 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 2). 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 marginal kernels.

Delimiting survey

Based on the described population growth model and selected 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 2). For each simulated outbreak, we randomly selected a single infested plant as the location of the first detection. This location was subsequently used as the centroid in the delimiting process for both the outward and inward strategies (Fig. 2).

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. Thus, delimitation is considered to be complete once disease freedom outside of an infested band has been substantiated. The finally delimited zone then includes all bands that were found to be infested (Fig. 2a). For the inward strategy, a potentially infested zone (initial estimate) with a radius R_{inward} was first established. In the first step, a survey band with a radius R_s was added around this potentially infested zone. If the pest was not detected in the first step, the survey proceeded inward by adding a new band within the potentially 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. However, if the pest was detected in the first survey band, additional survey bands with a radius R_s would be added on the outside until no detection was made in a newly added survey band (Fig. 2b), as in the outward strategy. All simulations were programmed in the computer language R (R Core Team 2024). The animations of the two strategies, data and R scripts to simulate the performance of the two strategies are available at https://zenodo.org/records/14176138.

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 defined confidence level CL[1] that the pest prevalence would be below a defined design prevalence DP[1] (prevalence being defined as a proportion of infested plants), when a detection method is used with a probability $MeSe$[1] (method sensitivity) that an infested plant is actually identified as positive (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 the guideline by 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 considered finite and the hypergeometric distribution was used.

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

$$CL = 1 - (1 - MeSe * DP)^n \quad (5)$$

(EFSA 2020b) Based on Eq. 5, the sample size per survey band is:

$$n = \frac{\log(1 - CL)}{\log(1 - MeSe * DP)} \quad (6)$$

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

$$CL = 1 - \left(1 - \frac{n * MeSe}{N - 0.5 * (N * DP * MeSe - 1)}\right)^{N*DP} \quad (7)$$

$$n = \frac{\left(1 - (1 - CL)^{\frac{1}{N*DP}}\right) * \left(N - \frac{1}{2} * (N * DP * MeSe - 1)\right)}{MeSe} \quad (8)$$

EFSA (2020b)

N is the total population size of host plants in the survey band, which we calculated by multiplying the host density (TD in Table 2) by the area size of the survey band.

Then, the testing procedure was simulated by applying a Bernoulli distribution to the infested plants to determine whether testing an infested plant would result in a positive result.

Metrics for assessing effectiveness and sampling effort

Effectiveness of the strategies was quantified for each simulated outbreak using three metrics: i) the proportion of infested plants enclosed within the delimited zone, ii) the sensitivity, which is proportion of the area of the true infested zone within the boundaries of the delimited zone. Hence, sensitivity can be calculated as the intersection (called A) of the true infested zone (B) and the delimited infested zone (C) divided by the area of the true infested zone (B; $\frac{A}{B}$, Fig. 3) and iii) the specificity, which is the proportion of the area of the delimited zone that overlapped with the true infested zone. Hence, the specificity can be calculated as A over the area of the delimited infested zone (C; $\frac{A}{C}$, Fig. 3). 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 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 other than the initial finding) 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 outperformed the outward strategy and (c) the outward strategy outperformed the inward strategy.

Sampling effort was quantified 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 procedure. These metrics were averaged across the 500 simulation replicates, and the SD and SE were also quantified.

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

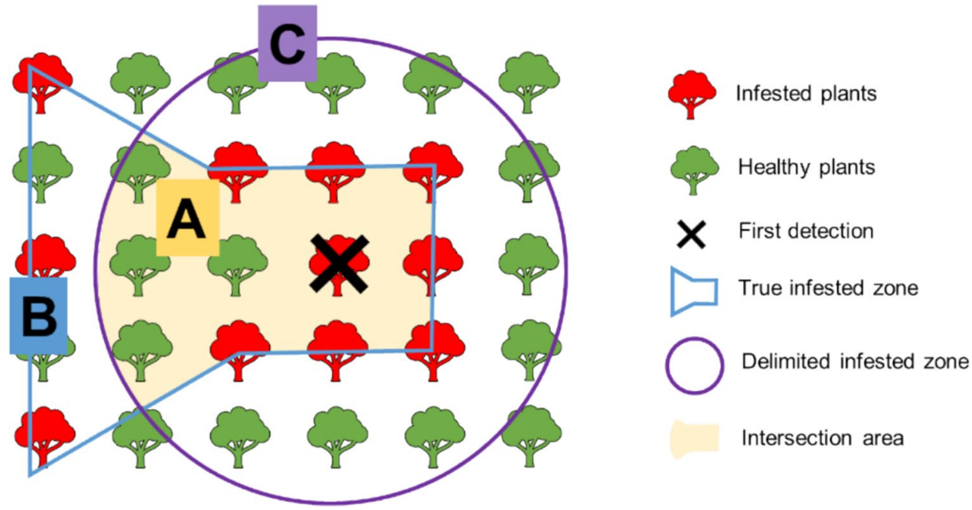

Fig. 3 Graphical representation of sensitivity ($\frac{A}{B}$) and specificity ($\frac{A}{C}$). A is the intersection between the delimited zone (C: *purple circle*) and the true infested zone (B: *blue*) which surrounds all infested plants (*red trees*)

In practice, there is a high degree of uncertainty about the position of the frontier. To capture this uncertainty, we varied the radius of the potentially infested zone. 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. Since the two strategies are based on the same 500 outbreak cases, we used paired t-tests to analyse where the simulation analysis indicates a significant difference between the two strategies.

Parameterizing the model taking *xylella fastidiosa* as an example

We used *Xylella fastidiosa* as an example organism to derive the parameter values to be used in simulations for the growth and spread model and the delimiting survey. *Xylella 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). It can also affect citrus plants and various ornamental plants (Schneider et al. 2020). Currently, *Philaenus spumarius* is known to be the main insect vector species in Europe (EFSA 2020a).

Growth and spread model parameters

In our spread model, we assumed that the outbreak started with one infested symptomatic plant (N_0 in Table 2), and the yearly multiplication factor was 19 (λ in Table 2). 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 2) 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 cross-section 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 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 2). 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 2) 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}): $\frac{R_F}{4}$, $\frac{R_F}{2}$, R_F, $2R_F$, $3R_F$ and $4R_F$. To ensure that the delimiting procedures for the two strategies can stop at the same position, we used the

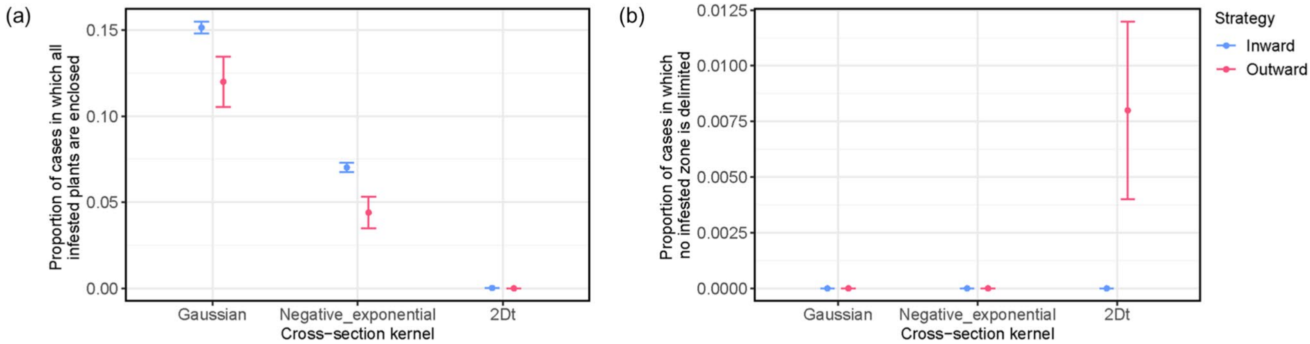

Fig. 4 Proportion of cases in which all infested plants are enclosed **a**, and proportion of cases in which no infested zone is delimited **b**, as a function of the cross-section kernel (x-axis). *Blue circle* data points and error bars represent the average ± standard error for the inward strategy 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

same 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 across all tested potentially infested zone (Table 2).

In line with the recommendations 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 2) (EFSA 2020b). Based on these 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 substantiate 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 surveillance in a band can be terminated as soon as the first infestation is found during the delimiting survey.

To assess how confidence level, design prevalence and the width of the survey band affect the effectiveness and sampling effort of the inward and outward strategies, we conducted further tests for each cross-section kernel (Appendix, Figs. S5–S12). 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.

Results

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. 1) had a large effect on the proportion of cases in which all infested plants were enclosed (Fig. 4a). 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. 4a). For the outward strategy, the proportions of cases in which all infested plants were enclosed were 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. S1). Despite both strategies performing poorly in enclosing all infested plants, the inward strategy was slightly better across the three different kernels examined (Fig. 4a).

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 epicentre of the infestation. In these cases, the infestation was only detected in this single plant, and the wrong conclusion was drawn that the pest had not yet spread. This problem did not occur with

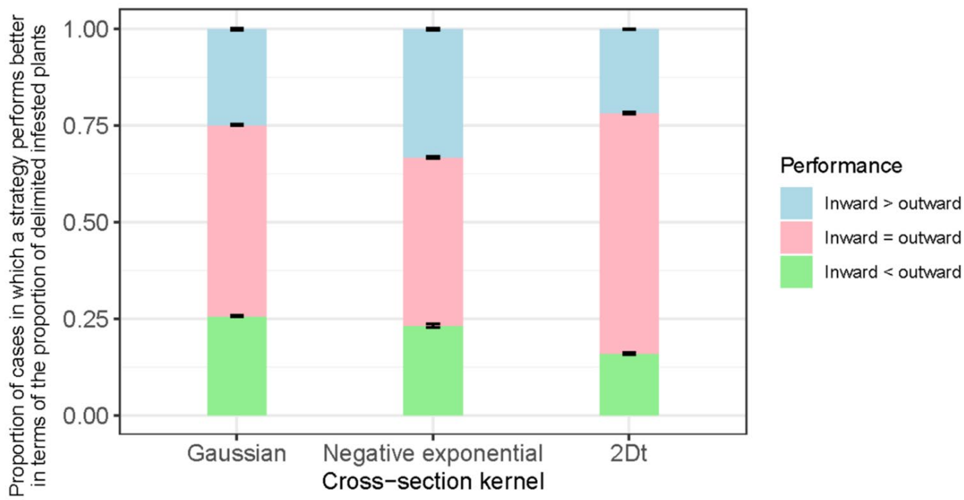

Fig. 5 Proportion of 500 outbreak simulation replicates in which a strategy performs better than the other strategy in terms of the proportion of delimited infested plants (y-axis), as a function of the dispersal kernel (x-axis). *Blue (pink, green)* areas represent the proportion of cases in which the 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

the inward strategy (Fig. 4b). It only occurred for the 2Dt cross-section kernel for the outward strategy, in a proportion of 0.008 ± 0.004 of the cases (Fig. 4b).

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. 5). 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. 5). 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. S3). However, this came at the cost of a large number of samples (Appendix, Fig. S2).

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 S1, S2, S5−S13 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. 6a). 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. 6a). 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. 6b). 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. 6b). 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. 6c).

The results show that the performance of the two strategies is highly similar, though not identical (Fig. 6). 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. 7a). The inward strategy used on average 12.5 ± 0.03 survey bands compared with 8.3 ± 0.05 for the outward strategy (Fig. 7b). 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. 7). 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.

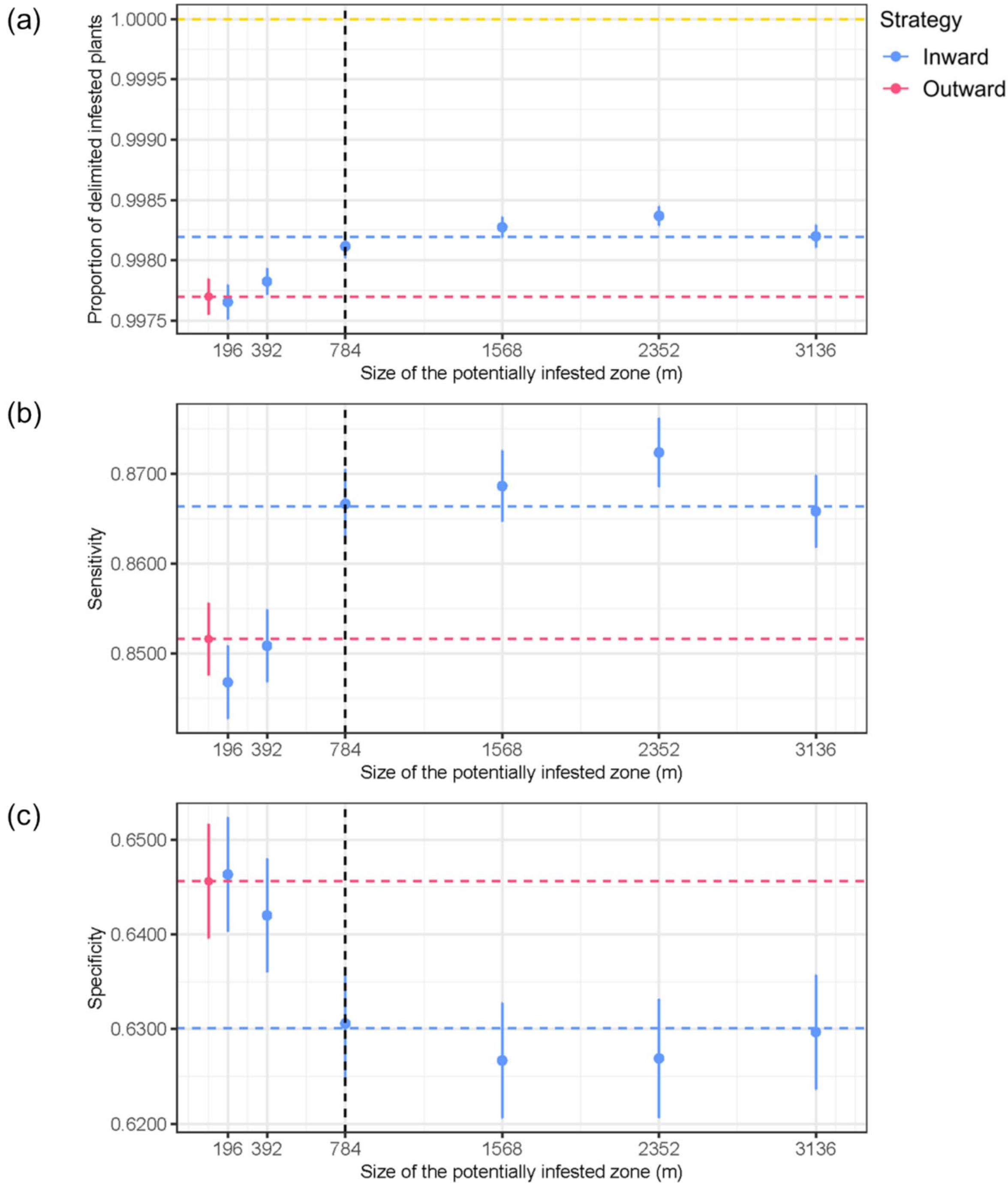

Fig. 6 Metrics for the effectiveness (y-axis), viz. the proportion of delimited infested plants **a**, the sensitivity **b**, and the specificity **c**, as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars 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 performance of the inward strategy across different initial estimates of the location of the outbreak frontier. This average performance was estimated by averaging over linearly interpolated values between the six simulation outcomes 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 2)

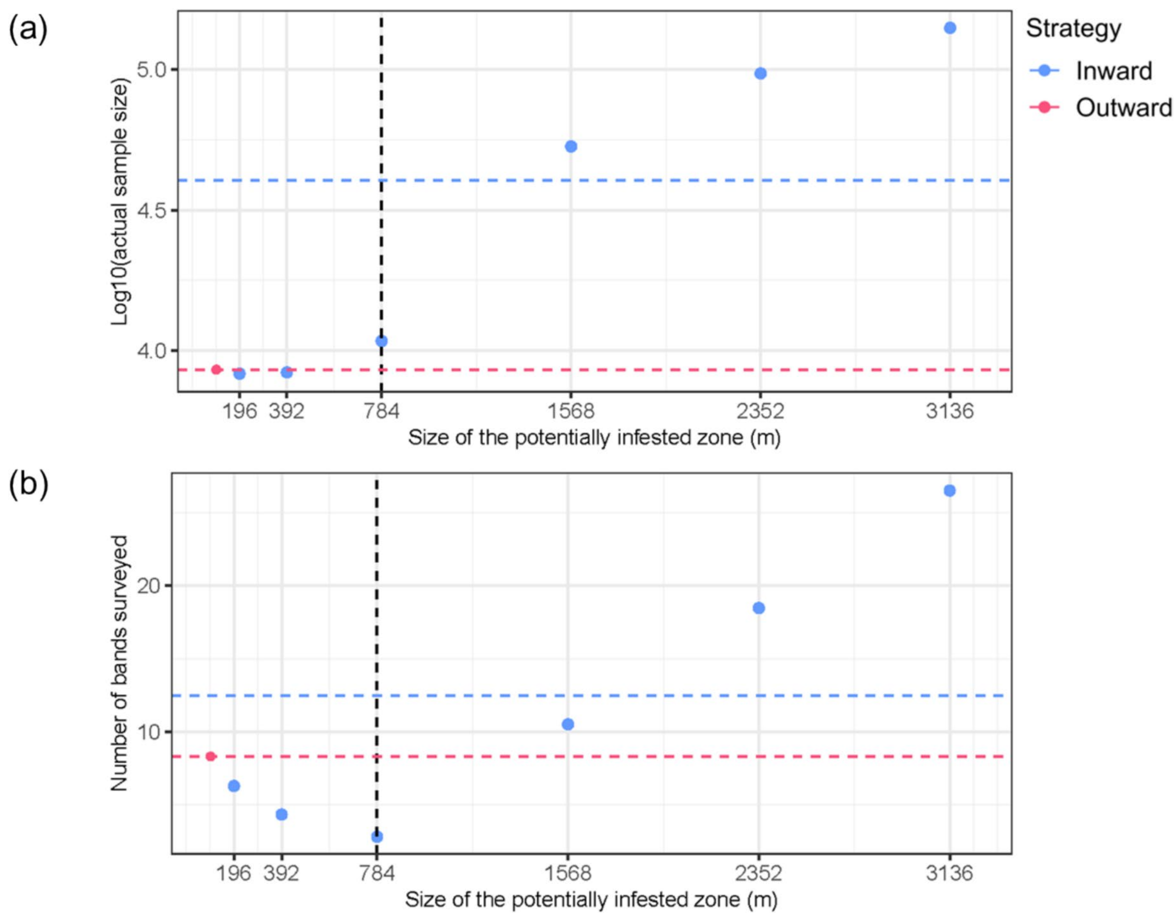

Fig. 7 Metrics for sampling effort (y-axis) including actual sample size on a log10 scale **a**, and number of bands surveyed **b**, as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars represent the mean ± 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 performance of the inward strategy across different initial estimates of the location of the outbreak frontier. This average performance was estimated by averaging over linearly interpolated values between the six simulation outcomes 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 2)

On average, the inward strategy delimited a slightly larger infested zone (732 ± 4 m) than the outward strategy (715 ± 50 m) (Fig. 8). Neither strategy delimited an infested zone larger than the average position of the frontier (784 m, Fig. 8).

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. 9a) but at a large cost of additional sampling (Fig. 9b). 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. 9b). Increasing the size of the survey band from 98 to 196 m decreased the proportion of delimited infested plants and the sample size (Appendix, Fig. S11).

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

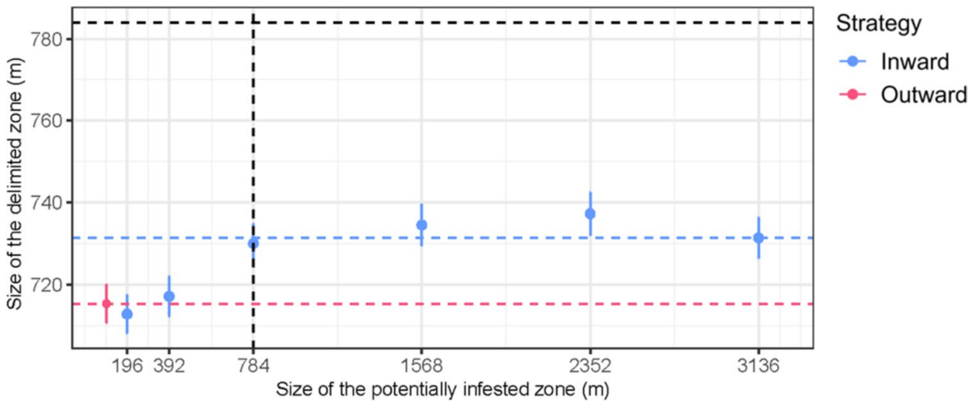

Fig. 8 Size of the delimited zone (y-axis), as a function of the size of the potentially infested zone (R_{inward}, x-axis) in the case of the inward strategy. *Blue* data points and error bars represent the mean ± standard error of 500 simulations for the inward strategy for six different sizes of the 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 performance of the inward strategy across different initial estimates of the location of the outbreak frontier. This average performance was estimated by averaging over linearly interpolated values between the six simulation outcomes 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 2)

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. 6a). 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 aesthetic 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

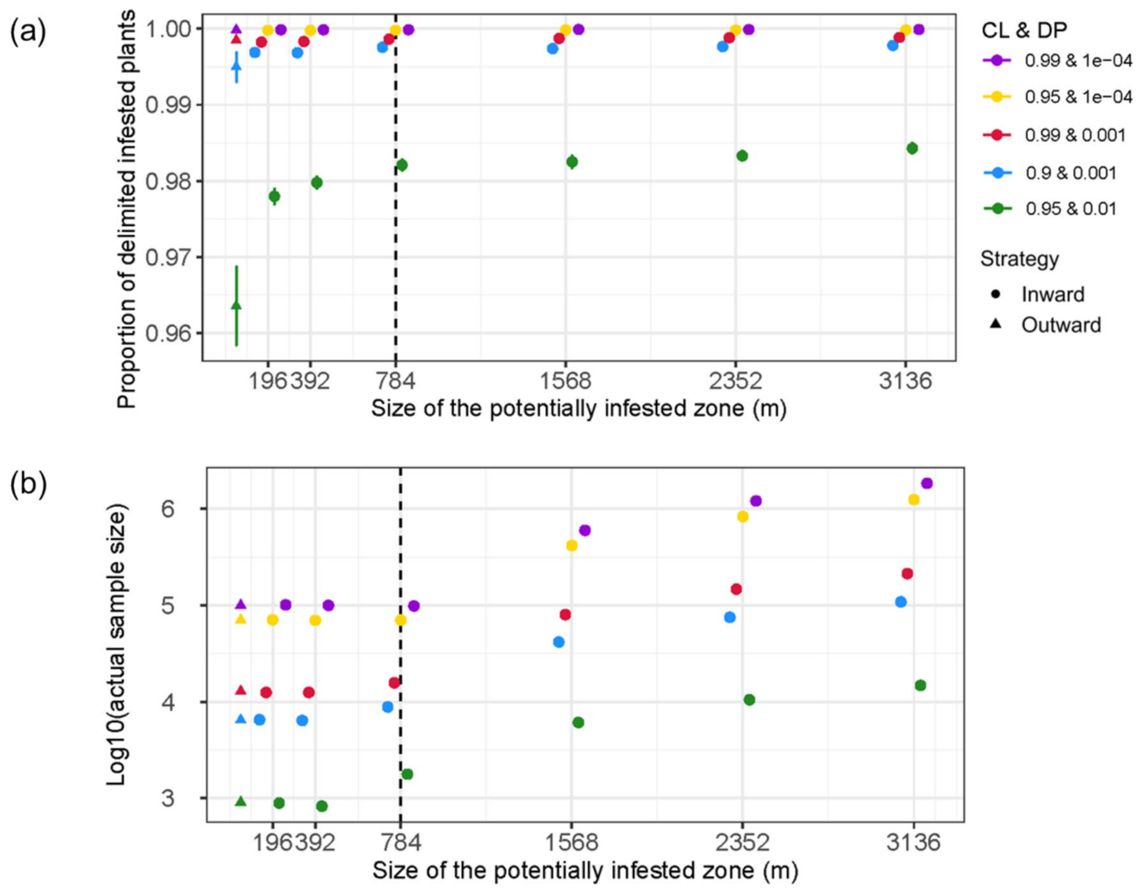

Fig. 9 Metrics for effectiveness, viz, the proportion of delimited infested plants **a**, and sampling effort, viz, actual sample size on a log10 scale **b**, as a function of the size of the potentially infested zone (R_{inward}, x-axis) in case of the inward strategy. Data points and error bars represent 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 indicate, 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 2)

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. 5, 6, and Appendix, Figs. S2, S3). This is because the first bands are skipped, thus saving samples (Fig. 7 and Appendix, Fig. S4). 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. 7b). 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, for example, 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. 5, 6, and Appendix, Figs. S2, S3, S5-S13). 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 centre, 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. 7). 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 delimitation based on detection results. For example, one could adjust the centroid of the bands based on the findings in the previous bands. Likewise, the results of sampling in previous bands (particularly the number of negative samples before a positive sample is found) 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. When the host occurs in a heterogeneous landscape, the surveillance strategy might need to be further adapted. 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. S14 and S15) 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. S14 and S15). 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. If diagnostic tests are expensive, composite samples might be used to reduce the number of tests needed, while still maintaining the required sample size to satisfy the requirements of confidence and design prevalence set during the development of the surveillance protocol. Hence, there are many opportunities to refine and tailor these outbreak delimitation approaches and optimize their performance.

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. 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 centre 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.

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Author contributions MS proposed the idea. HS, JD 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.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

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