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Assessing the probability of freedom from pine wood nematode based on 19 years of surveys

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Abstract

Many quarantine pests, such as the pine wood nematode (PWN, *Bursaphelenchus xylophilus*), are surveyed annually in all EU countries. Although a lot of resources are spent in the surveys, the confidence in pest freedom achieved with them is not commonly analysed. We assessed the probability that Finland is free from PWN, based on the surveys done in 2000–2018. We used the methods employed in the risk-based estimate of system sensitivity tool (RiBESS), which has recently been recommended for quarantine pest applications. We considered two scenarios: 1) the surveys aimed to justify phytosanitary import requirements and to facilitate exports and 2) the surveys aimed to detect invasions early to enable eradication of outbreaks. These differed only in the pest prevalence that the surveys were expected to detect. The surveys appeared to support the assumption that PWN is not present in Finland, but they did not seem extensive enough to ensure early detection of invasions. The sensitivity of the import-export surveys was greater than 0.6 in 13 years, whereas that of the early detection surveys was always below 0.25. The probability of freedom achieved in 2018 following 19 years of surveys increased asymptotically with the mean time between invasions. For the import-export surveys, this probability was at least 0.95 unless the mean time between invasions was less than 13 years. For the early detection surveys, the probability of freedom was less than 0.73 unless the mean time between invasions was 63 years or more. The results were rather robust with respect to the parameters for which exact information was lacking. To improve the assessment, a quantitative estimate of the probability of PWN invasion to Finland and a thorough assessment of the maximum area of an eradicable infestation would be needed. To gain an understanding about the true impact of quarantine pest surveys on biosecurity, more assessments, like the one presented in this paper, are needed.

Keywords

design prevalence, European Union, legislation, plant health law, quarantine pest, sensitivity

Introduction

All countries of the European Union (EU) are required, by legislation, to conduct annual surveys for several quarantine pests, such as the pine wood nematode (PWN, *Bursaphelenchus xylophilus*) (European Council 2000; EU 2016). One aim of the surveys is to show pest freedom to justify phytosanitary import requirements and to facilitate export to countries with corresponding requirements. In addition, the hope is that the surveys will detect pest invasions early enough to enable successful eradication of outbreaks. However, the confidence in pest freedom achieved with the surveys is not commonly assessed and thus their impact on biosecurity is not known.

PWN is the causal agent of pine wilt disease, which, under suitable conditions, can lead to mass mortality of susceptible pine trees (e.g. Futai 2013). It is thought to be native to North America and has been introduced in Asia, in Japan, China, Taiwan and South Korea (Mamiya 1988; Tzean 1997; Shin 2008; Zhao 2008) and in Europe, in Portugal and Spain (Mota et al. 1999; Robertson et al. 2011).

PWN can spread over long distances through the transport of wood and wood packaging material (Evans et al. 1996; EPPO 2009). From tree to tree, it is spread by longhorn beetles of the genus *Monochamus* via feeding and oviposition (e.g. Linit 1988). Feeding by an infested vector transmits PWN to healthy trees, whereas when being spread via oviposition, PWN is transmitted only to weakened trees, recently felled logs or logging waste, as the vectors do not breed on healthy trees (e.g. Akbulut and Stamps 2012). The most susceptible hosts to PWN are in the genus *Pinus*, but other conifers such as *Abies*, *Picea* and *Larix* can also be attacked (e.g. Takeuchi 2008).

PWN is not expected to cause pine wilt disease in areas where the mean temperature of the summer months is below 20 °C (Evans et al. 2008; Gruffudd et al. 2016). Hence, in much of Northern Europe, including Finland, PWN is unlikely to cause any symptoms. In such conditions, PWN is very unlikely to spread further from trees infected by feeding of the beetles. Moreover, as visible symptoms are not expected in these areas, PWN surveys must be based solely on laboratory analysis of asymptomatic samples.

In the EU, PWN is a quarantine pest, whose introduction into and spread within the Union is prohibited (European Council 2000; EU 2016; European Commission 2019a). Moreover, after PWN was first detected in the EU in 1999 (Mota et al. 1999), specific emergency measures that aim to prevent its further spread have been in force (EU 2012). The measures require all EU countries to conduct annual surveys to determine whether PWN is present in their territory.

In addition to PWN, EU member states must carry out annual surveys for several other quarantine pests. Regular surveys must be carried out for all quarantine pests and the so-called priority pests, such as PWN, must be surveyed every year (EU 2016; European Commission 2019b). The surveys of the priority pests must include a sufficiently high number of visual examinations, sampling and testing to ensure, as far as possible, the timely detection of the pest, with a high degree of confidence.

Due to these requirements, a lot of resources are being used in surveys of quarantine pests in the EU. For example, in the PWN surveys, approximately 16,000–21,000 samples were collected and analysed annually in 2014–2016 (European Commission

2018). In Finland alone, the cost of the PWN survey in 2000–2018 was up to approximately 100,000 euros per year (unpublished estimate based on information obtained from the Finnish Food Authority). Despite such significant investments, we did not find any published assessments of the confidence in pest freedom achieved with the surveys. However, if the confidence were assessed, it could be used to evaluate the benefit of the surveys and possibly to cut down the resources needed for future surveys.

The European Food Safety Authority (EFSA) is currently training the national plant protection organisations (NPPOs) of EU countries to plan the surveys required by the EU legislation with the risk-based estimate of system sensitivity tool (RiBESS) (EFSA 2012; EFSA 2018). The tool is based on principles presented by Cannon (2002) and Martin et al. (2007) and it was originally designed for estimating the sample size needed in the surveys of *Echinococcus multilocularis* infections in dogs and for calculating the survey sensitivity once the samples are collected (EFSA 2012). The methods employed in the tool have been used for designing surveillance of invasive species, including plant pests (e.g. Dominiak et al. 2011; Kean et al. 2015). However, quantitative assessments of the confidence in pest freedom are still exceptions rather than the rule.

We used the methods employed in RiBESS to assess the sensitivity of the annual PWN surveys carried out in Finland in 2000–2018 and the probability that Finland was free from PWN in 2018. We made these assessments for two separate scenarios with different assumptions: a) while assuming that the surveys were done to justify import requirements related to PWN and to facilitate exports to countries with respective requirements and b) while assuming that the surveys were aimed to detect invasions at an early stage to facilitate eradication. We show what kind of information is needed in the analysis and how the uncertainties of that information can be accounted for. Additionally, we highlight the value of quantitative estimates of the probability of pest invasion and demonstrate the dangers of using a seemingly uninformative prior probability of pest freedom when accumulating evidence for pest freedom from multiannual surveys.

Methods

The surveys

PWN surveys were conducted in 2000–2018 in all the fifteen Centres for Economic Development, Transport and the Environment of Finland (Fig. 1), but the self-governing province of the Åland Islands was not included in the surveys. The survey was conducted by inspectors of NPPO of Finland and regional bodies to which the tasks had been delegated.

The main body of the surveys consisted of sampling of wood of PWN host plants, i.e. Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). However, in 2012–2018, the PWN vector beetles present in Finland (*M. galloprovincialis*, *M. sutor* and *M. urussovii*) were also sampled using pheromone traps.

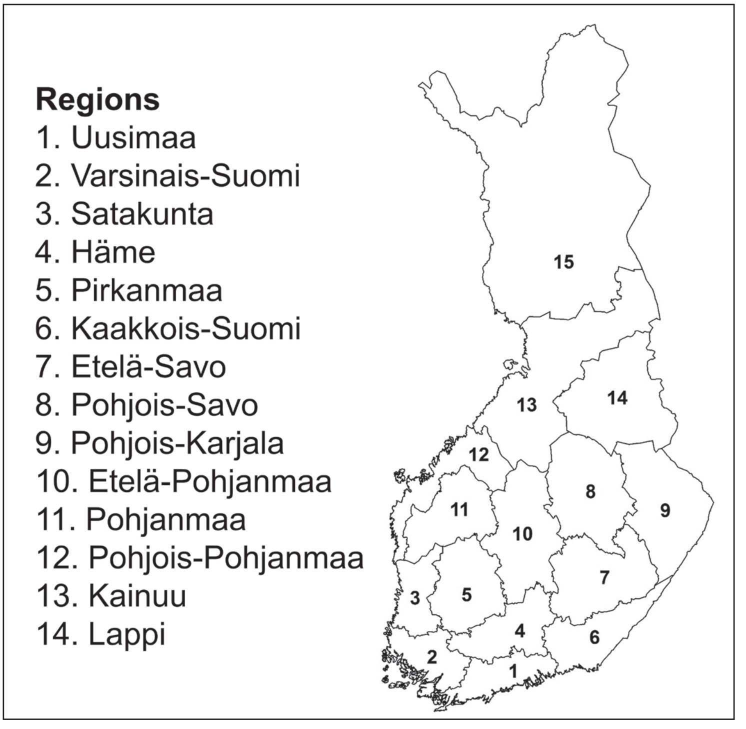

Figure 1. The fifteen administrative regions covered in the survey.

Wood sampling

Wood sampling was done according to the PWN survey guidelines of the NPPO, which were based on the EU PWN survey protocol (European Commission 2009). Samples were taken from risk areas, i.e. areas where the likelihood of PWN introduction is elevated and from regular forest areas. The risk areas were defined as pine forests at 5 km radius from harbours, industrial areas, landfills, wood storage areas and locations that receive imported wood packaging material.

All samples were taken from trees, wood or logging residuals that had signs of *Monochamus* activity or from pine trees that were dead or dying for no apparent reason. Each sample contained 0.5 l of wood chips and it was collected from an area that was, at most, 2 ha. If the whole sample was taken from one tree or a pile of logs, the distance between two samples was at least 200 m.

Samples were taken and stored so that their temperature was held below 26 °C, to ensure that the nematodes did not die in the process, as they needed to be alive to be detected. All samples were collected between April and October to maximise the probability that adult nematodes also would be present in the sample, as only adults can be identified to species, based on morphological features.

The number of wood samples collected from the different administrative regions in 2000–2018 is presented in Table 1.

Table 1. The number of wood samples collected in 2000–2018.

Region	Number of wood samples																		
	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Uusimaa	100	4	5	37	57	61	65	55	52	45	45	45	49	47	45	20	24	30	13
Varsinais-Suomi	75	3	3	30	50	50	51	29	45	50	45	57	45	45	46	46	46	45	20
Satakunta	75	0	0	50	50	50	40	46	50	50	42	43	47	43	45	45	45	42	45
Häme	50	0	0	0	0	0	0	25	25	25	19	18	22	19	20	20	20	22	21
Pirkanmaa	50	0	0	0	0	0	0	25	25	25	20	20	19	21	20	5	20	20	20
Kaakkois-Suomi	100	8	0	72	98	95	27	23	33	40	36	40	22	29	41	22	30	31	33
Etelä-Savo	50	1	0	0	0	0	0	54	52	53	46	46	45	45	45	45	45	50	23
Pohjois-Savo	50	0	0	0	0	0	0	24	23	26	28	20	17	10	20	10	20	7	29
Pohjois-Karjala	75	0	0	50	50	38	52	55	23	38	67	33	29	39	47	16	22	19	22
Keski-Suomi	50	0	0	0	0	16	52	52	53	51	45	47	29	9	20	20	15	20	20
Etelä-Pohjanmaa	50	0	6	0	0	0	0	25	25	27	21	20	20	20	20	20	20	20	20
Pohjanmaa	75	0	0	0	48	0	0	50	50	50	45	45	45	44	45	45	45	45	45
Pohjois-Pohjanmaa	75	0	0	51	54	51	50	54	50	53	45	45	45	44	45	45	20	17	16
Kainuu	50	0	0	0	0	0	16	28	15	27	20	20	19	28	20	9	9	9	5
Lappi	50	0	0	4	0	0	0	0	13	23	23	5	15	20	16	20	20	20	20
Total	975	16	14	294	407	361	353	545	534	583	547	504	468	463	495	388	401	397	352

Monochamus trapping

The traps were placed in places that were attractive to *Monochamus* beetles, such as storage areas of wood with bark and places with plenty of fresh logging residuals. The distance between traps was at least 500 m. The traps were set up in early June, inspected every other week and taken down at the end of August.

The trap type and attractant used varied between years and locations. Both multi-funnel and cross-vein traps and several pheromone and kairomone products, such as Gallowit, Galloprotect 2 D, and Galloprotect Pack, were used. In addition, some beetles were collected by hand. All samples were mailed to the laboratory with an ice brick that kept them cool.

The number of traps and the number of *Monochamus* individuals caught in the different administrative regions in 2012–2018 are presented in Table 2.

Table 2. The number of traps used and the number of *Monochamus* individuals captured in 2012–2018. In some of the regions and years, *Monochamus* were caught by hand and, therefore, the number of *Monochamus* can be positive even though the number of traps is zero.

	Number of traps / *Monochamus*					
Region	**2012**	**2013**	**2014**	**2016**	**2017**	**2018**
Uusimaa					2 / 1	2 / 0
Kaakkois-Suomi	6 / 0	6 / 5	6 / 9	6 / 0	0 / 6	0 / 1
Etelä-Savo					0 / 2	
Pohjois-Savo					0 / 1	
Pohjois-Karjala	2 / 0	2 / 0	2 / 0	2 / 0		
Pohjois-Pohjanmaa						0 / 4
Kainuu	2 / 0	2 / 0	2 / 18	2 / 0		
Total	10 / 0	10 / 5	10 / 27	10 / 0	2 / 10	2 / 5

Analysis of the samples

Extraction and identification of nematodes from the samples was done by the authorised plant health laboratory of Finland, according to a protocol that was based on the standards of the European and Mediterranean Plant Protection Organization (EPPO) on nematode extraction (EPPO 2013a) and on the diagnostics of PWN (EPPO 2013b) and on Hooper (1986) and Bergdahl et al. (1991).

Wood samples were first incubated at 20–25 °C for 14 days to allow the nematodes to reproduce. Then, the nematodes were extracted to a Petri dish using the Baermann funnel technique (Baermann 1917).

From the *Monochamus* samples, nematodes were extracted by sectioning the beetles to four parts and by leaving them on a Petri dish with water overnight. From the Petri dish, nematodes were searched using a stereomicroscope. If potential PWN were found, they were placed on pine discs to moult to adults and to reproduce. After the discs had been incubated at 20–25 °C for 14 days, the nematodes were extracted to a Petri dish using the Baermann funnel technique (Baermann 1917).

While in the Petri dish, the adult nematodes were searched under a stereomicroscope and all potential PWN were placed on a microscope slide for morphological identification. From 2011 onwards, if PWN had been found, the identification would have been verified using a Real-time PCR protocol (François et al. 2007; Ye 2012).

Entry sites, risk areas, and the target population

The survey guidelines were based on the assumption that the probability of PWN introduction was elevated in harbours, industrial areas and landfills and that the probability of PWN infestation was elevated at 5 km radius from such areas. In this paper, the areas with elevated probability of PWN introduction (i.e. harbours, industrial areas and landfills) are referred to as entry sites. The areas with PWN host plants at 5 km radius from entry sites are referred to as risk areas.

In principle, the survey design was risk based, since samples were collected from the risk areas and from regular forest areas and the sampling site type was recorded for each sample. However, when we delineated the spatial extent of the risk areas using the Finnish Corine Land Cover 2012 data at 20-m^2 resolution (Härmä et al. 2015), we found that, in thirteen of the fifteen administrative regions, the risk areas covered more than 80% of the area with PWN host plants (see Table 3). Since the inspectors did not have such delineation available when collecting the samples, we considered that the sampling site type data were likely to be flawed and decided not to use it. As sampling in the remote locations that did not fit the definition of the risk areas was probably rare, we assumed that all sampling was done in the risk areas. Thus, the target population of the survey was the risk areas.

Table 3. The area with PWN host plants, the area of entry sites (*EA*), the area of the target population (*Pop*, i.e. risk areas) and the mean area covered with PWN host plants in hypothetical PWN infestations with a 20-km diameter (*InfA*). Entry sites are areas with elevated probability of PWN introduction, i.e. harbours, industrial areas and landfills. Target population is the areas with PWN host plants at 5 km radius from entry sites.

Region	Host plants, km²	Entry sites, km²	Target population, km²	Host plant area in hypothetical infestations, km²
Uusimaa	5,640	940	5,260	156
Varsinais-Suomi	6,713	604	5,678	149
Satakunta	5,609	474	5,486	185
Häme	7,285	486	7,199	192
Pirkanmaa	9,566	546	9,475	202
Kaakkois-Suomi	8,042	604	7,774	170
Etelä-Savo	11,832	214	11,102	202
Pohjois-Savo	13,593	454	12,657	209
Pohjois-Karjala	15,003	293	12,301	200
Keski-Suomi	14,220	384	13,681	224
Etelä-Pohjanmaa	9,520	380	9,423	210
Pohjanmaa	9,391	443	8,437	187
Pohjois-Pohjanmaa	27,607	667	22,717	212
Kainuu	19,150	209	13,627	239
Lappi	61,783	538	31,229	210
Total	224,956	7,236	176,046	

Defining the aim of the survey with design prevalence

Proving that a pest is absent from a host population is not possible unless all members of the population are tested with a perfect test. Therefore, the aim of a survey must be defined in terms of design prevalence and sensitivity. Roughly, design prevalence determines the minimum prevalence that the survey is aimed to detect and sensitivity determines the probability with which the survey is expected to succeed in this aim. If the pest prevalence is equal to or greater than the design prevalence, at least one infested individual will be detected in the survey, with the probability equal to the sensitivity of the survey.

If the survey has not yet been done, the number of samples needed can be determined so that the survey fulfils its aim and proves that the pest prevalence is below the design prevalence with the desired sensitivity. In an ex-post analysis, such as this study, the sensitivity of the surveys, given a predefined design prevalence, can be determined, based on the number of samples taken.

Since the aim of the Finnish PWN surveys was not predefined in terms of design prevalence, we had to start by doing that. We did it by assuming the aim was a) to provide evidence to justify import requirements related to PWN and to facilitate export to countries with corresponding requirements and b) to detect possible PWN invasions early enough to enable successful eradication. These two cases were analysed separately. The first is referred to as the import-export survey and the latter, as the early detection survey.

The sensitivity of the surveys was assessed so that each wood sample and *Monochamus* trap was assumed to represent an inspection of a fixed-sized area with PWN host plants, i.e. the inspection site. Therefore, design prevalence had to be defined at two levels, namely, at the level of inspection sites (local-level design prevalence) and at the level of the administrative regions and Finland (regional- and/or national-level design prevalence).

The local level design prevalence refers to the proportion of PWN-infested wood objects and *Monochamus* beetles per inspection site. Regional- and/or national-level design prevalence refers to the proportion of PWN-infested area (where the PWN prevalence is at or above the local level design prevalence) of the total target population (i.e. risk area) in the region or the country.

At both levels, design prevalence had to be such that PWN could reach it, at least at some point in time, if it were established in the considered area. Additionally, design prevalence had to be such that it corresponded to, at least, one whole infested unit (i.e. wood object, *Monochamus* beetle or inspection site) per considered area (i.e. inspection site, region or country). The design prevalences used in this study are summarised in Table 4 and the justification for them is given below.

Local level design prevalence

We defined the local level design prevalence, based on the prevalence of *Bursaphelenchus mucronatus* in the wood samples collected in the Finnish PWN surveys in 2012–2018. This was considered appropriate, as *B. mucronatus* is closely related to PWN, widely established in Finland in coniferous forests (Tomminen et al. 1989) and, like PWN, it is vectored by *Monochamus* beetles (Tomminen 1990). Furthermore, *B. mucronatus*

Table 4. Local-, regional- and national-level design prevalences and effective probabilities of infestation used in the import-export and early detection surveys.

Parameter	Import-export	Early detection
Local-level design prevalence for the wood sampling component of the survey (DP_{wood})	0.12	0.06
Local-level design prevalence for the *Monochamus* trapping component of the survey ($DP_{Monochamus}$)	0.09	0.045
National-level design prevalence (*DPn*)	0.01	
Effective probabilities of infestation for the import-export survey (*EPI*) and regional-level design prevalence for the early detection survey (*DPr*)		
Uusimaa	0.020	0.030
Varsinais-Suomi	0.013	0.026
Satakunta	0.010	0.034
Häme	0.010	0.027
Pirkanmaa	0.012	0.021
Kaakkois-Suomi	0.013	0.022
Etelä-Savo	0.005	0.018
Pohjois-Savo	0.010	0.017
Pohjois-Karjala	0.006	0.016
Keski-Suomi	0.008	0.016
Etelä-Pohjanmaa	0.008	0.022
Pohjanmaa	0.009	0.022
Pohjois-Pohjanmaa	0.014	0.009
Kainuu	0.004	0.018
Lappi	0.011	0.007

does not cause any symptoms (Tomminen 1993), which is expected to be true also for PWN in the current Finnish climate (Gruffudd et al. 2016).

Information about the presence or absence of *B. mucronatus* was available for 2,876 wood samples and *B. mucronatus* was detected in 353 of these samples. Thus, using the binomial probability distribution, the apparent prevalence of *B. mucronatus* in the wood objects that were considered suitable for sampling in the PWN survey was estimated to be 0.12, with 95% confidence limits of 0.11 and 0.14.

To translate this estimated apparent prevalence to true prevalence, the sensitivity of the analysis (i.e. the probability that the pest is detected in the analysis, given that it was present in the object from which the sample was taken) should be known. Unfortunately, this information was not available for *B. mucronatus* or PWN. However, we concluded that by defining the local level design prevalence as the apparent local level design prevalence, we could link it directly to the estimated apparent prevalence of *B. mucronatus*. This is because the sensitivity of the analysis is likely to be roughly similar for the two species and, thus, a given true prevalence is likely to result in a similar apparent prevalence for both species.

To define the local level design prevalence for the *Monochamus* trapping component of the survey so that it matched the local level design prevalence of the wood sampling component, we used an estimate provided by Økland et al. (2010). They estimated that most likely 75% of *Monochamus* offspring emerging from PWN-infested objects are infested with PWN. Based on this, we assumed that the PWN prevalence in *Monochamus* adults should be 75% of that in wood objects suitable for sampling, i.e. 0.09. This is a rough estimate since it is based on the apparent prevalence of *B. mucronatus* in the wood samples instead of the true prevalence of *B. mucronatus* in wood objects, used for breeding by *Monochamus* beetles.

Finally, for the import-export surveys, the apparent local level design prevalence was set equal to the estimated apparent prevalence of *B. mucronatus* (Table 4). This was assumed to represent a prevalence of a PWN population that has been established long enough to reach its maximum density. For the early detection surveys, the apparent local level design prevalence was set to half of the estimated apparent prevalence of *B. mucronatus* (Table 4). This was assumed to represent a prevalence of a PWN population that is in the exponential phase of the sigmoid growth curve, i.e. the population is established, but still clearly growing.

Regional- and/or national-level design prevalence

When the aim of the survey is to show pest freedom to justify import requirements or to facilitate exports, design prevalence at the level of the region or country cannot be defined objectively. Furthermore, the design prevalence that should be used in such surveys is not defined in the Food and Agriculture Organization of the United Nations (FAO) standard on surveillance (FAO 2018) or the one on the requirements for the establishment of pest-free areas (FAO 2017). In this study, the national-level design prevalence of the import-export survey was set to 0.01, corresponding to 1,760 km^2 of forest with coniferous trees.

The probability that the region j is infested, given that the country is infested at the national-level design prevalence, was defined by the effective probability of infestation (*EPI*). It was calculated for each region as (Martin et al. 2007; Efsa 2012)

$$EPI_j = DPn \cdot \frac{RP_j}{\sum_{j=1}^{15} \left(PropPop_j \cdot RP_j \right)} \tag{1}$$

where j denotes the administrative region, DPn = the national-level design prevalence, RP_j = the relative probability of PWN invasion to the region j and $PropPop_j$ = the proportion of the target population (i.e. risk areas) in region j of the target population in Finland. The relative probability of PWN invasion to region j (RP_j) was assumed to be equal to the proportion of the area of entry sites in region j of the area of entry sites in Finland, i.e.

$$RP_j = \frac{EA_j}{\sum_{j=1}^{15} EA_j} \tag{2}$$

where EA_j = the area of entry sites in region j. The area of entry sites was obtained from the Finnish Corine Land Cover 2012 data with a resolution of 20 m^2 (Härmä et al. 2015) (Table 3). The effective probabilities of infestation defined in the above manner for the import-export survey ranged from 0.004 to 0.02 (Table 4).

For a survey that aims to detect invasions early enough to enable the eradication of outbreaks, regional- and/or national-level design prevalence can be determined, for example, based on the maximum area from which eradication could be attempted. The EU emergency measures for PWN (EU 2012) allow member states to refrain from attempting eradication if the diameter of the infested area exceeds 20 km. Therefore, we assumed that, in the early detection survey, infestations should be detected before they reach this size.

The regional-level design prevalences (*DPr*) of the early detection survey were defined assuming that, within the early stages of invasion, PWN infestations would be confined to one region. Thus, the regional-level design prevalences were calculated as:

$$DPr_j = \frac{InfA_j}{Pop_j} \tag{3}$$

where $InfA_j$ = the mean area covered with PWN host plants in hypothetical PWN infestations with a 20-km diameter in region j and Pop_j = the area of the target population (i.e. risk areas) in region j.

To estimate the mean area with PWN host plants in hypothetical PWN infestations with a 20-km diameter ($InfA_j$), we assumed that the infested area would be circular and that its centre would be in an entry site. Then to simulate such circular PWN infestations with a 20-km diameter, we selected hundred points randomly in the entry sites of each administrative region and delineated the area at 10-km radius from the randomised points. Finally, we calculated the mean area with PWN host plants within those areas separately for each region. The regional-level design prevalences defined in the above manner for the early detection survey ranged from 0.007 to 0.034 (Table 4).

Assessment of the probability of freedom from PWN

We assessed the probability of freedom from PWN with the methods used in RiBESS (EFSA 2012), which is based on principles developed by Cannon (2002) and Martin et al. (2007). We applied a hierarchical procedure 1) starting from the sensitivity of inspections per inspection site, 2) moving on to the sensitivity of the annual surveys at the regional and 3) the national level and 4) finally arriving at the probability of freedom achieved, based on the multiannual survey at the regional and national level. The hierarchy of the calculation of the sensitivity of the annual surveys is presented in Figure 2.

For some of the parameters needed in the assessment (such as the density of wood objects suitable for sampling and the density of *Monochamus* adults), information was uncertain or lacking. To account for this, the parameters were expressed as probability distributions and the assessment was done with Monte Carlo simulation. The number of iterations used was 10,000 in all the simulations. The simulations were done with R version 3.52 (R Core Team 2018) and the package mc2d version 0.1–18 (Pouillot and Delignette-Muller 2010).

The sensitivity of inspections

The sensitivity of inspections (inspection sensitivity, *ISe*) is the probability that the pest will be detected at an inspection site when it is present in the site at a prevalence equal to the local-level design prevalence. Inspection sensitivity was assessed separately for wood sampling (ISe_{wood}) and *Monochamus* trapping ($ISe_{Monochamus}$). It was calculated, based on the hypergeometric probability distribution, which is suitable for assessing the sensitivity of sampling from a finite population. The round of inspection sensitivity for hypergeometric distribution is (Cameron and Baldock 1998):

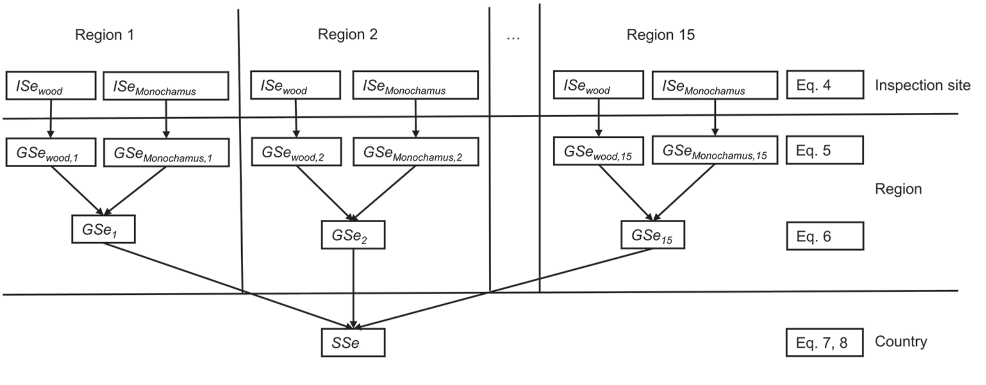

Figure 2. A schematic presentation of the analysis of the sensitivity of the annual surveys. The equation numbers (Eq. 4–8) refer to the equations presented in the main text. Abbreviations: *ISe* = the sensitivity of the inspections, *GSe* = the sensitivity of the annual surveys in the fifteen administrative regions and *SSe* = the sensitivity of the annual surveys in Finland.

$$ISe_i \cong 1-(1-\frac{n_i \cdot TSe_i}{p_i - 0.5 \cdot (p_i \cdot DP_i \cdot TSe_i - 1)})^{p_i \cdot DP_i} \tag{4}$$

where i denotes either the wood or *Monochamus* and p_i = the total population size, i.e. the number of wood objects suitable for sampling or the number of adult *Monochamus* per inspection site, n_i = the number of wood objects or *Monochamus* adults sampled per inspection site and DP_i = the local level design prevalence. TSe_i = the test sensitivity for wood or *Monochamus* samples, i.e. the probability that the pest is detected in the laboratory analysis, given that it was present in the object from which the sample was taken. However, since the local level design prevalence was defined as the apparent prevalence, *TSe* was set equal to one.

The sensitivity of the annual surveys

The sensitivity of the annual surveys is the probability that the pest will be detected in an area (that may be an administrative region or the entire country) in a given year if it is present in the area at a prevalence equal to the design prevalence of the considered area.

The sensitivity of the annual surveys in the 15 administrative regions (group sensitivity, *GSe*) was first calculated separately for wood sampling (GSe_{wood}) and *Monochamus* trapping ($GSe_{Monochamus}$), which were then combined to obtain an overall sensitivity for each region (*GSe*). Then, the sensitivity of the annual surveys at the national level (system sensitivity, *SSe*) was obtained by combining the overall sensitivities of the annual surveys in the different regions (*GSe*).

The wood and *Monochamus* components of the group sensitivity were calculated, based on the binomial probability distribution, which is suitable for assessing the sensitivity of sampling from an infinite population (e.g. EFSA 2012):

$$GSe_{i,j} = 1-(1-DPr_j \cdot ISe_{i,j})^{N_{i,j}} \tag{5}$$

where i denotes either wood or *Monochamus* and j denotes the administrative region, $N_{i,j}$ = the number inspection sites in the region, with either wood sampling or *Monochamus* trapping, $ISe_{i,j}$ = the inspection sensitivity in the region for wood sampling or *Monochamus* trapping and DPr_j = the region level design prevalence. For the import-export survey, effective probability of infection (*EPI*, see equation 1) was used as the regional-level design prevalence.

Binomial distribution was considered appropriate for this assessment because the total area of the target population (i.e. risk areas) per administrative region (Table 3) was high compared to the number of inspection sites (Tables 1, 2). The rule of thumb is that a population can be considered infinite when the sample size is less than 10% of the total population size (Evans et al. 2000). This condition was fulfilled for all the regions for both wood and *Monochamus* samples.

The overall group sensitivity for each administrative region was obtained from:

$$GSe_j = 1 - \left(1 - GSe_{wood,j}\right) \cdot \left(1 - GSe_{Monochamus,j}\right) \tag{6}$$

which is the complement of the probability that, if PWN is present in the region at or above the design prevalence, it is not detected in wood sampling or *Monochamus* trapping.

Finally, the sensitivity of the annual surveys at the country level (system sensitivity, *SSe*) was calculated. For the import-export survey, it was obtained as the complement of the probability that, if PWN is present in Finland, it is not detected in any of the regions as follows:

$$SSe = 1 - \prod_{j=1}^{15} (1 - GSe_j) \tag{7}$$

where j denotes the administrative region. For the early detection survey, it was calculated as the sum of the regional-level sensitivities weighted by the relative probability of PWN invasion in the respective region as:

$$SSe = \sum_{j=1}^{15} GSe_j \cdot RP_j \tag{8}$$

where RP_j = the relative probability of PWN invasion in region j (see equation 2).

The probability of freedom from PWN based on evidence from several years

The probability of pest freedom is the probability that the prevalence of the pest is below the design prevalence if the pest is not detected in the surveys. It was estimated for each administrative region and for the entire country in a stepwise manner by progressively updating the estimate with evidence gained in the surveys in 2000–2018 using Bayes' theorem as follows:

$$Pfree_{t,j} = \frac{PriorPfree_{t,j}}{PriorPfree_{t,j} + \left[(1 - PriorPfree_{t,j}) \cdot (1 - Se_{t,j})\right]} \tag{9}$$

(Martin et al. 2007), where j denotes the area considered (that may be an administrative region or the entire country), t = time, $PriorPfree_{t,j}$ = the prior probability of pest freedom and Se = the sensitivity of the survey. For the administrative regions, $Se = GSe_j$ (i.e. group sensitivity) and, at the national level, $Se = SSe$ (i.e. system sensitivity).

The initial prior probability of freedom, (i.e. the prior probability of freedom for the first time-step) was assumed to be 0.5 for all the regions and for the entire country, indicating that no information was available about the presence/absence of PWN before the surveys were started. To study the impact of this assumption on the probability of freedom achieved by 2018, the assessment was done also assuming an initial prior probability of freedom equal to 0.25.

For all the other time steps, the prior probability of freedom was calculated as the complement of the probability that a) the prevalence of the pest was above the design prevalence although it was not detected in the previous survey or b) the pest was introduced to the area after the previous survey as (Martin et al. 2007):

$$PriorPfree_{t,j} = 1 - \left[\left(1 - Pfree_{t-1,j}\right) + Pinv_{t,j} - \left(1 - Pfree_{t-1,j}\right) \cdot Pinv_{t,j} \right] \quad (10)$$

where $Pinv_{t,j}$ = the probability that the pest was introduced to the considered area after the survey conducted at time t—1.

The probability of invasion to the region j was calculated as:

$$Pinv_j = Pinv_{FINLAND} \cdot RP_j \quad (11)$$

where $Pinv_{FINLAND}$ = the probability of invasion to Finland and RP_j = the relative probability of PWN invasion to region j (see equation 2). Since the probability of PWN invasion to Finland was not known, a wide range of probabilities was studied. When presented in the results, the probability of invasion per year was translated to mean time between invasions to make the results easier to comprehend.

The parameters needed in the assessment

The number of wood objects and *Monochamus* sampled per inspection site

According to the survey guidelines of the NPPO of Finland, one wood sample could be composed of wood extracted from one or several trees or dead wood objects suitable for sampling. Unfortunately, information on the number of objects from which the samples were collected was not recorded. Based on discussions with inspectors who had undertaken the surveys, we concluded that the samples were typically composed of wood from a minimum of one, maximum of five and most often two objects.

These estimates were used to define a Pert probability distribution, which describes the probability distribution of the number of wood objects sampled per inspection site (n_{wood}). The lambda parameter, which defines the peakedness of the Pert distribution, was set to one, implying low confidence in the most likely estimate.

The number of *Monochamus* sampled per inspection site ($n_{Monochamus}$) in a given year and region was estimated by dividing the number of *Monochamus* caught by the number of traps used (Table 2). In the cases where *Monochamus* were caught by hand, each *Monochamus* was assumed to have been caught from a different inspection site.

The density of wood objects suitable for sampling

The density of wood objects suitable for sampling (D_{wood}) was estimated based on 1) the density of wood objects that are suitable for *Monochamus* breeding and 2) the proportion of these objects that is suitable for sampling, i.e. the proportion of objects that have signs of *Monochamus* activity.

Since data from Finland were not available, the density of dead wood objects that are suitable for *Monochamus* breeding was estimated, based on data from Norway. According to Økland et al. (2010) in Norway, the number of dead wood objects suitable for *Monochamus* breeding per km^2 is most likely to be 288, whereas the minimum number is 166 and the maximum, 398. These estimates were used to define a Pert distribution describing the probability distribution of the density of dead wood objects suitable for *Monochamus* breeding (*obj*). The lambda parameter, which defines the peakedness of the Pert distribution, was set to one, implying low confidence in the most likely estimate.

The proportion of the *Monochamus* suitable dead wood objects (*obj*) that is suitable for sampling (*psam*) was not known and, therefore, it was described with a uniform distribution between 0.05 and 0.95. Finally, an estimate of the density of wood objects suitable for sampling (D_{wood}) was obtained by multiplying the two distributions ($obj \times psam$) using Monte Carlo simulation. The median of the resulting distribution was 136 objects per km^2 and the 2.5^{th} and 97.5^{th} percentiles were at 19 and 309 wood objects per km^2, respectively.

The density of *Monochamus* adults

Two *Monochamus* species (*M. galloprovincialis* and *M. sutor*) are known to be widely present in Finland (Heliövaara et al. 2004; Rassi et al. 2015), but information about their density was not available. Therefore, the density of *Monochamus* adults ($D_{Monochamus}$) was estimated using the following data from Norway. The number of dead wood objects occupied by *Monochamus* per km^2 (*obju*) is most likely to be 28.8 (min 13.3, max 47.8), the number of *Monochamus* eggs laid per *Monochamus*-suitable dead wood object (*fobj*) is most likely to be 31 (min 6, max 88) and the proportion of *Monochamus* surviving from egg to egg-laying adults (*surv*) is most likely to be 0.25 (min 0.1, max 0.4) (Økland et al. 2010).

These figures were used to define the Pert distributions describing the probability distributions of the above-listed parameters (*obju*, *fobj* and *surv*). The lambda parameter of the Pert distributions was set to one, implying a low confidence in the most likely estimate. An estimate of the probability distribution of the density of *Monochamus* adults was obtained by multiplying these Pert distributions ($obju \times fobj \times surv$) using Monte Carlo simulation. The median of the resulting distribution was 266 adults per km^2 and the 2.5^{th} and 97.5^{th} percentiles were at 47 and 862 adults per km^2, respectively.

The size of the inspection sites

To convert the density of wood objects suitable for sampling (D_{wood}) and the density of *Monochamus* adults ($D_{Monochamus}$) to the number of wood objects suitable for sampling per inspection site (p_{wood}) and the number of *Monochamus* adults per inspection site ($p_{Monochamus}$), respectively, we needed to define the size of the inspection sites.

If the size of the inspection sites were defined based on the instructions given in the survey guidelines of the NPPO, it would have been, on average, 3 ha for the wood sampling (a sample per 2 ha or at least 200 m between samples) and 25 ha for the *Monochamus* trapping component of the survey (at least 500 m between traps). To control whether these sizes were appropriate considering the selected design prevalences, we checked if they were such that the number of infected individuals per inspection site at the design prevalence would be at least one. This was done by studying the estimated probability distribution of the density of wood objects suitable for sampling and that of the density of *Monochamus* adults.

The probability that the number of wood objects per inspection site was high enough was only 3.3%, whereas, for the number of *Monochamus* adults per inspection site, it was 97.6%. Hence, in the wood sampling component of the survey, the original size of the inspection site was too small, but in the *Monochamus* trapping component, it was adequate. We corrected this by adjusting the size of the inspection sites so that, at the apparent local level design prevalence, the number of infected individuals was at least one with a 95% probability. This adjusted size was 35 ha for the import-export survey and 63 ha for the early detection survey.

Adjusting the size of the inspection sites retrospectively was somewhat problematic. This is because some of the samples may have been collected so close to each other that, when the size of the inspection sites was increased, all samples did not actually represent the different inspection sites. However, this was deemed unlikely to have an impact on the results because the number of samples (Table 2) was very low compared to the total area covered by the surveys (Table 3).

Results

The PWN was not found in any of the 8,097 wood or 47 *Monochamus* samples collected and analysed in Finland in 2000–2018.

The sensitivity of inspections

The sensitivity of inspections was clearly higher for the wood sampling than for the *Monochamus* trapping component of the surveys (Table 5). In the import-export surveys, the median inspection sensitivity of the wood sampling component was 0.32 and, in the early detection surveys, it was 0.17. For the *Monochamus* trapping, the median inspection sensitivity was 0.00 in both types of surveys.

Table 5. The sensitivity of inspections of the import-export and early detection surveys. Only the regions and years with sampling activity were included. Abbreviations: ISe_{wood} = the inspection sensitivity of the wood sampling component, $ISe_{Monochamus}$ = inspection sensitivity of the *Monochamus* trapping component.

	Import-export			Early detection		
	Median	**2.5%**	**97.5%**	**Median**	**2.5%**	**97.5%**
ISe_{wood}	0.32	0.12	0.48	0.17	0.06	0.27
$ISe_{Monochamus}$	0.00	0.00	0.60	0.00	0.00	0.36

The sensitivity of the annual surveys

At the level of the administrative regions, the sensitivity of the annual surveys was rather low in most years and regions (Fig. 3). For the import-export surveys, it was at most 0.62 and, for the early detection surveys, it was at most 0.55 in all the regions and years with 97.5% probability.

At the national level, the sensitivity of the annual surveys was clearly higher than at the regional level for the import-export surveys, but not for the early detection surveys (Fig. 4). It was also clearly different for the two surveys types. For the import-export surveys, the sensitivity was at least 0.6 in 13 years with 97.5% probability, whereas, for the early detection surveys, the sensitivity was below 0.15 in 18 years, with 97.5% probability.

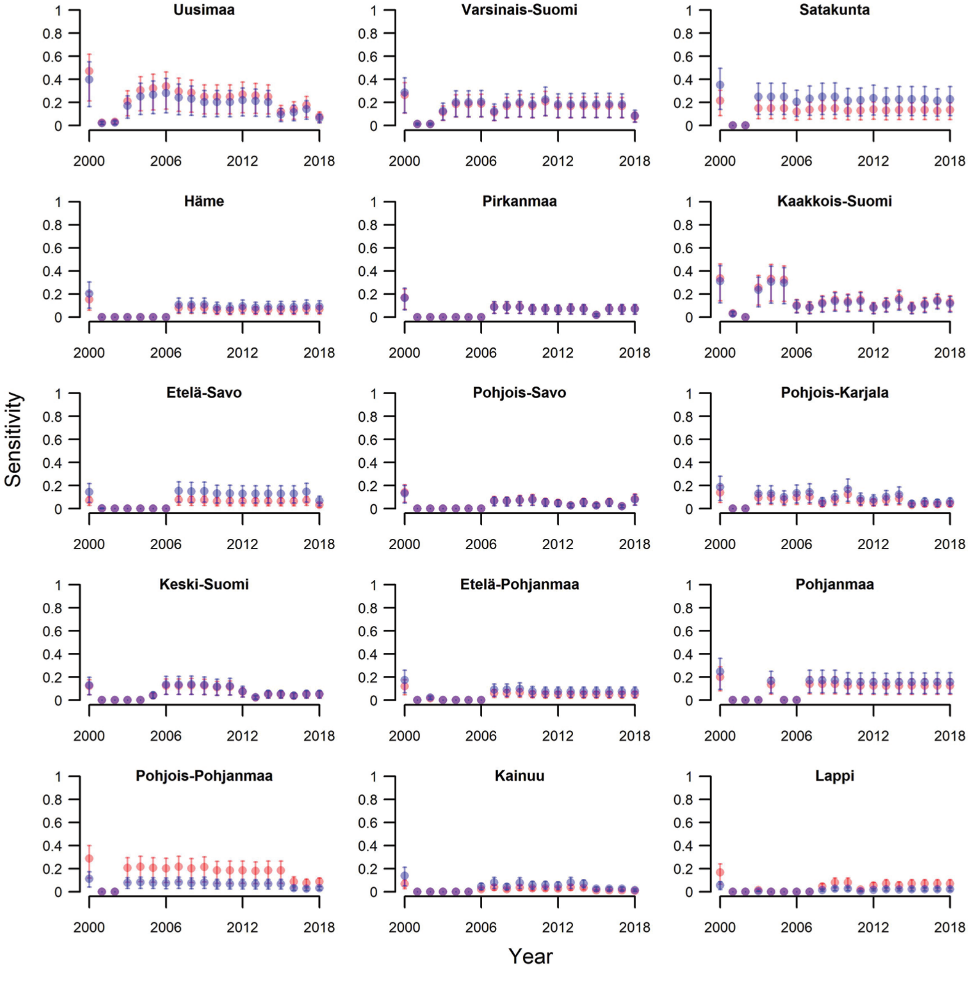

Figure 3. The sensitivity of the annual surveys in 2000–2018 in the administrative regions of Finland. The dots denote the medians and the bars the 95% confidence intervals of the assessment results. Red denotes the import-export surveys and blue denotes the early detection surveys.

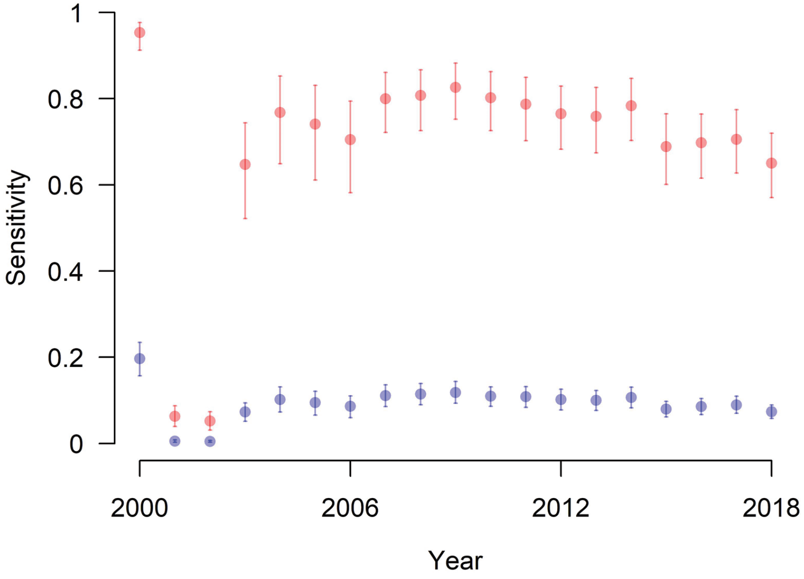

Figure 4. The sensitivity of the annual surveys in 2000–2018 in Finland. The dots denote the medians and the bars, the 95% confidence intervals of the assessment results. Red denotes the import-export surveys and blue denotes the early detection surveys.

The probability of freedom from PWN based on 19 years of surveys

The probability of pest freedom achieved by 2018 increased asymptotically with the mean time between PWN invasions (Figs 5, 6). In the administrative regions, the increase levelled out when the mean time between invasions was equal to 6–14 years and 6–17 years for the import-export and early detection surveys, respectively. At this levelling-out point, the probability of freedom was, at most, 0.05 lower than if the mean time between invasions was 100 years. At the national level, a similar levelling-out point occurred when the mean time between invasions was equal to 13 and 63 years for the import-export and early detection surveys, respectively.

The probability of pest freedom at the above-defined levelling-out point was rather high in many regions, both for the import-export and early detection surveys (Fig. 5). For both survey types, it was greater than 0.8 in five regions (with 97.5% probability). However, at the national level, the probability of pest freedom at the levelling-out point was clearly different for the two survey types (Fig. 6). It was 0.95 for the import-export and 0.73 for the early detection surveys (Fig. 6). The uncertainty of the assessment appeared to be low, since the probability distributions of the probability of pest freedom were narrow for both types of surveys (Figs 5, 6).

The used initial prior probability of freedom did not affect the probability of freedom achieved by 2018 in the import-export surveys, as it was similar for initial prior probabilities of freedom equal to 0.5 and 0.25 (Fig. 7). However, the probability of freedom achieved in the early detection surveys by 2018 was affected by the

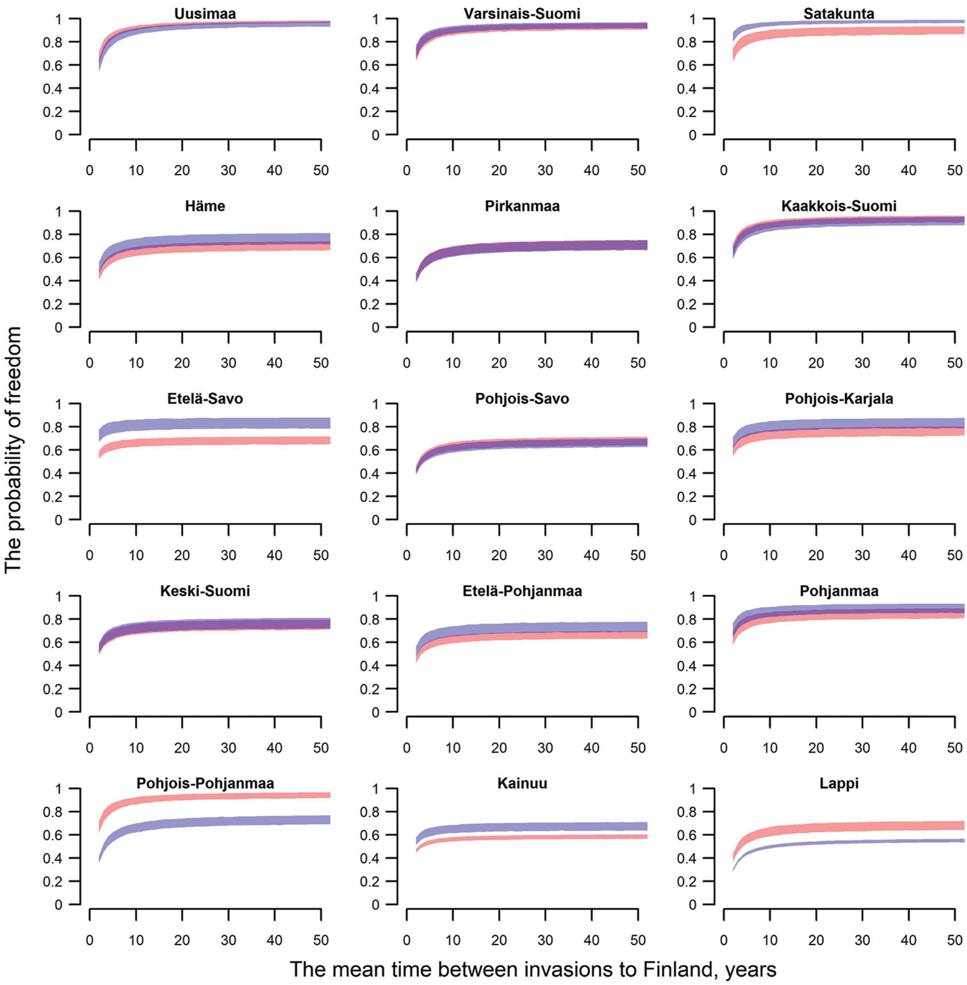

Figure 5. The probability of freedom from PWN achieved by 2018 in the administrative regions of Finland. The coloured areas show the 95% confidence intervals of the assessment results. Red denotes import-export surveys and blue denotes the early detection surveys.

initial prior probability of freedom that was used. It was clearly higher if the initial prior probability of freedom was 0.5 than if it were 0.25. This was true for all probabilities of invasion, except for those that were very high (Fig. 7).

Discussion

Reliable information about the distribution of quarantine pests is needed to prevent the pests from spreading with international trade. Additionally, if pest invasions are to be eradicated, they must be detected at an early stage, because, if the pest is widespread,

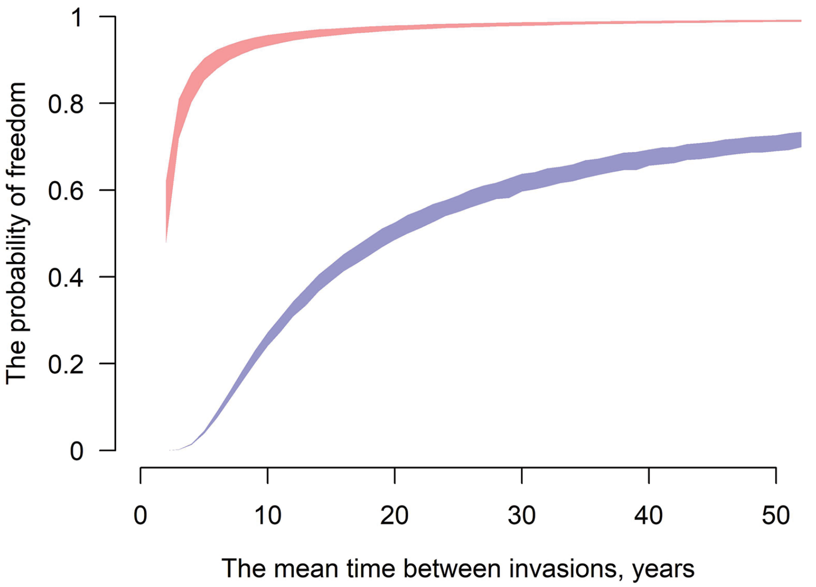

Figure 6. The probability of freedom from PWN achieved by 2018 in Finland. The coloured areas show the 95% confidence intervals of the assessment results. Red denotes the import-export surveys and blue denotes the early detection surveys.

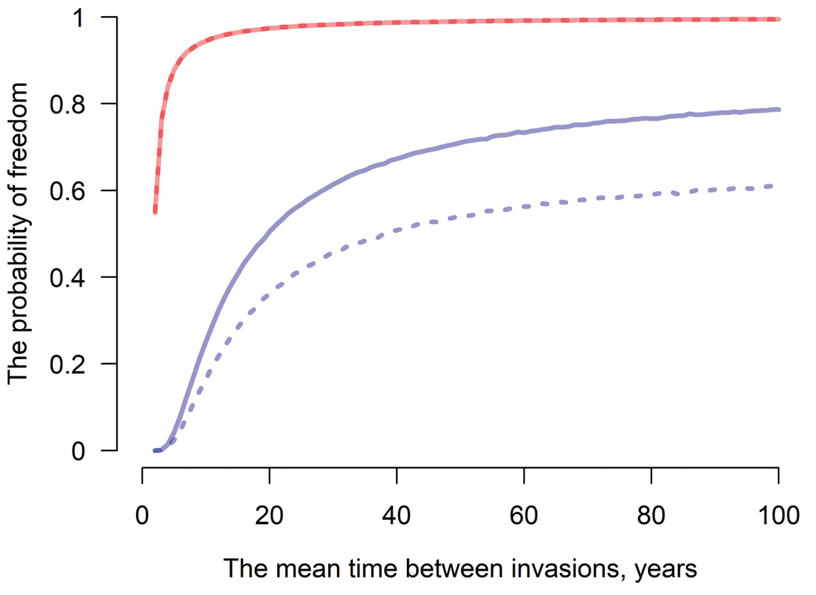

Figure 7. The probability of freedom from PWN by 2018 for two initial prior probabilities of freedom. The solid lines indicate the median of the assessment results when the initial prior probability of freedom was equal to 0.5 and the dashed lines indicate the results when the initial prior probability of freedom was equal to 0.25. Red denotes the import-export surveys and blue denotes the early detection surveys. Only one red line is visible, as the two lines overlap.

eradication is usually not feasible (Pluess et al. 2012a, b) To this end, all EU countries are required to conduct annual surveys for several quarantine pests, including PWN (European Council 2000, EU 2016). However, the sensitivity of these surveys has not yet been commonly analysed and, thus, it is not known if they are as useful for biosecurity as aspired.

Guidance on how to assess the sensitivity of annual surveys and the probability of freedom achieved in multiannual surveys is available (Cannon 2002; Martin et al. 2007; EFSA 2012, 2018), yet, so far, it has been widely applied mainly in the field of infectious animal diseases (e.g. Willeberg et al. 2011, but see, for example, Dominiak et al. 2011; Kean et al. 2015). Therefore, practical examples from the field of plant pests, such as the one presented in this paper, are essential for promoting a more objective analysis of official quarantine pest surveys and their impact on biosecurity.

The probability that Finland is free from PWN

The surveys support the assumption that PWN is not established in Finland. This is because the PWN was not found in any samples, although the sensitivity of the import-export surveys was rather high in many years and the probability of pest freedom achieved by 2018 was very high (≥ 0.95), unless the mean time between invasions was short (< 13 years). However, the surveys did not appear to be extensive enough to ensure early detection of PWN invasions. The sensitivity of the early detection surveys was very low in all years and the probability of freedom achieved by 2018 was rather low (< 0.73) unless the mean time between invasions was long (≥ 63 years).

The assessment seemed to be rather robust with respect to the parameters for which exact information was lacking (i.e. the density of wood objects suitable for sampling, the density of *Monochamus* adults and the number of wood objects from which a sample was collected). This is evident since the probability distributions of the sensitivity of annual surveys and especially those of the probability of pest freedom achieved by 2018 were rather narrow. Better data on the uncertain parameters would obviously improve the quality of the assessment, but acquiring such data does probably not deserve a high priority due to its minor impact on the outcome. It is noteworthy that aleatoric uncertainty (i.e. variation), which in these cases is inevitably large, cannot be reduced by more or better data.

Strictly speaking, the assessment of the probability of freedom did not cover the whole country, since the target population of the surveys was only the area with PWN host plants at 5 km radius from harbours, industrial areas and landfills (i.e. risk areas). However, these areas cover about 78% of the total area with PWN host plants in Finland (Table 3) and the probability of PWN infestation in the remaining remote locations is probably very low.

We did not find any published assessments of the sensitivity of PWN surveys done in other counties. However, Økland et al. (2010) assessed the probability with which the PWN surveys in Norway, together with the eradication measures proposed in the

Norwegian contingency plan for PWN, would result in successful eradication of a PWN outbreak. They did not report the sensitivity of the surveys for detecting a predefined pest prevalence (i.e. design prevalence), but they did report that the probability with which a PWN outbreak would be detected during the first years of invasion was extremely low (0.00013 and 0.011 for the 1st and 4th year, respectively).

Quantitative estimates of the probability of invasion are needed

Being able to accumulate evidence for pest freedom from consecutive surveys would be very useful. For both survey types, the support for the assumption that PWN is absent from Finland was much stronger if the evidence from all the years were pooled than when the surveys done in different years were analysed separately. This was true for all except high probabilities of invasion.

To pool evidence from consecutive surveys, a quantitative estimate of the probability of pest invasion is needed. However, very rough estimates apparently may be sufficient because, when the mean time between PWN invasions was above a certain level, its increase had only a very small impact on the probability of pest freedom.

A quantitative estimate of the probability of PWN invasion to Finland is not available, although the probability of PWN entry to new areas in the European and Mediterranean countries has been assessed as “considerable” and the probability of PWN establishment as “highly likely” (EPPO 2009). Moreover, Douma et al. (2017) assessed the exposure of European pines to PWN via the trade of wood and they estimated that in Finland, at most, approximately 1.2 PWN per year come into contact with a host tree. However, to be able to translate this figure into probability of invasion, the probability that such a contact results in the establishment of a PWN population should be assessed too.

Most pest risk assessments are qualitative and, therefore, quantitative estimates of the probability of invasion are available only for some pest species/area at risk combinations, such as *Sirex noctilio* and North America (Koch et al. 2009; Yemshanov et al. 2009; 2010). EFSA Panel on Plant health (EFSA PLH Panel) has recently published a protocol for quantitative pest risk assessment (EFSA PLH Panel 2018a), which has been, this far, applied to nine assessments (EFSA PLH Panel 2016a; 2016b; 2016c; 2016d; 2017a; 2017b; 2017c; 2017d; 2018b), some of which report estimates that could be translated to probability of invasion per year. Although the assessments were done at the EU level, they could probably be used to obtain an indication about the order of magnitude of the probability at the national level too.

Defining meaningful design prevalence is crucial

Defining design prevalences with care, so that they reflect the aims of the survey, is central. Unfortunately, very little guidance is available for defining design prevalences for quarantine pests. Martin et al. (2007) advise that the design prevalences for infectious animal diseases should be based on international standards, requirements of the trading partners, political considerations, availability of resources and/or biological plausibility. The list is relevant also for quarantine pest surveys if the aim of the survey is to justify import requirements and to facilitate export. However, if the aim of the survey is to detect pest invasions early enough to enable successful eradication of outbreaks, only the last two (availability of resources and biological plausibility) are relevant.

The international standard for phytosanitary measure that sets the requirements for surveillance (FAO 2018) encourages NPPOs to report the minimum pest prevalence that a survey is aiming to detect (i.e. design prevalence) and the probability with which it is expected to succeed in this aim (i.e. sensitivity). However, the standard comments neither on the appropriate levels of those parameters nor on how they should be defined. Additionally, EU legislation leaves the definition of the design prevalence to the member states, although it requires that sound scientific principles are used and timely detection of the pests is ensured with a high degree of confidence. EFSA is currently preparing survey guidelines for several quarantine pests (EFSA 2018), which will hopefully aid NPPOs in defining design prevalences.

We defined the local-level design prevalences of PWN, based on the prevalence of a closely-related species, *Bursaphelenchus mucronatus*, in the samples collected in the PWN survey. Thus, all the biases in the sampling process of *B. mucronatus* and PWN were the same, which was perfect for our purpose. However, the reported prevalence of *B. mucronatus* cannot be expected to correspond to the prevalence of *B. mucronatus* in standing trees, because the sampling was targeted at material that had signs of *Monochamus* activity.

We defined the regional- and national-level design prevalences for the early detection surveys based on article 7 of the EU emergency measures for PWN (EU 2012), which allows member states to refrain from attempting eradication if the diameter of the infested area is more than 20 km. However, it is not clear if such a large infestation could be eradicated with the resources available for delimiting the infested area and conducting the eradication measures.

Misinformed initial prior probability of freedom may distort the assessment

The prior probability of freedom at the first time-step (i.e. the initial prior probability) should be in line with the probability of invasion, unless reason exists to assume that the probability of invasion was different before the survey was initiated. In other words, if the probability of invasion is assumed to be high, assuming the initial prior probability of freedom is low is not logical and vice versa.

This appeared to be worth considering even when using a seemingly uninformative initial prior probability of freedom equal to 0.5. In the early detection survey, in which the sensitivity of annual surveys was low, the initial prior probability of freedom had an impact on the probability of freedom even after 19 years of surveys, unless the probability of invasion was very high.

This shows that, if the sensitivity of the survey is low, the initial prior probability of freedom can have an impact on the probability of freedom for several years. Thus, in such cases, the results from the first years of surveys should be interpreted with caution if the initial prior probability is uncertain. This is especially relevant if the trend in the probability of freedom is decreasing because, in such cases, the results for the first years are likely to be too optimistic.

Statistical analysis should be considered already when planning surveys

Some complications encountered in the current assessment emphasise the importance of proper survey planning and indicate some of the issues that one should be aware of when planning surveys. First, risk areas should be defined so that they cover a sensible proportion of the total area at risk. Otherwise, the value of classifying areas according to risk is compromised. In the Finnish PWN survey guidelines, the definition of risk areas was such that they covered most of the area with PWN host plants and, therefore, the risk-based survey design could not be used in the assessment. The probability of freedom from PWN achieved with the surveys would probably be higher if a risk-based design were used.

Second, local design prevalence should be defined and the density of objects suitable for sampling should be estimated before the area covered by one inspection (inspection site) is defined. This is because the size of the inspection site should be such that, at the local level design prevalence, the number of infected objects per inspection site is at least one. In the Finnish PWN survey guidelines, the area covered by one inspection was so small that, at the local level design prevalence, the number of infested wood objects was less than one and, therefore, we had to redefine the size of the inspections site for this assessment.

Conclusions

The PWN surveys conducted in Finland in 2000–2018 appeared to support the assumption that PWN is not present in Finland, but they did not seem extensive enough to ensure early detection of PWN invasions. Without corresponding assessments, it is not possible to tell if, for example, the PWN surveys in the other EU countries have been any better or how much the surveys of other quarantine pests benefit biosecurity.

The efficiency of the surveys could probably be improved by revising the definition of risk areas (e.g. to 2 km radius form harbours and industrial areas) and by optimising the number of inspected sites versus the number of samples collected per inspected site. However, without a thorough assessment, it is impossible to know if such revisions could improve the efficiency enough, i.e. so much that PWN outbreaks would be detected, with a high degree of confidence, early enough to facilitate eradication.

To enable analysis of pest freedom, based on multiannual surveys, quantitative estimates of the probability of invasion are needed, but rather rough estimates may be sufficient. Furthermore, methods for determining meaningful design prevalence, especially for early detection surveys are needed. Ideally, the design prevalence in early detection surveys should represent the area from which eradication of the pest is feasible.

To learn whether the current quarantine pest surveys, in the EU and elsewhere, are as beneficial for biosecurity as aspired, we need many more examples of the sensitivity that is, in practice, achieved in the surveys. Otherwise, the only result of the surveys may be a false sense of biosecurity.

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Supplementary material 1

readme.txt

Authors: Salla Hannunen, Juha Tuomola

Data type: instructions

Explanation note: Instructions on how to run the R-scripts needed to make the assessments presented in "Assessing the probability of freedom from pine wood nematode based on 19 years of surveys" by Hannunen and Tuomola.

Link: https://doi.org/10.3897/neobiota.58.38313.suppl1

Supplementary material 2

Sensitivity.R

Authors: Salla Hannunen, Juha Tuomola

Data type: R code

Explanation note: This script calculates the sensitivity of the annual surveys in 2000-2018 for all the administrative regions and Finland and plots them as figures.

Link: https://doi.org/10.3897/neobiota.58.38313.suppl2

Supplementary material 3

Probability_of_freedom.R

Authors: Salla Hannunen, Juha Tuomola

Data type: R code

Explanation note: This script calculates the probability of freedom achieved by 2018 for a range of probabilities of invasion for all the regions and Finland and plots them as figures.

Link: https://doi.org/10.3897/neobiota.58.38313.suppl3

Supplementary material 4

Data.R

Authors: Salla Hannunen, Juha Tuomola

Data type: R code

Explanation note: This script contains the data used in the assessment.

Link: https://doi.org/10.3897/neobiota.58.38313.suppl4

Supplementary material 5

Sensitivity_function.R

Authors: Salla Hannunen, Juha Tuomola

Data type: R code

Explanation note: This script contains a function that returns the sensitivity of the annual surveys in 2000-2018 for all the regions and Finland in one array.

Link: https://doi.org/10.3897/neobiota.58.38313.suppl5

Supplementary material 6

Probability_of_freedom_function.R

Authors: Salla Hannunen, Juha Tuomola

Data type: R code

Explanation note: This script contains a function that returns the probability of freedom achieved by 2018 for a range of probabilities of invasion for all the regions and Finland in one array.

Link: https://doi.org/10.3897/neobiota.58.38313.suppl6