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Abstract

Emerging and invasive tree pests and pathogens in Europe are increasing in number and range, having impacts on biodiversity, forest services, ecosystems and human well-being. Stakeholders involved in tree and forest management contribute to the detection and management of new and emerging tree pests and pathogens (PnPs). We surveyed different groups of stakeholders in European countries. The stakeholders were mainly researchers, tree health surveyors and forest managers, as well as forest owners, nurseries, policy-makers, advisors, forestry authorities, NGOs and civil society. We investigated which tools they used to detect and manage PnPs, surveyed their current PnP awareness and knowledge and collated the new and emerging PnP species of concern to them. The 237 respondents were based in 15 European countries, with the majority from the United Kingdom, France and the Czech Republic. There was a strong participation of respondents with a work focus on research and surveying, whereas timber traders and plant importers were less represented. Respondents were surveyed on 18 new, emerging PnPs in Europe and listed an additional 37 pest species and 21 pathogen species as potential future threats. We found that species on EPPO's list of 'priority pests' were better known than those not listed. Stakeholders working in urban environments were more aware of PnPs compared to those working in rural areas. Stakeholders' awareness of PnPs was not related to the number of new, emerging PnP species present in a country.

Stakeholders want access to more detection and management tools, including long-term citizen-science monitoring, maps showing spread and range of new PnPs, pest identification smartphone apps, handheld detection devices, drone monitoring and eDNA metabarcoding. To help facilitate better forest health across Europe, they called for mixed forest development, reduced nursery stock movement, biosecurity and data sharing amongst organisations. These results indicate that stakeholder knowledge of a few key PnP may be good, but given that the large diversity of threats is so large and future risks unknown, we conclude that multiple and varied methods for generic detection, mitigation and management methods, many in development, are needed in the hands of stakeholders surveying and managing trees and woodlands in Europe.

Keywords

Forest management, invasive alien species, new methods and tools, participatory research, risk management, stakeholder survey, tree health biosecurity

Introduction

Trees and forests provide a multitude of environmental and socio-economic benefits (Trumbore et al. 2015; Baral et al. 2016); however, they face serious threats from new and emerging forest pests and pathogens (PnPs) (Wingfield et al. 2010). Global trade and international travel have resulted in the increasing introduction of invasive non-native tree pests and diseases (Roques 2010; Brockerhoff and Liebhold 2017; Meurisse et al. 2019) and their establishment and impacts are being exacerbated by climate change (Pautasso et al. 2015; Linnakoski et al. 2019) and degradation of forest land. Climate change also puts abiotic stress on trees making them more vulnerable to attack by PnPs (Tubby and Webber 2010; Bentz et al. 2010; Kubiak et al. 2017; Kim et al. 2021). Recent examples of alien PnPs in Europe include: *Xylella fastidiosa* subspecies *pauca* attacking olives and other plants (Desprez-Loustau et al. 2021) where *X. fastidiosa* was identified in Italy in 2013 (Saponari et al. 2019); *Phytophthora pluvialis* attacking Western hemlock, first recorded in UK in 2021 (Pérez-Sierra et al. 2022); and *Agrilus planipennis*, the emerald ash borer, found in European Russia since 2003 and in Ukraine since 2017 (Orlova-Bienkowskaja et al. 2020). An increase in forest damage caused by a native PnP, *Ips typographus*, the European spruce bark beetle, has recently been observed in many European forests, causing increased damage to forests. such as those in the Central German uplands (Zimmermann and Hoffmann 2020).

These alien and emerging PnPs are impacting trees in both natural and planted forests and rural and urban settings, by reducing the ecosystem services they provide. The impacts affect a wide range of stakeholders, thus emphasising the need to involve these groups also in their prevention and management. One of the first steps in this process is the understanding of stakeholder perceptions and suggestions for management solutions (Novoa et al. 2018). For tree and forest health, stakeholder perceptions have been investigated by Marzano et al. (2016); however, stakeholders' views and suggestions for management, in particular at the level of practical tools for management, have not been investigated so far.

Management of PnPs involves multiple stakeholders working in different areas who are involved at the different invasion stages of prevention, eradication, containment and control (Fig. 1) (Ambrose-Oji et al. 2019; Marzano et al. 2020). Furthermore, stakeholder awareness of PnPs and their management options and tools may differ between PnPs depending on PnP abundance or distribution. It is well established that the cost-effectiveness of a management method is inversely related to the abundance/ spread of a PnP (Turner et al. 2004). When targeting the first stages of the invasion process, management steps include preventing the introduction of new PnPs, detecting

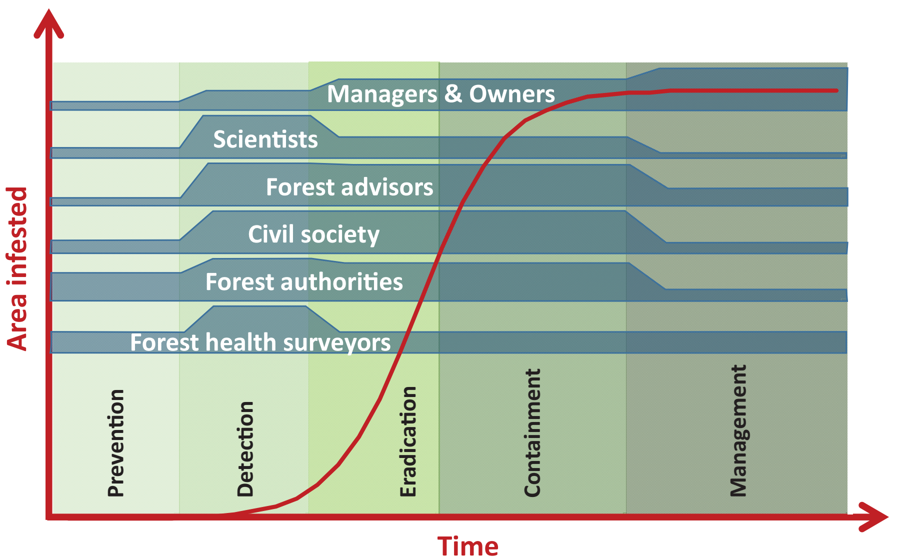

Figure 1. Engagement of different stakeholder groups in the management responses to the different stages of the invasion process of a generalised pest population infestation. Fig. 1 is a conceptual diagram intended to summarise how the various stakeholders interviewed in our survey position their involvement along the various stages of the invasion curve. The thickness of the bars is proportional to their relative involvement in these five steps. The six stakeholder groups were obtained by hierarchically clustering their responses to the questionnaire, assigning a generic name to the group, based on their reported profession. "Managers and Owners" The six stakeholder groups were obtained by grouping the respondents according to their declared professions. "Forest managers" are responsible for the management or maintenance of forests. "Scientists" do research in entomology and forest pathology. "Forest advisors" advise owners on the management of their forest. "Civil society" includes forest users or members of NGOs. The "Forest authorities" are in charge of the implementation of legal measures on forest management. "Forest health surveyors" refers to engineers and technicians in charge of monitoring and controlling forest pests and pathogens. The superposition of the bars corresponding to these six groups does not follow any particular hierarchy. It was chosen to maximise the clarity of the figure.

PnPs early and rapidly responding to those that are introduced and limiting PnP spread (Liebhold et al. 2016). When PnPs have become widespread and abundant, management steps include mitigating their impacts, containing them, protecting assets or salvaging damaged or dead trees (Holmes et al. 2009). As the size of an infested area increases over time, the eradication possibilities become less feasible. Stakeholders' ability to prevent PnP spread as early as possible depends on their awareness of new PnPs or PnPs that have not yet arrived, their role with respect to emerging PnPs, the sources of information available to them, the tools and resources they can use and their motivation of action (Marzano et al. 2015). Likewise, Marzano et al. (2015) also found that the approach to managing established PnPs depends on the focus of a stakeholders' role and the information, tools and resources available to them, regardless of the scale of the outbreak. The stakeholders involved in managing established PnPs are likely different from those involved in early detection and monitoring, so it is important to know what tools and methods stakeholders use currently for PnP detection, identification and management, as well as what stakeholders would like to use to improve management of PnPs in the future.

Gaining understanding of stakeholder awareness of PnPs and their engagement with management tools for PnPs can help to identify groups that may benefit from targeted information about PnPs or highlight areas in need of investment for the development and access to new detection and management tools. The few Europe-wide studies that have been conducted on this also indicate that there is a need to increase the opportunities for knowledge sharing by more experienced tree health practitioners (Marzano et al. 2015; White et al. 2018). Given this, we sought to discover the current knowledge and awareness held by stakeholders in order to provide information about how to target and pitch such knowledge sharing opportunities.

We studied stakeholders' awareness and knowledge of the presence or absence of 18 new and emerging PnPs (Table 1) in their country and of various management practices, using an online questionnaire survey shared with forest health stakeholders from 15 European countries. For our study, forest health stakeholders included all stakeholders engaged with tree work or tree monitoring whether for employment or voluntarily. We formed groups of stakeholders, based on their types of work using cluster analysis and we compared the level of awareness, knowledge and tool use between different groups. Knowledge and awareness are often considered together, for example, Marzano et al. (2016) assessed different levels of knowledge and awareness (without making a distinction) on a scale of four levels ranging from low, where people had never heard about a PnP, to high, where they said they knew a lot about a PnP. However, these responses were not verified. In our study, we use awareness following the definition used by Sudarmadi et al. (2001) as "the attention, concern and sensitivity of the respondent to environmental problems" and for knowledge as "a body of facts and principles concerning the environment that have been accumulated by mankind through study". We, therefore, distinguish awareness, where a stakeholder comments on the status of a PnP independently of whether this is correct or not, from knowledge, where they are correct in their comment about the status of a PnP in their country. Bet-

Table 1. Species and common names of 18 PnPs listed in the survey of forest health stakeholders to answer if they were aware of their presence and abundance in their country and which methods are used to detect and manage it.

The 18 PnPs in the survey	
Common name	**Latin name**
Asian longhorn beetle	*Anoplophora glabripennis*
Box tree moth	*Cydalima perspectalis*
Asian chestnut gall wasp	*Dryocosmus kuriphilus*
Oak processionary moth	*Thaumetopoea processionea*
Douglas-fir needle midge	*Contarinia pseudotsugae*
Emerald ash borer	*Agrilus planipennis*
Eucalyptus snout beetle	*Gonipterus platensis*
Black twig borer	*Xylosandrus compactus*
Oak lace bug	*Corythucha arcuata*
Shot-hole borer	*Euwallacea fornicatus*
Pine wood nematode	*Bursaphelenchus xylophilus*
Pine pitch canker	*Fusarium circinatum*
Pine red band needle blight	*Dothistroma septosporum*
Pine brown spot needle blight	*Lecanosticta acicola*
Root rot fungi	*Heterobasidion irregulare*
Phytophthora ramorum blight	*Phytophthora ramorum*
Ash dieback	*Hymenoscyphus fraxineus*
Xylella wilt	*Xylella fastidiosa*

ter information about these two levels of understanding of stakeholders is important to guide communication about PnPs. Furthermore, we analyse how stakeholder awareness and knowledge are dependent on a range of factors, including presence/absence of PnPs in their country, the urban/rural setting of their work, regulatory status and taxonomic group of the PnPs. We then asked which other PnPs outside our survey list of 18 species were of concern to them. We modelled the responses to determine if the tools used by stakeholders for detection and management depended on their type of work, the PnP species and how long they had experienced the PnP and gathered suggestions for other tools they want access to or to see developed.

Three PnPs were chosen as case studies (*Phytophthora ramorum*, Asian longhorn beetle *Anoplophora glabripennis* and Oak Processionary Moth *Thaumetopoea processionea*) to gain further insight into how effective detection and management methods were perceived to be and whether the methods used varied according to the PnP species and the urban/rural setting of stakeholders' work. These data will help policy-makers, researchers and communicators to appreciate the current understanding and wishes of tree health stakeholders working in different countries, roles and scales, to be able to create tools and resources that are more effective to protect forests from PnPs.

Materials and methods

The study was conducted using an online survey distributed within Europe from October 2019 to March 2020. The survey was designed in English (see Suppl. material 1) and then translated into eight further languages (French, Czech, Italian, Bulgarian, German, Portuguese, Dutch and Swedish). For each language version, there was a national contact person who translated the survey and who was responsible for its distribution to stakeholder groups in the country and, later, the translation of results into English. The questionnaire was designed using the 'Online surveys' platform (https://onlinesurveys.ac.uk/) and first tested via a pilot version in English.

We used a snowball approach in order to reach a wide range of target groups involved in the tree health sector and working across the invasion stages. Initially, a volunteer project partner in each country sent the survey and an explanation of its aims, to relevant academic and professional contacts in their networks. They also e-mailed a list of suggested contacts in a variety of relevant work sectors, generated by other project partners, which included local and national interest groups and forestry newsletter editors. Those contacted were encouraged to share the survey link further in their relevant networks. In addition, we shared the survey link of the questionnaire in relevant languages on social media such as Facebook, Twitter and LinkedIn, encouraging readers to share it with their social media networks.

Questionnaire design

The questionnaire (see Suppl. material 1) addressed issues relating to new, emerging forest pests and diseases and was organised into three sections. The first section asked about the socio-environmental characteristics of respondents. The second section asked about their awareness and knowledge of 18 new and emerging forest PnPs in Europe (Table 1). The third section asked about the tools and methods that they used and would like to use, for detecting, identifying and managing new, emerging tree PnPs. The survey questions included some with required answers. The respondents selected which categories they found most relevant to them using their own judgement and experiences of their environment. Most of the questions were closed-ended, of which some were binary, some had a mixture of multiple possible answers and some had free text answers.

The socio-environmental characteristics asked about in section one comprised the main country and sector(s) of the stakeholder's work role, where their work relates with regard to the invasion stages, geographic scale of their work and urban/rural focus of their work. In section two, respondents were asked to comment on the presence in their country of a list of 18 PnPs and to name any other PnPs they were concerned about. In order to explore the knowledge and perceptions of stakeholders in more depth, this section enabled respondents to give further details of three PnPs (Asian longhorn beetle (ALB), Oak processionary moth (OPM) and *Phytophthora ramorum* (PRA)) regarding how long each PnP had been in their country, the main method used to manage the PnP and how effective they found their chosen management method. The third section asked respondents to select which tools and methods they use from a list of 17 for detecting and identifying PnPs and eight for managing PnPs, then asked open-ended questions for the tools and methods they would like to use in the future.

Informed consent was obtained from all participants. Personal data and responses were stored separately and processed in accordance with the UK General Data Protection Regulation 2016 (UK GDPR 2016) and the Data Protection Act 2018. The survey was approved through Coventry University's ethical approval review process (CU ethics number – Project P90536). A limitation of the study was the time that could reasonably be asked of stakeholders to complete the survey and that stakeholders may suffer from survey fatigue (Fan and Yan 2010). We shortened the survey to focus on further questions for three PnPs rather than the 18 listed and formed the case studies of three PnPs on Asian longhorn beetle, Oak processionary moth and *Phytophthora ramorum*. The choice of 18 PnPs reflected a mix of pests and pathogens at various invasion stages within the European continent. Once a stakeholder had answered the questions on one of the 18 listed PnPs (Table 1), they could not add it to be counted to their list of 'PnPs of concern' in the free text. This means that, within this study, it was not possible to compare the level of stakeholder concern between various PnPs.

Data analysis

The results from all surveys were translated to English where applicable and combined into one dataset. For each country and for each of the 18 PnPs listed, we determined their status at the time when the survey was conducted using the EPPO database (EPPO 2019) and checked if a PnP was listed in the European Commission's list of priority pests (Commission Delegated Regulation (EU) 2019/1702 2019). All statistical analyses were conducted in R version 4.2.2 (R core team 2022).

Clustering and groups

The survey question on stakeholders' work role was multiple choice and, from the 17 roles listed, respondents could choose all categories that applied to them. From the responses provided, we applied a clustering method to detect six separate groups of respondents in terms of their sectors of work. The input variables were binary. We used hierarchical clustering of a distance matrix calculated using a Euclidean distance measure (Hastie et al. 2001). The six groups formed (Table 2; Suppl. material 2: fig. S1) are used in our subsequent analyses to help understand stakeholder experiences and awareness of forest PnPs, as well as stakeholders' tool use for PnP identification, detection and management.

Stakeholder awareness of the 18 PnPs listed in the survey

We analysed stakeholders' awareness and knowledge from their responses to the question in the survey asking them about their experience of the 18 listed PnPs (see survey question 7 in Suppl. material 1). Any response, independent of whether the response was correct with regard to a PnP's presence or absence in a country, was regarded as being aware of a PnP, whereas any other responses ('not applicable', 'I don't know this PnP') or if respondents chose not to answer were interpreted as being unaware.

Table 2. Composition of six stakeholder groups.

Stakeholder group number and name	Stakeholder Group composition
Group 1 – Managers and Owners	This group is formed of 45 stakeholders mainly working in forest and tree management, some of whom may also be woodland or forest owners and, to a lesser extent, some stakeholders may also work in landscape architecture, NGOs, consultancy, education or arboreta. An example of a member in this cohort is a forest owner with a plant nursery, working in forest and tree management.
Group 2 – Scientists	This group comprises 28 people who selected their work as scientific researchers only. An example is a scientist researching tree pests and pathogens.
Group 3 – Forest Advisors	This is the largest group, 66 respondents, who are generalist practitioners and advisers. Many may work in scientific research, as well as forest and tree health surveys. Some combine these roles with forest and tree management, education or consultancy, plant health law, plant nursery or a related role. An example member is a respondent who works in scientific research and at an arboretum.
Group 4 – Civil Society	This is a group of 44 respondents with a mixed variety of roles, many relating to civil society, with a garden or amenity horticulture and plant nursery focus. Volunteers and interested citizens who are also researchers or working for NGOs may be included. An example is a respondent who works in gardens and amenity horticulture and scientific research, is a volunteer or interested citizen and a woodland or forest owner.
Group 5 – Forest authorities	Members of this group of 36, may be working in plant health law enforcement and forest authority organisations and at once be involved with forest and tree health surveys and policy-making. Examples of a member of this group is a respondent who works in plant health law enforcement and another respondent, involved in policy-making, forest authority work, forest and tree health surveys. as well as plant health law enforcement.
Group 6 – Forest Health Surveyors	This group comprises 16 stakeholders who are forest and tree health surveyors, one of whom is also a woodland or forest owner. An example is a respondent doing forest and tree health surveys.

Generalised linear mixed effect models (GLMMs) with binomial error distribution were then used with awareness (yes/no) as the dependent binary variable in our first model (model 1a). The independent variables were all categorical variables: respondents' stakeholder group allocation (six groups as described in Table 2); working scale (local/regional/national/European/global); PnPs, invasion status of PnPs (present, absent, eradicated); and the number of 18 PnPs present at country level. All explanatory variables were included as fixed effects, whilst country and respondent ID were included as random effects (see Suppl. material 2: table S2 for all variables).

In a second model (model 1b), we replaced the individual PnPs with two variables, "EU priority pest" (yes/no) and "insect" (Insect pest or not). This was done to avoid fitting an overly complex model while still being able explore further variables. Our list of 18 PnPs included 10 insects with the remaining species being fungal and bacterial pathogens and one nematode (Table 1). We also included the variable "urban" (yes/no). This variable was not included in model 1a because of missing values; however, model 1 including this variable is shown in the Suppl. material 2: table S3).

Stakeholder knowledge about the invasion status of the 18 PnPs in the survey

We then analysed respondents' knowledge of presence and absence of the 18 PnPs in their country by comparing their answers to the status (presence or absence) of the PnPs in the EPPO Global Database at the time when the survey was conducted (EPPO 2019). We excluded all responses of whether a PnP was 'unknown' to respondents or that no answer was given for, as well as responses where the pest had been eradicated in a country (227 observations) because respondents' choice of answer could not be consistently evaluated as correct or incorrect. We then modelled the correct score (yes/

no) at the level of each response for each PnP as a dependent variable using the same modelling framework as above (model 2a, b).

For the last GLMM analysis (model 3), we aggregated the data at the respondents' level to examine what determines a respondents' accuracy about the status of a pest. This was measured as the proportion of PnPs they reported correctly as present/absent for their country out of the total number they scored. Observations of eradicated PnPs were again excluded from this analysis. We also included the number of PnPs scored by each respondent (our measure of awareness) and the respondents' answers with regard to their main focus of work as a series of seven binary variables (detection, education, control, restoration, research, recording, adaptation).

All these models were analysed in R using the package glmmTMB for fitting GLMMs (Brooks et al. 2017).

In the final analysis, we considered the three status categories of the PnPs for each country: present, absent (never present) or eradicated (absent, but was previously present). We then considered three answers from the stakeholders: (present, absent, eradicated) and scored their answers as correct or incorrect according to a confusion matrix (Suppl. material 2: table S1). We awarded a score of one if their answer matched the PnP invasion status or zero if it was different, in addition to awarding a score of one if a respondent said a PnP was eradicated when the PnP status was actually absent. We calculated the overall percentage of correct scores for the list of 18 PnPs per respondent, then pooled the responses from each country to create a country-wide percentage score. Finally, we used countries as "replicates" to calculate the mean and standard error of these percentages of correct score to produce the results.

New and emerging PnPs of concern to stakeholders

Respondents' free text responses regarding further new, emerging tree pests and diseases of concern were gathered, translated and cleaned to remove ambiguous entries or broad groups of organisms. The data were then grouped by frequency, organism type and country of the respondent. The 18 PnPs listed in the survey in Table 1 were excluded. A combined list of all EPPO priority pests (from the EPPO A1 List of pests recommended for regulation as quarantine pests, EPPO A2 List of pests locally present in the EPPO region and EPPO Alert list of pests possibly presenting a risk to EPPO member countries) was edited to exclude non-tree pests. Then, species listed by respondents that were currently, or had ever been, EPPO priority pests (EPPO 2019) and EU Priority pests (EFSA 2019) were noted. From the combined EPPO list, a percentage was calculated to show the proportion of the list which was represented in the free text responses.

Case studies on Asian longhorn beetle, Oak processionary moth and *Phytophthora ramorum*

Further information was gathered about which primary management method was used by respondents against three case study PnPs, (Asian longhorn beetle, Oak processionary moth and *Phytophthora ramorum*) and how effective the method was perceived to be. To reflect the invasion stage of each PnP in a country, data were obtained from the EPPO distribution maps in April 2022 (EPPO 2022a).

Ninety responses were received for Asian longhorn beetle, 119 for *Phytophthora ramorum* and 104 for Oak processionary moth. The null hypothesis that there was no difference in the use of each management method for each PnP was tested using a Chi squared test for twelve degrees of freedom in R (R core team 2022). The observed frequency of use of each method was compared to the expectation that use of each tool would be equally represented if the null hypothesis were true. Efficacy perception ratings were transcribed into scores where five points corresponded to the most effective rating and one point for the least effective. Mean scores were calculated for the perceived efficacy of each method used against each PnP and for perceived efficacy of management for each PnP according to the urban/rural setting of respondents' work. A top-down approach of a maximal linear model was taken to analyse efficacy scores. The PnP, management method, urban/rural setting of respondents' work and all interaction terms were included initially as explanatory variables. The least significant terms were removed one at a time in a stepwise fashion until all variables with p values less than 0.05 could be identified.

Use of tools for detection and management of PnPs

A PERMANOVA (Anderson 2017) was used to study differences in detection and management tools and methods used across stakeholders. The binomial distance was used to calculate the distance amongst respondents in terms of the methods they used against PnPs. Next, we tested whether the distances between groups was significantly larger than within groups. In case the overall test revealed a significant effect of stakeholder groups, a post hoc test with Bonferroni correction was used to show which stakeholder groups were significantly different from each other.

Stakeholders' desired tools and methods

Respondents' answers to open ended questions relating to tools and methods used and those desired to help with PnP detection and management, along with their suggestions for future tool development, yielded a large number of diverse responses. These were extracted, analysed and presented in the Results as tables of the most frequent themes, together with a description of the themes, as drawn from stakeholder comments.

Results

Participant profile

The survey was completed by 237 respondents from 15 European countries. The majority of respondents were from the United Kingdom (69 responses), France (46) and the Czech Republic (28) (Suppl. material 2: fig. S2a for other countries). Respondents could select multiple foci of their work regarding tree PnPs (prevention of entry at border, early detection/rapid response, recording, control and management, adaptation, restoration, education, research). Early detection and rapid response was selected by the greatest number of respondents as their focus of work regarding PnPs, (n = 117; Suppl. material 2: fig. S2b), followed closely by those with a control or management focus (n = 113). Research and recording, for example, surveillance, were well-represented with over a quarter of respondents answering for each (n ≥ 87). Adaptation, or the change of cultural techniques and practices (n = 45), then restoration were the least represented answers (n = 25) and just ten respondents selected "other" as their working focus.

We formed groups of stakeholders for the analysis from the clustering methods, relating to the respondents' sectors of work (Table 2). Group 1 is formed of 'Managers and Owners', respondents who are mainly working in forest and tree management. Group 2, 'Scientists', is formed of scientific researchers only. Group 3, 'Forest advisors', is the largest group of 66 respondents and contains generalist practitioners and advisors. Group 4, 'Civil Society' includes volunteers, NGO workers and those with a mix of backgrounds relating to civil society. Group 5, 'Forest Authorities', include respondents working in plant health law enforcement, forest authority organisations, tree surveying and policy-making. Group 6, 'Forest Health Surveyors' is the smallest group of 16 respondents, who exclusively work in forest and tree health surveying. Table 2 also describes an example respondent from each group. Stakeholder groups differed in their awareness of PnPs and this is described in the results section on stakeholder awareness.

Research scientists were the best represented group by work role profile (n = 91; Suppl. material 2: fig. S2c; Question 3 in the survey in Suppl. material 1), followed by forest and tree health surveyors and those working in forest and tree management (n ≥ 70 each), whereas timber traders and plant importers were less represented (n < 10 each). The remaining groups covering forest authorities and policy-makers, educational and horticultural practitioners contained between 11 and 35 respondents each. Respondents were working at spatial scales from less than a hectare to worldwide. The majority of respondents were working at national scale (n = 79, 33%; Suppl. material 2: fig. S2d) and regional/sub-national scales (n = 60, 25%). Far fewer were working at European (n = 24, 10%) and worldwide (n = 19, 8%) scale. Seventeen (7%) respondents were working at 10 km^2 to regional area scales. Amongst the local scales, most respondents worked at scales between one and 99 hectares (ha) (n = 22, 9%), followed by 100–999 ha (n= 7, 3%) with few working at less than one ha (n = 6, 3%).

The majority of respondents worked with trees in mostly rural (n = 124, 52%) or completely rural (n = 54, 25%) environments. Considerably fewer worked in mostly urban (n = 34, 14%) or completely urban (n = 3, 1%) areas.

Stakeholder awareness of the 18 PnPs in the survey

Of the overall 4266 scores received for the 18 PnPs, 58% indicated that respondents were aware of the respective PnP (i.e. they said they were aware of a PnP, independent of whether they scored presence/absence correctly). The remaining 42% of scores related to responses where either no score was received or the respondents did not know the PnP. On average, respondents were aware of 10.5 (SE 0.32) of the 18 listed PnPs, ranging from four respondents not answering to any of the PnP scoring questions of the survey to 19 respondents scoring all of them.

Results from model 1a (Suppl. material 2: table S4) demonstrate that respondents' awareness was dependent on whether a PnP was present in their country or not ($F = 103.87$, $df = 2$, $p < 0.001$) with respondents more likely to be aware of PnPs that were present in their country. Awareness of PnPs differed significantly between the stakeholder groups ($F = 28.5$, $df = 5$, $p < 0.001$). Awareness of the individual PnPs varied significantly ($F = 466.24$, $df = 17$, $p < 0.001$), but the total number of PnPs present in a country did not have an impact on the probability that respondents were aware of individual species ($F = 2.35$, $df = 4$, $p = 0.672$).

When individual PnPs in model 1b (Suppl. material 2: table S4) were replaced with variables stating if a species were an insect or not, its status as EU priority pest and the urban or more rural working scale variable (reducing the number of observations), we found that all these variables were significant to explain increased awareness by respondents (Insect: $F = 47.18$, $df = 1$, $p < 0.001$; EU priority: $F = 221.72$, $df = 1$; Urban/rural working scale: $p < 0.001$, $F = 6.66$, $df = 1$, $p < 0.01$; Suppl. material 2: table S4). As in the full model, the status of the PnP species was significant ($F = 449.65$, $df = 2$, $p < 0.001$), as was the stakeholder group ($F = 29.44$, $df = 5$, $p < 0.001$). In particular, respondents in the 'Civil Society' group were less likely to be aware of a PnP, but respondents in the 'Forest Authority' group were more likely to be aware. Neither the number of PnPs present in a country ($F = 1.75$, $df = 1$, $p = 0.185$) nor the working scale ($F = 2.13$, $df = 4$, $p < 0.712$) had an impact on the probability of being aware of a PnP.

Stakeholder knowledge about the invasion status of the 18 PnPs in the survey

Respondents scored on average 8.2 (SE 0.29) of the 18 PnPs correctly with regard to their presence or absence in their country, with a range from two respondents (of 234) not getting any correct scores to four respondents being correct about the status of all of the PnPs in their country. The correctness of respondents' knowledge (model 3) was highly dependent on the PnP itself ($F = 97.19$, $df = 17$, $p < 0.001$; Suppl. material 2: table S3), but whether a PnP was an insect or an EU priority species did not correspond to differences in correctness. There were significant differences in correctness according to the scale stakeholders were working on ($F = 23.31$, $df = 4$, $p < 0.001$), with stakeholders working at national scale significantly more likely to know the status of a PnP correctly. Amongst the PnPs, the status of ash dieback (*Hymenoscyphus fraxineus*) was scored with the highest accuracy, whereas root rot fungi (*Heterobasidion irregulare*) were most likely to be scored incorrectly.

When we aggregated the data to look at the proportion of PnPs for which individual respondents reported the correct invasion status (model 3, Suppl. material 2:

table S5), we found that the scale people worked at still strongly corresponded with their ability to correctly report the invasion status of the PnPs ($F = 29.06$, $df = 4$, $p < 0.001$). Once again, those working at national scales had the highest likelihood to be correct. Those reporting their main work focus to be on detection ($F = 4.52$, $df = 1$, $p = 0.036$), education ($F = 4.77$, $df = 1$, $p = 0.029$) or research ($F = 4.18$, $Df = 1$, $p = 0.04$) were most likely to be correct; however, correctness across all the PnPs invasion statuses did not differ significantly between the stakeholder groups. The level of awareness (i.e. number of PnPs scored by individual respondents) was not a significant factor explaining the proportion of PnPs scored with the correct invasion status.

Looking at correctness across all respondents for individual PnPs, stakeholders were overwhelmingly correct (~ 80%) about the presence or absence of PnPs, but few knew about past eradications (< 20%). Stakeholders seem to know more about absence than presence (Fig. 2), as correct negative responses were consistently more common than correct positive responses.

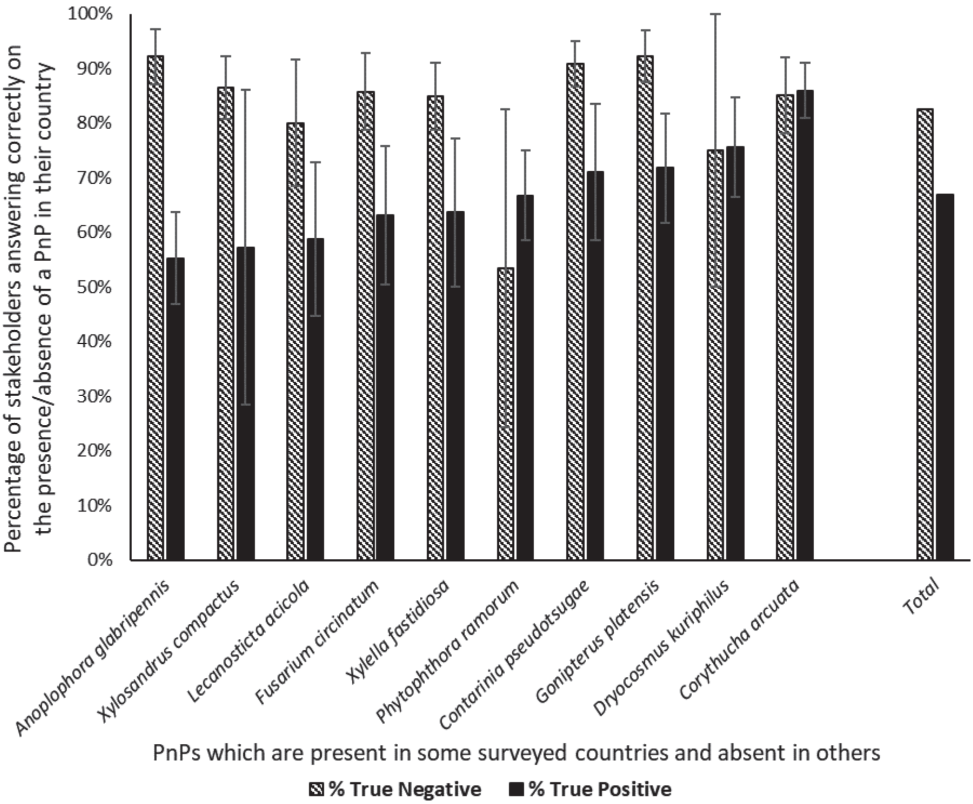

Figure 2. Stakeholder knowledge about the invasion status of PnPs, showing the percentage of true positive and negative results of PnP awareness for named PnPs which are both present in some countries and absent in others.

New and emerging tree PnPs of concern to stakeholders

Further to the 18 PnPs listed in the survey structure, (Table 1) respondents listed 37 additional invertebrate (Table 3) and 21 pathogen species (Table 4) of concern to them. Nine of the invertebrate and four pathogen species are EPPO-listed species, while just five invertebrates and no pathogens are EU priority pests. The species listed by our respondents represent 6% of the species on the combined lists of EPPO priority pests and pathogens of trees. Most pests reported were beetles (Coleoptera), comprising longhorn (Cerambycidae), jewel (Buprestidae), bark

Table 3. Invertebrate pests of trees and the frequency and countries of stakeholders that listed them as organisms of concern in addition to the list of 18 PnPs referred to in the survey.

Latin name	Common name	Frequency	Countries
Anoplophora chinensis‡	Citrus longhorn beetle	9	CR, F, SWI
Agrilus anxius†‡	Bronze birch borer	5	CR, UK
Ips typographus	Larger eight-toothed European spruce bark beetle	5	B, N, UK
Vespa velutina	Asian hornet	4	F, P, UK
Xylotrechus chinensis†	Tiger longhorn beetle	4	F, GE, GR
Cameraria ohridella†	Chestnut leaf miner	3	B, UK
Dendrolimus sibiricus‡	Siberian silk moth	3	F
Popillia japonica‡	Japanese beetle	3	I, SWI
Thaumetopoea pityocampa	Pine processionary moth	3	P, UK
Xylosandrus crassiusculus†	Granulate ambrosia beetle	3	F, GE
Aromia bungii†‡	Red-necked longhorn beetle	2	F, I
Dendroctonus micans	Spruce bark beetle	2	F, UK
Ips sexdentatus	Six-toothed bark beetle	2	CR, F
Phloeomyzus passerinii	Poplar woolly aphid	1	F
Eriosoma lanigerum	Woolly aphid	1	F
Dryocoetes himalayensis	Himalayan bark beetle	1	CR
Euwallacea whitfordiodendrus	Polyphagous shot-hole borer	1	UK
Gnathotrichus materiarius	American utilizable wood bark beetle	1	CR
Pityophthorus juglandis†	Walnut twig beetle	1	CR
Ips amitinus	Small spruce bark beetle	1	SWE
Ips cembrae	Larch bark beetle	1	SWE
Xylosandrus germanus	Black timber bark beetle	1	CR
Melolontha hippocastani	European forest cockchafer	1	F
Melolontha melolontha	Cockchafer	1	F
Trachymela sloanei	Small eucalyptus tortoise beetle	1	P
Phoracantha semipunctata	Australian Eucalyptus longhorn beetle	1	P
Psacothea hilaris†	Yellow spotted longhorn beetle	1	I
Tetropium gabrieli	Larch longhorn beetle	1	SWE
Thaumastocoris peregrinus†	Bronze bug	1	P
Oxycarenus lavaterae	Lime seed bug	1	CR
Corythucha ciliata	Plane lace bug	1	UK
Halyomorpha halys	Brown marmorated stink bug	1	I
Leptoglossus occidentalis	Western conifer seed bug	1	F
Glycaspis brimblecombei†	Red gum lerp psyllid	1	P
Trioza erytrae	African citrus psyllid	1	P
Hylobius abietis	Large pine weevil	1	F
Rhynchophorus ferrugineus†	Red palm weevil	1	F
Total organisms = 37			

Key: † = EPPO priority pest (past or present); ‡ = EU priority pest; B = Belgium; CR = Czech Republic; F = France; GE = Germany; GR = Greece; I = Italy; N = the Netherlands; P = Portugal; SWE = Sweden; SWI = Switzerland; UK = United Kingdom.

Table 4. Tree pathogens and the frequency and countries of stakeholders who listed them as organisms of concern in addition to the list of 18 PnPs referred to in the survey.

Latin name	Common name	Category	Freq.	Country listing
Bretziella fagacearum (syn. *Ceratocystis fagacearum*)	Oak wilt	Fungus	14	F, N, SWI
Cryphonectria parasitica	Chestnut blight	Fungus	7	CR, N, SWI, UK
Ceratocystis platani	Plane wilt	Fungus	5	F, N, SWI, UK
Sphaeropsis sapinea (syn. *Diplodia pinea*)	Tip blight & canker	Fungus	4	F, SWE
Phytophthora cambivora	Root rots/Ink disease of European sweet chestnut	Oomycete	3	F, UK
Phytophthora cinnamomi	Root rots/Ink disease of European sweet chestnut	Oomycete	3	F
Cronartium flaccidum	Blister rusts of Scots Pine	Fungus	2	F, SWE
Sphaerulina musiva	Poplar leaf spot	Fungus	2	F
Pseudomonus syringae pv. *aesculi*†	Horse chestnut bleeding canker	Bacterium	1	B
Erwinia amylovora	Fireblight	Bacterium	1	P
Geosmithia morbida†	Thousand cankers disease	Fungus	1	CR
Melampsora larici-populina†	Poplar rust	Fungus	1	F
Sirococcus tsugae†	Sirococcus blight	Fungus	1	UK
Chrysomyxa abietis	Needle rust of fir	Fungus	1	SWE
Chrysomyxa weirii	Spruce needle rust	Fungus	1	SWE
Cronartium ribicola	White pine blister rust	Fungus	1	F
Cryptostroma corticale	Sooty bark disease of Maple	Fungus	1	N
Lecanosticta acicola	Pine needle blight	Fungus	1	A
Ophiostoma novo-ulmi	Dutch elm disease	Fungus	1	B
Splanchnonema platani	Massaria disease	Fungus	1	UK
Thekopsora areolata	Cherry/spruce rust	Fungus	1	SWE
Total organisms = 21				

Key: † = EPPO priority pest (past or present); A = Austria; B = Belgium; CR = Czech Republic; F = France; GE = Germany; GR = Greece; I = Italy; N = Netherlands; P = Portugal; SWE = Sweden; SWI = Switzerland; UK = United Kingdom.

(Scolytinae), leaf (Chrysomelidae) and chafer (Scarabaeidae) beetles. The largest number of species from these groups were bark beetles (11 species), then longhorn beetles (six species). The three pests reported most frequently were beetles, *Anoplophora chinensis* (Citrus longhorn beetle), *Agrilus anxius* (Bronze birch borer) and *Ips typographus* (Larger eight-toothed European spruce bark beetle; Table 3). Citrus longhorn beetle, the pest named by the most respondents, affects broadleaved trees and conifers. Furthermore, of the thirteen pests reported more than once, six affect broadleaves, five affect conifers, one affects both and one does not directly affect trees (*Vespa velutina*).

The pathogens most frequently listed of concern to respondents (Table 4) were *Bretziella fagacearum* (Oak wilt), *Cryphonectria parasitica* (Sweet chestnut blight) and *Ceratocystis platani* (Plane wilt). Most species listed were fungi (17/21) and there were just two species each of bacteria and oomycetes.

Eleven respondents listed groups of invertebrates of concern. The most frequently mentioned group was non-European bark beetles and *Ips* species (n = 6). There were two mentions of *Hylobe* species and one entry each for *Xylosandrus* species, *Contarina* species and tropical xylophagous species (data not shown). Thirteen respondents described groups of pathogens or diseases of concern. Of these, five related to *Phytophthora* species, two each for *Ceratocystis* species and *Armillaria* species, plus one mention each for needle diseases of fir and pine, fungal root rot and *Fusarium* dieback.

Case studies on Asian longhorn beetle, Oak processionary moth and *Phytophthora ramorum*

The primary management method used for each of the three case study PnPs (Asian longhorn beetle (ALB), Oak processionary moth (OPM) and *Phytophthora ramorum* (PRA)) varied significantly between organisms (F = 82.99, df = 12, p < 0.001; Fig. 4). The greatest number of respondents (40%) said that eradication was the primary management method used against ALB, followed by surveillance/monitoring (23%) and early detection/rapid response (20%). Control and management was the primary tool used for OPM (35%) and PRA (25%). The other two frequently chosen methods for OPM were surveillance/monitoring (23%) and education (21%). The other three methods selected more frequently for PRA were eradication (21%), surveillance (18%) and early detection (17%).

The perceived efficacy of the primary management method used most frequently was high for ALB (eradication: mean score = 4.3 ± 0.18 SE, Suppl. material 2: table S6), but lower for OPM and PRA (control and management: 3.4 ± 0.23, OPM; 3.6 ± 0.25, PRA). For PRA, early detection and rapid response received the highest efficacy rating (3.85 ± 0.24), whereas for OPM eradication was perceived as the most effective (4 ± 0.32). The lowest efficacy score for all PnPs was found when the respondents selected "no management" (2.5 ± 0.29, ALB; 2.86 ± 0.46, OPM; 2.5 ± 0.87, PRA).

Perceived efficacy scores of the primary management method used (Suppl. material 2: fig. S4) against ALB were consistently higher across all urban/rural working remits compared to those used for OPM and PRA. Perceived efficacy of methods used against OPM and PRA were similar in all urban/rural settings. The PnP was highly significant in the linear model (Suppl. material 2: table S7) to account for variation in efficacy score of the primary management method used (p < 0.001). The method used was also strongly significant in determining the efficacy perception (p = 0.002), whereas the urban/rural setting of respondents' work was only significant at the 10% level (p = 0.057). There is a slight trend for efficacy to be perceived less positively the more rural the respondent's work remit. Where urban/rural was not deemed applicable to their work, respondents gave the lowest efficacy scores for the primary management method for OPM and PRA (mean score 3 ± 0.49 SE, OPM; 3.11 ± 0.48, PRA).

Use of tools for detection and management of PnPs

Survey respondents answered whether they used 17 tools and methods for detecting and identifying PnPs or eight tools for managing PnPs. Most respondents indicated that they use monitoring of infected areas, books, websites, experts or tree health advisory services, plant health policies and advice and research publications for detecting and identifying PnPs (Fig. 3a).

We found there were significant differences in methods used for detecting and identifying PnPs across stakeholder groups (F = 5.29, df = 5, p < 0.001; Suppl. material 2: fig. S3a). The 'Managers and Owners' group use different tools compared to

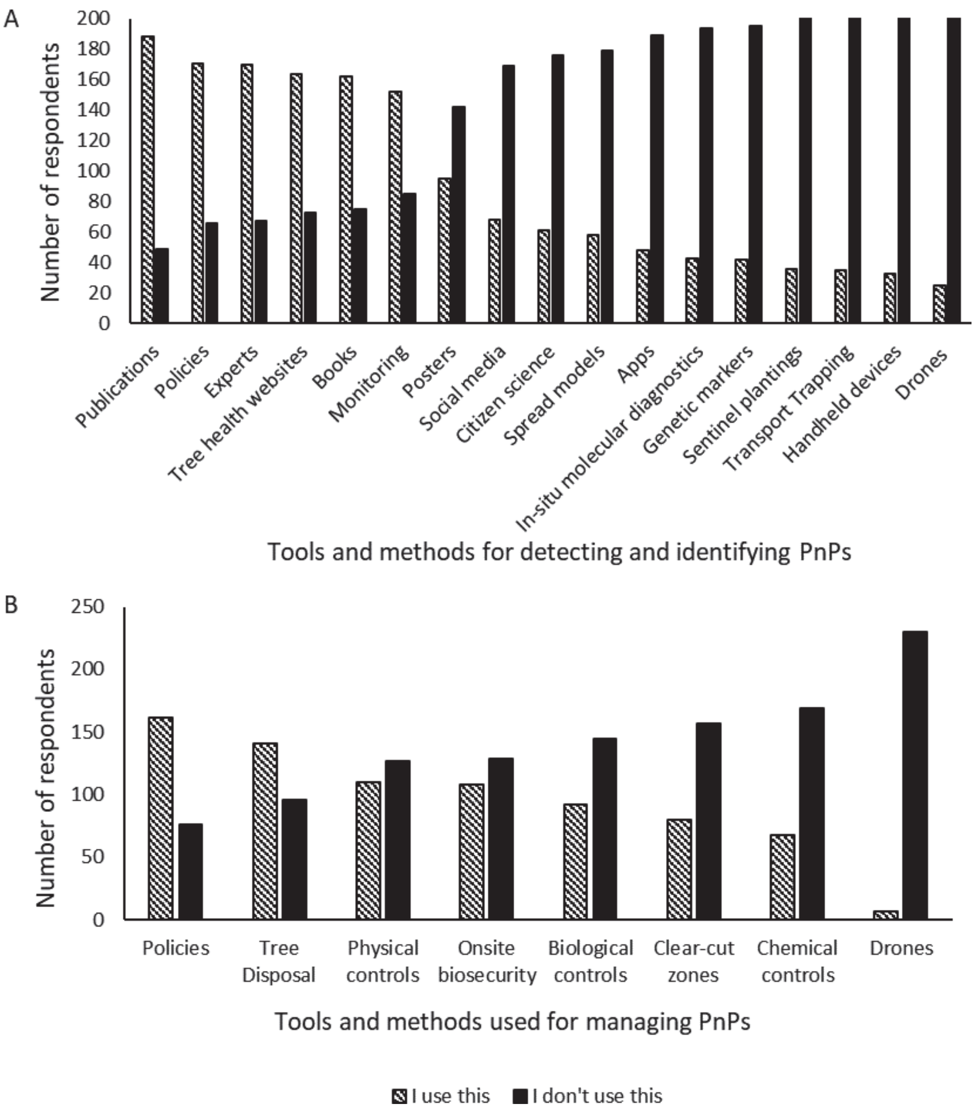

Figure 3. Number of respondents who said they used each of (**A**) 17 tools and methods used for detecting and identifying and (**B**) eight tools and methods for managing new and emerging forest PnPs (required answer for all respondents).

'Forest Advisors', 'Forest Health Authorities' and 'Forest Health Services'. Likewise, 'Civil Society' use different tools to 'Forest Advisors', 'Forest Health Authorities' and 'Forest Health Surveyors'. The 'Forest Advisors' used more of the detection and identification tools in total.

Some tools and methods for detection and identification had very low use by certain groups, with no responses from 'Civil Society' for the use of drones, which was the least used method across all groups. Other than for 'Forest Advisors', the use of

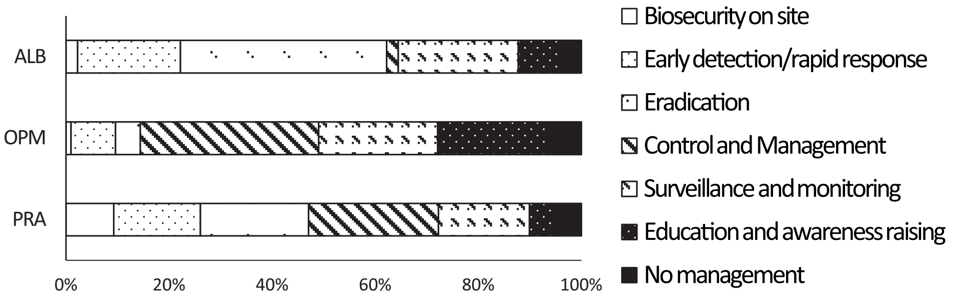

Figure 4. The primary management tool used by stakeholders against three case study PnPs (ALB = Asian longhorn beetle; OPM = Oak processionary moth; PRA = *Phytophthora ramorum*). Tools displayed left to right are listed in order top to bottom in the key from biosecurity on the left to no management on the right.

genetic markers, transport trapping, *in situ* molecular diagnostics, hand-held devices, spread prediction models, sentinel plantings and identification and recording apps were also low. Citizen-science reporting was not widely used by any groups, except 'Civil Society' and 'Forest Advisors' where around one in three and one in four used this method, respectively.

For management of PnPs (Suppl. material 2: fig. S3b), most respondents used plant health policies (68%) and disposal of infected trees or tree parts (59%). In contrast, most respondents did not use biosecurity, biological control, clear-cut zones, chemical or physical controls or drones. Drones with sensors and sprayers were the least used method for managing PnPs.

Stakeholders' desired tools and methods

There were 403 stakeholder comments and suggestions for future development and access to tools and methods for PnP detection and management beyond those listed within the survey, which fell into six themes: surveillance and trapping; education, information and data sharing; tools and techniques; citizen science and 'eyes on the ground'; inspections and import restrictions; experiments and research. The numbers of comments in each theme are shown in Table 5.

Surveillance and trapping

The comments within this theme centred on the use of pheromone, multilure and spore traps, as well as drones, sniffer dogs, aerial surveillance and LiDAR. Respondents desired trapping and surveillance to be more widely used, including for domestic and public gardeners to use pheromone traps. However, there were concerns about the (unspecified) limitations of drones, to whom the financial costs of surveillance and trapping would fall and when in a plant's life trapping and surveillance should be performed.

Table 5. Themes of stakeholder comments for their desired future detection and management tools.

Theme of stakeholder comments	For detection and identification		For management		Total number of comments
	No. of stakeholder suggestions for developments of isted tools and methods for PnP detection and identification	No. of stakeholder comments on other tools and methods used, and wanted for IEFP detection	No. of stakeholder suggestions for developments of listed tools and methods for PnP management	No. of stakeholder comments on other tools and methods used, and wanted for PnP management*	
Surveillance and trapping	"Trapping devices = 4, Monitoring = 11, Drones=10	19	NA	13	57
Education, information and data sharing	Plant Health policies and advice = 18, Books = 3,Research pubilcations = 10,Tree Health advisor services and Experts = 7	24	Plant health policies and advice = 8	29	99
Tools and techniques	Genetic Markers = 2,Prediction models = 5, in-situ molecular diagnosis = 3, handheld devices = 3	35	On-site biosecurity practices = 11, Physical control methods = 6, Chemical control methods = 7,Biological control methods = 7,Clear-cut zones = 7, Disposal = 2, Drones with multisensors, processors and sprayers = 4	47	139
Citizen science and "eyes on the ground"	Social media = 12, Citizen Science = 13, Apps =10	9	NA	4	48
Restricted imports and inspections	Posters = 10	5	NA	20	35
Experiments and research	Sentinel plantings = 8	3	NA	14	25
Total	129	95	52	127	403
Numbers shown are the no. of respondent comments					

*this includes comments on tools, bodies or regulations stakeholders would like to see developed.

Education, information and data sharing

Stakeholder suggestions encompassed ideas on accessibility, social media, information sharing and an educational network with training opportunities. The range of professionals that stakeholders rely on come from many sectors: governmental officers, charities, industry, academia and volunteer networks. Collaborations and knowledge sharing were called for amongst plant health bodies, professionals, industry and interested citizens. Respondents wanted access to maps showing range and recent sightings of PnPs. They recommended using social media for horizon scanning and sharing cases of interceptions. One suggestion called for long-term establishment of existing citizen-science tree health programmes with sufficient expert support.

Respondents envisaged that Pest Risk Analysis following horizon scanning and liaising with networks of scientists and experts inside and outside the country could be further developed. Stakeholders found search engine landing pages which synthesise the most up-to-date and relevant content for forest health the most useful.

Tools and techniques

While some stakeholders saw a need for vastly improved biosecurity, particularly at borders, others found biosecurity recommendations impractical and unrealistic and saw a need for revision of required practices in proportion to the risk, invasion stage and mobility of the organism. There was a wish to develop secure methods for onsite biosecurity and movement, cleaning and management of suspected and affected material and to work together with local neighbours for better biosecurity outcomes.

An increased hesitancy in using chemical control methods was expressed by stakeholders. Prohibitive legislation and an appreciation of environmental harm were given as reasons for this. Stakeholders also noted that approval of new chemicals is slow. Desired methods include chemical insecticide netting on woodpiles, spray, injection, fumigation and electric current. It was also noted that chemical tools vary in their ‘greenness’ and there was a call for a list of disinfectants and accompanying information on their efficacy against different pests and pathogens.

Other tools suggested by respondents include better and quicker diagnostic tools, such as *in situ* tests, particularly ‘cheaper devices for more widespread use’ for rapid confirmation of *Phytophthora* spp. and *Xylella fastidiosa*. Furthermore, they wanted field tests and molecular test kits that were easy to use, ways to diagnose from eDNA in air or water samples including non-destructive meta-barcoding approaches, LAMP, qPCR, electronic noses, the ability to send samples for identification in laboratories, drone monitoring of spectral signatures and insect identification from picture galleries. These suggestions were made mainly by tree health surveyors, who may also be working in other sectors concurrently.

Other stakeholder suggestions relate to biodiversity and better underlying plant and ecosystem health to limit the impact of PnP outbreaks.

Citizen science and ‘eyes on the ground’

Training, funding, automatic warning systems and better integration of citizen science into official monitoring programmes were suggested to improve the current offer. Interested citizens and professionals reported their use of social media for the detection and identification of PnPs. Further suggestions include to develop a daily PnP learning update to be shared via Twitter. Eight percent of respondents named Facebook and 6% of respondents named Twitter as a social media method they use for detection and identification of PnPs. Stakeholders wanted future developments of apps including an app with keys for identifying PnPs, illustrating symptoms of specific diseases or pests, plus pictures of other types of tree damage that could be confused with damage caused by the pathogen or pest. They had concerns regarding privacy, data sharing, access and record validation within such apps.

Inspections and import restrictions

There was a common desire towards locally-sourced and grown trees instead of importing them, for imports to have greater restrictions with checks implemented by more inspection personnel at borders and inland and inspection checks to be performed for high-risk plants from retail to final planting. Several respondents wanted more content to be displayed on posters and for these to be placed at all departure and arrival areas in transport hubs. Consistency of branding was deemed important and it was suggested that posters could show maps that highlight the range and spread of recent PnP sightings locally to raise public awareness of current issues.

Experiments and research

Other suggested research topics were to improve isolation of pathogens in pure culture from infected plants and find new fungicides. Stakeholders suggested that both formal International Plant Health Sentinel Network sites and informal sentinel trees and plantings could be used to support further research, such as identifying tolerance levels of trees to widespread PnPs. They called to extend citizen-science tree health projects to monitor local trees as sentinels. Plus, stakeholders perceive that it is important to develop high throughput screening for effective selection of resistant breeding stocks alongside traditional breeding.

Discussion

We found that the stakeholders of European forests that we surveyed are relatively aware and knowledgeable about the 18 PnPs we selected for this study, although our group does not represent all stakeholder types or locations equally, with a particular need to look in more detail at those working in the timber trade and from countries other than UK, France and Czech Republic. We also found that there were gaps in awareness and knowledge held by stakeholders, but there is a demand for better support and access to tools for PnP detection and management.

Stakeholder awareness of tree pests and diseases in Europe has been previously studied by Marzano et al. (2016) in a survey of 392 tree and forest professionals in nine countries. When asking these stakeholders about their level of awareness for five PnPs, Marzano et al. found, on average, about 20% of respondents were not aware of these PnPs. In our survey, we found an average of 42% of respondents were not aware of the PnPs we listed. However, our sampling approach differed, as our longer list of PnPs included species that are in an early invasion stage. For the three species included in both surveys (Emerald ash borer, Asian longhorn beetle, Ash dieback), we found similar levels of 'non-awareness' to the study of Marzano et al. (2016). For Emerald ash borer, in our sample, 34.6% of respondents were not aware of the species, compared to 36.3% in Marzano et al. (2016), whereas awareness for Asian longhorn beetle was lower (25.7% vs. 20.4%) despite the fact that several additional outbreaks of Asian longhorn beetle have been recorded in Europe in the meantime (Branco et al. 2022), which could have resulted in an increase in awareness of this species. Only for Ash dieback did we find awareness had improved, from 21.1% of non-awareness in Marzano et al. (2016) to 16% in our sample. This could be attributed to the increasing spread and impacts of the disease, particularly in Britain (Enderle et al. 2019; Hill et al. 2019), where a large number of our participants were based and consistent media coverage during this timeframe. Our respondents' awareness also differed significantly between the 18 PnPs included in our survey, potentially because certain PnPs may pose a larger threat to forests in their country, symptoms are easier to spot or the PnP is easier to identify compared to others (Boa and Nations 2003). Changing taxonomy species, particularly fungi, could be another barrier to accurate stakeholder knowledge (Steenkamp et al. 2018), contributing to the finding that, of the 18 PnPs in the survey, *Heterobasidion irregulare* was most likely to be scored incorrectly by stakeholders.

We found stakeholders seem to be better informed about pests that were absent in their countries than those present. This could suggest that their knowledge is lagging behind the actual invasions and there is a need for better information on newly-established PnPs or it may indicate that stakeholders are well prepared to initiate specific prevention measures against PnPs not yet present. It is important to acknowledge the risk of the yet unknown PnPs and their potential pathways and the need for pathway focused prevention measures (Evans 2010; Webber 2010) and Jactel et al. (2020) also recommend the development of generic tools or methods for pest and pathogen management and capacity building for all stakeholders involved in forest health. Stakeholders knew EU priority pests better than non-priority pests, suggesting that EU and EPPO priority pest lists and plant health authorities' dissemination work (EFSA 2019, EPPO 2022a) has been effective. People working in urban environments were aware of more PnPs compared to people working in rural areas. This could be because of higher diversity of tree species occurring in urban areas, as more imported stock is planted in cities or first arrives in a country via trading ports close to urban areas (Branco et al. 2019). By assigning individual respondents into groups according to their working roles, we were able to identify socio-environmental factors that are linked with varying levels of awareness and knowledge about PnPs. Stakeholders in Civil Society were less likely to know a PnP than those working in Forest Authorities, but all groups can benefit from improved forest health communication, collaboration and knowledge exchange.

The PnPs of concern listed by respondents included more pests than pathogens – consistent with the EU priority list which has very few pathogens and combined EPPO lists, in which, of 260 species that can affect trees, 164 (63%) are insects and mites. The low representation of EPPO priority pests and pathogens affecting trees (6%) by our respondents indicates that, if we are to effectively involve stakeholders in prevention activities, then communication and awareness raising for priority tree PnP species needs to be increased. Frequently-listed species were widespread across the continent (e.g. both *Cryphonectria parasitica* and *Agrilus anxius* were listed from the Czech Republic to UK and *Xylotrechus chinensis* was listed from Greece to France). The high number of bark beetles mentioned could perhaps mirror the visual damage level that has been caused by these groups or simply the great diversity of tree health problems they cause. (Christiansen and Bakke 1988; Ploetz et al. 2013). Interestingly, there was an absence of nematodes and viruses listed by respondents: stakeholders may lack awareness of these groups and diagnostic symptoms can closely resemble those of other pathogens and abiotic stresses (Boeri and Chung 2012; Hassan et al. 2013). Although the diagnostic symptoms for many nematode and virus infections may be hard to separate from other pathogens and abiotic stresses, literature shows that at least one new syndrome, Beech Leaf Disease (BLD), recently found to be associated with the nematode *Litylenchus crenatae mccannii* (Carta et al. 2020), has symptoms that are recognisable and suitable for tree PnP citizen-science surveillance (Woodland Trust 2022).

A limitation in the interpretation of the data is that, since half of the respondents are from the UK and France, the results reflect the situation in these countries more than for other parts of Europe; future work is needed to gather more data for comparison between all European countries. In addition, responses largely reflect stakeholders involved in research and tree health surveying. We did not gather information on the forest types (forest management practices, forest legislation etc.) in the different countries investigated which would be an interesting topic for further study.

Regarding the three case study PnPs (Asian longhorn beetle, Oak processionary moth and *Phytophthora ramorum*), the primary method reported for their management varied significantly depending on the organism and this could reflect their different stages of the invasion process (Blackburn et al. 2011) and/or the policy direction from plant health authorities. As is consistent with EU policy (Commission Delegated Regulation (EU) 2019), eradication of Asian longhorn beetle was listed as the primary method of management by most respondents, which accurately reflects that the species has been eradicated in most of Europe, with only restricted populations remaining in France and Italy as of 2022 (EPPO 2022b). This approach was perceived as highly successful and significantly more so than the approaches used for managing Oak processionary moth and *Phytophthora ramorum*. Oak processionary moth is native to many countries in continental Europe (Austria, Belgium, France, Germany, Italy and the Netherlands (Moran et al. 2015)), but the emerging nature of the problem is reflected in that respondents who said no management was performed against Oak processionary moth gave the lowest efficacy scores.

There was a weak trend in the efficacy scores for the primary management method used against PnPs where stakeholders in urban environments thought the methods were more effective than for stakeholders working in mostly or completely rural environments. However, stakeholders with a national perspective (where urban/rural labelling of their working remit did not apply) were even more sceptical of the primary management methods' efficacy. We suggest that this may be because their perceptions of what is expected, or possible, varies. In urban areas, interventions may be more noticeable and stakeholders in urban areas may be more likely to detect new pests and diseases (Branco et al. 2019). Furthermore, fragmented private ownership of trees and greater oversight by plant health authorities in urban areas could lead to faster intervention and lower costs of interventions incurred by individuals. This is consistent with Branco et al. (2019) who found that eradication in open-field environments is more difficult to achieve than in urban areas and highlights that PnP management in rural areas, which is a target for improvement. It is also consistent with (Paap et al. 2017) who found that urban trees, for example, in botanical gardens and arboreta, may be useful for detecting PnPs in the initial stages of establishment, where early detection in urban environments offers the only realistic prospect of eradication.

Stakeholders reported a range of suggestions for tools to be developed and made available for use in the field for detection and management of PnPs in the future. This shows that, for developers of new tools, there is much to learn from working closely with stakeholders to provide information for their designs and that there is a widely held desire to update the forest health management practices that stakeholders currently rely on.

There is substantial scope to improve usability, visibility and uptake of forest health citizen science, smartphone applications, social media and public information posters. The results indicate that conventional methods of sharing information, i.e. discussion amongst peers and networks, publications, posters, pictures, websites and correspondence, are the preferred means for identifying PnPs currently, which is consistent with previous reports (White et al. 2018). Good examples of peer-to-peer communication exist in Europe, such as UK networks of stakeholders that have been provided with an arena for social learning about tree health (O'Brien et al. 2021). Posters and social media were used successfully to raise public awareness for the eradication of longhorn beetles *Anoplophora chinensis* and *A. glabripennis* in the Lombardy Region of Italy after first detection in 2010 (Ciampitti and Cavagna 2014; Marchioro and Faccoli 2021). Initiatives to educate children about forest health demonstrate the different levels to which effective forest health communications can be pitched. The 'Izzy the Inspector' character and cartoon in the UK (APHA 2020) which is available in two European languages and school citizen-science projects, such as 'backyard beetles' in Italy (Colombari et al. 2022) are diverse examples of ways to engage children. Their efficacy hinges on creating memorable learning experiences to convey understanding of the threats to forest health from PnPs.

Recruiting citizen scientists to monitor tree health (Slawson and Moffat 2020) helps raise the profile of forest health and fulfils stakeholders' wishes to stop delegating surveillance to professionals. Forest health data provided by citizens can be used by local authorities and scientific community, but requires significant effort for moderation and verification (Baker et al. 2021; Balázs et al. 2021). If reports can be incorporated into the Global Biodiversity Information Facility (GBIF 2022) or similar repository, rather than local databases, data sharing is more accessible (Saarenmaa 2005).

Suggested improvements to smartphone applications include featuring spread models, keys for identifying PnPs, illustrations of PnP symptoms, comparative images of easily-confused symptoms and phytosanitary guidance and pest profile information that is available already online (EFSA 2020, IEFC 2022). Ideally, stakeholders could use a single app that is applicable to all of Europe. Europe-wide tools currently under development, such as silvalert.net, could be developed to meet these expectations (Orazio 2019).

The development of molecular tools that are more accessible for civil society may help better PnP identification and we suggest that the lower level of tool use by 'Civil Society' compared to 'Forest Authorities' is partly due to having less access to methods, such as molecular diagnostics, that are traditionally delivered by professionals. The capability for citizens to engage in molecular methods is being demonstrated in the case of fungal biodiversity recording in the UK and USA, by using PCR 'bento boxes', where amateur mycologists barcode specimens and contribute to publications. Their data provide policy-makers with evidence to grant sites with protected status and, thus, preserve their biodiversity, in addition to increasing the output that could be achieved by the professional sector alone (Douglas 2020; Bierend 2021). The bottleneck to productivity caused by the limited availability and high costs of laboratory testing for samples from damaged trees could be alleviated by engaging groups usually excluded from molecular technology, be they surveyors, forest managers, traders or supportive citizens.

Our stakeholder group called for updating forestry practices to better protect forest health. They suggested improving forest biodiversity and planting species mixtures as a means to improve forest resilience in relation to PnPs, an approach which is supported by recent research findings (Randall and Smith (2019) and Jactel et al. (2017)). Local provenance planting stock was favoured as a way to reduce the risks of international trade; however, business problems (e.g. variability in commercial demand) associated with local tree nurseries (Alonso Chavez et al. 2019) and a lack of scientific literature on the topic of local sourcing prevents this from being viable at present.

Stakeholders also saw the value in biosecurity practices (preventing PnP spread by controlling movement of plants and practising hygiene and quarantine). They specified a need for better-developed on-site biosecurity procedures and to expand the labour force of inspectors and administrators who could ensure tree health is checked before, during and after trade, including at final planting and into maturity. However, given that less than half of the study's respondents were using biosecurity tools, it follows that finding ways to overcome the barriers to uptake, such as inconsistency between countries and lack of evidence for the efficacy of practices (Eschen et al. (2015) is worth investigating in future studies (Marzano et al. 2018, 2021). Important concepts around complex epidemiological and political issues were raised during to the COVID-19 pandemic and widespread discussion of key messages from public information campaigns has helped raise the profile and explain the principles of plant health (MacLeod and Spence 2020). This parallel with COVID-19 may continue to serve as a useful framework to influence biosecurity uptake. Poignant concepts that apply in each scenario include that the need for biosecurity extends beyond borders, that risk management is key to mitigating harm (MacLeod and Lloyd 2020) and that biosecurity is a shared responsibility for all (White et al. 2019; Nahrung et al. 2023).

Conclusions

Our results showed that stakeholder knowledge of a few key PnP is good, but the broad diversity of threats may be too large to expect stakeholders to be able to be aware of them all (only 6% of the EPPO list came up in free text). This could be solved by a better Europe-wide communication strategy with alerts and the ability to see which PnPs are causing problems in neighbouring countries. This means that international cooperation is necessary and desired, inside and outside of the EU, highlighting valuing the importance of EPPO and EFSA. There is still much to be done to reach safe standards for trading and biosecurity practices and improving localised nursery stock production is essential to lower the demand on high-risk trade practices.

Stakeholders are using and developing multiple tools and methods for PnP identification and management and show desire for access to new tools to help with PnP early detection and rapid response, as well as improved data sharing across Europe. Engaging new audiences across both urban and rural environments and equipping more people to monitor and detect PnPs can help increase surveillance levels and promote better forest health.

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Supplementary material 1

HOMED stakeholder survey

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Supplementary material 2

Supplementary tables and figures

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Data type: tables and figures

Explanation note: fig. S1: Role types and group sizes represented within each of the six stakeholders' groups produced by cluster analysis; fig. S2: Respondent profiles regarding country, sector, focus and geographic range of work relating to PnPs; fig. S3: Tools and methods used by the 6 stakeholder groups for (A) detection and identification of PnPs and (B) for management of PnPs; fig. S4: Efficacy rating for methods to manage three PnP case studies: ALB = Asian longhorn beetle (*Anoplophora glabripennis*), OPM = Oak processionary moth (*Thaumetopoea processionea*), PRA = *Phytophthora ramorum*. table S1: Confusion matrix; table S2: All GLMM variables; table S3: Model including urban variable in first model shown in table S4; table S4: Factors explaining stakeholders' awareness of PNPs (model 1 a, b), i.e. if they scored a species or not and how correct (Knowledge) their scores were with regard to presence or absence of PNPs in their country (model 2a, b). Anova results of GLMMs. Both models are presented in two versions, with the second version replacing the PNP variable with the binary variables "insect" and "EU-priority" pest; table S5: Factors explaining individual respondents' proportion of PnPs scored correctly as present or absent in their country (model 3). Anova results of the GLMM model; table S6: Efficacy of three PnP methods (no urban/rural grouping); table S7: Linear model for efficacy rating of primary management methods used against 3 PnP case studies.

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