Improved preparedness for *Phytophthora* prevention in Scotland

Project Final Report

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This work was commissioned by Scotland's Centre of Expertise for Plant Health Funded by Scottish Government through the Rural & Environment Science and Analytical Services (RESAS) Division under grant agreement No PHC2023/02

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Please cite this report as follows: L. J. Barwell, G. Amankwaa, F. Asaaga, K. Turvey, D. E. L. Cooke, R. Mitchell, & B. V. Purse (2025). Improved preparedness for *Phytophthora* prevention in Scotland: Project Final Report. PHC2023/02. Scotland's Centre of Expertise for Plant Health (PHC). DOI: https://doi.org/10.5281/zenodo.18163347

Available online at: planthealthcentre.scot/publications

Dissemination status: Unrestricted

Acknowledgements: We would like to thank all of the stakeholders who kindly contributed their time and expertise to the project.

Contents

1 Executive summary

Emerging pests and diseases pose a serious threat to Scotland's crops, forests, horticultural sector and priority native species and habitats. To improve preparedness to *Phytophthora* threats in Scotland, this project used an iterative and co-production process that brought together stakeholders with diverse expertise from across Scotland's plant health sector to address the following objectives:

i. identify priority plants and habitats in Scotland at risk from *Phytophthora* via an initial self-completion survey (April 2024) and cross-sectoral framing workshop (6th June 2024).
ii. translate existing models and global databases into tools to support horizon-scanning (ranked *Phytophthora* threats to Scotland) and spatial risk analysis, integrating stakeholder priorities and knowledge of risk factors identified in i).
iii. validate project outputs and assess potential impacts on decision-making through a second stakeholder workshop (13th November 2024), followed by a further phase of model and database development to incorporate feedback, tailor and finalise the model outputs.

<u>Priority plants and habitats in Scotland at risk from *Phytophthora*</u>

Stakeholder-identified priority *Phytophthora* threats included *P. ramorum*, *P. austrocedri*, *P. x alni* (already present across a range of plant species) and *P. pinifolia* (not yet present) as a threat to Scots pine. Habitats of concern included diverse woodland types, heathland, riparian habitats and gardens as well as woodland scrub and grassland with juniper.

High levels of stakeholder concern were consistent with analysis of updated models and cross-sectoral databases that indicate a high likelihood of arrival or repeated introductions, and potential future impacts in Scotland of *Phytophthora* species found globally. In Scotland, 45 *Phytophthora* species have been detected to date, 26 have been detected only within trade premises and 15 have been detected in both trade and the wider environment. An additional 63 *Phytophthora* species have been described or informally named worldwide since 2020, but limited knowledge of global source regions prevents assessment of transport, introduction and establishment risks in Scotland. There are 89 exotic *Phytophthora* species having no global distributional records pre-dating 2005 and representing less well understood risks of arrival through horticultural trade flows. This highlights the need to increase global efforts in discovering and mapping *Phytophthora* species (potentially using novel eDNA barcoding techniques) and enhancing and maintaining integrated global cross-sectoral databases. Such databases were found to substantially enhance knowledge of distributions, host ranges, and sectoral impacts of *Phytophthora* species in Scotland compared to datasets from any single data provider. Less than 10% of the data collated from any single data provider (Scottish Forestry, SASA, Forest Research) overlapped spatially with another source.

<u>Ranking of *Phytophthora* threats to Scotland</u>

We leveraged existing models of arrival into the UK through global trade networks, climate suitability for establishment in Scotland, and information on *Phytophthora*-host interactions and interceptions extracted from the global database of *Phytophthora* records to rank *Phytophthora* threats to Scotland. Climate suitability model outputs for Scotland indicated that 117 *Phytophthora* species are predicted to be able to grow in at least 2/3 of Scotland's land mass in at least three seasons of the year. Analysis of updated global host-pathogen data identified 30-50 exotic *Phytophthora* species very likely to arrive in the UK through horticultural trade with source regions, and with high climate suitability for establishment in Scotland. Moreover, these species are known to affect key host genera on the Scottish Biodiversity List (e.g. *Salix*, *Juncus*, *Juniperus*, *Rosa* and *Trifolium*), National Vegetation Classification (NVC) habitats (especially woodlands, scrub and vegetation of open habitats) or thousands of Scottish National Forest estate sub-compartments containing *Quercus*, *Salix* and *Alnus*. Together, these analyses identify potential for future broad cross-sectoral impacts and a need to strengthen surveillance and interception efforts for these pathogens, hosts and habitats. Among the top future (yet to arrive) *Phytophthora* threats to Scotland are *P. europaea* (risks to *Abies*; *Alnus*; *Quercus* and *Juncus*), *P. crassamura* (risks to *Alnus*; *Artemisia*; *Castanea*; *Fraxinus*; *Juncus*; *Juniperus*; *Picea*; *Pinus*; *Prunus*; *Quercus*; *Rosa*; *Salix*; *Salvia*; *Sambucus*; *Vicia*) and *P. asparagi* (risks to *Juniperus*; *Quercus*, in addition to *Asparagus*).

<u>Spatial risk analyses for priority *Phytophthora* species, habitats and hosts</u>

Responding to this degree of threat and stakeholder priorities, this project integrated models of climate suitability for pathogen growth with stakeholder knowledge on best available datasets to describe the distribution of priority hosts and habitats, risk factors for *Phytophthora* establishment/infection, and mitigation of risks through policy and best-practice. Adapting the methods of Purse et al. (2016), we present co-designed risk frameworks for *P. ramorum* infection of Larch and heathland fragments, *P. x alni* infection of alder, *P. pluvialis* infection of Douglas fir and Western hemlock and *P. pinifolia* risks to the Caledonian Pinewood Inventory (CPI).

<u>Validation with stakeholders</u>

Further quality assurance is required for the current risk frameworks using future, independent surveillance data, when available, and it will be important to re-evaluate the credibility and perceived value of the models among stakeholders when these future validation steps are possible. When the databases and models were validated with stakeholders for value for decision making, several potential uses were identified at policy-level in relation to horizon scanning, risk assessment and risk management. The *Phytophthora* threats to Scotland integrated their arrival into the UK through global trade networks, climate suitability for establishment in Scotland, and information on *Phytophthora*-host interactions and interceptions extracted from the global database of *Phytophthora* records. Rankings of *Phytophthora* species across these risks were considered helpful for informing the UK plant Health Risk Register (UK PHRR), targeting surveillance and identifying regulatory gaps for particular trade routes and traded products.

Further development and next steps to improve the value of the tools for decision-making (not addressed in this project) include the need for metrics capturing severity of disease impacts on different host species (e.g. outcomes of pathogenicity tests, or mortality rates), and the integration of economic metrics (e.g. value at risk, yield) where possible. Stakeholders suggested dissemination through integration with existing tools like the UK PHRR and plant passporting systems. Whilst not within the scope of this project, a key need identified was to understand how the distributions of risks from different *Phytophthora* species would change under future climate conditions in 5 to 50 years' time. This project underscores the scale of current and future threats from *Phytophthora* and the value of co-production of tools integrating cross-sectoral knowledge to enhance preparedness and protect plant health in Scotland.

2 Introduction

New and established pests and diseases pose a serious threat to Scotland's crops, forests, horticultural sector and priority native species and habitats. The introduction of novel pests and diseases is facilitated by the international trade of live plants and large-scale planting activities across multiple sectors. Changes in climate and the use of novel plant species can promote the emergence of established and new introduced pests. Enhanced preparedness against plant health threats is central to the [Scottish Plant Health Strategy 2024-2029] (The Scottish Government, 2024) and the [Plant Biosecurity Strategy for Great Britain] 2023-2028 (Defra, 2023). Scotland's generic and pest-specific contingency plans are designed to promote early detection and rapid action to eradicate or control new outbreaks where significant impacts on plant health in Scotland are anticipated. Existing tools for prioritisation of threats include the UK Plant Health Risk Register and the EFSA pest prioritisation methodology (EFSA, 2022), but priority pest lists are often biased towards hosts of commercial and economic importance (Mitchell 2023). There is often a lack of evidence and limited scientific data available at the time of emergence (Roy et al. 2017). As a result, newly emerging pathogens can be excluded from risk or impact assessments, assessed but with high levels of uncertainty, or assessed but with no impacts on plant health yet identifiable. Compiling global cross-sectoral databases of pest and pathogen traits, hosts, distributions, and impacts can enhance preparedness by providing tools to rapidly identify known pests and diseases already impacting priority plant species (or their close relatives) elsewhere in the world. Global databases can also identify source regions of pests yet to arrive and underpin models and tools for an initial assessment of new and emerging pests and diseases (in the absence of sufficient data for full pest risk assessments) with the greatest potential to arrive (Barwell et al. 2021; Barwell et al. 2025), establish and cause harm to Scotland's priority plants and habitats and the economies and ecosystems that depend on them. Surveillance for pests and diseases in Scotland is undertaken by multiple agencies using different risk-based strategies to prioritise host plants and locations and with different requirements for reporting. There are finite resources and different responsibilities among agencies for surveillance across imported and domestically traded plants, amenity plantings, forestry and woodlands, and other priority habitats in the wider environment. Spatial models of pest-specific establishment risk that account for host use across sectors can guide surveillance activities, improve early detection of new outbreaks and raise awareness of potential threats across agencies, sectors and regions where plant health surveillance is limited in Scotland.

The United Kingdom has experienced a series of damaging *Phytophthora* invasions and emerging diseases, with many linked to trade in live plants (Green et al., 2021; Jung et al., 2016) and large-scale planting or restoration activities (Donald et al., 2021; Dunn et al., 2021; Karlsdóttir et al., 2021). Of the 69 *Phytophthora* species reported in the UK, 60 are present in trade premises, 42 have been detected in the wider environment and 34 are present in both trade and the wider environment. On a global scale a further 50 described *Phytophthora* species that have yet to be detected here have known source regions connected to the UK through trade in horticultural commodities (Green et al., 2024). Of the approximately 240 described *Phytophthora* species, 26 are listed on the UK Plant Health Risk Register as of July 2025; some of which are present while others have not been reported in the UK.

To enhance preparedness against novel *Phytophthora* threats to Scotland, this project aimed to:

- i) review and collate the contemporary data and evidence on *Phytophthora* discovery, species descriptions and ecological traits to update global databases compiled in Phyto-threats and other projects.
- ii) with stakeholders, map the greatest threats to priority plants and habitats in Scotland from *Phytophthora* species already present and those yet to arrive.
- iii) translate models and databases into tools to support horizon-scanning and preparedness for disease threats in Scotland.

To increase the value of the tools for decision-making (Barwell et al., 2021; Donald et al., 2024; Jones & Kleczkowski, 2020), this project further aimed to engage with those responsible for managing and protecting Scotland's natural and managed environments, to identify different priorities and needs for assessing plant health risks and tailor evidence to these needs. Our mixed methods, co-production approach involved engagement via a self-completion survey and two multi-sector workshops to frame evidence needs, integrate knowledge and validate impacts of project outputs on decision making with 12 stakeholders across sectors including Scottish Government, Forestry, Nature Conservation and Plant Health (Sections 3.2, 3.3 and full report on the first workshop in Appendix 7.8).

Key project outputs comprise an updated database of *Phytophthora* species, traits, distributions, and plant host ranges (Section 4.1), ranked lists of threats from *Phytophthora* species yet to arrive in Scotland (Section 4.2) and new and updated *Phytophthora* spatial risk frameworks co-designed with stakeholders (Section 4.3). We provide a set of recommendations for enhancing preparedness and early detection through risk-based prioritisation of pathogens most likely to arrive and their hosts, habitats and spatial locations (Section 5).

Table of abbreviations used:

Abbreviation	Full
AD	Additional Declaration
APHA	Animal and Plant Health Agency
CABI	CAB International
EIDC	Environmental Information Data Centre
EPPO	European Plant Protection Organisation
FGS	Forestry Grant Scheme
LCM	UKCEH Land Cover Map
NFES	National Forest Estate Sub-compartments
x.NFI	National Forest Inventory
NVC	National Vegetation Classification
NWSS	Native Woodland Survey of Scotland
PHC	Plant Health Centre
SASA	A division of the Scottish Government Agriculture and Rural Economy Directorate
SPHN	Statutory Plant Health Notice
UKCEH	UK Centre for Ecology & Hydrology
UK PHRR	UK Plant Health Risk Register
USDA	United States Department of Agriculture

3 Methods

In this project, we adopted a mixed-methods approach for tailoring *Phytophthora* databases, quantitative models and spatial risk frameworks to decision-making through a participatory co-production process. Stakeholders responsible for managing priority plant species and habitats in Scotland were initially identified through the project team networks developed through previous projects (Phyto-threats, Diversitree, the Future Proofing Plant Health programme and Scotland's Plant Health Centre PHC2019/05 and PHC2019/06), supplemented with input from the project steering group. The project's stakeholder engagement strategy was reviewed and approved by UKCEH's Human Research Ethics Committee and conducted in line with the UKCEH Privacy Notice.

3.1 Existing ecological modelling and risk mapping methods

3.1.1 Database of Phytophthora species, traits distributions and plant host ranges

A global cross-sectoral database of *Phytophthora* species, hosts, distributions and traits was compiled during the Phyto-threats project (2016-2019), comprising morphological identifications following isolations of pathogens into culture and DNA-based identifications using PCR and other sequencing technologies. Records were extracted from open access databases (EPPO, CABI Digital Library, USDA fungal-host), published papers, and contributed datasets from an international network of >100 pathologists.

3.1.2 Modelling arrival of Phytophthora species to UK and Scotland

The relative risk of arrival in the UK through horticultural trade networks has been predicted for 109 *Phytophthora* species with known source regions (Barwell et al., 2025). Global patterns of new *Phytophthora* detections at country-level were matched with patterns in horticultural trade connectivity and climate similarity with known source regions and pathogen biological traits to understand how these different factors affect the probability that new *Phytophthora* species will arrive and be detected in a country. Metrics of horticultural trade connectivity to the known source regions of *Phytophthora* quantify the pathways of movement between different countries, as a proxy for propagule pressure (the number and frequency of *Phytophthora* introduction events). Climate matching with known source regions is measured as the Mahalanobis distance (Etherington, 2021) between source and sink country conditions (lower mean Mahalanobis distance = stronger climate match between source and sink countries) based on four variables that could influence *Phytophthora* infection and dispersal processes: Minimum temperature of the coldest month (bio6), mean temperature of the warmest quarter (bio10), precipitation seasonality (bio15) and potential evapotranspiration (Trabucco & Zomer, 2018). The models also integrate importer biosecurity effort (based on historical reporting activity in the EPPO reporting service archive), pathogen traits measuring thermal tolerance range and dormancy adaptations and phylogenetic relatedness between pathogen species. These risk factors together with phylogenetically structured and species- and country-level errors explained between 72.4% (95% credible interval 52.0, 83.1) and 78.0% (61.8, 84.6) of variance in the probability that a *Phytophthora* species was newly detected in a country since 2005, increasing our confidence in extrapolating the model to predict future *Phytophthora* arrivals. Unknown species origins are partially accounted for in our models by integrating across potential sources of uncertainty using random effects at species and country level and accounting for the effect of national surveillance effort and species knowledge on the probability of a non-detection.

3.1.3 Risk mapping Phytophthora species

Spatial risk frameworks combine risk factors for *Phytophthora* establishment and spread, including climate suitability, proximity to known and potential sources of infection, proximity to spread pathways and distribution of key susceptible or reservoir plant hosts. Previous spatial risk frameworks for *Phytophthora ramorum* and *Phytophthora kernoviae* informed surveillance of heathland fragments by Scottish Natural Heritage (now NatureScot) (Searle et al., 2016) and Larch and core woodland fragments by Forestry Commission Scotland (now Scottish Forestry) (Purse et al. 2016) between 2010 and 2017. The risk analysis for *P. ramorum* infection of Larch was last updated in 2013 (Purse et al. 2016).

A new model was developed in 2024 to predict climate suitability for establishment in Scotland (and Europe) for 179 *Phytophthora* species using data for four widely measured *Phytophthora* traits (minimum, optimum and maximum temperatures for growth, and growth rate at the optimum temperature) to parameterise temperature response curves. Predictions from these climate suitability models integrate laboratory data on responses of mycelial growth to temperature and relative humidity, with gridded annual and seasonal climate data (Green et al. 2024; Purse et al. 2016).

3.2 Co-production process: multi-stakeholder participatory workshops, surveys and consultations

As part of the project, we employed an iterative and co-production process that brought together stakeholders with diverse expertise from across Scotland's plant health sector. Building on established networks from previous projects and project steering group inputs, we mapped out and engaged stakeholders from forestry, conservation, horticulture, and government agencies through a semi-structured process of survey and workshops.

Initially, stakeholders identified were invited to participate in an online survey (April 2024) administered via Kobo Toolbox (SPHC Stakeholder Engagement Phase 1 Survey). This preliminary engagement gathered baseline perspectives on *Phytophthora* impacts, priority species, and spatial risk mapping needs. From approximately 15 invitations, we received nine detailed responses that helped shape the subsequent workshop designs. A detailed copy of overall results from the self-completed survey can be found in the full report of the first workshop (Appendix 7.8). The key findings of the survey in relation to the spatial risk frameworks are also highlighted in Section 4.3.1 and Table 3.

Following the survey, we conducted an online framing workshop (June 6, 2024) that utilized Microsoft Teams for video conferencing alongside Miro interactive whiteboards for collaborative activities. Nine participants (experts), who had already been engaged in the survey, participated in three strategically designed breakout sessions focusing on: (i) risk prioritization and threats, where participants systematically ranked priority species, hosts, and habitats; (ii) risk framework assessment, exploring and weighting key risk factors; and (iii) management and dissemination strategies. In September, we shared with participants a short report on the first workshop identifying four main thematic findings from the participants perspectives: *Phytophthora* risk priorities; data sources and layers; risk factors and risk scoring; assessment approaches, use of risk maps and end-user engagement.

Building on these insights which informed the model development, we organised a knowledge integration and validation workshop (November 13, 2024) focused on synthesizing and validating the developed frameworks. This 3-hour session examined the practical applications of project models and databases for horizon scanning and decision-making across sectors. Through two focused 30-minute breakout sessions, eleven participants spanning forestry, horticulture and nature conservation sectors evaluated database and tool utility for risk assessment and explored the application of spatial risk frameworks across different contextual settings. Across both workshops, we used a participatory consensus-building technique–nominal group technique (NGT) at each breakout session which were led by a member of the ecological modelling team and co-facilitated by a social scientist. An accompanying Miro board with guiding questions was used to structure the discussions and capture participants priorities, feedback and inputs. We also had an additional member per group who took additional notes and observations. After each workshop, the team also conducted follow-up consultations or email correspondence with key actors and stakeholders to gather any additional feedback and suggestions on key issues (particularly those that were not discussed, not clear or required further in-depth testing or experimentations with developed frameworks).

3.3 Data Analysis

Quantitative data (including surveys) were analysed using R software (version.4.4.1.). These data were triangulated alongside data from the two workshops (n=9 and n=11, respectively) and three informal stakeholder discussions/consultations with experts from Scottish Forestry, Sylva Foundation and Plant Healthy. To ensure robust analysis of the participatory data, we employed reflexive thematic analysis (Braun & Clarke, 2020) using NVivo software. This analysis incorporated multiple data sources including video conference transcriptions, Miro board outputs, expert observation notes during workshops, and notes from informal follow up consultations/discussions.

4 Results

In this section, we present a summary of the updated global, cross-sectoral *Phytophthora* database, and derived metrics of risks and impacts used to rank *Phytophthora* threats to Scotland's priority plant species and habitats. Co-produced risk maps are presented for 5 combinations of *Phytophthora* species and priority hosts or habitats in Scotland including *P. ramorum* risks to Larch and heathland fragments, *P. x alni* risks to alder and riparian habitats, *P. pluvialis* risks to Douglas fir and Western hemlock and *P. pinifolia* risks to the Caledonian pinewood inventory.

4.1 Updated global database of Phytophthora species, traits, host plants and distributions

During this project, a total of 18,616 new records have been integrated into the global database initiated during the Phyto-threats project. The global data are sourced from published papers, publicly accessible online databases, the project teams' metabarcoding datasets (using the THAPBI PICT classification tool) and Scottish Forestry surveillance data.

Figure 1 shows that Scottish Forestry contributed the most distributional records of *Phytophthora* species across Scotland's inspected premises and wider environment, followed by SASA and Forest Research. The degree of overlap between distribution data sources is very small, with less than 10% of the data provided by a provider overlapping spatially with another source, highlighting the value of integrating data across sectors for a more complete picture of pathogen species distributions and host ranges.

In Scotland, 45 *Phytophthora* species have been detected to date, 26 have been detected only within trade premises, 15 have been detected in both trade and the wider environment and 4 in the wider environment only. Novel *Phytophthora* threats to the UK and Scotland are therefore very likely to emerge with clear pathways of spread through trade and planting coupled with natural dispersal events.

An additional 63 *Phytophthora* species have been described or informally named since 2020. The 63 *Phytophthora* species that were newly described between 2020 and 2024 identify a new range of potential threats. A selection of key species is detailed here. In addition to descriptions of new species, other publications expand the host range of existing species, and a key example is raised here.

There are 12 recognised clades within the genus *Phytophthora*, representing broad taxonomic groups of species based on their genetic and evolutionary relationships. Surveys of sub-alpine mountain vegetation in Europe have identified new species of *Phytophthora* and threats to plant species that are also key in Scottish ecosystems. For example, a novel clade 6 species *Phytophthora pseudogregata sp. nov.* was detected on *Alnus, Juniperus* and *Rhododendron* in Italy and Slovenia (Bregant et al. 2023). Similarly, a survey of *Alnus* and other riparian vegetation in Italy identified new associations of *Phytophthora* with *Alnus* and other hosts, new clade 6 species, *Phytophthora alpina sp. nov.*, *Phytophthora heteromorpha sp. nov.* and *Phytophthora debattistii sp. nov.,* plus a conclusion that multiple species of *Phytophthora* are implicated in alder decline (Bregant et al. 2020; Bregant et al. 2024; Senanayake et al. 2023). A newly described species, *Phytophthora viadrina* on *Quercus* in Poland (Tan et al. 2022) also has relevance to Scotland.

A substantial contribution to the understanding and diversity in *Phytophthora* emerged via a recent description of 43 new Clade 2 species from a comprehensive global geographical range and diverse ecosystems (Jung et al. 2024). In addition to the identification of host species (if available) the paper examined the global biogeography of each sub-clade and considered the climatic adaptation of each. Clade 2 is not thought to be native to Europe with only *P. siskiyouensis* being low-temperature adapted. Nonetheless, the authors concluded that Clade 2 and other taxa comprise a significant threat to plant health in Europe (Jung et al. 2024).

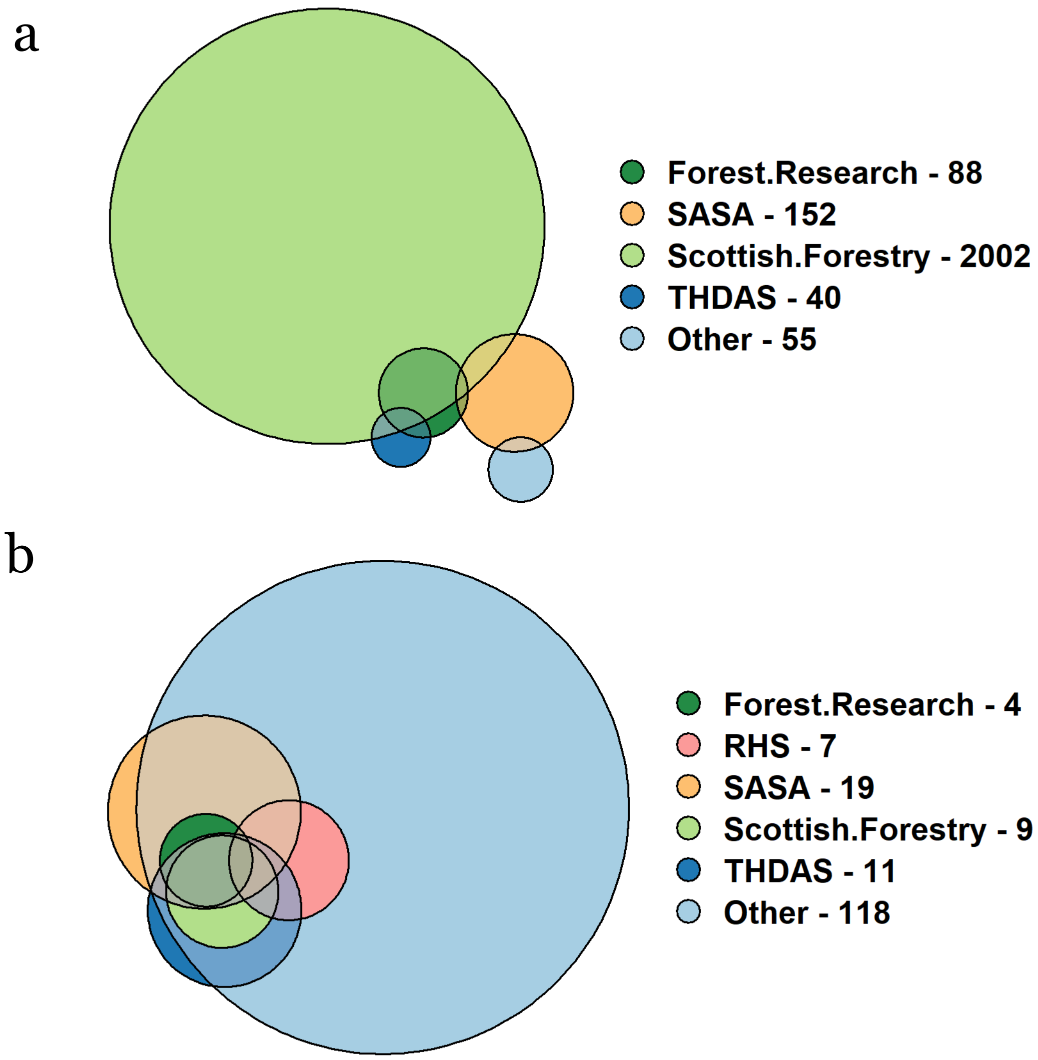

Figure 1 Amount of Phytophthora distributional data (a) and host genera (b) contributed by different cross-sectoral data sources for Scotland. The sizes of the circles in (a) indicate how many 1km squares (of the Ordnance Survey Great Britain grid) of distributional data are contributed by each source, with the areas of overlap indicating how many grid squares are common to two or more sources and the colours representing different data providers. It is not possible to fully represent all the geographical and taxonomic overlaps between all data providers and some of the smaller scale overlaps are not captured in this diagram. The 'Other' category comprises data extracted from publications and unpublished datasets shared by researchers including metabarcoding data sets from water, soils and nurseries.

A highly relevant example of host range expansion came from surveys of *Phytophthora* species in Sardinia that detected *P. asparagi* on *Juniperus*, *Quercus* and *Olea* (Scanu et al. 2015; Deidda et al. 2025); hosts beyond the expected members of the Asparagales (*Asparagus*, *Agave* and *Aloe*, for example).

Lastly, data on novel species and host associations were gained from in eDNA barcoding studies on Scottish nurseries and natural ecosystems (Green et al. 2025). For example. *P.*

cinnamomi, a pathogen historically associated with warmer southern climes in Europe was detected in samples from Scotland.

An experimental interactive version of the database was developed for this project (*Phytophthora* and Hosts in the UK and Globally). Users can query the database by *Phytophthora* species, region, host plant species, genus and family and region to provide a summary of reported host-*Phytophthora* associations and interceptions/detections by geographical region, priority plant species or for a *Phytophthora* threat of concern. There is a specific tab allowing users to interrogate the *Phytophthora* records on different hosts within Scotland.

4.2 Ranked list of threats from Phytophthora species yet to arrive in Scotland

To develop a ranked list of threats to Scotland from *Phytophthora* species we joined predictions from existing models of arrival into the UK through trade, and climate suitability for establishment in Scotland, with information on *Phytophthora*-host interactions and interceptions extracted from the global database of *Phytophthora* records. Each risk metric was scored from 0 (low risk) to 3 (high risk) and these scores were summed for each *Phytophthora* species to produce an overall risk ranking to support prioritisation among future *Phytophthora* threats to Scotland (Table 1). The impact metrics were compiled for 196 global *Phytophthora* species, but some species are missing scores for climate suitability (n=37) in Scotland or UK arrival risk (n=89) due to the absence of data on source regions or thermal tolerance traits to inform the underlying models.

4.2.1 Arrival risk metrics

Phytophthora arrival risk model predictions (Barwell et al. 2025) are probabilities constrained between 0 and 1. We used the quantiles of the distribution of predicted probabilities to select thresholds for scoring relative risks across the 107 *Phytophthora* species for which arrival probabilities were available (Table 1). Of these 107 species, 40 species had a probability of arrival exceeding 0.8. It should be noted that the global source regions of *Phytophthora* are often poorly documented, and this will lead to underestimates of arrival risks for species that are poorly studied, or very recently described. There were 89 *Phytophthora* species for which this risk metric is not available at all because no source region was recorded prior to 2005 from which to calculate trade connectivity and climate matching. This highlights how poorly recorded some species can be before emergence which is a limiting factor in this type of horizon-scanning analyses.

4.2.2 Climate suitability in Scotland

Climate suitability predictions for each meteorological season were extracted for 342 pixels (approximately 15x15 km grid) in Scotland to measure total growth per season. Climate suitability in Scotland was scored for each species as the number of seasons in which there was non-zero growth in more than 66% of the 342 pixels in Scotland. This metric measures risk as the length of the suitable growing season for each *Phytophthora* species. Pathogen species that can maintain growth across multiple seasons are assumed to be more likely to establish and may have greater potential for spread and more severe impacts on susceptible hosts each year compared to *Phytophthora* species with a more restricted growth season, though it should be considered that growth rate does not necessarily imply or correlate with sporulation (production of infective propagules) and this metric may therefore overestimate climate suitability for infection and transmission of disease in Scotland. Of the 171 species with growth response curve data for which climate suitability could be calculated, 118 species were predicted to be capable of growth in at least two thirds of Scotland's land mass in three seasons of the year.

4.2.3 Surveillance of known hosts in trade/ public gardens/ landscaped sites

For each of the 196 Phytophthora species, we assessed host samples (both positive and negative) collected during SASA inspections from trade premises and public gardens or landscaped sites across Scotland for 22 quarantine or regulated non-quarantine pest species and compared these host samples against the known host range of each *Phytophthora* species (Table 1). This inspection data was received from SASA on 27th June 2023 and does not include all inspections carried out by SASA, but only those targeting quarantine/regulated pests and pathogens. The data comprise samples since 2012 from known hosts of quarantine or regulated non-quarantine pests, including five *Phytophthora* species. This metric is intended as a proxy for the risk-based approach to surveillance used by SASA to target high risk hosts for quarantine/regulated pests and pathogens in trade, public gardens and landscaped sites, but excludes tree health wider environment ground surveys and import checks carried out at border control posts located outside Scotland by the relevant plant health inspectors. *Phytophthora* species associated with hosts that are more regularly inspected may be considered at lower risk of arrival or repeated introductions given the greater likelihood of interception and subsequent eradication/containment. In contrast, the 72 *Phytophthora* species that do not share any host genera with any of the 22 quarantine pests may be at higher risk of a new or repeated introduction, as they would be unlikely to be detected through existing surveillance mechanisms that focus inspections on hosts of quarantine pests.

Nursery Trade / Garden Centres

For context, nurseries producing susceptible plants have largely been clear of *P. ramorum* and *P. kernoviae* and continue to receive two site inspections a year plus one based on risk. Inspections at nurseries and garden centres have also included visual checks of *P. austrocedri*, *P. lateralis* and *P. pluvialis* hosts.

4.2.4 Potential impacts on Scotland's priority plants, habitats and forest estate

The metrics selected for ranking threats to Scotland were also guided by the need to capture potential impacts on native species and habitats where threats to plant health are less well documented compared to economically important species (Mitchell 2024). To assess the potential impacts on priority plant species in Scotland, we used the global *Phytophthora* database to intersect the reported host genera for each *Phytophthora* species with vascular and non-vascular plant genera on Scotland's Biodiversity List and scored the numbers of at-risk host genera for each *Phytophthora* species. The NVC floristic tables can be used to map species to the 12 broad NVC habitats. We intersected the global host genera of each *Phytophthora* species captured in our database with plant genera in the NVC floristic tables to identify broad NVC habitat classes that may be at risk from *Phytophthora* species. There are 31 *Phytophthora* species with between 2 and 10 potential host genera that are listed on the Scotland Biodiversity List and 58 *Phytophthora* species that threaten more than 8 different NVC habitats. The potential scale of impacts on native woodland and forestry species is scored by intersecting the global database of *Phytophthora* species hosts with the genus of the primary, secondary or tertiary species recorded in the NFES data for Scotland 2019. We extracted and scored the number of sub-compartments containing potential host genera for each *Phytophthora* species. For 56 *Phytophthora* species, there are over 4000 sub-compartments that contain known potential host genera.

4.2.5 Future Phytophthora threats with potential to impact native plants, habitats and forestry in Scotland

The database of risk and impact scores for Scotland and information on the hosts and habitats at risk for each *Phytophthora* species are provided as an comma separated file, so that users can generate bespoke rankings that reflect sector-specific priorities or impacts, or focus on one or a subset of the risk and impacts scores. In Table 2, we rank predicted threats from 123 known *Phytophthora* species that have yet to arrive in Scotland by combining scores of arrival risk, climate suitability, levels of host surveillance, and potential to impact Scotland's native species (Scottish Biodiversity List), NVC habitats (via species components in NVC Floristic tables) and forestry species widespread within the NFES 2019 for Scotland. The global database of distributions and hosts of *Phytophthora* can be intersected with any list of priority plant species, genera, or families for which a ranking of potential *Phytophthora* threats is required. Examples of priority species lists may include widely planted or newly available ornamental or crop species or proposed alternative forestry species. It is important to note that our database does not contain information about the severity of disease on different hosts species or in different regions, only that an interaction has been reported. The ranking of these threats is therefore most appropriate to identify key knowledge gaps to fill for particular *Phytophthora* species to inform full pest risk assessments or contingency plans. For example, it may be necessary to review or commission pathogenicity tests for priority host species in Scotland that are identified in this report as being at risk from *Phytophthora* species likely to arrive and establish.

Of the top ten identified *Phytophthora* threats to Scotland (Table 2), the *Phytophthora* species most likely to arrive in the UK are *P. europaea*, *P. crassamura* and *P. asparagi*. *Phytophthora sansomeana*, *P. clandestina* and *P. polonica* were identified as species with potentially large impacts on priority hosts or habitats in Scotland, but for which arrival risks could not be estimated due to the unknown origins of these species prior to their descriptions in 2009, 1985 and 2006, respectively. Therefore, users of the list should be mindful that due to missing knowledge some global *Phytophthora* species of potential concern may not be included in the ranking presented here. Note that the scoring places equal weighting on all criteria to produce the overall risk score.

Table 1 Scoring of risk and impact metrics to rank relative threats that Phytophthora species pose to Scotland's priority plants and habitats

Risk / impact metric	**Values**	**Risk score**	**Number of *Phytophthora* species in each risk category**
Predicted relative risk of arrival / repeated introduction into the UK	Probability of arrival >0 <= 0.4	0	30
	Probability of arrival >0.4 <= 0.8	1	37
	Probability of arrival >0.8 <= 0.9	2	17
	Probability of arrival >0.9	3	23
	Unknown source regions for modelling trade connectivity and climate matching	NA	89
Predicted climate suitability for mycelial growth	Non-zero growth across 66% of grid cells in Scotland in **0** seasons in 2022	0	8
	Non-zero growth across 66% of grid cells in Scotland in **1** season in 2022	1	23
	Non-zero growth across 66% of grid cells in Scotland in **2** seasons in 2022	2	22
	Non-zero growth across 66% of grid cells in Scotland in **3** seasons in 2022	3	118
Surveillance of host genera in inspected premises since 2012	> 1000 samples of known host genera	0	50
	> 100 ≤ 1000 samples of known host genera inspected	1	31
	> 1 ≤ 100 samples of known host genera	2	43
	No samples of known host genera	3	72
Threat to Scottish Biodiversity List	No known host genera on SBL	0	116
	> 0 ≤ 2 known host genera on SBL	1	51
	> 2 ≤ 9 known host genera on SBL	2	22
	> 10 known host genera on SBL	3	7
Threatened NVC habitats	No NVC habitats containing known host genera	0	62
	>0 ≤ 4 NVC habitats containing known host genera	1	37

	> 4 ≤ 8 NVC habitats containing known host genera	2	39
	> 8 NVC habitats containing known host genera	3	58
Threat to National Forest Estate sub-compartments primary, secondary or tertiary species	No sub-compartments containing known global host genera	0	91
	>0 ≤ 1000 sub-compartments containing known global host genera	1	19
	> 1000 ≤ 4000 sub-compartments containing known global host genera	2	30
	> 4000 sub-compartments containing known global host genera	3	56

Of the ten greatest *Phytophthora* threats to Scotland identified, climate suitability for establishment was scored as 3 (highest risk) for 9 of the 10 species, meaning that there is non-zero growth in 3 seasons of the year in at least 66% of Scotland, indicating that climatic conditions are highly suitable for establishment.

There were three *Phytophthora* species within the top ten threats to Scotland whose known hosts have not been sampled in routine plant health inspections (*P. borealis*, *P. clandestina* and *P. trifolii*). This may be because these host genera (including *Salix*, *Melilotus* and *Trifolium*) are rarely or never grown or traded in inspected premises or because the hosts are not considered high risk for other quarantine pest and diseases. These *Phytophthora* species are therefore unlikely to be intercepted if introduced and pose a greater risk for establishment and spread prior to detection.

Across the ten *Phytophthora* species yet to arrive and be identified as the greatest future threats to Scotland (Table 2), there are four *Phytophthora* species with potential to impact *Salix*, of which there are 3 species on the Scottish Biodiversity List. These three species of *Salix* are flagged as either Vulnerable or Endangered, two are on the UK Biodiversity Action Plan List, one (Downy Willow: *Salix lapponum*) has experienced a 25% decline in Scotland and another (Whortle-leaved willow: *S. myrsinites*) is rare in the UK (present in <16 10km grid cells). Other genera on the Scottish Biodiversity List at risk of *Phytophthora* impacts include *Juncus*, *Juniperus*, *Rosa* and *Trifolium*, all of which are congeners of species known to be associated elsewhere in the world with the *Phytophthora* species in Table 2.

We intersected the known global host plant species, genera and families of *Phytophthora* species with NVC floristic tables (Mitchell, 2024) to identify habitats most at risk (Fig. 2). There were 19 *Phytophthora* species not yet present but with a probability of arrival >0.5 (Fig. 2b). For these species, the NVC habitats most at risk due to the presence of known *Phytophthora* host genera were Woodlands and scrub (10 *Phytophthora* threats), Heaths (9 threats), Vegetation of open habitats (9 threats) and Mires (8 threats). Across the 74 *Phytophthora* species already present in the UK, habitats most at risk are Woodlands and scrub (70 *Phytophthora* species), Vegetation of open habitats (63 *Phytophthora*) and Calcicolous grasslands (61 *Phytophthora*) due to the presence of known *Phytophthora* host plant species in these habitats (Fig. 2b). The NVC habitats most at risk from the ten future *Phytophthora* threats identified in Table 2 include Vegetation of open habitats and Woodlands and scrub. Open habitats in NVC are varied community types including disturbed or colonising habitats, arable weed communities, weedy pastures, gates, paths, verges, wasteland and urban habitats (Pigott et al., 2000). Four *Phytophthora* species yet to arrive in Scotland are already associated elsewhere, globally, with species listed in the NVC floristic tables for these habitats and are also predicted to have high probability of arrival and or climate suitability in Scotland. Other potentially impacted NVC habitat types include Calcifugous grasslands and montane communities, Mesotrophic grasslands, Shingle and sand dune communities (Table 2). One or more future *Phytophthora* threats in Table 2 are already associated globally with NVC-listed species in Calcicolous grasslands, Heaths, Maritime cliff communities, Mires, Swamps and tall-herb fens and Swamps and tall-herb fens.

Among the ten greatest future *Phytophthora* threats to Scotland, potential impacts on the National Forest Estate include sub-compartments with *Quercus*, *Salix* and *Alnus* as primary tree species. Congeners of *Quercus* species are associated, globally, with *P. europaea, P. crassamura*, *P. asparagi*, *P. polonica* and *P. quercetorum* (but also other Phytophthoras with lower predicted risks of arrival, and climate suitability). Congeners of *Salix* species are associated with four of the *Phytophthora* species most likely to arrive (*P. crassamura*, *P. polonica*, *P. borealis*, and *P. parvispora*) and congeners of *Alnus* are associated with *P. europaea*, *P. crassamura* and *P. polonica (Table 2)*.

Table 2 Ten top-ranked future Phytophthora threats to Scotland ranked based on probability of arrival, climate suitability in Scotland, level of known host surveillance, and known global host genera on Scotland's Biodiversity List, in NVC habitats, or forming a substantial portion of the National Forest Estate (primary, secondary or tertiary species). Full scoring of each risk factor using the criteria in Table 1 can be accessed at

Phytophthora	**PHRR**	**Global source regions**	**At Risk National Forest Estate genera**	**At risk NVC habitat genera[1]**	**At risk Scottish Biodiversity List genera**	**Overall risk score**
P. europaea	no	Austria; California; France; Germany; Michigan; Minnesota; Missouri; Ohio; Oregon; Pennsylvania; Poland; Switzerland; West Virginia; Wisconsin	*Abies; Alnus; Quercus*	A; CG; H; M; MC; MG; OV; S; SD; SM; U; W	*Juncus*	14
P. crassamura	no	California; Iran; Italy; Minnesota; New South Wales; Oregon; Sardegna; Sicilia; Spain; Switzerland; Turkey; Western Australia	*Alnus; Castanea; Fraxinus; Juniperus; Picea; Pinus; Prunus; Quercus; Salix*	A; CG; H; M; MC; MG; OV; S; SD; SM; U; W	*Artemisia; Juniperus; Juncus; Vicia; Rosa; Salix; Salvia; Sambucus*	14
P. asparagi	no	California; France; Italy; Michigan; Netherlands; New Zealand North; Sardegna; Sicilia; Switzerland; Yunnan	*Juniperus; Quercus*	CG; H; M; OV; S; SD; U; W	*Juniperus*	12
P. polonica	yes	Croatia; Czech Republic; Hungary; Massachusetts; Poland; Serbia; Sicilia; Switzerland; Ukraine	*Alnus; Chamaecyparis; Fraxinus; Populus; Prunus; Quercus; Salix; Tilia*	CG; H; M; MC; MG; OV; S; SD; U; W	*Populus; Rubus; Salix*	12
P. borealis	no	Alaska; California; Massachusetts; Western Australia	*Salix*	CG; H; M; MC; OV; S; SD; U; W	*Salix*	11
P. clandestine	no	Victoria		CG; H; M; MC; MG; OV; S; SD; SM; U; W	*Trifolium*	11
P. sansomeana	no	Croatia; Czech Republic; Illinois; Indiana; Iowa; Iran; Kansas; Michigan; Minnesota; Mississippi; Nebraska; New York; Ohio; Ontario; South Dakota; South Korea; Spain; Switzerland; Wisconsin	*Abies; Chamaecyparis*	CG; H; M; MC; MG; OV; S; SD; SM; U; W	*Lathyrus; Silene*	10
P. quercetorum	no	California; Maryland; South Carolina	*Acer; Quercus*	CG; H; MC; MG; OV; SD; U; W	*Rosa*	10
P. trifolii	no	Mississippi		CG; H; M; MC; MG; OV; S; SD; SM; U; W	*Trifolium*	10
P. parvispora	no	California; Colombia; Croatia; Germany; Italy; Portugal; Sardegna; Sicilia; Taiwan; Tamil Nadu; Turkey; Vietnam; Western Cape Province	*Pinus; Salix*	CG; H; M; MC; OV; S; SD; U; W	*Salix*	9

[1] A = Aquatic communities; W = Woodlands and scrub; M = Mires; H = Heaths; MG = Mesotrophic grasslands; CG = Calcicolous grasslands; U = Calcifugous grasslands and montane communities; S = Swamps and tall-herb fens; SD = Shingle, strandline and sand-dune communities; SM = Salt-marsh communities; MC = Maritime cliff communities; OV = Vegetation of open habitats

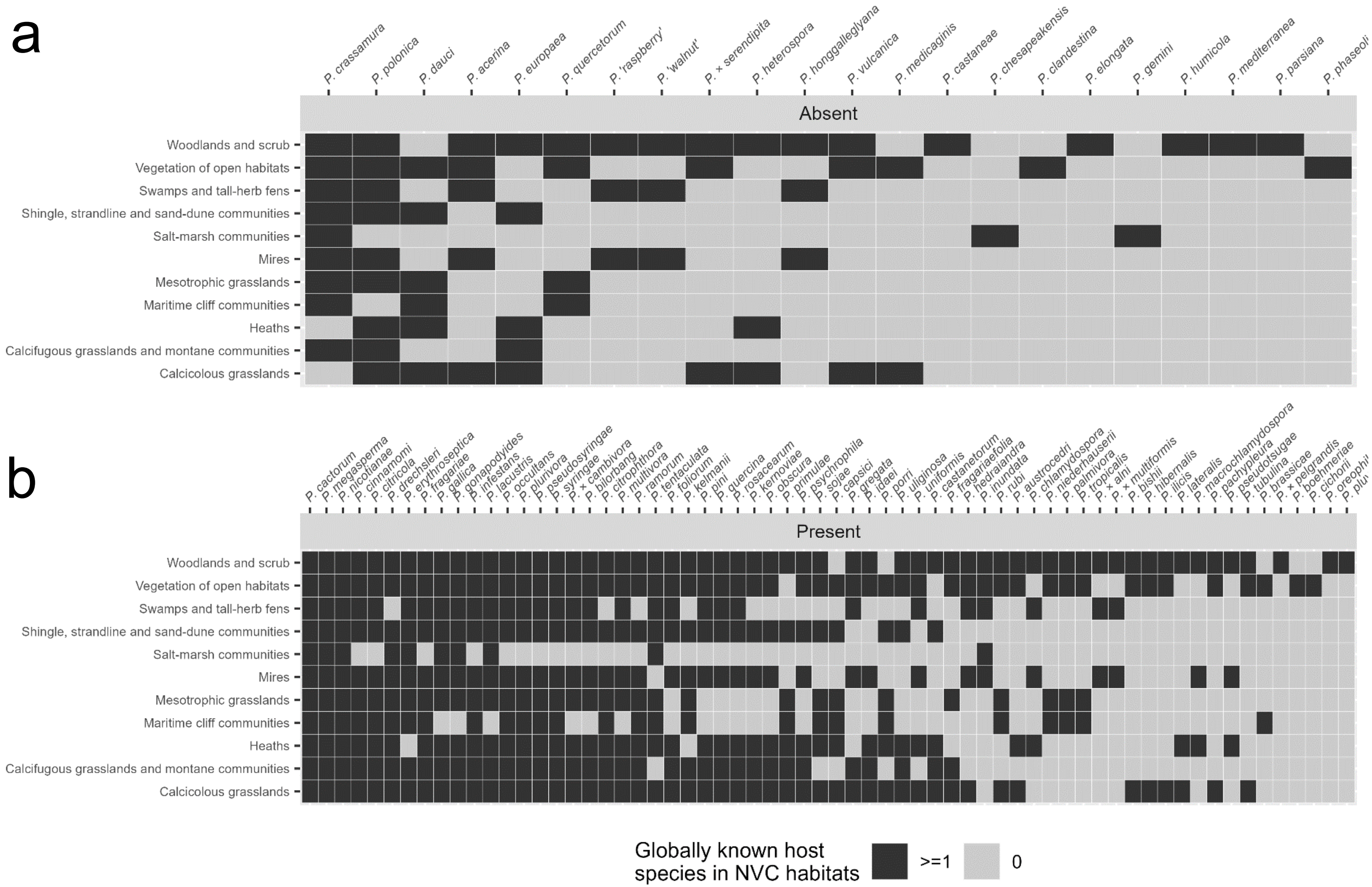

Figure 2 Intersection of known global host plant species of Phytophthoras with NVC Floristic tables to identify broad NVC habitats at risk (>=1 globally known host species within the NVC habitat) compared to those considered low risk (0 known Phytophthora hosts within the habitat). The top panel are Phytophthora species not yet known to be present in the UK, while the bottom panel are Phytophthora species already reported in the UK.

4.3 *Co-designed spatial risk frameworks for mapping relative risks of Phytophthora infections in focal habitat fragments*

This section describes the five risk frameworks co-designed with stakeholders, tailored to the priority threats (combinations of *Phytophthora* species-host/habitat) and risk factors and their scoring identified during the initial self-completion survey and first online workshop described in Section 3. Initial model outputs were shared in the final workshop on 13th November 2024. Outputs were then revised following analysis of the workshop transcripts and one-to-one follow up meetings or correspondence to seek specific guidance on input data or end-use. Here we describe first stakeholder priorities in relation to risk assessments, and then for each of the five risk assessments, the key risk factors and weighting used to identify relatively high-risk habitats for *Phytophthora* infection. We also summarise brief key outcomes in terms of extent of risk and identified value for decision making. Appendices and links to the EIDC datasets provide a fuller description of the methods, outputs and their interpretation and potential impacts on decision-making identified by stakeholders. All risk frameworks presented use a new climate suitability model to estimate climate-driven risk that is based on pathogen-specific temperature dependent growth curves and relative humidity thresholds (Green et al., 2024), coupled with hourly gridded temperature and relative humidity data from ERA5 (Hersbach et al., 2020; Muñoz Sabater, 2019).

4.3.1 *Prioritisation of hosts, habitats and Phytophthora threats*

The co-production of the risk frameworks were initiated by identifying priority hosts, habitats and *Phytophthora* threats among the consulted stakeholders to select the combinations of *Phytophthora* species and habitat or host fragments for which spatial risk frameworks were perceived as most valuable, though we acknowledge that the restricted sample size of participants in the survey (n = 9) may limit the breadth of threats identified. Potential biases include over-representation of habitats and *Phytophthora* species relevant to sectors with a stronger history of engagement with research (e.g. forestry) and *Phytophthora* threats for which there are greater documented impacts and awareness. Through the initial surveys and workshop, stakeholders identified and ranked their top five pest or disease threats in their sectors. In the pre-workshop survey, all participants demonstrated a high level of awareness and self-reported as either very knowledgeable (78%, n=7) or knowledgeable (22%, n=2) about plant health. Additionally, all respondents considered Phytophthoras as either a very important (78%, n=7) or important (22%, n=2) disease threat in their sector or area of work (see Appendix S1). When asked to identify the top five pest or disease threats to plant health in their sector or area, respondents most frequently mentioned *Phytophthora* species (n=8).

Reasons underpinning participants' concerns included the wide host range of *Phytophthora*, the ability to spread in soil and water, ability to adapt to new hosts and climates, potential for rapid and serious devastation, and difficulty of detection (due to asymptomatic infection) and control. The *Phytophthora* species of most concern and high priority were *P. ramorum*, *P. austrocedri*, and *P. x alni* (n=7), which were ranked as very serious threats. Participants also identified all the threats/species as current concerns, except for *P. pinifolia* on Scots pine, which was indicated as an anticipated concern. Impacts on blueberry (*Vaccinium myrtillus*) were also indicated as a current concern (see Table 3). Other participants also noted the need to consider regionally important and under-researched key priority hosts and habitats such as Aspen, pines and woodlands in general and *P. pluvialis* threats to Western hemlock and Douglas fir. Informed by these inputs and prioritisations, we produced three new and two updated spatial risk frameworks for Scotland:

- *P. ramorum* risks to Larch (4.3.3, Appendix 7.1) and heathland (4.3.4, Appendix 7.2) fragments
- *P. x alni* risks to alder fragments (4.3.5, Appendix 7.3)
- *P. pluvialis* risks to Douglas fir and Western hemlock fragments (4.3.6, Appendix 7.4)
- *P. pinifolia* risks to the Caledonian Pinewood Inventory (4.3.7, Appendix 7.5).

Where full risk frameworks, integrating multiple risk factors, could not be developed for priority *Phytophthora* threats (e.g. due to lack of available data on the distribution of priority hosts or recent pathogen detections as sources of infection: Table 3), we provide species-specific current climate suitability maps for associated *Phytophthora* species. We also excluded hosts and habitats for which no specific *Phytophthora* species threats were identified. For example. our global database includes only three *Phytophthora* detections on Aspen globally (*P. idaei* and *P. lacustris*) originating from metabarcoding studies without confirmation of the causal agent of symptoms. Therefore, there is significant uncertainty around the relevant *Phytophthora* threats to Aspen to inform spatial risk frameworks. Mapping of threats to woodlands more generally would require a more generic approach than the pathogen-specific threats for which these methods were originally developed (e.g. to include proximity to infected sites, and pathogen-specific climate suitability). Such approaches would instead need to develop risk factors relating to specific pathways of introduction and spread, and for which there are often limited data (e.g. domestic supply chains, recreational use).

Table 3 Ranked threats from Phytophthora species identified in the survey, representing unique combinations of Phytophthora species, host and/or habitat and how they were addressed in framework. Rows in grey highlight risk frameworks implemented.

***Phytophthora* (n=7, 78%)**	**Host (n=6, 67%)**	**Habitat (n=7, 78%)**	**Rank** 1= most serious, 4= serious	**Pathogen Impact Status**	**Spatial risk framework developed in this project**
P. x alni	Alder	Wet woodlands	1	Current	Yes, for all alder fragments including wet woodlands and riparian
P. x alni	Alder	Riparian	1	Current	
P. austrocedri	Juniper	Native Caledonian woodland	1	Current	No, *P. austrocedri* spatial risk models developed by Donald, 2020
P. austrocedri	Juniper	Woodland	1	Current	
P. cinnamomic	Oak species	Oak woodland	4	Anticipated	Climate suitability only, but future climate scenarios not yet integrated
P. kernoviae	Oak species	Oak woodland	4	Anticipated	Climate suitability only, insufficient new detections to update.
P. pinifolia	Scots Pine	Caledonian Pine Inventory sites	4	Anticipated	Yes
P. pseudosyringae	Oak species	Oak woodland	4	Anticipated	Climate suitability only
P. ramorum	Blueberry	Heathland	4	Anticipated	Yes, updated risk frameworks for heathland fragments
P. ramorum	Blueberry	Pinewoods	-	Anticipated	No, insufficient data on Blaeberry distribution in pinewoods
P. ramorum	Blueberry	Woodlands with Larch and other sporulating species	1	Anticipated	No, insufficient data on Blaeberry distribution in woodlands
P. ramorum	Larch	Forest	1	Current	Yes, updated risk framework

P. ramorum	Oak species	Oak woodland	1	Anticipated	No, but a priority for future work

4.3.2 *Stakeholder perspectives and feedback on risk assessment frameworks*

A wide range of key stakeholder evidence needs and risk assessment priorities were highlighted during the first workshop, including considerations for data requirements, risk factors, assessment approaches and risk-scoring methods for developing a *Phytophthora* risk assessment framework (Table 4). In terms of data sources and layers for mapping of susceptible hosts and habitats, stakeholders suggested and emphasised the importance of integrating traditional surveys (NWSS, NFI) with advanced data types including satellite imagery and Earth Observation data for mapping susceptible hosts and habitats. There was particular emphasis on climate data and future projections, and novel datasets for mapping (e.g. Zulu Lost Woods data, remnant ancient woodlands, SEPA Water Level data, Strava data for assessing forest footfall).

Table 4 Stakeholder priorities, evidence needs and decision making processes identified in the first framing workshop and how these were integrated into the risk frameworks

Thematic focus	**Key priorities, evidence needs and decisionmaking approaches identified by participants**	**Integration into risk frameworks**
Risk Prioritisation	• *P. ramorum*, *P. x alni*, *P. austrocedri* as key threats • Focus on native species (oak, Scots pine, alder) • Inclusion of non-tree species (e.g., *Vaccinium*) • Consideration of key host priorities and threats (*P. pluvialis*, *aspen* and *P. pinifolia*)	• See Table 3 above for details. *P. austrocedri* risk models already developed (Donald et al., 2020, 2021) • Yes, focal native species included alder and Caledonian Pinewood Inventory. • Yes, risks *P. ramorum* to heathlands containing *Vaccinium* and other native, susceptible hosts. • Yes, *P. pluvialis* risks to Douglas fir and Western hemlock and *P. pinifolia* threats to CPI
Data sources and layers	• Integration of traditional surveys (NWSS, NFI) with advanced data (satellite imagery, Earth Observation • Emphasis on climate data, including future projections • Interest in other datasets and novel data sources (e.g., Zulu Lost Woods data etc)	• Partly integrated: The LCM 2023 was used to identify heathland fragments and the NFI data to identify felled areas, but in future EO data could be also used to identify areas of high host stress, disturbance or co-occurring disease. • Partly, climate suitability treated as primary risk factor through scoring/relative weighting, but future projections are beyond the scope of this project and models would require some adaptation due to the coarse temporal resolution of future temperature and relative humidity data (daily/hourly is ideal) • No, but the climate suitability outputs can be overlaid with any spatial habitat, premise or host layers for which *Phytophthora* risks of establishment are a concern
Risk Factors	• Climate suitability identified as a key risk factor; followed by water-related factors which were highlighted as key determinants of *Phytophthora* spread • Recognition of the importance of host distribution and alternative hosts; • Consideration of human activity as a significant risk factor • Few mentioned connectivity of suburban/urban gardens as risk factor	• Scoring scheme weights climate suitability as most important risk factor in all risk frameworks. Climate suitability models integrate water availability (relative humidity). Presence of water courses (for *P. ramorum, P. pluvialis*) or flood risk (for *P. x alni*) in focal fragments also scored. • Proximity to alternative hosts is scored for known hosts/habitats with available distribution data • Human activity not integrated as spatial data on recreational and vehicle/machinery use not available for Scotland • Further research needed to understand role of garden connectivity in *Phytophthora* spread

Risk assessment approaches	• Varied risk assessment approaches proposed • Preference for a two-stage process combining species-specific and habitat-level assessments but recognition of the need to consider both ecological importance of threatened hosts and *Phytophthora* impact	• Integrated knowledge of relevant risk factors for focal *Phytophthora* species and, where possible, tailored outputs to relevant agencies. • Species-level (CPI, Douglas fir/Western hemlock), genus-level (Larch, alder) and habitat level (heathland) approaches developed
Risk scoring and weightings	• There is need for validation of risk scoring methods, as well as the use of data driven approaches • Climate hazard and host distribution suggested as baseline elements. • Interest in flexible, interactive risk scoring tools	• Previous risk framework for Larch was evaluated against subsequent, independent outbreak data (e.g. for *Phytophthora ramorum*) • All methods score climate suitability and proximity to other hosts • Not yet developed, but a priority next step
Use of the risk maps	• Primarily useful for informing surveillance strategies, guiding resource allocation and supporting policy development	• Key actors in agencies to which the risk maps should be transferred have been identified • Identified key repositories on which the risk maps can be made widely available to actors across sectors • Repositories will be linked to Scottish Plant Health Centre portal and other portals to facilitate further access
Stakeholder Engagement	• The need for accessible, tailored outputs for diverse stakeholders, using multiple communication channels (Plant Health Portal, events, networks, reports)	

Discussions of key risk factors for *Phytophthora* establishment/spread, identified climate suitability as the primary concern, followed by water-related factors as key determinants of *Phytophthora* spread. Host distribution and the role of alternative hosts were also recognised as key elements, while human activity was highlighted as a significant risk factor. Some stakeholders identified large nurseries and garden centres as potential hotspots for pathogen introduction and spread and noted land use change, trade patterns and connectivity with gardens as potential risk considerations. Large nurseries and garden centres were also identified as potential hotspots for pathogen introduction and spread. In the second workshop for instance, trade metrics were seen as relevant for *Phytophthora* management through two specific regulatory processes such as plant passport authorization and import/export decisions. However, some participants stressed the need for simplification and regular updates to make the tool practically useful.

Another important aspect regarding assessment approaches was the stakeholder preference for varied methods, with some favouring a two-stage process combining species-specific and habitat-level assessments. However, there was a consensus that a more generic framework that considers multiple factors and pathogen threats simultaneously would be of value. For risk scoring and weightings, participants emphasised the need for validation of scoring methods and data-driven approaches, suggesting climate hazard and host distribution as baseline risk factors to include. There was significant interest in developing flexible, interactive risk scoring tools. In the second workshop, there were suggestions to cross-check and make sure host databases were searchable by family, genus and species level. These identified priorities and evidence needs and informed the development, updates and refinement of some of the risk assessment frameworks (Sections 4.4.3 – 4.3.7, Appendix 7.7, Table A16).

4.3.3 Updated spatial risk analysis for Phytophthora ramorum infection for Scotland's Larch fragments

4.3.3.1 Methods and stakeholder needs

Full methods and results are given in Appendix 7.1. We updated a prior risk analysis (Purse et al. 2016) to (i) remove Larch fragments felled since 2013 through Statutory Plant Health

Notices and other clear-felling; (ii) include new P. *ramorum* detections in Larch woodlands and inspected premises (Scottish Forestry, SASA) (iii) score risk of establishment using new climate suitability models of pathogen growth; (iv) score risks of transmission from alternative host species of *P. ramorum* using new host distribution models. Stakeholder's felt that climate suitability should be the primary risk factor for all *Phytophthora* species and emphasis on proximity to inspected premises as a pathway for introduction to the wider environment should be reduced, reflecting perceived improved biosecurity practices in trade. We acknowledge that other pathways of introduction and spread (e.g. large-scale planting within different sectors, recreation, forestry machinery) may also present risks to Larch and are not accounted for here due to lack of spatial data on these practices. Larch fragments were assigned a risk score for each of the seven risk factors (Table 5, Appendix 7.1, Table A2). The scores and relative weightings (defined by maximum score of each individual risk factor) were validated with stakeholders (2nd workshop and Scottish Forestry meetings, Appendix 7.1). The maximum possible risk score for *P. ramorum* is 12.

Table 5 Risk factors for Phytophthora ramorum *risks to Larch, ordered from most important (climate suitability) to least important (proximity to importing trade premises) factors. See Appendix 7.1 for relative weightings and score levels for each risk factor.*

Risk factor	**Parameter scored for fragment**
***P. ramorum* climatic suitability (average within fragment)**	Whether average growth in mm/day falls within different percentile ranges of values across GB
Proximity of fragment to other Larch	Whether other larch or infected larch present within 5000m or not
Alternative host suitability (*R.ponticum*, *V. myrtillus*, *V. vitis-idaea*, *A. uva-ursi*)	Whether habitat suitability values fall within percentile ranges of habitat suitability for each host species
Other wider environment detections	Presence-absence of Pr detections within 1500m
Watercourses (within fragment itself)	Presence-absence within fragment
Proximity to detections in inspected premises	Whether intersects postcode district of infected premises or not
Proximity to importing trade premises	Whether there are premises importing live plants within 1500m or not

4.3.3.2 Distribution of Phytophthora ramorum risks to Larch fragments in Scotland

Scottish Forestry divides Scotland into five geographical regions (conservancies) responsible for managing regional forestry activities. We report the number of fragments at low, medium and high risk of *P. ramorum* infection within each of the five conservancies to compare the geographical distribution of risks (Table 6). Larch risk of *P. ramorum* infection was greatest within South Scotland, where 97% of Larch fragments were assessed as high or medium risk. Within Perth and Argyll conservancy 89% of fragments were assessed as high or medium risk (Table 6). There was a lower but still substantial percentage of high and medium risk Larch fragments in the Highland and Islands (73%), Central Scotland (64%) and Grampian (32%) conservancies.

Of the 20317 Larch fragments assessed as high risk, 16728 (82%) have remained uninfected (do not intersect any SPHN) despite high climate suitability, proximity to other infected sites, high suitability for alternative hosts and presence of water courses. Within the *P. ramorum* Risk Reduction Zone, 78% of high risk Larch fragments are currently uninfected. In the Priority Action Zone, 89% of high risk Larch fragments remain uninfected (Table 7). Across Larch fragments assessed as medium and low risk 89% and 97%, respectively, have remained uninfected. Absence of disease in high risk areas may arise from successful prevention of spread through measures such as aerial and ground surveys and rapid felling of infected trees in the Priority Action Zone and Risk Reduction Zone, but may also indicate cryptic infection, disease dispersal limitations or a need for refinement of risk factors.

Table 6 Number of Larch fragments per conservancy in each risk category for P. ramorum infection

Conservancy	Low (0 <=3)	Medium (>3 <= 6)	High (>6)
Central Scotland	2118	3446	363
Grampian	6192	2853	3
Highland and Islands	4562	10363	2255
Perth and Argyll	2882	15312	8870
South Scotland	558	10457	8826

Table 7 Number of Larch fragments assessed as high risk with an SPHN or without SPHN within each policy zone.

SPHN	Priority Action Zone	Risk Reduction Zone	Management Zone
SPHNs issued/in progress/complete	890	2551	152
No SPHN	7295	2867	6562

4.3.3.3 Perceived value of P. ramorum risk maps for decision-making

Key uses identified for the *P. ramorum* risk maps for Larch at policy level included informing decisions on new planting of Larch, which is still eligible for grant support in low *P. ramorum* risk areas. The Scottish Forestry policy zone boundaries could also be compared to the risk predictions to help assess the efficacy of containment policy for *P. ramorum*. If large numbers of high risk fragments have remained free of *P. ramorum* infection, this may indicate that biosecurity measures are successful in preventing spread. The spatial risk framework for *P. ramorum* on Larch was felt to be supportive evidence for the review of existing legislation and regulatory control, that aims to assess effectiveness for biosecurity measures laid out in the *P. ramorum* Action plan. A role for the risk framework in resource allocation planning was suggested, for example, in targeting environmental surveillance for *P. ramorum*. Participants also highlighted a potential role in informing future productive tree species in Scotland.

Users of the risk frameworks should also be aware that potentially important social factors in *P. ramorum* outbreaks (and *Phytophthora* outbreaks generally) are not captured in the risk scoring. For example, key data gaps prevent the inclusion of spatial variation in biosecurity awareness and practices in trade (e.g. higher risk business typologies and supply chains), habitat restoration and other plantings, and the risk of spread via recreational use of landscapes (but see Hooftmann et al. 2023 for predicted recreational demand across UK), which may enhance or mitigate the overall risks predicted for Scotland's Larch fragments.

4.3.4 Updated spatial risk analysis for Phytophthora ramorum infection within Scotland's heathland fragments

4.3.4.1 Methods and stakeholder needs

We updated a prior risk analysis framework (Searle et al., 2016) to include (i) new *P. ramorum* detection data in Larch woodlands and inspected premises (Scottish Forestry, SASA); (ii) new climate suitability models for *P. ramorum* growth. Risks to heathland fragments from *P. ramorum* were scored using the protocol in Table 8 and Appendix 7.2.

Table 8 Risk factors for Phytophthora ramorum risks to heathland comprising Heather (H9) or Heather grassland (H10), ordered from most important (climate suitability) to least important (proximity to detections in inspected premises). See Appendix 7.2 for relative weightings and score levels for each risk factor.

Risk factor	Parameter scored within fragment
***P. ramorum* climatic suitability (average within fragment)**	Whether cumulative annual growth in mm falls within different percentile ranges of values across GB

Proximity to Larch/infected Larch	Whether larch or infected larch present within 5000m or not
Susceptible hosts within fragment (*R.ponticum, V. myrtillus, V. vitis-idaea, A. uva-ursi*)	Whether habitat suitability values fall within percentile ranges of habitat suitability for each host species
Other wider environment detections	Presence-absence of non-larch *P. ramorum* detections within 1500m
Watercourses (within fragment itself)	Presence-absence of water courses within fragment
Proximity to detections in inspected premises	Whether fragment does or does not intersect postcode district of infected premises

4.3.4.2 Distribution of risks to heathland fragments in Scotland

The maximum risk score value assigned for any fragment was 10.5 for Heather (H9) and 11 for Heather grassland (H10). There were more high-risk fragments for *P. ramorum* establishment across heather grassland than heather (Appendix 7.2, Fig. A4) due to the western distribution of the habitat coinciding with greater climate suitability for *P. ramorum* establishment and more widespread infections in Larch woodlands in southern and western regions (Appendix 7.2, Fig. A3). Whilst the majority of high risk heather (H9) fragments for *P. ramorum* establishment are in Highland, Aberdeenshire and Perth and Kinross, there are also high risk fragments in the west and south of Scotland particularly Stirling, Argyll and Bute and Dumfries and Galloway and the Scottish Borders (Table 9). High risk heather grassland (H10) fragments were predominantly distributed in Highland, Argyll and Bute, Stirling and Dumfries and Galloway (Table 9). High risk heathland fragments for *P. ramorum* establishment include 1509 fragments of heather and 3207 fragments of heather grassland that are within or intersect protected areas within Scotland (30x30 project).

Table 9 Risks to heathland fragments from P. ramorum by local authority region. Overall risk scores were binned to identify low, medium and high-risk areas. Note that regions with no high-risk heathland fragments are not shown.

	Heather H9			**Heather grassland (H10)**			**Total high risk**
Local authority	**Low (0<=3)**	**Medium (>3<=6)**	**High (>6)**	**Low (0<=3)**	**Medium (>3<=6)**	**High (>6)**	
Highland	6254	14724	2735	5943	24541	5238	7973
Argyll and Bute	612	742	390	4395	6423	5043	5433
Stirling	10	162	790	70	1262	1456	2246
Dumfries and Galloway	0	62	257	3	439	962	1219
Perth and Kinross	398	4140	1064	81	672	62	1126
Scottish Borders	215	568	283	354	935	239	522
South Lanarkshire	2	151	75	112	330	62	137
South Ayrshire	0	6	1	17	782	106	107
Inverclyde	9	19	2	3	282	101	103
North Ayrshire	21	839	18	412	1116	58	76
West Dunbartonshire	0	28	8	5	127	63	71
Renfrewshire	1	17	0	0	230	70	70
East Ayrshire	4	41	22	35	356	27	49
East Renfrewshire	0	0	0	1	99	16	16
North Lanarkshire	4	48	3	83	258	11	14
East Dunbartonshire	0	11	4	11	107	4	8
Aberdeenshire	841	5024	4	170	542	0	4
Falkirk	7	41	1	51	162	1	2

4.3.4.3 *Perceived value of maps for decision-making*

There was agreement that the risk maps for heathland fragments could be useful for surveillance targeting, habitat protection and conservation planning, especially for institutions such as NatureScot. Dissemination pathways identified included sharing risk maps through conservation networks (via NatureScot) and integrating with existing systems used by land owners such as MyForest (integration into the web-based forest mapping tool).

The lack of host specificity of *P. ramorum* is a source of uncertainty in the models (Appendix 7.7), with risks potentially underestimated if additional species within heathland are susceptible. Host associations of *P. ramorum* are likely to be biased towards economically important species, with hosts within native habitats like heathland underreported.

4.3.5 *Spatial risk analysis for Phytophthora x alni infection of alder fragments in Scotland*

4.3.5.1 *Methods and stakeholder needs*

Phytophthora disease of alder has been widespread in southern England since at least 1995 and became more prevalent in annual surveys between 1994 and 2003 (Gibbs et al., 2003; Webber et al., 2004). It has been confirmed at several riparian sites in Scotland. Disease caused by *P. x alni* has only been reported on the alder genus *Alnus* to date. Species affected include Common alder, Italian alder and Grey alder, therefore we include all species of alder in the mapping of fragments at risk from *P. x alni*.

Alder fragments were scored for each risk factor identified in Table 10. For detailed methods for compilation of alder fragments, risk layers and their scoring see Appendix 7.3. Risk factors discussed in the first workshop included the role of environmental stress, especially flooding (e.g. Webber et al. 2004), in driving susceptibility to *P. x alni* disease (Table 10). It was stressed that risk maps should be able to identify high and low risk areas, therefore the overall risk scores, summed across the different factors, were grouped into low, medium and high-risk classes. In addition, the scored alder fragments were joined with polygons of conservancies and local authority areas to enable summarising comparative risks across broader regions in Scotland.

Table 10 Risk factors and scoring of Phytophthora x alni risks to alder containing fragments. See Appendix 7.3 for relative weightings and score levels for each risk factor.

Risk factor	Parameter
Climatic suitability for *P. x alni* growth (ERA5)	Whether average growth in mm/day falls within different percentile ranges of values across GB
Flood risk within alder fragment (SEPA Flood Maps)	Level of flood risk (categories of % chance of flooding each year)
Density of alder fragments within areas connected by high-risk flood extent	Number of alder fragments in area overlapping high flood risk area /km2 flood area
Proximity to alder/riparian planting (FGS scheme)	Presence-absence of alder/riparian native mixed broadleaves planted within 250m

Table 11 Risks to alder fragments by conservancy region. Overall risk scores could range from 0 to 11 (summed across the risk factors) and were binned to identify low, medium and high risk areas

	Low (0-3)	Medium (4-7)	High (8-11)
Central Scotland	6104	2720	401
Grampian	4392	1924	28
Highland and Islands	4472	4273	1068
Perth and Argyll	6618	6065	2189
South Scotland	4004	4082	1692

4.3.5.2 Distribution of risk scores for alder fragments across Scotland

High risk fragments for *Phytophthora* disease of alder were distributed in Perth and Argyll (41% of high risk fragments: Appendix 7.3, Fig. A5), likely driven by the greater numbers and connectivity of fragments in these regions, coupled with the greater climate suitability for *P. x alni* in western parts of Scotland. South Scotland (31%) and Highland and Islands (20%) conservancies contained 31% and 20% respectively of high risk alder fragments (Table 11). Together the Central Scotland and Grampian conservancies contained 31% of alder fragments mapped, but relatively few (8%) of these alder fragments were predicted to be high risk for *P. x alni*. There were also disproportionately more medium risk alder fragments in Perth and Argyll (32% of high and medium risk fragments), Highland and Islands (22%) and South Scotland (21%) and conservancies.

4.3.5.3 Perceived value of maps for decision-making

It was agreed that the maps could provide useful information for the management of riparian habitats, including riparian planting and land use planning. For NatureScot and Scottish Forestry, there was a concern around communication of the maps in case the risks were interpreted in ways that would discourage planting, rather than acting as a tool to enhance awareness and surveillance of disease symptoms in alder stands.

P. x alni is established in the UK and has been detected at several riparian sites in Scotland (Hendry & Elliot, 2024). The full extent of the disease in trade and the wider environment is uncertain, and alder decline can be difficult to attribute to *Phytophthora* disease due to multiple other stressors impacting alder health (Hendry & Elliot, 2024), therefore proximity to infected sites is not scored within the risk framework. Evidence indicates an association between outbreaks of *Phytophthora* disease of alder and flood events as a pathway of spread from infected sites via water flow (Jung and Blaschke 2004) though flooding may also stress trees and predispose them to disease. Riparian planting is also known to increase the risk of introduction (Jung and Blaschke, 2004), but the level of risk will vary significantly depending on the biosecurity of planting projects and the suppliers, neither of which are captured in the risk frameworks.

4.3.6 Spatial risk analysis for Phytophthora pluvialis infection of Douglas fir and Western hemlock in Scotland

4.3.6.1 Methods and stakeholder needs

Infections of *P. pluvialis* have been reported on Douglas fir and Western hemlock in England Wales and Scotland since the outbreak was first detected in 2021. Outside of the UK, pine species (*Pinus radiata*, *P. strobus*, *P. patula*) are also susceptible to the pathogen. We identified 11098 fragments containing Douglas fir or Western hemlock potentially susceptible to *P. pluvialis*. Risk factors and the final scoring protocol agreed with stakeholders is shown in Table 12 and described in Appendix 7.4. The maximum possible risk score for *P. pluvialis* infection was 11. In practice, no fragment scored higher than 8 across the five risk factors. The scored fragment data were intersected with the boundaries of conservancies, local authorities and active *P. pluvialis* demarcated areas to summarise the distribution of risks across regions in Scotland.

Table 12 Risk factors for P. pluvialis infection and risk scoring of woodland fragments containing Douglas fir and Western hemlock

Risk factor	**Parameter scored per fragment**
Climate suitability for *P. pluvialis* growth (ERA5)	Whether average growth in mm/day falls within different percentile ranges of values across GB
Proximity to other Douglas fir/Western Hemlock and infected sites (Scottish Forestry surveillance data)	Presence-absence of other Douglas fir / Western Hemlock within different distances <1500m of fragment

Proximity to woodland creation schemes using Douglas Fir and Western hemlock	Presence-absence of FGS woodland creation schemes within different distances <1500m of fragment
Proximity to higher risk inspected premises	Fragment does/does not intersect postcode district of SASA inspections of Tsuga or Pseudotsuga
Presence of water courses in fragment (OS Open Rivers)	Presence-absence of water course in the fragment

4.3.6.2 Distribution of Phytophthora pluvialis risks to Douglas fir and Western hemlock forest fragments in Scotland

High and medium risk fragments for *P. pluvialis* infection were distributed mostly in Perth and Argyll and South Scotland conservancies (Table 13) where 83% and 88% of fragments were either high or medium risk. A smaller percentage of fragments were high or medium risk within the Highland and Island (46%), Grampian (40%) and Central Scotland conservancies (35%). The risk scoring identified 457 high risk forest fragments containing Douglas fir or western hemlock. Of these high risk fragments 27% were within Demarcated areas (Table 14) from which the movement of plants for planting of *Tsuga*, *Pseudotsuga* and *Pinus* is prohibited (Fig. A7a). An additional 331 high risk fragments were identified outside of the demarcated areas (Fig. A7b) representing stands containing Douglas fir or western hemlock where the climate suitability for establishment is high, there is close proximity to other stands, recent planting of the species and regional proximity to inspected premises where the hosts are present or watercourses. The risk maps for *P. pluvialis* were mentioned within the breakout groups, but the impacts on decision-making within Scotland were not discussed.

Table 13 Number of Douglas fir or western hemlock fragments in each risk score category within the conservancy regions

Conservancy	Low (0-2)	Medium (3-5)	High (6-8)
Central Scotland	307	164	1
Grampian	1037	699	0
Highland and Islands	1792	1446	108
Perth and Argyll	565	2697	155
South Scotland	264	1670	193

Table 14 Number of Douglas fir or western hemlock fragments in each risk score category within the Phytophthora pluvialis Scotland Demarcated Areas

	Low (0-2)	Medium (3-5)	High (6-8)
Phytophthora pluvialis Scotland Demarcated Area No.4	0	2	7
Phytophthora pluvialis Scotland Demarcated Area No.5	71	0	17
Phytophthora pluvialis Scotland Demarcated Area No.6	55	49	628
Outside demarcated areas	331	3914	6024

4.3.7 Spatial risk analysis for Phytophthora pinifolia infection of Caledonian Pinewood Inventory fragments

4.3.7.1 Methods and stakeholder needs

Risks from *Phytophthora pinifolia* were calculated for 82 fragments of core zone Caledonian Pinewood from the Caledonian Pinewood Inventory (CPI). *P. pinifolia* has not been detected in the UK but is included on the UK PHRR. All known host species are within the genus *Pinus*, either recorded as naturally occurring disease affecting the shoots and needles of *Pinus radiata* (Durán et al., 2008), or established through pathogenicity trials on other species within the genus, albeit with varying levels of susceptibility (Ahumada et al., 2013). The only known source region for the pathogen is Chile. A Rapid Pest Risk Analysis for *P. pinifolia* considered it unlikely to enter the UK and there was a consensus among participants that restrictions on import of known hosts from non-EU countries would reduce the risk of arrival through trade. The risk maps for Caledonian Pine therefore assess the vulnerability of CPI fragments, if *P. pinifolia* were to arrive, and the most probable areas of introduction and establishment within the CPI.

The risk factors and scoring protocol identified with stakeholders are set out in Table 15 and described in Appendix 7.5. It was recommended that only CPI core zones should be scored for proximity to woodland creation schemes, and not the regeneration or buffer zones. Since 2013, there have been restrictions on planting within 600m (buffer zone) of core CPI set out in Scottish Forestry guidance on planting Caledonian Pinewoods and within the Dothistroma Needle Blight Action Plan. Risks from planting within 1500m were considered an increased risk (+1), but down weighted relative to climate suitability and other risk factors to reflect that the risks from planting should be partly mitigated by the CPI buffer zone.

Table 15 Scoring of risk factors assessing vulnerability of 82 core Caledonian Pinewood Inventory fragments to the threat of Phytophthora pinifolia arrival in the UK

Risk factor	Parameter scored per fragment
Climate suitability for *P. pinifolia* growth (ERA5)	Whether average growth in mm/day falls within different percentile ranges of values across GB
Connectivity to other *Pinus* sub-compartments	Presence-absence of *Pinus* sub-compartments at distances within 1500m of core zone
Proximity to higher risk inspected premises	Does /does not intersect postcode district of SASA-inspected *Pinus*
Proximity to planting pathways	Presence-absence of FGS woodland creation schemes using *Pinus* within 1500m of core zone

4.3.7.2 *Distribution of risk scores for Caledonian pinewood inventory fragments across Scotland*

Medium or high-risk CPI fragments for *P. pinifolia* introduction or establishment are predominantly within the Highland region, with a smaller number of high-risk fragments in Perth and Argyll and the Grampian region (Appendix 7.5, Fig. A8). The very highest risk fragments (relative risk = 5) are all in the western areas of the Highland Conservancy, due to the greater climate suitability and connectivity to other pine in this area. However, there is a large and contiguous area of high risk for *P. pinifolia* (relative risk = 4) towards the eastern border of the Highland Conservancy also (Table 16).

The forest reproductive materials Scots pine seed zones represent regions where climatic and ecological conditions are similar for sourcing seed. The majority of medium and high risk fragments are in the South West and North East seed zones, but the North Central seed zone also contains a number of high or medium risk CPI fragments for *P. pinifolia* (Table 17).

Table 16 Number of core CPI fragments of low, medium and high risk by conservancy region

Conservancy	Risk rating		
	Low (0-1)	Medium (2-3)	High (4-5)
Grampian	0	12	0
Highland and Islands	6	23	28
Perth and Argyll	2	5	6

Table 17 Number of core CPI fragments of low, medium and high risk per Scots pine seed zones

Seed Zone	Risk rating		
	Low (0-1)	Medium (2-3)	High (4-5)
South West	1	16	18
North Central	2	1	8

East Central	2	4	3
North West	0	3	3
South Central	1	1	2
North	2	2	0
North East	0	13	0

4.3.7.3 Perceived value of maps for decision-making

The workshop discussions identified that risk maps for *P. pinifolia* to the CPI could be useful for policy and decision planning in relation to protected site management, seed zone planning and planting decisions. Risks from *P. pinifolia* could be integrated into seed zone guidance. Dissemination through forestry networks and through newsletters and relevant WhatsApp groups of HTA Grower members would support awareness across different sectors of *P. pinifolia* threat to Pine species in Scotland. Integrating the risk maps should link with existing planning tools like the Defra Plant Health Portal. Risks to specific fragments (granularity) were less useful than summarising regional-level risks, given the pathogen has yet to arrive. A concern was how to interpret and communicate the risks, especially in relation to planting decisions, in a way that acknowledges how current restrictions and regulations on import of Pine species reduces the likelihood of arrival and balances the threat against other priorities in planting decisions.

4.4 The application and value of models and tools for decision making

During the second workshop, five main general uses were identified by participants for the tools developed in this project. These included primarily informing surveillance strategies, guiding resource allocation, supporting policy development and future-proofing landscape management and awareness raising (Table 18). In terms of surveillance planning, participants saw potential in using the frameworks to guide monitoring efforts. While they might not significantly change surveillance for regulated species, the frameworks could help target limited resources for non-regulated species in the wider environment (though organisational responsibility for this has yet to be agreed) and help inform horizon scanning of which species may need regulation.

Table 18 Stakeholder perspectives on the Phytophthora databases and tools developed for assessing threats from Phytophthora, including impacts on decision making, pathways for disseminating the outputs and additional functionality requirements

Outputs/ databases	**Value for decision making**	**Dissemination pathway(s)**	**Functionality needed/ suggested**	**Feedback integrated into tools**
Global, cross-sectoral database of *Phytophthora* species hosts and distributions	• Useful for decision and budget holders for objective prioritisation process but will require prioritisation of impact and ranking	• Linking with SASA, and other knowledge management systems such as DEFRA, for instance Rob Worth tool. • Also useful to organisations such as Scottish Forestry and channels such as Plant Health Portal	Need for devolved nation-level data/ regional consideration	Yes
			Need to include impact severity scale particularly among forestry	No, but identified potential to integrate data from pathogenicity trials
			Host database searchable by family, genus and species level.	Yes, searchable by species, genus and family, but interactive tables can be slow to load
			Considering level of uncertainty in predicting host-*Phytophthora* interactions	No, but estimates of uncertainty will be available when models are finalised
			Consideration of the likelihood of hybridisation	No
Ranked lists of *Phytophthora* species threats to Scotland	• Database useful more for policy-level (than individual businesses) and for decision makers such as horizon scanning and targeting surveillance. • Helpful in informing risk register rankings • Useful for (Scottish) forestry policy planning e.g. flag trade routes / products where there might be a regulatory gap	• Integration with existing systems such as Rob Worth's Defra import tool, plant passport systems and risk register	Include economic impact metrics consideration and need clearer risk indicators	Partly, quantitative metrics scored from 0 to 3. Economic metrics not integrated as requires integration of forest productivity models.
			Convert numerical scores into relative risk metrics (high/medium/low) for easier interpretation.	Overall risk scores converted to low, medium and high-risk categories.
			Consideration for non-plant pathways (soil, compost)	No, not captured in global horticultural trade flow data

Spatial risk frameworks	• Informing surveillance strategies • Future proofing (species) and landscape planning • Awareness raising • Useful for Policy level planning (planting decisions, containment policies) • Resource allocation planning (particularly useful for surveillance, and biosecurity)	• Integration with Scottish Forestry systems, Plant Health Portal, Risk register, and existing tools such as MyForest • Dissemination through conservation networks, newsletters, HTA WhatsApp groups etc • Potential key end users include Scottish Forestry, Botanic Gardens, Land managers etc	Reduce emphasis on trade premises, better define habitat (heathland) composition	Yes, revised risk frameworks remove generic trade risk and down weight proximity to importing premises
			Clarify host specificity via NVC overlap. Include land use change and vegetation cover	Integration of habitat suitability models of known *P. ramorum* hosts in heathlands (Vaccinium and others) but not linked to NVC composition or land use change.
			Integrate seed zone data (See Appendix 7.7 for feedback on specific frameworks)	Yes, risk outputs for CPI fragments intersected with seed zones.

Regarding resource allocation, the frameworks were seen as valuable tools for prioritizing limited resources for *Phytophthora* management, particularly for emerging threats or in non-commercial settings. This was exemplified by past experiences with large-scale tree removal due to the establishment and rapid spread of *Phytophthora ramorum*. Stakeholders emphasized the need for clear severity metrics to guide resource allocation decisions.

Others also viewed risk maps as tools for future-proofing. For instance, in the second workshop discussion, participants discussed how risk assessments could inform plant species selection for new plantings, helping create more resilient landscapes in the face of climate change and evolving disease pressures.

Across all our engagements, there were suggestions that the risk frameworks could contribute to broader policy decisions related to land use, forestry practices, and biodiversity conservation. Many participants noted how accessible and tailored models would be useful in guiding and convincing higher-level actors such as 'steering committees' in decision-making and for advocacy purposes. The need for regional specificity was particularly emphasized, with distinct processes noted across different UK nations regarding species selection and planting strategies.

The models were also seen as valuable for awareness raising across multiple sectors. Stakeholders suggested developing simplified versions of risk assessments for public education campaigns to promote responsible behaviour in natural areas. For instance, the models could serve as visual aids for communicating *Phytophthora* risks, especially in garden premises. Whilst the risk factors we assess do not include public behaviour or use of habitats, the mapped risks could be adapted to emphasise highly susceptible and currently uninfected areas or premises, and to list key species and habitats that may be impacted by the spread of *Phytophthora* to these locations. The awareness raising was also mentioned for conservation sector, where resources for surveillance are very limited.

5 Conclusions and recommendations

This report highlights the high level of concern about threats from *Phytophthora* species among cross-sectoral stakeholders with all respondents considering Phytophthoras to be very important or important and to rank highly among plant health threats citing reasons such as their wide host range, ability to spread in soil and water, adapt to new hosts and climates, potential for rapid and serious devastation, and difficulty of detection (due to asymptomatic infection) and control.

5.1 Ranking Phytophthora *threats to Scotland*

Top perceived priority *Phytophthora* threats tended to be species already present in Great Britain including *P. ramorum, P. austrocedri* and *P. alni,* (except for *P. pinifolia* potential risks to Scots pine) suggesting a lack of information to support risk assessors and stakeholders with horizon-scanning for future threats from *Phytophthora* species that are yet to arrive in Scotland. Impacts on a wide range of habitats were of concern including diverse woodland types (oak, wet, pine woodlands), heathland, riparian habitats and gardens as well as woodland scrub and grassland with juniper. This was consistent with findings from analysis of global host-pathogen data that 30-50 exotic *Phytophthora* species, that are likely to arrive, are known to affect key host genera on the Scottish Biodiversity List (e.g. *Salix*, *Juncus*, *Juniperus*, *Rosa* and *Trifolium*) and hosts that are key components of broad NVC habitats (especially woodlands, scrub and OV) and 1000s of National forestry sub-compartments (especially *Quercus*, *Salix* and *Alnus* species), indicating the potential for future broad cross-sectoral impacts and a need to strengthen surveillance and interception efforts for these pathogens, hosts and habitats.

The updated models and databases indicate the high likelihood and future high potential impact of *Phytophthora* species, both from those species that are yet to arrive in the UK and those already here. In Scotland, 45 *Phytophthora* species have been detected to date, 26 have been detected only within trade premises and 15 have been detected in both trade and the wider environment. This indicates future potential spread from trade to the wider environment, consistent with stakeholder perception that large nurseries and garden centres represent potential hotspots for pathogen introduction and spread. Of the 107 exotic global species modelled, 50 species have known source regions that are connected to the UK through horticultural trade (Green et al. 2024; Barwell et al. 2025) and 40 of these have a predicted probability of arrival exceeding 0.8. An additional 63 *Phytophthora* species have been described or informally named since 2020 worldwide highlighting the rapid change in knowledge about *Phytophthora* threats, yet knowledge of global source regions is still very limited (with 89 exotic *Phytophthora* species having no distributional records pre-dating 2005). Cross-sectoral collation of data across forestry, horticulture, agriculture and plant health substantially extended the known host ranges and distribution of *Phytophthora* species with generally < 10% geographical overlap between data sources. This improved the understanding of potential sectoral impacts compared to approaches that considered data from only one source or sector.

5.2 *Spatial risk analyses for priority* Phytophthora *species, habitats and hosts*

Stakeholder identified risk factors for *Phytophthora* establishment and spread included those that were perceived as important across *Phytophthora* as a genus and those that were important for individual *Phytophthora* species and many of these could be feasibly integrated into the co-developed risk frameworks. General *Phytophthora* risk factors included climate suitability for growth and infection and host distribution and susceptibility whilst water related factors such as soil moisture levels or specific land uses were considered important for selected species. A further indication of the potential scale of future *Phytophthora* impacts is that 118/171 modelled species are predicted to be able to grow on at least 2/3 of Scotland's land mass in at least three seasons of the year. Responding to this degree of threat and stakeholder need we were able to integrate existing mechanistic models of seasonal and geographical variation in climate suitability for growth into all priority species risk frameworks as well as water metrics for individual species where particularly relevant (e.g. *P. alni*). We were also able to leverage stakeholder knowledge on best available datasets to describe the distribution of priority susceptible and reservoir hosts and habitats. Stakeholders also identified as a key priority understanding how climate suitability for growth of individual Phytophthoras might change under future climate conditions in 5 to 50 years' time to aid future planning and management. While the existing model frameworks can logistically be applied to gridded spatio-temporal data on future climate scenarios, this work was beyond the scope of the current project but is a key priority for future research.

Other general risk factors identified by stakeholders included trading patterns and proximity to large nurseries and garden centres, as well as suburban/urban gardens, as potential hotspots for *Phytophthora* introduction and spread and proximity to trade premises and infected trade premises was consequently included in the risk framework. However, during the validation of the risk frameworks for selected priority *Phytophthora* species-habitat combinations, it was generally agreed that uninfected trade premises could be down-weighted or excluded as potential infection sources due to improvements in biosecurity practices within trade and horticultural supply chains over the 10-15 years since the initial outbreaks of *P. ramorum*. Overall, data sharing restrictions and reduction in surveillance effort in highly affected zones made it difficult to identify and accurately locate infected trade premises for many *Phytophthora* species (already in the UK) or to categorise trade and garden premises with more risky trade or biosecurity behaviours (cf. Green et al. 2024).

Overall, the stakeholder framing endorsed the general approach of scoring *Phytophthora* risk levels across the distribution of susceptible hosts, habitats or premises of interest, within broad categories of (i) climate suitability for growth/infection, (ii) proximity to sources of infection (iii) proximity to relevant spread pathways, (iv) pathogen species specific water/vegetation effects of establishment, with a preference for higher weighting of climate suitability and alternate host distributions within the risk scoring frameworks, mirroring the original approach of Purse et al. (2016). They also provided critical inputs in terms of data sources for appropriate description of geographical patterns in these risk factors, further highlighting the value of the cross-sectoral knowledge integration step of the co-production process.

When the resulting outputs were validated with stakeholders, several potential uses were identified in relation to horizon scanning, risk assessment and risk management. Species level rankings by arrival risk, impacted host and habitats and other key risk factors were felt to be helpful for informing UK PHRR rankings, targeting limited surveillance resources and identifying regulatory gaps for particular trade routes and traded products. Additional functionality to enhance the value for decision-making included the addition of economic metrics of impacted host species value and the need for clearer indicators of severity of risk posed by Phytophthoras. Integration with existing tools like the UK PHRR and plant passporting systems would improve dissemination.

Specific uses for spatial risk frameworks for priority *Phytophthora*-host-habitat combinations were also identified. For example, stakeholders envisaged a role for the spatial risk framework for *P. ramorum* on Larch in supporting the review of existing legislation and regulatory control laid out in the *P. ramorum* Action plan and in geographical and host targeting of environmental surveillance and grants for new larch plantings (the latter in lower risk zones). The individual spatial risk frameworks also gave important indications of the geographical scale of *Phytophthora* risks to priority habitats. For example, a large proportion of heathland fragments in Scotland's protected areas are at high risk for *P. ramorum* establishment (particularly heather grassland in the south and west that overlaps with highly suitable climate conditions for growth and existing larch infections in woodland). The extent of high and medium risk areas for both *P. ramorum* infection on larch largely mirrored that from prior risk frameworks, being greatest within South Scotland, Perth and Argyll (97% and 88% of larch fragments at high or medium risk respectively) but still substantial within the Highland and Islands (73%), Central Scotland (64%) and Grampian (32%) conservancies. Alder fragments with a high risk of *Phytophthora* disease were also disproportionately distributed in Perth and Argyll where there are high numbers of alder fragments and increased climate suitability for *P. x alni*. These outputs were identified as being valuable for riparian planting and landscape planning (e.g. for NatureScot) though care was needed to avoid discouraging planting by wider actors. Participants also highlighted a potential role of the host-pathogen association data and pathogen species risk rankings in tree species selection for new plantings to enhance resilience to climate change and emerging disease threats, for example to inform the future productive tree species in Scotland (Edwards *et al.* 2025).

Outputs were perceived to have value for awareness raising across multiple sectors, for example, with simplified versions of risk assessments contributing to public education campaigns to promote responsible behaviour in natural and conservation areas and gardens. Stakeholders highlighted the potential for outputs to contribute to broader policy decisions related to land use, forestry practices, and biodiversity conservation by providing accessible visualisation of the scale and level of risk from *Phytophthora* species for advocacy purposes, given adequate tailoring to regional policy contexts for tree species selection, planting and biosecurity.

Overall, the perceived value of the outputs for decision making and tangible dissemination pathways identified indicated that the co-production process had been broadly successful in aligning the models and databases produced with stakeholder priorities (framing) and integrating a diverse range of current knowledge, expertise and relevant context (e.g. mitigation of risks). Further work would be needed to follow up whether these perceived uses were realised by stakeholders (an experimentation phase), though it is notable that previous risk frameworks, co-developed in a similar way (Purse et al., 2016) subsequently informed climate risk zones for the management of the *P. ramorum* outbreaks between 2012 and 2017 and surveillance of larch by Scottish Forestry and heathlands by NatureScot. Using mixed methods of engagement across the project (self-completion survey, online workshops, email correspondence and one to one meetings) allowed for flexibility and different levels of stakeholder engagement and commitment, whilst still reaching a range of agencies and sectors. Specific needs from risk models varied across sectors, agencies and roles and ongoing engagement is needed to tailor outputs for different use cases.

5.3 Limitations and caveats of risk analyses

The restricted sample size (≈ 15 unique participants across the surveys, workshops and consultations) for co-production of risk frameworks may bias our outputs towards priority habitats and *Phytophthora* species most relevant to more engaged sectors and actors (e.g. forestry) and is likely to underrepresent *Phytophthora* threats within harder-to-reach sectors. *Phytophthora* species with little evidence of historical impacts may be low priority due to a lack of available information, despite potentially high risks. In addition, the risk analyses in this project do not address how human behaviours influence introduction, establishment and spread of *Phytophthora*, partly because of a lack of spatial data on social factors and limited understanding of the relative importance of different human-mediated pathways. For example, spatial and sectoral variation in biosecurity, recreational pressure and large- and small-scale planting activities may enhance or mitigate the risks identified here. The lack of surveillance data for unregulated pests means that assessing proximity to infected premises and likely pathways of introduction is not feasible for most *Phytophthora* species. Whilst the movement of infected plants through supply chains is considered a major pathway for introduction, domestic trade networks have yet to be mapped and our models capture only proximity to inspected premises, and not the final destinations of these plants.

There are also uncertainties in the underlying models used to rank threats from *Phytophthora*. Poorly documented source regions of *Phytophthora* species will likely lead to underestimation of arrival probabilities for most species. Climate suitability models assume that daily growth is indicative of establishment risk, but the relationship between growth and infection or transmission of disease may not be straightforward. Although this means that the 117 species for which Scotland is predicted to be climatically suitable may be an overestimate, a precautionary approach may be favoured. A major caveat of the ranked threats from *Phytophthora* is that the methods cannot assess risks for species that have yet to be described (known unknowns). In several cases, the *Phytophthora* with the greatest impact have been described only after they emerge in new regions or infect economically important hosts and may be missed by species- and host-based approaches (Mitchell, 2021).

The evaluation of spatial risk framework predictions against independent surveillance data had not been completed by the final workshop therefore the impacts of validation on perceived confidence in the models has yet to be assessed. Further validation is required for the current risk frameworks using future surveillance data, and it will be important to re-evaluate the credibility and perceived value of the models among stakeholders when these future validation steps are possible.

The model outputs and databases described in this report can be accessed using the links in Table 19.

Table 18 Access to online tools, model outputs and databases linked to project PHC2023/02

Project output	**Stakeholder-identified value for decision making**	**Link to access**
Interactive online global database of *Phytophthora* hosts and distributions	Improving awareness of threats and ideally linking to existing tools (e.g. Plant Health Portal).	https://kattur.github.io/Phytophthora-and-Hosts-in-the-UK-and-Globally/
Ranked list of *Phytophthora* threats to Scotland's priority plants, habitats and forest estate	Informing UK plant Health Risk Register rankings, targeting limited surveillance resources and identifying regulatory gaps for trade routes and traded products, ideally linking to existing tools.	https://doi.org/10.5285/72e8f817-01a6-42d2-b187-a5ebf43853a1
Spatial analyses of *Phytophthora* risks to priority host plants and habitats in Scotland (listed below).	Listed below	Listed below
• *P. ramorum* risks to larch fragments	Guiding decisions about planting of new Larch in areas of Scotland at lower predicted risk from *P. ramorum* and supporting the review of existing legislation and regulatory control (*P. ramorum* Action Plan)	https://doi.org/10.5285/f6809e00-91cb-494d-babd-5d60d938ad97
• *P. ramorum* risks to heathland	Environmental surveillance for *P. ramorum*, especially in heathland	https://doi.org/10.5285/00601c2a-ac86-467d-8696-689cf20e35d3
• *P. x alni* risks to alder fragments	Integrating *P. x alni* risk into riparian planting and landscape planning decisions in the conservation sector (though care is needed to avoid discouraging planting by other actors).	https://doi.org/10.5285/824f9ba8-7d1c-4a82-b5ec-a4f850f1d370
• *P. pluvialis* infection risks to Douglas fir and Western hemlock fragments	Not discussed	https://doi.org/10.5285/921fcc2e-7491-4058-a21b-3d1de0be1507
• *P. pinifolia* establishment in Caledonian Pinewood Inventory	Understand which CPI areas are at highest risk of *P. pinifolia* establishment following arrival (Highlands and Islands conservancy, South West and North East seed zones) and to reduce potential spread from moving planting material between seed zones.	https://doi.org/10.5285/ddee75ae-2ad0-4d16-81a9-20928d89e872

Overall, our findings lead to the following broad recommendations:

Recommendation 1: Retain *Phytophthora* as priority pathogens for horizon scanning and risk assessment as well as biosecurity measures to prevent and intercept species arrival to reduce impacts. Tens of species arrive through trade per decade with 40 *Phytophthora* species predicted to have a high probability (>0.8) of arrival in the UK, and 117 species with potential to establish in Scotland due to favourable climatic conditions (predicted non-zero growth in at least 2/3 of Scotland's land mass in at least three seasons of the year).

Recommendation 2: Enhance research to (i) discover and map *Phytophthora* species diversity (potentially using novel barcoding techniques) in different global regions, and (ii) integrate these data within accessible cross-sectoral databases to predict and understand pathogen behaviour including (iii) phylogenetic and ecological modelling and empirical data for predicting establishment and the likelihood and severity of *Phytophthora* species impacts on host plants. Barriers to this integrative research include the need to secure regular funding to develop and interact with global and regional open access databases and networks and to negotiate ethically sound but flexible agreements with plant health agencies and researchers contributing unpublished and/or potentially sensitive data.

Recommendation 3: Adopt an approach of assessing and scoring *Phytophthora* risks among species and locations, integrating the following key risk factors; (i) distribution of susceptible hosts, habitats or premises of interest; (ii) climate suitability for growth/infection; (iii) proximity to sources of infection; (iv) proximity to relevant spread pathways; (v) pathogen species specific water/vegetation effects on establishment; with higher weighting given to climate suitability and alternate host distributions.

Recommendation 4: Consider the following factors not addressed in this project, but key next steps for research:

i) the development of more generalisable spatial risk frameworks relevant to a wider group of pest and pathogen threats to habitats and hosts
ii) the overlay of risks with a broader range of habitats and premise types (e.g. public and private gardens, trade premises)
iii) integrating human behaviours into risk analysis leveraging knowledge about recreational demand, and improved mapping of business/site typologies, including biosecurity practices in trade and conservation settings
iv) further and ongoing validation of risk factors against pathogen outbreak data to enhance the credibility and uptake of model-based tools
v) the extension of climate suitability models for *Phytophthora* species to include projections of risk under future climate conditions (5 to 50 years' time)

Recommendation 5: Improve understanding of *Phytophthora* risks linked to different pathways of introduction and local spread as a key future research need. This research would require integration and collaboration of actors, data and expertise across sectors (horticulture, forestry, conservation) to understand and predict pathogen impacts, including collection of potentially sensitive data from premises on business types, management and biosecurity practices, host supply chains and relevant planting/restoration activities as well as pathogen detections by governmental agencies.

Recommendation 6. Develop tailored risk and prioritisation tools for Scotland that exploit existing knowledge and data sources used by different agencies (e.g. the UK Plant Health Risk Register, planting guidelines). Prioritise scoping the pathways to integrate model outputs with existing tools. Balance plant health risks against other considerations when managing for desired outcomes (e.g. planting decisions). The flexible, mixed-methods co-production approach adopted in this study provides one model for such co-design.

Overall, our findings lead to the following specific recommendations for *Phytophthora* species risk assessment:

Recommendation 6a. *Phytophthora ramorum* risks to larch
Use maps of *P. ramorum* risks to larch to guide decisions about planting of new larch in lower risk areas of Scotland and for geographical targeting of environmental surveillance with Scottish Forestry and NatureScot identified as key end users to which outputs should be transferred.

Recommendation 6b. *Phytophthora ramorum* risks to heathland
Assess the threat posed by *P. ramorum* to conservation goals and national targets for nature recovery in Scotland (particularly in Highland, Aberdeenshire and Perth and Kinross but also in south and westerly heather grassland).

Recommendation 6c P. x alni risks to alder
Re-evaluate the risks to alder in GB from P. *x alni*, a pathogen whose prevalence in trade and the wider environment is uncertain. In particular, Perth and Argyll is disproportionately affected due to the prevalence of alder and the greater climate suitability for *P. x alni* growth. Consider *P. x alni* risks alongside the benefits of planting alder within all restoration projects, riparian planting and landscape planning decisions across sectors, with due care to avoid discouraging planting by other actors.

Recommendation 6d. *Phytophthora pinifolia* risks to Caledonian pinewood inventory
Keep *P. pinifolia* on the radar as it has a relatively high predicted risk of arrival (probability = 0.76) and maintain tight regulation on the trade of known hosts. Focus on the majority of medium and high risk fragments in the South West and North East seed zones. Should *P. pinifolia* arrive, exploit the maps to identify susceptible populations and consider the risks of pathogen spread on ecologically adapted planting material moved between seed zones.

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7 Appendices

7.1 *Full methods for updated spatial risk analysis for* Phytophthora ramorum *infection for Scotland's Larch fragments*

The previous risk analysis for *Phytophthora ramorum* infection for Scotland's Larch fragments (B. Purse et al., 2016) has been updated to reflect the removal of Larch since 2013 through Statutory Plant Health Notices and other clear-felling, to include new P. *ramorum* detection data in Larch woodlands and inspected premises provided by Scottish Forestry and SASA. In addition, new climate suitability models of pathogen growth are used to score risk of establishment and new species distribution models have been used to score risks of transmission from alternative host species of *P. ramorum*.

7.1.1 *Larch fragments*

Risk factors were assessed for Larch fragments in Scotland compiled from the National Forest Estate Sub-compartments Scotland 2019, the Native Woodland Survey of Scotland, Scottish Forestry survey data, Statutory Plant Health Notices and Larch layers, and the *Phytophthora* database described in section 3 of this report representing the period 2013-2019 (the most recent year for which National Forest Estate Subcompartments for Scotland were available). Any areas felled since 2013 were identified and removed using the National Forest Inventory GB from 2013 to 2023 and Scottish Forestry Statutory Plant Health Notices marked as completed (Table A1). Once removed, there were 79062 Larch fragments identified in Scotland, of which 79060 were assigned a risk score. Two fragments without climate and/or habitat suitability scores were excluded.

Table A1 Source data used to derive a layer of Larch fragments in Scotland for risk scoring

Larch data source	**Reference/link**	**Criteria for fragment inclusion/exclusion**
National Forest Estate Subcompartments Scotland 2019	https://data-forestry.opendata.arcgis.com/search?tags=Scotland	Include: Primary, secondary or tertiary species is Larch
Native Woodland Survey of Scotland Species Structures	https://open-data-scottishforestry.hub.arcgis.com/datasets/6d27b064fcba471da50c8772ad0162d7_0/about	Include: SPECIES_speci contains Larch[2] and percentage cover >0%
Scottish Forestry *Phytophthora* survey data	Provided by Scottish Forestry	Include: Host_speci contains Larch AND survey year >= 2013
Scottish Forestry Statutory Plant Health Notices	https://open-data-scottishforestry.hub.arcgis.com/datasets/5e598aa24e8f4ab69c8afd7d5cfa40c8_497	Include: host_1 OR host_2 contains Larch AND date issue/ sphn_ref >= 2013 AND percentage cover >0
Scottish Forestry Larch layers 2017	Provided by Scottish Forestry	Include all
Phytophthora database (this project)	Full database not publicly available due to restrictions from data providers. Summary data and interactive tables available at *Phytophthora* and Hosts in the UK and Globally	Include: Host genus is Larix AND wider Environment is Wider environment AND YEAR >=2013. For point data, polygons were created using a 2m buffer.
National Forest Inventory GB 2013-2023	https://data-forestry.opendata.arcgis.com/search?q=national%20forest%20inventory%20GB&tags=GB	Exclude: IFT_IOA contains fell OR Fell

[2] Habitat components were not used because there are no woodland NVC with *Larix* as named species

7.1.2 Risk factors and scoring

Larch fragments were assigned a risk score for each of the seven risk factors considered (Table A2). These were climate suitability for *Phytophthora ramorum* growth, proximity to other Larch/infected Larch within 500m or 5000m, proximity to other (non-Larch) wider environment infections within 1500m, habitat suitability for alternative sporulating hosts in heathland (*Vaccinium myrtillus, V. vitis-idaea, Arctostaphylos uva-ursi*) and the reservoir host *Rhododendron ponticum,* proximity to inspected and importing premises and the presence of water courses. The Scottish Forestry *P. ramorum* Action Plan defines two zones delineating regions in which *P. ramorum* spread can still be controlled through rapid action (Priority Action Zone, PAZ) and the area where local control measures are intended to slow spread but eradication is unlikely to succeed with the available resources (Risk Reduction Zone). Within the risk reduction zone there is also a Management Zone where the disease is so established that no further SPHNs will be issued within this region (since 2014) and, instead, long-term management plans are in place. The management zone represents a challenge to scoring risks to fragments using proximity to infected Larch, there are no SPHNs to score proximity to other Larch/infected Larch. All Larch fragments within the management zone are therefore scored as if they are within 500m of standing infected Larch with an incomplete SPHN.

The relative weighting and scoring of risk factors were validated through the second online workshop and agreed with Scottish Forestry through follow up meetings and email correspondence (Table A2). The maximum possible risk score for *P. ramorum* is 12. The relative weighting of the risk factors is inherent in the maximum score of each individual risk factor, with a higher maximum score for a risk factor implying greater weighting compared to others with lower maximum scores. There was broad consensus that climate suitability should be the primary risk factor and the climate suitability within fragments was therefore given a maximum score of 4.

7.1.2.1 Proximity to Larch

In scoring proximity to other Larch (Table A2), SPHN felled areas were scored with a small additional risk (+0.25) with the rationale that a residual risk of infection to neighbouring sites may remain from inoculum in soil, debris, or from the disturbance or movement of infected material. The removal of the reservoir hosts *R. ponticum* from the understory is not mandatory in SPHN sites since 2020 and could represent a potential source of infection. However, this additional risk (+0.25 compared to uninfected Larch and -1 compared to standing infected Larch) is considered small due to the strict biosecurity practices in place for three years on SPHN sites, including disinfection and drying of footwear, clothing, tools, vehicles and machinery, burning of plant material in situ and Movement Licenses for processing roundwood (https://www.forestry.gov.scot/publications/966-biosecurity-on-sites-served-with-a-statutory-plant-health-notice-for-phytophthora-ramorum-on-larch-pdf/download).

Table A2 Risk factors and risk scoring for Phytophthora ramorum risks to Larch. Note that the relative weighting of different risk factors is proportional to the top value of the scoring scale. Risk factors are ordered from most important (climate suitability) to least important (proximity to importing trade premises).

Risk factor	Parameter	Score	Number of fragments
***P. ramorum* climatic suitability (average within fragment)**	(~ < 20th percentile) 0 to <14 mm/day	0	16764
	(~20th - 40th percentile) >=14 to <19 mm/day	1	16440
	(~40th - 80th percentile) >= 19 to < 30 mm/day	2	28023
	(~ 80th - 90th percentile) >= 30 to < 35 mm/day	3	10670

	(~ > 90^{th} percentile) >= 35 mm/day	4	7163
Proximity of fragment to other Larch	No other larch present within 5000m	0	21
	Other standing Larch without Pr infection with no SPHN within 5000m	0.5	32018
	Completed SPHN within 5000m	0.75	6783
	Completed SPHN within 500m	1	1353
	Other standing Larch with incomplete SPHN within 5000m	2	16078
	Other standing larch with incomplete SPHN within 500m (including all fragments in the management zone)	3	22807
Alternative host suitability (*R.ponticum*, *V. myrtillus*, *V. vitis-idaea*, *A. uva-ursi*)	~ <=50^{th} percentile habitat suitability)	0	10975
	~ >= 50^{th} <=80^{th} percentile habitat suitability	1	27298
	~ >= 80^{th} percentile habitat suitability	2	40787
Other wider environment detections	No non-larch Pr detections within 1500m	0	77182
	Wider environment Pr (non-Larch) detection with no or incomplete SPHN within 1500m	1	1878
Watercourses (within fragment itself)	None	0	74778
	Present	1	4282
Proximity to detections in inspected premises premises	Does not intersect postcode district of infected premises	0	59087
	Intersects postcode district of infected premises	0.5	19973
Proximity to importing trade premises	No premises importing live plants within 1500m	0	78900
	Premises importing live plants within 1500m	0.5	160

7.1.2.2 Alternative host suitability

The risk of infection from alternative hosts including *R. ponticum* (a reservoir host), *Vaccinium myrtillus*, *V. vitis-idaea* and *A. uva-ursi* was incorporated by scoring suitability within Larch fragments. The presence of the reservoir host *R. ponticum* in the understory of Larch fragments was considered an important risk factor for Larch infection. Data on Rhododendron infection are limited, but the distribution of alternative hosts can be predicted with species distribution models (Purse et al., 2013). Predicted habitat suitability surfaces for each alternative host species were obtained from UK-wide species distribution models at OSGB 1km resolution using presence-only species occurrence records from national recording schemes available through the Biological Records Centre hosted at UKCEH (Boyd et al., 2022). Risk scores were based on the percentiles of habitat suitability across the Larch fragments (Table A2) and the score was assigned across all alternative host species (e.g. high suitability for ANY alternative host was scored as 2).

7.1.2.3 Proximity to infected and importing premises

Workshop participants questioned retaining the scoring of proximity to inspected premises from the original risk frameworks. There was a preference that proximity to inspected premises, per se, should not be interpreted as posing an increased risk of *Phytophthora ramorum* infection especially if routine testing had not detected the pathogen in these premises. There was agreement that there have been substantial improvements in biosecurity awareness and practices within trade and horticultural supply chains since the start of the *P. ramorum* outbreak and since the original risk frameworks were developed, including the development and dissemination of best practice guidelines (Elliot et al., 2023; Green et al., 2025; Marzano et al., 2021) and certification schemes (e.g. the Plant Healthy Management Standard). It was recommended to work with SASA to improve the scoring of risks from inspected premises. However, restrictions on data sharing precluded the use of georeferenced infection data that could reveal the locations of infected premises. *P. ramorum* detections in SASA-inspected premises were provided at postcode district level (median postcode district size of 101.9km² ranging from 0.5km² to 3569.6km²). The SASA inspection data yielded 119 positive detections of *P. ramorum* between 2017 and 2022 in 50 unique postcode districts, but only 14 of these detections were within trade premises (nurseries and garden centres), supporting the lower scoring of risk from trade premises. The final scoring of risks from inspected premises were addressed with two risk factors: proximity to importing premises and proximity to infected premises with confirmed *P. ramorum* infection (by SASA). SASA hold limited information on the origin of imported plant material, and do not have capacity to provide summary data on commodity groups and volumes. Therefore, premises importing from EU and non-EU countries were identified by querying UK Trade Info tables for importer addresses using the Harmonised System commodity code 06 - Live trees and other plants; bulbs, roots and the like; cut flowers and ornamental foliage (06 - Search traders). The results were further filtered by the CN8 descriptions in Table A3 to identify imports of woody plant material destined for outdoor use. The majority of the available import data (98.7%) was from 2022 and 2023. We identified and georeferenced 43 traders in Scotland importing the selected commodity types. Thresholds for reporting may mean premises importing smaller volumes are not captured in the risk scoring.

Table A3 Commodity descriptions used to identify premises importing material posing a risk of P. ramorum infection

CN8 descriptions in UK Trade Info
Outdoor rooted cuttings and young plants of trees, shrubs and bushes (excl. fruit, nut and forest trees)
Trees, shrubs and bushes, grafted or not, of kinds which bear edible fruit or nuts (excl. with bare roots, citrus, and vine slips)
Outdoor trees, shrubs and bushes, incl. their roots (excl. with bare roots, cuttings, slips, young plants, conifers, evergreens and fruit, nut and forest trees)
Conifer and evergreen outdoor trees, shrubs and bushes, incl. their roots (excl. with bare roots, cuttings, slips, young plants and fruit, nut and forest trees)
Rhododendrons and azaleas, grafted or not
Live forest trees

Proximity (within 1500m) to importing premises was given an additional risk of 0.5 reflecting that live plant imports represent the major pathway for introduction of *Phytophthora* species. Importing activity is linked to the diversity and prevalence of *Phytophthora* found in UK nurseries (Barwell et al. 2021) and *P. ramorum* is linked to a broad range of hosts within the horticultural sector. In addition, any Larch fragment intersecting a SASA-inspected postcode district with a *P. ramorum* detection between 2017 and 2022 was given an additional risk of 0.5. Note that together these risk factors have a maximum score of 1, therefore proximity to importing and infected premises has a lower relative weighting in the overall risk compared to climate suitability (maximum score 4) and proximity to Larch/infected Larch (maximum score 3).

7.1.2.4 Proximity to wider environment infections

Proximity to wider environment, non-Larch detections in Scotland since 2017 were sourced from georeferenced data within the cross-sectoral database of UK *Phytophthora* (Section 4 of main report) and included 102 records from Rhododendron).

7.1.2.5 Presence of watercourses

Watercourses within Larch fragments represent a potential pathway of spread from infected areas to the fragment. Larch fragments intersecting linear features in the OS Open Rivers data were scored with an additional risk of 1.

7.1.3 Distribution of Phytophthora ramorum risks to Larch fragments in Scotland

The highest score assigned for any fragment was 12. Larch risk of *P. ramorum* infection was greatest within South Scotland, where 97% of Larch fragments were assessed as high or medium risk. Within Perth and Argyll conservancy 89% of fragments were assessed as high or medium risk (Table A4). There was a lower but still substantial percentage of high and medium risk Larch fragments in the Highland and Islands (73%), Central Scotland (64%) and Grampian (32%) conservancies (Table A4).

Of the 20317 Larch fragments assessed as high risk, 16728 (82%) have remained uninfected (do not intersect any SPHN) despite high climate suitability, proximity to other infected sites, high suitability for alternative hosts and presence of water courses (Table A5). Absence of disease in high risk areas may arise from successful preventative action, inapparency of infection in some hosts and disease dispersal limitations, or indicate a need for refinement of risk factors.

Table A4 Number of Larch fragments per conservancy in each risk category for Phytophthora ramorum infection

Conservancy	**Low (0 <=3)**	**Medium (>3 <= 6)**	**High (>6)**
Central Scotland	2118	3446	363
Grampian	6192	2853	3
Highland and Islands	4562	10363	2255
Perth and Argyll	2882	15312	8870
South Scotland	558	10457	8826

Table A5 Number of infected (SPHN issued) and uninfected (no SPHN) high risk Larch fragments within each policy zone.

SPHN status	**Priority Action Zone**	**Risk Reduction Zone**	**Management Zone**
SPHN	890	2551	152
No SPHN (presumed uninfected)	7295	2867	6562

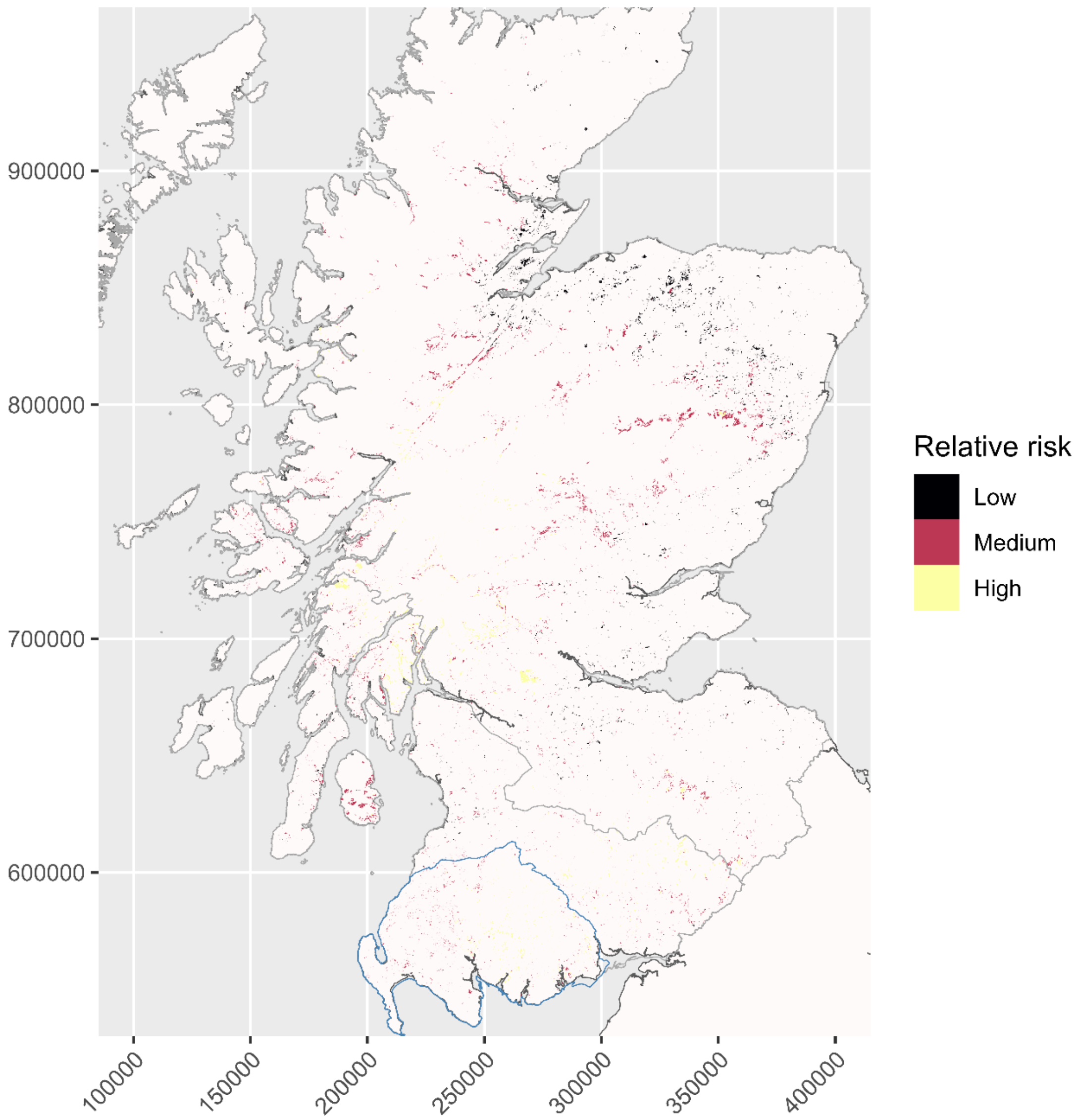
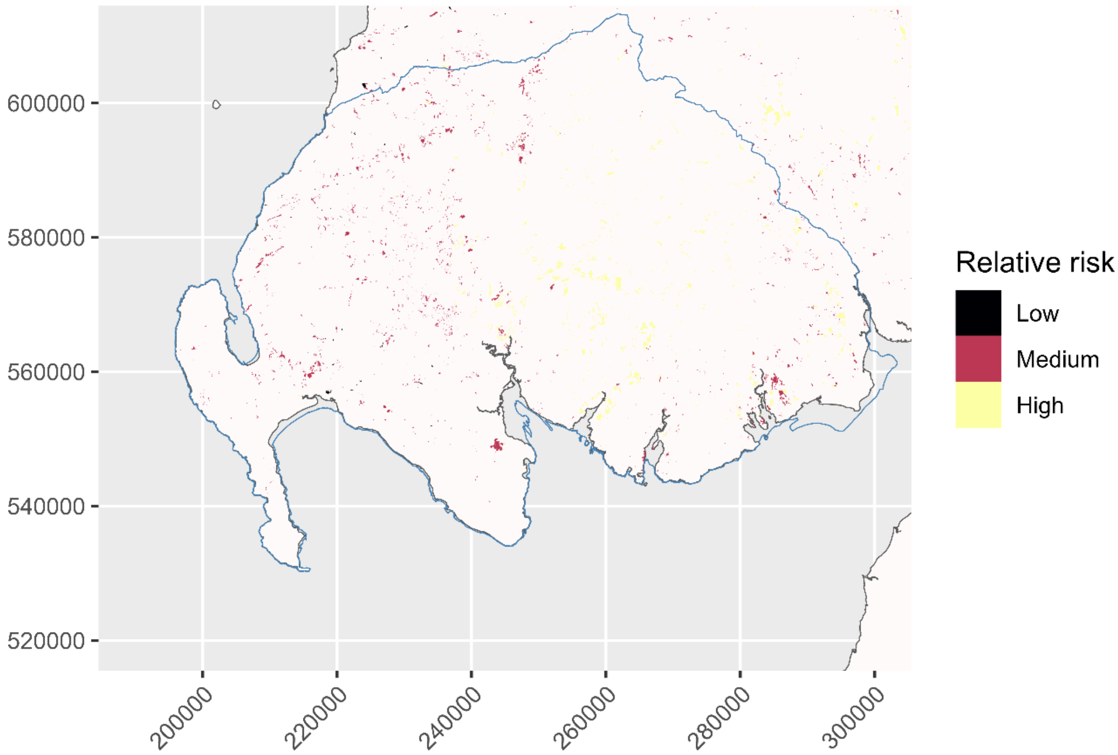


Figure A1 Risks to Larch fragments in Scotland from P. ramorum. The blue boundary is the Management zone. Grey boundaries delineate the Risk Reduction Zone and the Priority Action Zone.



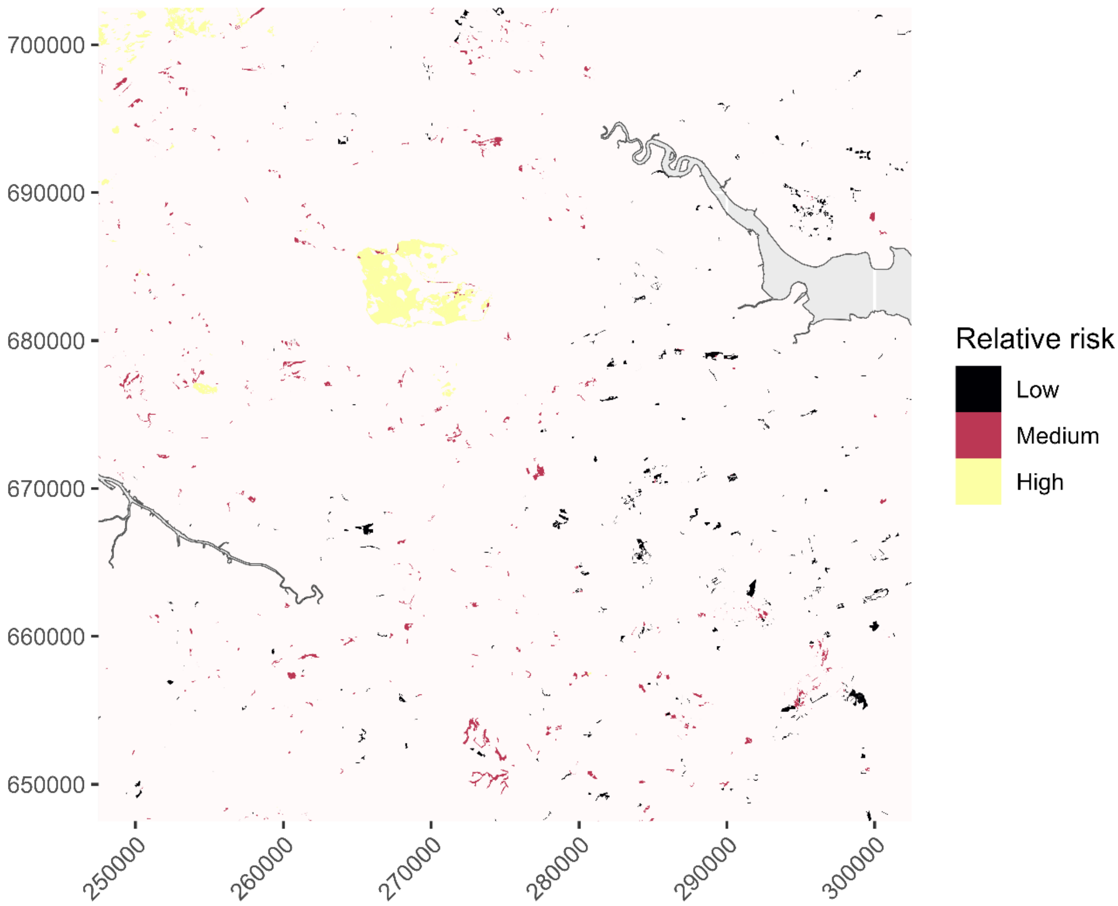


Figure A2 P. ramorum risks to Larch fragments in a) the Management Zone and b) an area of the Priority Action Zone in central Scotland

7.1.4 Value for decision-making

Through the final workshop a number of potential uses were identified for the *P. ramorum* risk maps for Larch, predominantly at the policy level. These included a discussion of the relevance for decisions on new of planting of Larch, which is still eligible for grant support in low *P. ramorum* risk areas. The Scottish Forestry policy zone boundaries could also be compared to the risk predictions to help assess the efficacy of containment policy for *P. ramorum*. For example, if large numbers of high risk fragments have remained free of *P. ramorum* infection, then biosecurity measures may be successfully preventing spread. It was noted that the spatial risk framework for *P. ramorum* on Larch could provide evidence supporting the review of existing legislation and regulatory control, which aims to assess whether the biosecurity measures laid out in the *P. ramorum* Action plan are proportionate and effective. A role for the risk framework in resource allocation planning was suggested, for example, in targeting environmental surveillance for *P. ramorum*. Participants also highlighted a potential role in informing future productive tree species in Scotland (Edwards *et al.* 2025).

7.2 Full methods for updated spatial risk analysis for Phytophthora ramorum infection within Scotland's heathland fragments

The previous risk analysis for *P. ramorum* risks to heathland fragments (Searle et al., 2016) has been updated to include new *P. ramorum* detection data in Larch woodlands and inspected premises provided by Scottish Forestry and SASA. New climate suitability models for *P. ramorum* growth have been integrated into the risk scoring. The risk scoring has been adjusted to reduce the emphasis on proximity to inspected premises as a pathway of spread, reflecting stakeholder perspectives on improved biosecurity practices in trade.

7.2.1 Compiling heathland fragments in Scotland

Heathland fragments in Scotland were identified using the Land Cover Map 2023 (land parcels, GB) (Morton et al., 2024). Risks were scored separately for the two classes of heathland defined in the LCM. Heathland 9 relates to LCM Class 'Heather' (>25% cover Heather) and heathland 10 is Heather grassland (≤25% cover heather). We identified 47587 fragments of Heather heathland (H9) and 74869 fragments of Heather grassland (H10) in Scotland (Fig. A3). Heathland fragments were assigned a risk score for each of the risk factors in Table A6, comprising climate suitability for *P. ramorum* growth, proximity to Larch/infected Larch within 500m or 5000m, proximity to other (non-Larch) wider environment infections within 1500m, habitat suitability within the fragment for sporulating hosts (*Vaccinium myrtillus*, *V. vitis-idaea*, *Arctostaphylos uva-ursi*) and the reservoir host *R. ponticum*, proximity to inspected premises with confirmed infections and the presence of water courses. However, the stakeholder engagement highlighted questions about the LCM habitat classification, specifically whether the composition of the broad heathland fragments could be better defined by joining with information on NVC communities to capture the distribution of susceptible hosts (e.g. *Vaccinium*) within different heathland fragments.

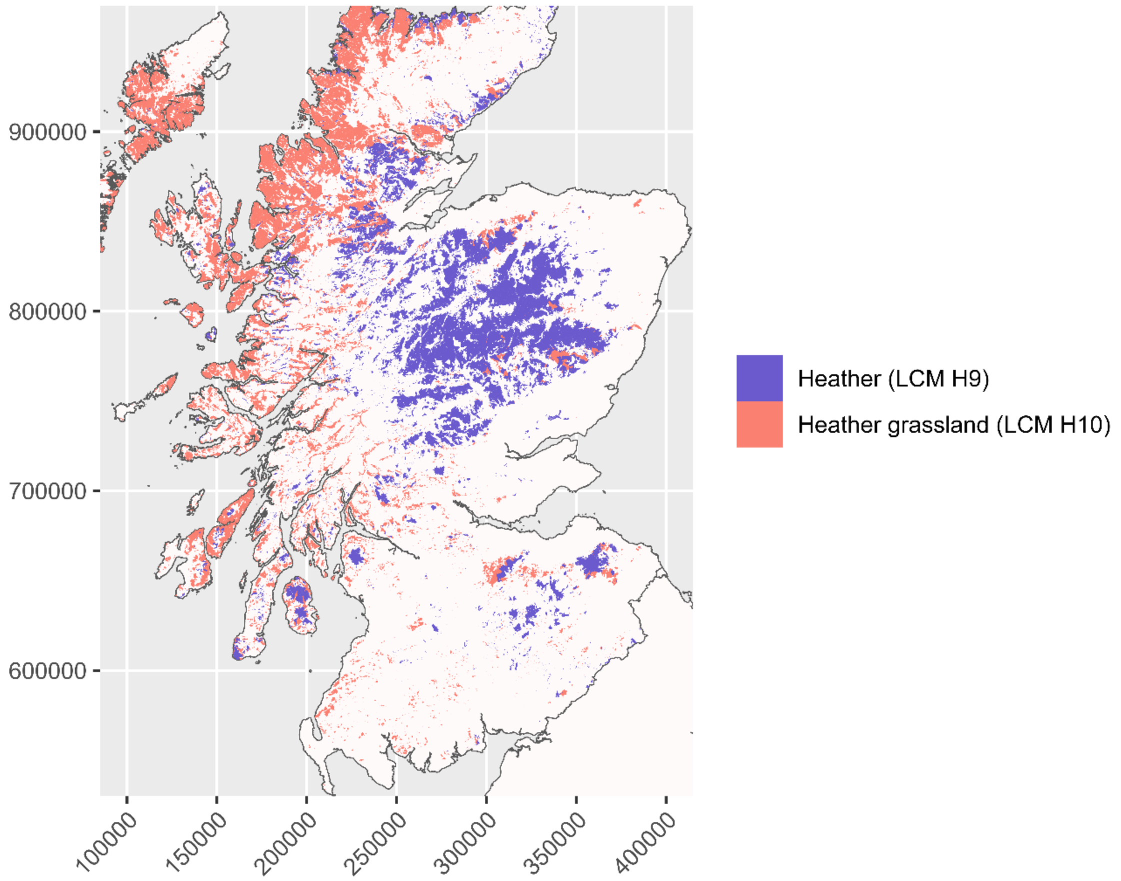


Figure A3 Distribution of heathland fragments in Scotland identified using LCM 2023 classes Heather and Heather grassland

7.2.2 Risk factors and risk scoring of P. ramorum risks to heathland

Risks to heathland fragments from *P. ramorum* were scored using the protocol in Table A6. For mapping, risk scores were binned into broader risk categories identifying fragments of low (>=0 <=3), medium (>3<=6) and high (>6) risk.

7.2.3 Distribution of risks to heathland fragments in Scotland

The maximum possible score for heathland fragments across all risk factors was 11.5, but in practice the maximum value assigned for any fragment was 10.5 for Heather (H9) and 11 for Heather grassland (H10). There were more high risk fragments for *P. ramorum* establishment across heather grassland than heather due to the western distribution of the habitat coinciding with greater climate suitability for *P. ramorum* establishment and the more widespread infections in Larch woodlands in southern and western regions (Fig. A4).

Whilst the majority of high risk heather (H9) fragments for *P. ramorum* establishment are in Highland, Aberdeenshire and Perth and Kinross, there are also high risk fragments in the west and south of Scotland particularly Stirling, Argyll and Bute and Dumfries and Galloway and the Scottish Borders. High risk heather grassland (H10) fragments were predominantly distributed in Highland, Argyll and Bute, Stirling and Dumfries and Galloway (Table A7).

Table A6 Risk factors and risk scoring for Phytophthora ramorum risks to heathland comprising Heather (H9) or Heather grassland (H10) categories in the Land Cover Map 2023. Note that the relative weighting of different risk factors is proportional to the maximum value of the scoring scale. Risk factors are ordered from most important (climate suitability) to least important (proximity to importing trade premises).

Risk factor	Parameter	Score	Number of LCM H9 fragments	Number of LCM H10 fragments
***P. ramorum* climatic suitability (average within fragment)**	(~ < 20th percentile) 0 to <14 mm/day	0	10410	15534
	(~20th - 40th percentile) >=14 to <18 mm/day	1	8337	16224
	(~40th - 80th percentile) >= 18 to < 28 mm/day	2	18697	28902
	(~ 80th - 90th percentile) >= 28 to < 33 mm/day	3	5496	6451
	(~ > 90th percentile) >= 33 mm/day	4	4647	7758
Proximity to Larch/infected Larch	No other larch present within 5000m	0	6739	17865
	Other standing Larch without Pr infection with no SPHN within 5000m	0.5	32959	35615
	Completed SPHN within 5000m	0.75	3964	4341
	Completed SPHN within 500	1	191	193
	Other standing Larch with incomplete SPHN within 5000m	2	3211	12489
	Other standing larch with incomplete SPHN within 500m (including all fragments in the management zone)	3	523	4366
Susceptible hosts within fragment (*R. ponticum, V. myrtillus, V. vitis-idaea, A. uva-ursi*)	~ <= 50th percentile habitat suitability)	0	3478	6249
	~ >= 50th <= 80th percentile habitat suitability	1	16219	29229
	~ >= 80th percentile habitat suitability	2	27890	39391
Other wider environment detections	No non-larch Pr detections within 1500m	0	47480	74779
	Wider environment Pr (non-Larch) detection with no or incomplete SPHN within 1500m	1	107	79
Watercourses (within fragment itself)	None	0	36817	51938
	Present	1	10770	22920
Proximity to detections in inspected premises	Does not intersect postcode district of infected premises	0	43202	74003
	Intersects postcode district of infected premises	0.5	4385	866

High risk heathland fragments for *P. ramorum* establishment include 1509 fragments of heather and 3207 fragments of heather grassland that are within or intersect protected areas within Scotland (30x30 project).

Table A7 Risks to heathland fragments from P. ramorum by local authority region. Overall risk scores were binned to identify low, medium and high risk areas. Note that regions with no high risk heathland fragments are not shown.

	Heather H9			**Heather grassland (H10)**			**Total high risk**
Local authority	**Low (0<=3)**	**Medium (>3<=6)**	**High (>6)**	**Low (0<=3)**	**Medium (>3<=6)**	**High (>6)**	
Highland	6254	14724	2735	5943	24541	5238	7973
Argyll and Bute	612	742	390	4395	6423	5043	5433
Stirling	10	162	790	70	1262	1456	2246

Dumfries and Galloway	0	62	257	3	439	962	1219
Perth and Kinross	398	4140	1064	81	672	62	1126
Scottish Borders	215	568	283	354	935	239	522
South Lanarkshire	2	151	75	112	330	62	137
South Ayrshire	0	6	1	17	782	106	107
Inverclyde	9	19	2	3	282	101	103
North Ayrshire	21	839	18	412	1116	58	76
West Dunbartonshire	0	28	8	5	127	63	71
Renfrewshire	1	17	0	0	230	70	70
East Ayrshire	4	41	22	35	356	27	49
East Renfrewshire	0	0	0	1	99	16	16
North Lanarkshire	4	48	3	83	258	11	14
East Dunbartonshire	0	11	4	11	107	4	8
Aberdeenshire	841	5024	4	170	542	0	4
Falkirk	7	41	1	51	162	1	2

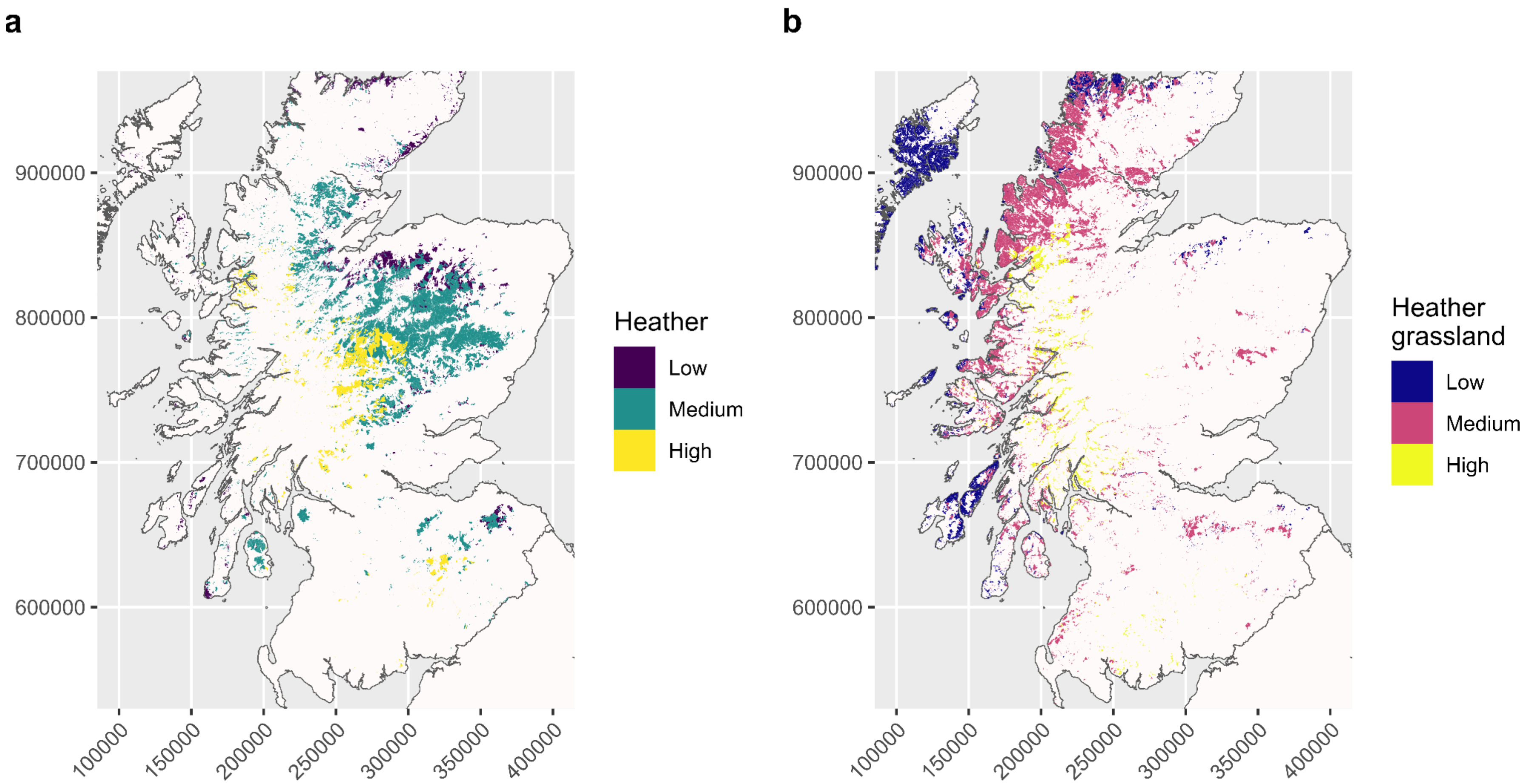


Figure A4 Risk of P. ramorum establishment in heathland fragments of LCM 2023 class a) Heather (H9) and b) Heather grassland (H10)

7.2.4 Stakeholder perspectives on impacts on decision-making of heathland risk maps

There was agreement that the risk maps for heathland fragments could be useful for surveillance targeting, habitat protection and conservation planning, especially for institutions such as NatureScot. However, organisational responsibility for plant health in the wider and natural environment has yet to be established (The Scottish Government, 2024). Dissemination pathways identified included sharing risk maps through conservation networks (via NatureScot) and integrating with existing systems used by land owners such as MyForest (integration into the web-based forest mapping tool).

7.3 Full methods for spatial risk analysis for Phytophthora x alni infection of alder fragments in Scotland

Phytophthora disease of alder has been widespread in southern England since at least 1995 and became more prevalent in annual surveys between 1994 and 2003 (Gibbs et al., 2003; Webber et al., 2004). It has been confirmed at several riparian sites in Scotland. Disease caused by *P. x alni* is reported only on the genus *Alnus*. Species affected include Common alder, Italian alder and Grey alder, therefore we include all species of alder in the mapping of fragments at risk from *P. x alni*.

7.3.1 Compiling alder fragments across Scotland

Risk factors for *P. x alni* infection were scored for fragments containing alder species extracted from the National Forest Estate Sub-compartments 2019 where an alder species is recorded as the primary, secondary or tertiary species. In addition, fragments from the Native Woodland Survey of Scotland were included where the species structures data indicated the species included alder or the NVC habitat components were W5, W6 or W7 (NVC communities including *Alnus glutinosa*). Additional point data from the global *Phytophthora* database was included where the host species was alder, with a small buffer to convert points to polygons. Felled areas reported in the National Forest Inventory since 2013 were removed from the alder fragments identified, including small areas of <20m^2 within 50m of a felled area (unless adjacent to unfelled areas). The primary reason for doing this was to remove thin habitat polygons that arose through the removal of felled areas due to inexact alignment of polygons. It is considered likely that 'on the ground' there was no such disparity. We identified 50034 fragments in Scotland containing alder species.

7.3.2 Risk factors and scoring Phytophthora x alni risks to alder fragments

Alder fragments were scored for each risk factor identified in Table A8. Climatic suitability for *P. x alni* growth was scored from 0 to 4 using percentiles of growth across the relevant fragments. This risk factor is therefore considered more important than other risk factors with lower maximum values.

Whilst the disease symptoms of *P. x alni* infection are relatively widespread, there are few confirmed detections of *P. x alni* in Scotland. Within our database, we have just 43 spatially referenced records for GB and only 4 in Scotland. Proximity to infected sites or premises therefore cannot be scored in this risk framework. The risk of introduction via trade and other inspected premises is also not captured within the risk framework because SASA inspection data do not include any detections of *P. x alni*, as it is present and widespread in the UK and it not reportable under UK regulations. We did attempt to identify higher risk premises using a Google search of traders and growers of alder in Scotland, but the results may not adequately capture the distribution of alder in trade and for mapping the risks and only 25alder fragments were within close proximity of the identified premises. Therefore, whilst the original introduction of *P. x alni* via trade pathways is likely, the disease is now widespread in the wider environment, and inspected premises are not considered a major source of new infections relative to widespread infected alder stands in the wider environment. Instead of proximity to known infections, we focus on integrating knowledge of factors linked to observed disease symptoms/impacts in the field and the map can be interpreted as identifying potential areas where trees may be more susceptible to the disease due to additional environmental stress or more at risk due to connectivity to other stands.

Risk factors discussed in the first workshop included the role of environmental stress, especially flooding (e.g. Webber et al. 2004), in driving susceptibility to *P. x alni* disease. River proximity, land use change and vegetation cover factors were also identified as potential risks. It was stressed that risk maps should be able to identify high and low risk areas, therefore the overall risk scores, summed across the different factors, were then binned and grouped into low, medium and high-risk classes. In addition, the scored alder fragments were joined with polygons of conservancies and local authority areas to enable summarising comparative risks across broader regions in Scotland.

7.3.2.1 Proximity to rivers and frequency of flood events

We used the SEPA River Flood Risk map data to capture proximity of alder fragments to rivers and the predicted frequency of flood events as a measure of regular stress on trees. The river flood risk map assigns areas adjacent to rivers a percent chance of flooding each year (Table A8). Alder fragments that did not intersect the river flood risk map were given the lowest risk, while fragments intersection areas with increasing chance of flood each year were assigned higher risk score for P. *x alni* infection.

7.3.2.2 Connectivity through flood events

Another mechanism by which flood events may increase risks to affected alder fragments is by acting as a pathway of spread connecting uninfected and infected alder stands and creating a potentially large influx of infective propagules. *P. x alni* has a history of rapid spread through waterways in Europe (Bjelke et al., 2016; Jung and Blaschke 2004). We scored the density of alder fragments within the extent of SEPA River Flood high risk flood areas, with the assumption that alder stands that are frequently connected to many other stands by frequent flood events may be higher risk for disease transmission.

7.3.2.3 Proximity to recent planting

Proximity (within 250m) to recent planting schemes including alder or other riparian broad-leaved plantings are also considered to represent a potential risk for *P. x alni* infection. Planting of nursery grown stock has potential to introduce pests and diseases (including *P. x alni*). Disturbance from the use of machinery, vehicles and the movement of soil on boots may also be greater in areas proximal to recent planting. The distances used to score risk are shorter than for previous risk frameworks for *P. ramorum* and *P. kernoviae* because *P. x alni* is a root disease and not thought to be aerially dispersed. Longer distance dispersal is more likely via waterways and is captured by risk factors describing flood risk and connectivity of flooded stands.

Table A8 Risk factors and scoring of Phytophthora x alni risks to alder containing fragments.

Risk factor	Parameter	Score	Number of alder fragments in each risk category
Climatic suitability for *P. x alni* growth (ERA5)	0-15 mm/day (< 10th percentile)	0	4212
	>15 < 25 mm/day (~10th - 40th percentile)	1	8801
	25 – 35 mm/day (~40th - 80th percentile)	2	17888
	> 35 <= 45 mm/day (80th - 90th percentile)	3	8009
	> 45 mm/day (> 90th percentile)	4	11124

Flood risk within alder fragment (SEPA Flood Maps)	No flood risk (does not intersect flood risk map)	0	32089
	Low flood risk (0.1% chance of flooding each year)	1	307
	Medium flood risk (0.5% chance of flooding each year)	2	704
	High flood risk (10% chance of flooding each year)	3	16934
Density of alder fragments within areas connected by high-risk flood extent	Not overlapping high flood risk area	0	33100
	>0 <=1alder fragments/km2 flood area	1	11847
	>1 <=5alder fragments/km2 flood area	2	3662
	>5alder fragments/km2 flood area	3	1425
Proximity to alder/riparian planting (FGS schemes)	Noalder/riparian native mixed broadleaves planted within 250m	0	48353
	Alder/riparian native mixed broadleaves planted within 250m	1	1681

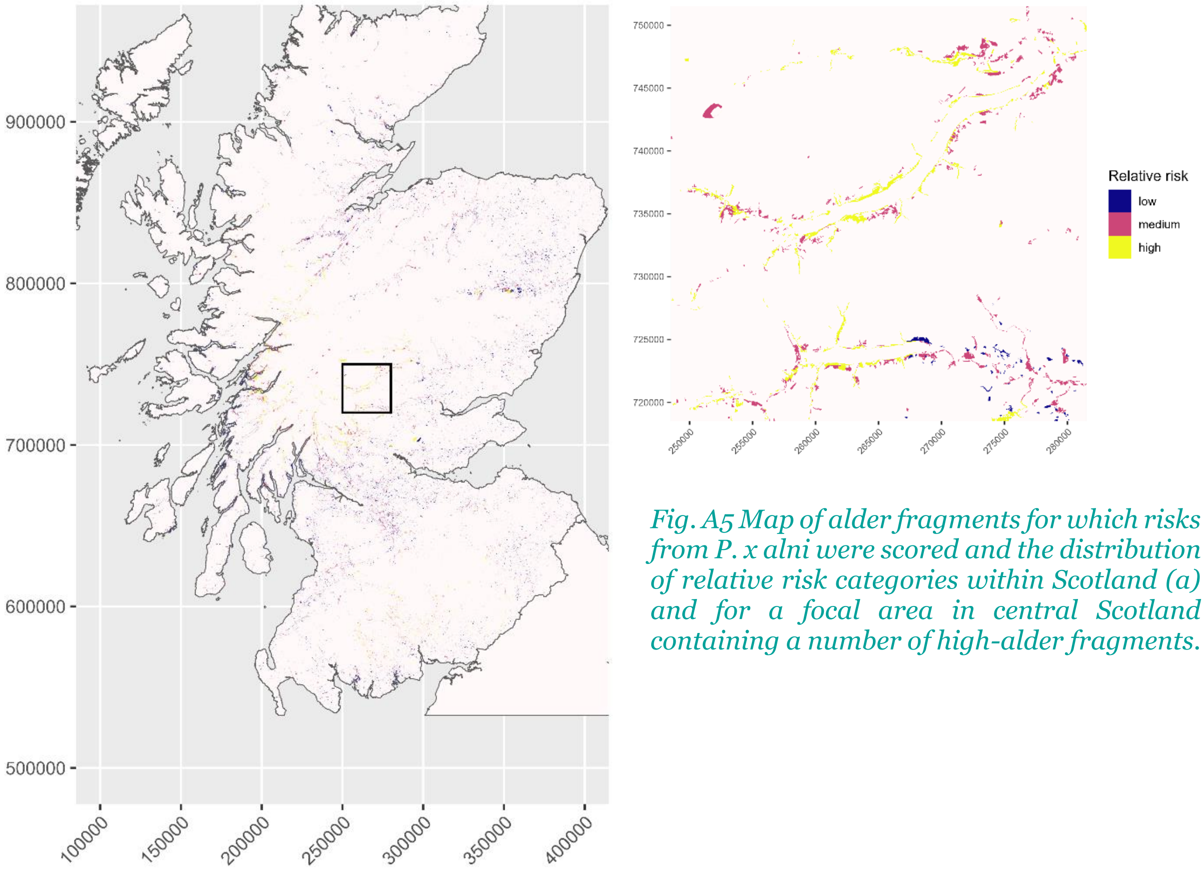


Fig. A5 Map of alder fragments for which risks from P. x alni were scored and the distribution of relative risk categories within Scotland (a) and for a focal area in central Scotland containing a number of high-alder fragments.

Table A9 Risks to alder fragments by conservancy region. Overall risk scores could range from 0 to 11 (summed across the risk factors) and were binned to identify low, medium and high risk areas

	Low (0-3)	Medium (4-7)	High (8-11)
Central Scotland	6104	2720	401
Grampian	4392	1924	28
Highland and Islands	4472	4273	1068
Perth and Argyll	6618	6065	2189
South Scotland	4004	4082	1692

7.3.3 Distribution of risk scores for alder fragments across Scotland

The Perth and Argyll conservancy contains more alder fragments than any other conservancy (29% of all mapped alder fragments in Scotland). High risk alder fragments for *Phytophthora* disease of alder were also predicted to be disproportionately distributed in the Perth and Argyll conservancies (41% of high risk fragments), likely driven by the greater numbers and connectivity of fragments in these regions, coupled with the greater climate suitability for *P. x alni* in western parts of Scotland (Table A9). South Scotland (31%) and Highland and Islands (20%) conservancies contained 31% and 20% respectively of high risk alder fragments. Together the Central Scotland and Grampian conservancies contained 31% of alder fragments mapped, but relatively few (8%) of these alder fragments were predicted to be high risk for *P. x alni*. There were also disproportionately more medium risk alder fragments in Perth and Argyll (32% of high and medium risk fragments), Highland and Islands (22%) and South Scotland (21%) and conservancies.

7.3.4 Impacts of mapped P. x alni risks to alder on decision-making

It was agreed that the maps could provide useful information for the management of riparian habitats, including riparian planting and land use planning. For other conservation bodies such as Scottish Forestry, there was a concern around communication of the maps in case the risks were interpreted in way that would discourage planting, rather than acting as a tool to enhance awareness and surveillance of disease symptoms in alder stands.

7.4 Full methods for spatial risk analysis for Phytophthora pluvialis infection of Douglas fir and Western hemlock in Scotland

Infections of *P. pluvialis* have been reported on Douglas fir and Western hemlock in Cornwall, Devon, Cumbria, Wales and Scotland since the outbreak was first detected in 2021. Outside of the UK, pine species (*Pinus radiata*, *P. strobus*, *P. patula*) are also susceptible to the pathogen.

7.4.1 Compiling fragments of Douglas fir and Western hemlock in Scotland

The distributions of Douglas fir and Western hemlock fragments in Scotland were mapped using the National Forest Estate Subcompartments 2019 where the primary, secondary or tertiary species contained either ‘Douglas’ or ‘hemlock’. This was supplemented with Scottish Forestry *Phytophthora* surveillance data and SPHNs since 2013 where the host was either Douglas fir or Western hemlock. In addition, we included fragments from the NWSS where the species structures included Douglas fir or Western hemlock. We also included any records in Scotland from the global *Phytophthora* database (point data with a small 2m buffer) since 2013 where Douglas fir or Western hemlock were reported as the host. We used the NFI to identify clear felled areas since 2013 and remove these from the mapped Douglas fir and western hemlock fragments. One complete SPHN for *P. pluvialis* was removed from the layers as the affected hosts are felled. Together these data sources identified 11098 forest fragments in Scotland containing either Douglas fir or Western hemlock.

7.4.2 Risk factors and scoring

The consensus among workshop participants was for climate suitability to be the primary risk factor for all *Phytophthora* species, so predicted climate suitability for *P. pluvialis* establishment was scored from 0 to 4 using the percentiles in Table A10, with a maximum possible score higher than any other risk factor.

Proximity to other Douglas fir/Western hemlock stands and *P. pluvialis* infected stands was scored from 0 to 3 (Table A10). *P. pluvialis* can be aerially dispersed like *P. ramorum*, with potential for long distance dispersal of spores. There have been 28 confirmed detections of *P. pluvialis* in Scotland’s forests in 2021 and 2022, which may be potential sources of infection. We assume that proximity (within 1500m) of the fragments to other Douglas fir or Western hemlock stands poses an additional risk of infection (+1) compared to more isolated stands. Fragments within 1500m of *P. pluvialis* infected sites were assigned a greater risk (2) and the highest risk score for this factor was assigned if the fragment was within 250m of an infected stand.

To score the potential risk from planting of infected hosts, we also scored the proximity of stands to 141 recent FGS Grant schemes using Douglas fir or Western hemlock and approved since 2017. Additional risks were assigned for fragments within 1500m (+1) or within 250m (+2).

There have been only two positive detections of *P. pluvialis* in inspected premises since surveillance for *P. pluvialis* commenced in 2022. This suggests the pathogen is not widespread within trade networks and other inspected premises. The locations of inspected premises are shared by SASA at postcode district level because quarantine pest detections can be trade sensitive. The scoring gives this risk factor lower weighting compared to climate suitability, proximity to other hosts/infected hosts and proximity to FGS planting. This reflects the low spatial precision of data on higher risk inspected premises and the likely low prevalence of *P. pluvialis* across these premises. We score fragments as higher risk of *P. pluvialis* infection (+1) if they intersect the postcode district of premises where Douglas fir or Western hemlock have been inspected for *P. pluvialis*. This is intended to capture proximity to premises identified as higher risk for *P. pluvialis* by SASA inspectors.

The final risk factor included is the presence of watercourses within Douglas fir and Western hemlock fragments. One participant highlighted after the final workshop that pathologists have noted *P. pluvialis* infections are often seen adjacent to waterways and these may represent a pathway of spread to new areas. Fragments intersecting linear features within the OS Open Rivers data were therefore scored as greater risk for *P. pluvialis* infection.

The maximum possible risk score for *P. pluvialis* infection was 11. In practice, no fragment scored higher than 8 across the five risk factors. The scored fragment data were intersected with the boundaries of conservancies, local authorities and active *P. pluvialis* demarcated areas to summarise the distribution of risks across regions in Scotland.

Table A10 Risk factors for P. pluvialis infection and risk scoring of woodland fragments containing Douglas fir and Western hemlock

Risk factor	**Parameter**	**Score**	**Number of Douglas fir / Western hemlock fragments (n = 11098)**
Climate suitability for *P. pluvialis* growth (ERA5)	<=5 mm/day (~20th percentile)	0	1973
	>5 < 7 mm/day (~20th - 40th percentile)	1	2207
	>=7 <= 9 mm/day (~40th - 60th percentile)	2	2827
	> 9 =< 12 mm/day (60th - 80th percentile)	3	2243
	> 12 mm/day (> 80th percentile)	4	1848
Proximity to other Douglas fir/Western Hemlock and infected sites (Scottish Forestry surveillance data)	No other Douglas fir / Western Hemlock within 1500m of fragment	0	421
	Uninfected Douglas fir / Western Hemlock within 1500m	1	10167
	Infected Douglas fir / Western hemlock within 1500m	2	367
	Infected Douglas fir / Western Hemlock within 250m	3	143
Proximity to woodland creation	No FGS woodland creation schemes within 1500m	0	10730
	FGS woodland creation schemes within 1500km	1	339

schemes using Douglas Fir and Western hemlock (FGS - 141 claims)	FGS woodland creation schemes within 250m	2	29
Proximity to higher risk inspected premises	Does not intersect postcode district of SASA inspections of Tsuga or Pseudotsuga	0	10329
	Intersects postcode district of SASA inspections of Tsuga or Pseudotsuga	1	769
Presence of water courses in fragment (OS Open Rivers)	No water course present	0	10145
	Water course present	1	953

7.4.3 Distribution of Phytophthora pluvialis risks to Douglas fir and Western hemlock forest fragments in Scotland

High and medium risk fragments for *P. pluvialis* infection were distributed mostly in Perth and Argyll and South Scotland conservancies (Fig. A6; Table A11) where 83% and 88% of fragments were either high or medium risk. A smaller percentage of fragments were high or medium risk within the Highland and Island (46%), Grampian (40%) and Central Scotland conservancies (35%). The risk scoring identified 457 high risk forest fragments containing Douglas fir or Western hemlock. Of these high-risk fragments 27% were within Demarcated areas from which the movement of plants for planting of *Tsuga*, *Pseudotsuga* and *Pinus* is prohibited (Table A12). An additional 331 high risk fragments were identified outside of the demarcated areas representing stands containing Douglas fir or Western hemlock where the climate suitability for establishment is high, there is close proximity to other stands (possibly infected), recent planting of the species and regional proximity to inspected premises where the hosts are present or watercourses. The risk maps for *P. pluvialis* were mentioned within the breakout groups, but the impacts on decision-making within Scotland were not discussed.

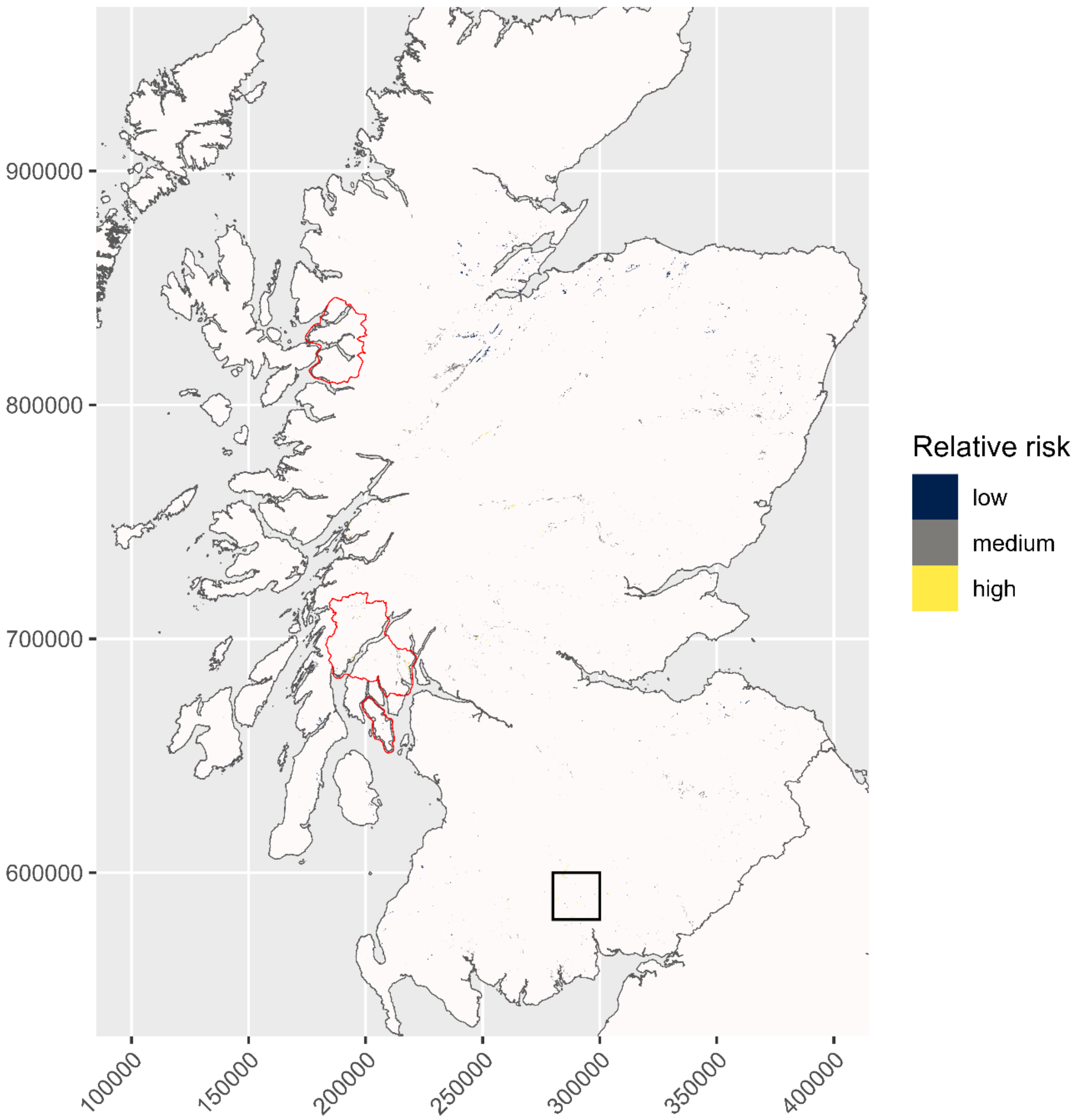


Figure A6 Distribution of Douglas fir or Western hemlock fragments for which risk of Phytophthora pluvialis infection was scored. The black box is the area of South Scotland mapped in Fig. A7b. The red boundaries are active Phytophthora pluvialis Scotland Demarcated areas.

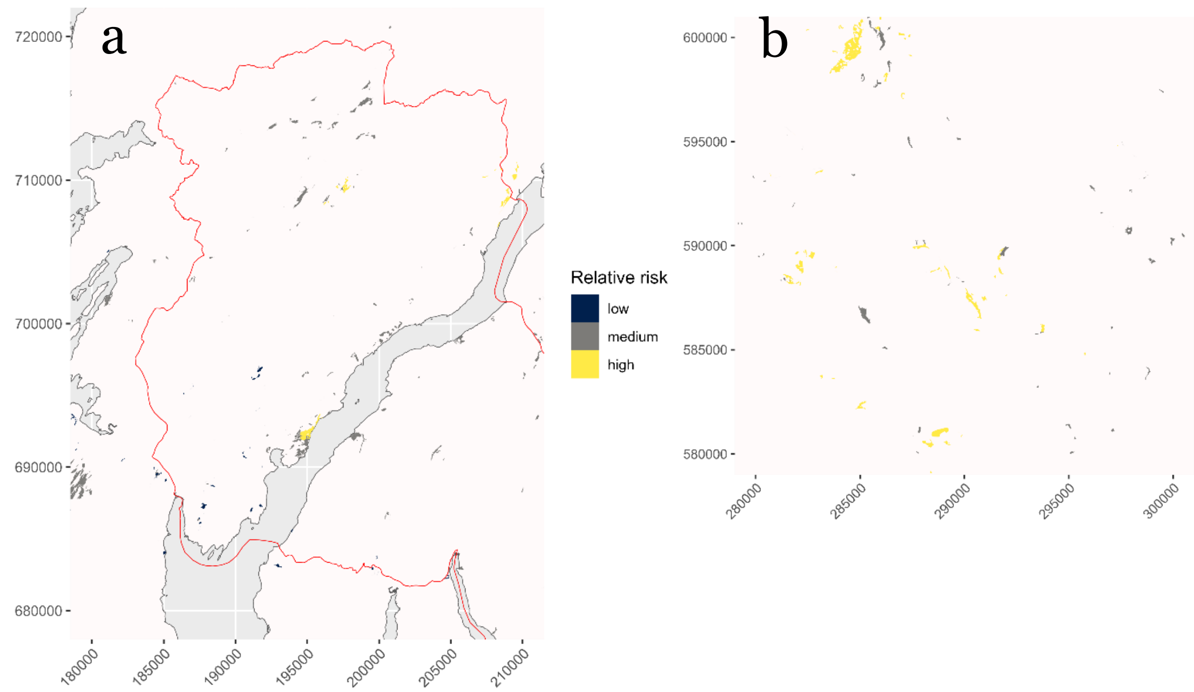


Figure A7 Predicted relative risk of P. pluvialis infection within a) Phytophthora pluvialis Scotland Demarcated Area 6 and b) an area of South Scotland conservancy, where there were a large number of high-risk fragments.

Table A11 Number of Douglas fir or western hemlock fragments in each risk score category within the conservancy regions

Conservancy	Low (0-2)	Medium (3-5)	High (6-8)
Central Scotland	307	164	1
Grampian	1037	699	0
Highland and Islands	1792	1446	108
Perth and Argyll	565	2697	155
South Scotland	264	1670	193

Table A12 Number of Douglas fir or western hemlock fragments in each risk score category within the Phytophthora pluvialis Scotland Demarcated Areas

	Low (0-2)	Medium (3-5)	High (6-8)
Phytophthora pluvialis Scotland Demarcated Area No.4	0	2	7
Phytophthora pluvialis Scotland Demarcated Area No.5	71	0	17
Phytophthora pluvialis Scotland Demarcated Area No.6	55	49	628
Outside demarcated areas	331	3914	6024

7.5 *Full methods for spatial risk analysis for Phytophthora pinifolia infection of Caledonian Pinewood Inventory fragments*

Risks from *Phytophthora pinifolia* were calculated for 82 fragments of core zone Caledonian Pinewood from the Caledonian Pinewood Inventory. *P. pinifolia* has not been detected in the UK but is on the UK Plant Health Risk Register. All known host species are within the genus *Pinus*, either recorded as naturally occurring disease affecting the shoots and needles of *Pinus radiata* (Durán et al., 2008), or established through pathogenicity trials on other species within the genus, albeit with varying levels of susceptibility (Ahumada et al. 2013). The risk maps for Caledonian Pine assess the vulnerability of CPI fragments, if *P. pinifolia* were to arrive, and the most probable areas of introduction and establishment. The only known source region for the pathogen is Chile. Arrival risk predictions are available for 54 *Phytophthora* species currently thought to be absent from the UK (Barwell *et al.* 2025). Risk predictions integrate horticultural trade connectivity with source regions, climate matching to source regions, importer biosecurity and pathogen-specific traits and phylogeny. *P. pinifolia* was ranked 8th mostly likely to arrive among the 54 *Phytophthora* species assessed, with this higher risk predominantly driven by the model component describing climatic similarity between forest, agricultural and urban habitats in the Chile and the UK. A Rapid Pest Risk Analysis for *P pinifolia* considered it unlikely to enter the UK due to restrictions on import of living pine species from non-EU countries, though is still possible if it is transported with other, as yet unknown, hosts.

7.5.1 Phytophthora pinifolia risk factors and scoring

Risk factors for *P. pinifolia* were scored using the protocol in Table A13. As agreed in the first workshop, climate suitability was given the greatest weight in the scoring of the risk factors. Due to the absence of any detections in the UK, the spatial risk frameworks exclude proximity to infected areas.

7.5.1.1 Connectivity to other Pinus fragments

Potential hosts in Scotland were assumed to be all *Pinus* species in Scotland. The connectivity of other *Pinus* stands to CPI fragments was assessed using the National Forest Estate Sub-compartments Scotland 2019. Sub-compartments were extracted if they contained *Pinus* as primary, secondary or tertiary species. The *Pinus* sub-compartments were intersected with the National Forest Inventory Scotland between 2017 and 2023 to remove subsequently felled areas. No SPHNs have been issued for felling of *Pinus* as a host.

7.5.1.2 Proximity to inspected premises

The workshop discussions highlighted that proximity to trade premises was considered less important for *Phytophthora* introduction than in the previous risk frameworks. This is partly because of the strict regulation of trade in hosts (*Pinus* - Regulated and notifiable) and a consensus that biosecurity awareness and practices within trade have improved. The proposed risk factor of proximity to any trade premises was considered too non-specific. Stakeholders identified a need for more specific knowledge on the relative risks posed by different types of businesses to justify inclusion of proximity to trade premises as a risk factor. We used SASA inspections of *Pinus* at postcode district level to assess risks from inspected premises. SASA confirmed that *Pinus* are targeted for inspections to detect Dothistroma Needle Blight and other quarantine pests, thus patterns of inspection represent a proxy for the risk-based approaches to *Pinus* surveillance used by plant health inspectors. CPI fragments (including regeneration and buffer zones) that intersect a postcode district with inspected *Pinus* were assigned an additional risk (+1) for *P. pinifolia* introduction/establishment compared to fragments not within an inspected *Pinus* postcode district. We assume that inspected post code districts include premises considered to be at risk by SASA inspectors for *Pinus* pests more widely (e.g. DNB) and therefore also for *P. pinifolia*. Postcode districts are relatively coarse (~10km^2) even compared to the large, assumed dispersal distances of aerial/foliar pathogens on sporulating hosts (up to 5000m). This spatial imprecision introduces some uncertainty in the risk scoring and is consequently weighted less than the other risk factors for introduction/establishment.

7.5.1.3 Proximity to planting pathways

It was recommended that only CPI core zones should be scored for proximity to woodland creation schemes, and not the regeneration or buffer zones. Since 2013, there have been restrictions on planting within 600m (buffer zone) of core CPI set out in Scottish Forestry guidance on planting Caledonian Pinewoods and within the Dothistroma Needle Blight Action

Plan. Risks from planting within 1500m were considered an increased risk (+1) but was weighted as the least important risk factor to reflect that the risks from planting should be partly mitigated by the CPI buffer zone.

Table A13 Final scoring of risk factors assessing vulnerability of 82 Caledonian Pinewood Inventory fragments to the threat of Phytophthora pinifolia arrival in the UK

Risk factor	Parameter	Score	Number of core CPI fragments (n = 82)
Climate suitability for *P. pinifolia* growth (ERA5)	<=0.25 mm/day (~10th percentile)	0	8
	>0.25 < 0.4 mm/day (~10th - 30th percentile)	1	17
	>=0.4 <= 0.6 mm/day (~30th - 60th percentile)	2	23
	> 0.6 =< 0.75 mm/day (60th - 90th percentile)	3	28
	> 0.75 mm/day (> 90th percentile)	4	6
Connectivity to other *Pinus* sub-compartments	No other *Pinus* sub-compartments within 1.5km of core zone	0	50
	Pinus sub-compartments within 1.5km of core zone	1	9
	Pinus sub-compartments within 250m of core zone	2	23
Proximity to higher risk inspected premises	Does not intersect postcode district of SASA-inspected *Pinus*	0	66
	Intersects postcode district of SASA-inspected *Pinus*	1	16
Proximity to planting pathways	No FGS woodland creation schemes using *Pinus* within 1.5km of core zone	0	71
	FGS Woodland creation schemes using *Pinus* within 1.5km of core zone	1	11

7.5.2 Distribution of risk scores for Caledonian pinewood inventory fragments across Scotland

Risk scores for CPI fragments are mapped across Scotland in Fig. A8 and represent the risk of introduction and subsequent establishment in these fragments, if *P. pinifolia* were to arrive in the UK. The risk score integrates given the connectivity to other *Pinus* stands, proximity to pathways of potential introduction (including via planting and inspected premises) and the climate suitability for pathogen growth. Fragments in darker colours have low risk, while brighter colours (pink to yellow) have medium or high risk for *P. pinifolia* introduction or establishment. Stakeholders identified that the fragment-level granularity added unnecessary complexity, therefore we also present summaries of *P. pinifolia* threat by region (Conservancy and Scots pine seed zones).

Medium or high-risk CPI fragments for *P. pinifolia* introduction or establishment are predominantly within the Highland region, with a smaller number of high risk fragments in Perth and Argyll and the Grampian region (Table A14). The very highest risk fragments (relative risk = 5) are all in the western areas of the Highland Conservancy, due to the greater climate suitability and connectivity to other pine in this area. However, there is a large and contiguous area of high risk for *P. pinifolia* (relative risk = 4) towards the eastern border of the Highland Conservancy also.

The forest reproductive materials Scots pine seed zones represent regions where climatic and ecological conditions are similar for sourcing seed (Table A15). The majority of medium and high risk fragments are in the South West and North East seed zones, but North Central seed zone also contains a number of high or medium risk CPI fragments for *P. pinifolia*.

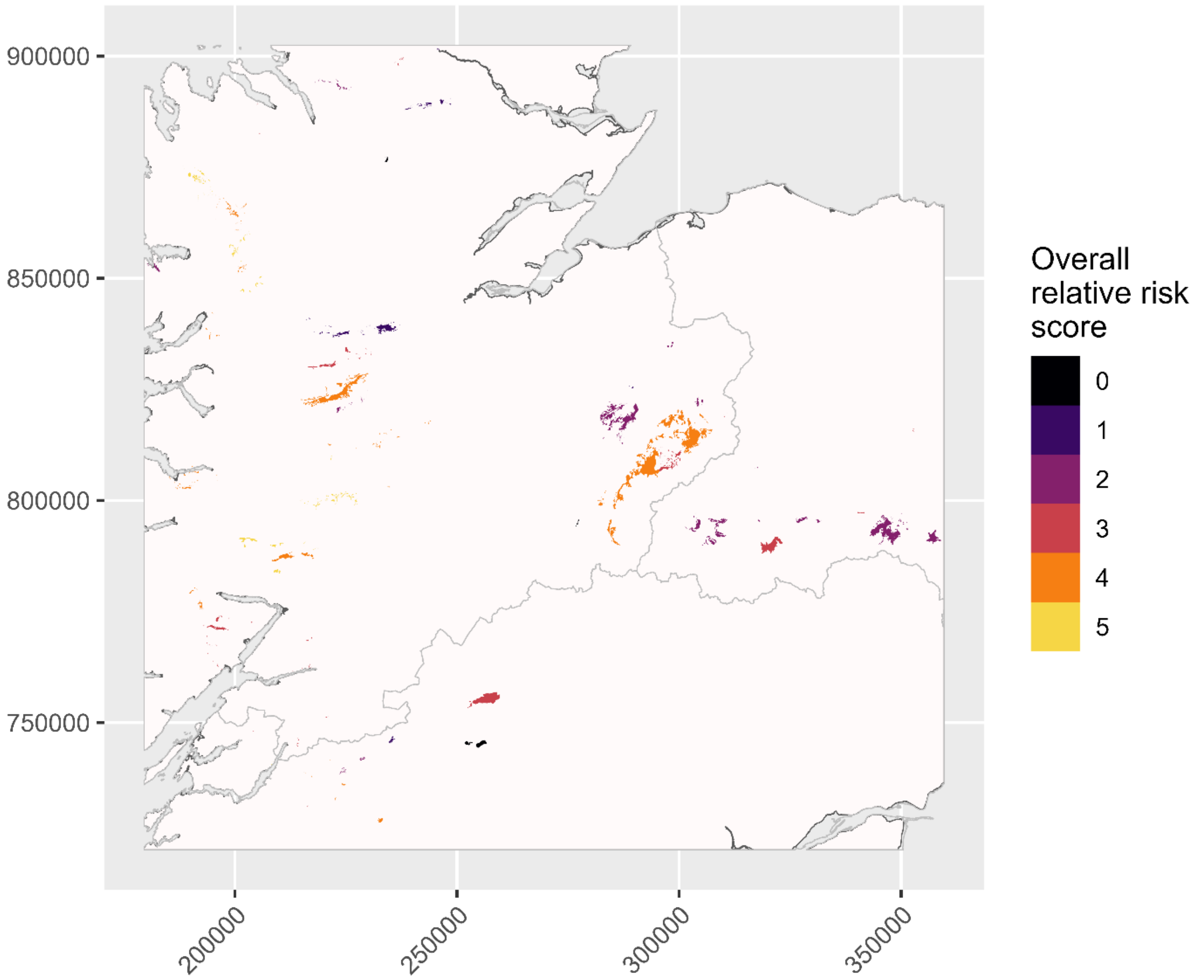


Fig. A8 Phytophthora pinifolia relative risk scores in Caledonian Pinewood Inventory fragments

Table A14 Number of core CPI fragments of low, medium and high risk by conservancy region

Conservancy	Risk rating		
	Low (0-1)	Medium (2-3)	High (4-5)
Grampian	0	12	0
Highland and Islands	6	23	28
Perth and Argyll	2	5	6

Table A15 Number of core CPI fragments of low, medium and high risk per Scots pine seed zones

Seed zone	Risk rating		
	Low (0-1)	Medium (2-3)	High (4-5)
South West	1	16	18
North Central	2	1	8
East Central	2	4	3
North West	0	3	3
South Central	1	1	2
North	2	2	0

North East	0	13	0

7.5.3 Stakeholder perspectives on potential value for decision-making of P. pinifolia risks to Caledonian Pinewood Inventory

The workshop discussions identified that risk maps for *P. pinifolia* to the CPI could be useful for policy and decision planning in relation to protected site management, seed zone planning and planting decisions. Risks from *P. pinifolia* could be integrated into seed zone guidance. Dissemination through forestry networks and through newsletters and relevant WhatsApp groups of HTA Grower members would support awareness across different sectors of *P. pinifolia* threat to Pine species in Scotland. Integrating the risk maps should link with existing planning tools like the UK Plant Health Information Portal / Plant Healthy Certification Scheme. Risks to specific fragments (granularity) were less useful than summarising regional-level risks, given the pathogen has yet to arrive. A concern was how to interpret and communicate the risks, especially in relation to planting decisions, in a way that acknowledges how current restrictions and regulations on import of Pine species reduce the likelihood of arrival and balances the threat against other priorities in planting decisions.

7.6 Validation of risk frameworks

Validation of the spatial risk frameworks, using data driven approaches, was identified as a key priority by stakeholders and end users (Table 4). Validation of the climate suitability component of the models has been attempted using UK and European detections for 18 *Phytophthora* species with >= 30 total detections in the UK or Europe (Green et al 2024, available on request). With the exception of *P. plurivora*, the predicted climate suitability across locations where the species was detected were greater than expected under a random distribution (measured by the Boyce index > 0). Climate suitability models predicted observed outbreaks particularly well (Boyce index >=0.75) for *P. ramorum*, *P. austrocedri*, *P. lateralis* and *P. pluvialis*. For the *Phytophthora* species with lower scores for validation metrics, there were generally limited data available for validation.

Risk models could be validated in different ways, for example by matching geographical patterns in establishment with geographical patterns in key risk factors to determine the relative important of the risk factors in driving establishment. Alternatively, we can examine whether an independent dataset of establishment patterns (e.g. from subsequent years) is well or poorly predicted by a multi-criteria risk framework such as ours (and potentially test out whether inclusion or exclusion of particular risk factor improves this match). As for many other pathogen species (Purse & Golding, 2015), available reported locations of *Phytophthora* occurrence are sparse relative to potential host distributions making the delineation of an independent dataset for model testing very difficult. Validation of the updated spatial risk frameworks with recent detection would not be robust because any available detections in trade and the wider environment are used in the scoring of proximity to these infected sites and are not independent of the risk scores. For *Phytophthora ramorum* only there are sufficient subsequent, independent detection data to assess whether future outbreaks were well or poorly predicted using the original risk frameworks that contained very similar risk factors and risk scoring to the updated frameworks.

To validate the original risk frameworks for Larch from 2013 (Purse et al., 2016), we used an independent data set of 1906 SPHNs issued for *P. ramorum* between 2014 and 2024. Risk scores for Larch fragments were intersected with SPHNs to identify those which had subsequently been infected (Table A16).

Table A16 Number of subsequently infected Larch fragments (SPHN issued) and without confirmed infections (no SPHN) for each risk score assigned in the spatial risk frameworks of 2013.

Risk score 2013	No SPHN (%)	No SPHN (%)
0	665 (97.4%)	18 (2.6%)
1	2404 (93.9%)	156 (6.1%)
2	3465 (85.9%)	568 (14.1%)
3	4072 (84.2%)	766 (15.8%)
4	3061 (79.9%)	769 (20.1%)
5	1609 (74%)	564 (26%)
6	578 (72.9%)	215 (27.1%)
7	167 (65%)	90 (35%)
8	33 (63.5%)	19 (36.5%)
9	11 (55%)	9 (45%)
10	7 (63.6%)	4 (36.4%)
11	3 (75%)	1 (25%)
Total	**16075**	**3179**

We used the Boyce index to assess the performance of the spatial risk frameworks in predicting subsequent infections. There are multiple metrics available for validating predicted suitability against observed data (Hirzel et al., 2006). The continuous Boyce index requires only presence data for validation (not presences and confirmed/assumed absences). The index assesses the model's ability to predict a monotonic increase in the ratio of observed to expected (under a random distribution) infections within binned classes of increasing risk. The values of the index span from -1 to +1. Positive values indicate the spatial risk framework predicted higher risk where *P. ramorum* was subsequently detected (an SPHN issued). Values close to zero mean that the model does not perform better than a random model (approximately equal detections in high and low risk fragments) and negative values indicate that the model predicts low risk where detections are more frequent (Hirzel et al., 2006). The accuracy of the Boyce index improves with the number of presences (e.g. confirmed infections) available and can be poor where there are low numbers of presences (Liu et al., 2025). There were very few Larch fragments with the highest risk scores (e.g. 8 or above). We therefore only attempted to validate predictions across risk score levels containing at least 2% of the Larch fragments to avoid inaccurate estimates of the Boyce index.

We could not assess model performance across very high risk Larch fragments (due to limited sample sizes of Larch fragments with these scores and relatively low numbers of SPHNs across the landscape). However, using the remaining overall risk score classes, the Boyce index was >0.9 across all Larch fragments (Table A17). This indicates that subsequent infections (between 2014 and 2024) occurred more often in Larch fragments with higher risk scores in the 2013 risk framework. The Boyce index improved when Larch fragments within the Scottish Forestry Management Zone (MZ) were excluded, presumably because few SPHN's (7) have been issued in this region since 2014 reflecting the move towards long-term management, rather than eradication or containment of the outbreak. This means there are few confirmed detections in the MZ with which to evaluate the performance of the model. The model performed less well in the Risk Reduction Zone (RRZ Boyce index = 0.628). One reason for this may be that *P. ramorum* on Larch is more widespread within this region with higher inoculum pressure potentially leading to more infections in fragments predicted to be lower risk given climate suitability and other risk factors. Alternatively, the management of *P. ramorum* through removal of larch may therefore have led to fewer subsequent infections across fragments predicted as higher risk based on their proximity to infected sites in the RRZ. A greater density of SPHNs (albeit with longer deadlines for completion) have been issued within the smaller RRZ area (Table A5) and the effects of such control measures are not captured in the risk framework. The spatial risk frameworks of 2013 performed best within the Priority Action Zone, suggesting higher risk fragments within this region have generally been the first to be infected.

We also evaluated the performance of two risk factors for which the quantitative predictions underpinning the risk scores were available (climate suitability for *P. ramorum* infection and habitat suitability for the reservoir host *R. ponticum*). Climate suitability alone performed well in predicting where SPHNs were issued across Larch fragments outside of the MZ (Table 19, Boyce index = 0.866), consistent with stakeholder perspectives that climate should be the primary risk factor in the frameworks. However, the Boyce index for climate suitability alone was lower than for the full spatial risk framework, implying that integration of climate suitability with other risk factors (including connectivity and proximity to spread pathways) does have potential to improve prediction of *P. ramorum* infection across Larch fragments. Habitat suitability for *R. ponticum* alone produced average model predictions (Boyce index = 0.517), highlighting the value of including this risk factor alongside others.

The validation step had not been completed by the final workshop therefore the impacts of validation on perceived confidence in the models has yet to be assessed. Further validation is required for the current risk frameworks using future surveillance data, and it will be important to re-evaluate the credibility and perceived value of the models among stakeholders when these future validation steps are possible.

Table A17 Performance of the original spatial risk frameworks of 2013 when evaluated against independent infection data comprising subsequent SPHNs issued between 2014 and 2024. Positive values of the Boyce index imply that the models predicted subsequent infections better than would be expected under a random distribution across fragments. Values close to 1 imply excellent model performance. Note that very high risk fragments (>7) are not included in the validation due to limited numbers of Larch fragments within these risk score classes and inadequate sample sizes for estimating the Boyce index accurately.

	Number of fragments evaluated	Maximum risk score (out of 11) included in validation	Boyce index validation metric
All Larch fragments	25832	7	0.912
Larch fragments excluding MZ	18910	6	0.99
Larch fragments in the RRZ	7277	7	0.628
Larch fragments in PAZ	11773	6	0.985
Larch fragments excluding MZ – climate suitability only	19077	NA	0.866
Larch fragments excluding MZ – *R. ponticum* suitability only	19254	NA	0.517

* MZ = Management Zone; RRZ = Risk Reduction Zone

7.7 *Stakeholder perspectives on use of spatial risk frameworks for decision-making, adequacy of risk factors and scoring and pathways for dissemination to key users.*

Table A18 Stakeholder perspectives on use of spatial risk frameworks for decision-making, adequacy of risk factors and scoring and pathways for dissemination to key users

Framework	How framework can inform decision making	Risk factors/scoring Feedback	Suggested changes/ comments	Dissemination approaches
P. ramorum - Larch	• Policy level planting decisions • Scottish Forestry containment policy for *P. ramorum* e.g. control zone boundaries, changes to the *P. ramorum* Action Plan • Resource allocation planning such as for environmental surveillance • Evaluating biosecurity measures • Future productive tree species in Scotland	• Climate suitability scoring considered appropriate and very useful • Some concerns about trade premises weight • Need to add score or risk probability	• A few suggestions to reduce emphasis on trade premises • Suggestion to work with SASA to capture trade pathway	• Integration with Scottish Forestry systems (they have already published maps on *P. ramorum*). • Also, through Plant Health Portal, • link to risk register and actors such as JNCC • It will also be helpful to raise awareness for institutions such as National Trust for Scotland.
P. ramorum - Heathland	• Framework useful for surveillance targeting, especially for institutions such as NatureScot, with responsibility for habitat protection, and conservation planning)	• Questions about habitat classification • Vaccinium susceptibility weighting • Clarify host specificity	• A need to better define heathland composition • Clarify host specificity by checking how it overlaps with the NVC, • Review habitat classifications, and consider combined risk mapping across Larch and heathland	• Through conservation networks such as NatureScot. • • Integration with existing web-based forest mapping systems such as MyForest (Sylva Foundation)
P. x alni - Riparian	• Riparian management and land use for environmental NGOs and regulators.	• The need to understand interactions between multiple factors • Land use change consideration needed	• Include land use change, vegetation cover, as well as river proximity • Map should be able to tell people about high-risk vs low-risk areas	• Integrated pest management tool on the Plant Health Portal
P. *pluvialis* - Douglas fir	Mentioned but not discussed due to low interest or preference for other frameworks	Mentioned but not discussed due to low interest or preference for other frameworks	Mentioned but not discussed	Mentioned but not discussed due to low interest or preference for other frameworks

P. *pinifolia* - Pine	• Useful for policy decisions on protected site management, seed zone planning, and planting	• Climate suitability very useful • Fine granularity of pine fragments makes it more complicated than it needs to be • Current trade restrictions/regulation of Pine might reduce utility/use • Consider seed zones	• The need to integrate seed zone data • Consider regional variations • Account for current trade restrictions	• Through forestry networks, via seed zone guidance • Link to existing planning tools like the Plant Health Portal • Newsletters and relevant WhatsApp groups of HTA Grower members

7.8 Report on survey and first stakeholder workshop

7.8.1 Introduction

The project that delivered the workshop described in this report is funded by Scotland's Plant Health Centre and aims to i) review and collate the contemporary data and evidence on *Phytophthora* discovery, species descriptions and ecological traits, ii) map the greatest *Phytophthora* threats to priority plants and habitats in Scotland and iii) translate models and databases into tools to support horizon-scanning and preparedness for disease threats in Scotland. To increase the value of the tools for decision-making, this project aims to engage with those responsible for managing and protecting Scotland's natural and managed environments to identify different priorities and needs for assessing plant health risks (Barwell et al., 2021; Jones & Kleczkowski, 2020). At the end of the project, the findings will be compiled into a report on updated *Phytophthora* risks with recommendations for enhancing preparedness and early detection through risk-based prioritisation of hosts, habitats and spatial locations.

The models used within this project focus on understanding how *Phytophthora* impacts depend on pathogen and host plant traits and their distributions and the invasion history of *Phytophthora* species. Spatial risk frameworks combine risk factors for *Phytophthora* establishment and spread, including climate suitability, proximity to known and potential sources of infection and proximity to spread pathways. Previous spatial risk frameworks for *Phytophthora ramorum* and *Phytophthora kernoviae* informed surveillance of heathland fragments by Scottish Natural Heritage (now NatureScot) (Searle et al., 2016) and large and woodland fragments by Forestry Commission Scotland (now Scottish Forestry) (Purse et al., 2016) between 2010 and 2017. This interim report describes the first engagement with stakeholders participating in this project (between April and June 2024), with stakeholder input via a self-completion survey and subsequent workshop. This first engagement was intended to frame the development of new and updated spatial risk frameworks for *Phytophthora* species and to facilitate a dialogue about the potential value of the model outputs for decision-making, to enable the subsequent tailoring of the risk frameworks for needs of end users across sectors.

7.8.2 Methods

Stakeholders responsible for managing priority plant species and habitats in Scotland were initially identified through the project team's networks (established through projects including Phyto-threats, Diversitree, the Future Proofing Plant Health programme and previous work for Scotland's Plant Health Centre) and with additional input from the project steering group.

7.8.2.1 Self-completion pre-workshop survey

Before the workshop, participants received email invitations to participate in the project and complete an online survey. The survey aimed to collate their knowledge and perceptions about *Phytophthora*, priority host plant species, *Phytophthora* impacts in their region, and preferences for spatial risk maps. In total, 9 responses were received out of approximately 15 invitations sent out. A detailed copy of overall results from the pre-workshop self-completed survey is appended at the end of the report, with some key findings highlighted below.

In the pre-workshop survey, all participants demonstrated a high level of awareness and self-reported as either very knowledgeable (78%, n=7) or knowledgeable (22%, n=2) about plant health. Additionally, all respondents considered Phytophthoras as either a very important (78%, n=7) or important (22%, n=2) disease threat in their sector or area of work (see Appendix S1). When asked to identify the top five pest or disease threats to plant health in their sector or area, respondents most frequently mentioned *Phytophthora* species (n=8). The *Phytophthora* species of most concern and high priority were ***P. ramorum***, ***P. austrocedri***, and *P. alni* (n=7), which were ranked as very serious threats. Participants also identified all the threats/species as current concerns, except for *P. pinifolia* on Scots pine, which was indicated as an anticipated concern. Impacts on blaeberry (*Vaccinium myrtillus*) were also indicated as a current concern (see Appendix S1).

7.8.2.2 Online workshop

As part of this project, a 3-hour online workshop, involving 9 participants from a range of organisations including forestry, conservation, horticulture, and government agencies was held on 6th June 2024 with the aim of i) validating the priority *Phytophthora* species, vulnerable habitats and hosts for which spatial risk frameworks should be developed and ii) identifying key risk factors, input and output data and iii) potential value of the spatial risk frameworks for decision making. A second workshop in Autumn 2024 will further experiment with and validate the spatial risk framework outputs as well as horizon scanning models and databases of *Phytophthora* arrival and host associations. These participants had already been engaged in a self-completion survey on the topic. The agenda for the event (Appendix S2) was shared with the participants prior to the event and on the day itself. The workshop began with introductions and a presentation of project information, including previous risk frameworks (Purse et al., 2016; Searle et al., 2016) and survey results. Participants were then divided into two breakout groups, each led by key experts and co-facilitated by a social scientist. The workshop used Microsoft Teams for video conferencing and Miro, an interactive online whiteboard, for collaborative activities. Three breakout sessions were conducted, focusing on the following sub-discussions and activities:

i. Risk prioritisation and threats: In the first breakout, participants used Miro to identify and rank priority species, hosts, and habitats at risk from *Phytophthora* based on a set of listed rank host threat species.
ii. Risk framework and assessment approaches: Using Miro, attendees explored key risk factors and discussed various approaches to assessing *Phytophthora* risks. They also discussed how risk factors should be weighted in the risk scoring for each species-host-habitat combination.
iii. Management and dissemination strategies: In the final Miro activity, participants proposed and discussed how the frameworks could inform decision making and key communication or engagement strategies for presenting risk maps outputs.

Each Miro activity was accompanied with a facilitated semi-structured group discussion, allowing for in-depth exploration of the issues raised, and two other experts from the UKCEH and JHI project team (one per group) who took additional notes and observations. The full team met briefly after each breakout to give feedback and other detailed discussions from the perspectives of other groups. Each breakout discussion session lasted 30-40 minutes with breaks in between. Following the workshop, a reflexive thematic analysis (Braun & Clarke, 2020) was conducted in NVivo. The team began analysis by compiling all data sources, including: (i) transcriptions of the video conference and breakout recordings, following participants prior-informed consent; (ii) Miro board outputs from the three breakout sessions (risk prioritisation, risk assessment approaches, and management strategies), (iii) additional notes and observations taken by the two experts during breakout discussions and (iv) notes from the full team feedback sessions following each breakout. This was then followed by reading carefully through the data and ascribing ‘codes or themes, to the content that emerged from participants’ responses.

7.8.3 Results and Discussion

Our workshop analysis captured participants perspectives into three main thematic findings (see Table 1).

7.8.3.1 Phytophthora risk priorities and threat assessment

Initial discussions revealed varying priorities across different sectors, reflecting their specific concerns and responsibilities. However, there was general agreement that the presented priorities (see Figure 1) aligned with stakeholder concerns. Participants largely validated these priorities from the survey whilst also highlighting additional concerns. For instance, *P. ramorum*, *P. alni*, and P. *austrocedri* were consistently emphasised as key threats across both groups. Native tree species such as oak, Scots pine, and alder received particular attention, with alder's unique ecological role being emphasised.

Interestingly, participants stressed the importance of broadening the scope to include less obvious species and habitats in the risk assessment. Non-tree species, particularly *Vaccinium myrtillus* (blaeberry), were highlighted as potentially understudied but ecologically significant. A participant in Group 2 suggested that studying blaeberry could serve as a model for understanding how to assess risks for smaller (herbaceous) plant species. It was explained that this approach could provide insights into the dynamics of *Phytophthora* in non-woody plants and potentially reveal different patterns of spread or impact.

Other regional and sectoral priorities also emerged during discussions. For instance, some participants noted their significant work with *aspen* and highlighted the need to consider it in the broader risk assessment framework. Workshop participants also suggested additions to the priority species list.

Some pointed out that they would like to see *P. pseudosyringae* considered for larch as well as oak, noting confirmed positive cases of this pathogen on larch. Others in both groups suggested including *P. pluvialis* on Western hemlock, Douglas fir, pines and woodlands.

Table A19 – Summary of key workshop findings

Break out room	**Theme**	**Key Findings**
Break out 1	Risk Prioritisation	• *P. ramorum*, *P. alni*, *P. austrocedri* as key threats • Focus on native species (oak, Scots pine, alder) • Inclusion of non-tree species (e.g., *Vaccinium*) • Consideration of regional and other key host priorities and threats (*P. pluvialis*, *aspen* and *P. pinifolia*)
Breakout 2	Data sources and layers	• Integration of traditional surveys (NWSS, NFI) with advanced data (satellite imagery, Earth Observation) • Emphasis on climate data, including future projections • Interest in other datasets and novel data sources (e.g., Zulu Lost Woods data etc)
	Risk Factors	• Climate suitability identified as a key risk factor; followed by water-related factors which were highlighted as key determinants of *Phytophthora* spread • Recognition of the importance of host distribution and alternative hosts; • Consideration of human activity as a significant risk factor • Few mentioned Connectivity of suburban/urban gardens as risk factor

	Assessment approaches	• Varied assessment approaches proposed • Preference for a two-stage process combining species-specific and habitat-level assessments but recognition of the need to consider both ecological importance and *Phytophthora* impact
	Risk scoring and weightings	• There is need for validation of risk scoring methods, as well as the use of data driven approaches • Climate hazard and host distribution suggested as baseline elements. • Interest in flexible, interactive risk scoring tools
Breakout 3	Use of the risk maps	• Primarily useful for informing surveillance strategies, guiding resource allocation and supporting policy development
	Stakeholder Engagement	• The need for accessible, tailored outputs for diverse stakeholders, using multiple communication channels (Plant Health Portal, events, networks, reports)

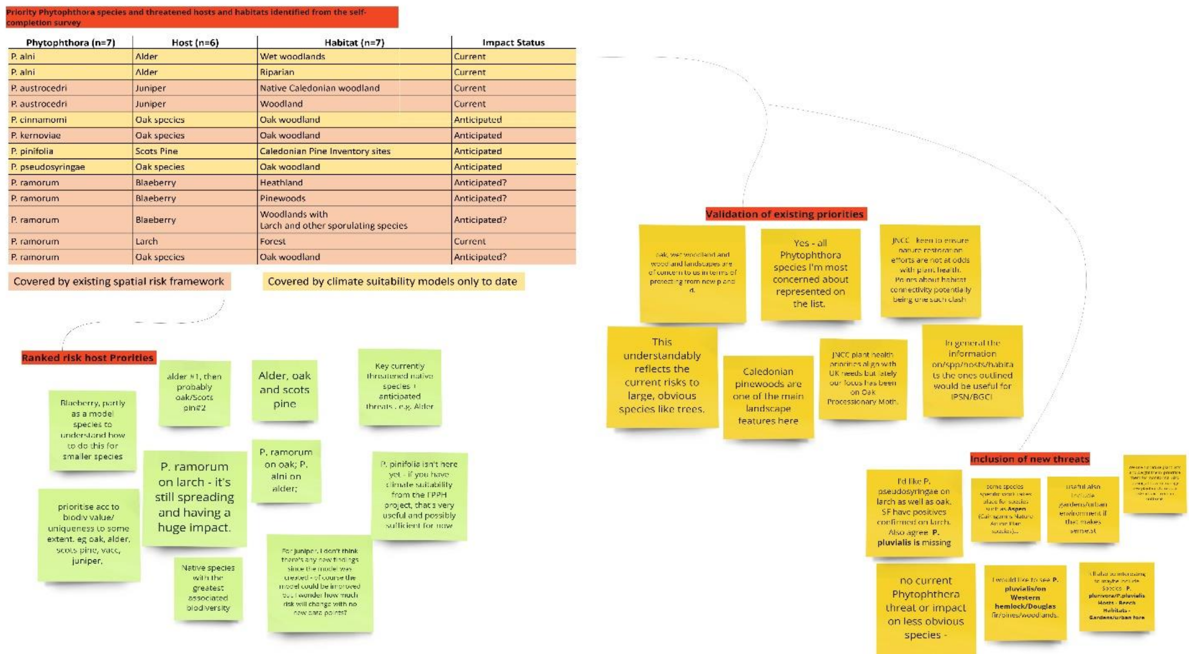


Figure A9 - Miro board frame showing participants responses to Phytophthora risk prioritisation.

7.8.3.2 Stakeholder perspectives and priorities on risk assessment framework

7.8.3.2.1 Data sources for risk assessment

Participants identified a wide range of potential data sources to inform *Phytophthora* risk assessments (see Figure 2). Existing surveys and inventories, such as the Native Woodland Survey of Scotland (NWSS), National Forest Inventory (NFI), BSBI (Botanical Society of Britain & Ireland) data, data from Botanic Garden collections Ancient Woodland Inventory and the NatureScot open-source data, were noted as foundational resources. The NatureScot open data, for instance, has layers and data on Riparian Woodlands and Habitats, among others. The BSBI (Botanical Society of Britain & Ireland) data is also publicly available at 2km and at finer resolution on request.

Building on these traditional sources, participants also expressed the need for incorporating more advanced data types. For instance, participants in Group 2 noted how the Earth Observation layers from JNCC and EUNIS landcover layer could provide valuable additional information, reflecting the growing interest in leveraging remote sensing data for more dynamic and up-to-date risk assessments. The importance of future-oriented data was also emphasised, with some participants highlighting the need for climate suitability predictions spanning 5-10 or 10 to 50 years to aid in long-term planning and management.

Some other key data sources suggested:

- Specialised datasets like the Zulu Lost Woods data (for mapping remnant ancient woodlands), the rare plant registers, and Cairngorms National Park Aspen data
- Other specific plant ecological datasets/information included data from RHS gardens which was suggested, particularly for rhododendron species.
- UKCEH hedgerow map to look at connectivity
- SEPA Water Level data for water level changes and flow rate variations
- Strava data (for assessing footfall in forests, specifically in relation to Scots pine)
- National Forest estate sub-compartments data
- For trade, SASA list of professional operators (businesses registered to issue plant passports) records or data of the locations of PODs (places of destination) was also suggested to help identify who was importing plants/ plant material.

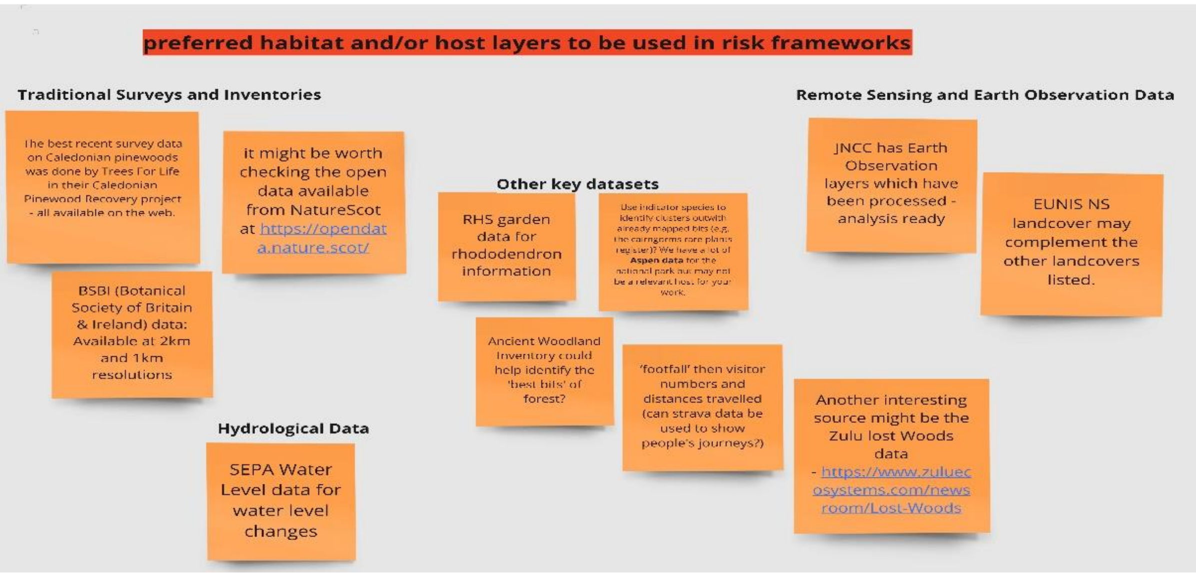


Figure A10 - Miro board frame showing participants responses to data layers and sources.

7.8.3.2.2 Other risk factors for framework

Building on the discussion of data sources, participants identified a complex interplay of risk factors that should be considered in the framework (see Table 2). Among these, climate suitability emerged as key, with participants stressing the need to incorporate both current and future climate scenarios. A participant in Group 1, for example, suggested that climate hazard should be given primacy in the models, with other risk factors modulating this primary driver.

Across the Miro boards and discussions, water-related factors were also highlighted as key determinants of *Phytophthora* spread and establishment. Participants emphasised the importance of soil water retention, surface water movement, and flooding patterns. For instance, a question raised in Group 2 about the relationship between soil type and water retention exemplified the group's priority and understanding of the complex interactions between soil properties, water dynamics, and *Phytophthora* risk.

Host distribution and susceptibility were identified as important risk factors, with participants recognising the ecological complexity of *Phytophthora* risk assessment. For instance, participants in Group 2 emphasised the need to consider not only primary host species but also alternative hosts and overall habitat composition. One highlighted the significance of host species composition within habitats, particularly noting the role of alternate hosts. Another pointed out that the function of hosts within their habitat, such as whether they are terminal (i.e. dead-end hosts, not involved in onward transmission) or sporulating (involved in onward transmission), affects their priority in risk assessment.

Other responses were related to factors such as connectivity, trade patterns, and land use change as stressors. For instance, trade networks emerged as a primary concern for pathogen spread, though participants acknowledged the difficulty in quantifying this factor (see Table 2). As a proxy for trade and plant movement, human population density was suggested, with the reasoning that areas with more people likely have more gardening activity. Large nurseries and garden centres were also identified as potential hotspots for pathogen introduction and spread. Similarly, while road and rail networks (connectivity) were mentioned, some participants expressed scepticism about their importance for *Phytophthora* spread at larger scales and their inability to capture specific high risk spread pathways.

7.8.3.2.3 Preferred risk assessment approach

When asked whether risk frameworks for *Phytophthora* should calculate risks to individual host species, or heathland and woodland habitats more broadly, participants expressed varying perspectives. Some participants valued species-level assessments for their ability to guide specific management actions, particularly for some of the identified species. Participants noted that the importance of certain risk factors might vary depending on the pathogen species being considered. One stakeholder explicitly stated that risk frameworks based on individual host species would be helpful to guide their day-to-day activities. While species-level assessments were deemed important, other participants also recognised the value of habitat-level assessments for understanding broader ecological impacts. For instance, in the Group 2 discussions, some participants noted that habitat-level assessments would be most useful to help complete risk assessments and raise awareness.

However, just a few participants agreed that a two-stage process combining both species-specific and habitat-level approaches would be beneficial. A participant proposed focusing first on host species, but then considering the role of that host in the wider habitat. Indeed, though noting the challenges such a binary approach might bring, the few participants expressed support for a risk assessment that goes beyond simply looking at the severity of impact on individual species, considering instead the ecological importance of a host species in its habitat alongside the severity of *Phytophthora* impact. Overall, the discussions pointed to a more generic approach in risk assessment, considering multiple (risk) factors and pathogen threats simultaneously rather than in distinct frameworks.

7.8.3.2.4 Risk scoring and weightings

Related to the risk factors, issues of risk scoring and weightings emerged as a key aspect of the assessment approach. When asked about how risk factors should be weighted in the risk scoring for each species-host-habitat combination, workshop participants expressed preference for data-driven approaches, for defining risks and weightings, which could then be validated through stakeholder input. They also showed interest in interactive and flexible tools that allow users to adjust weightings, and suggested prioritising climate hazard (including water, host and connectivity) in the model (see Table 2). On the need for validation, though not captured in Miro, many participants expressed strong interest in approaches to verify risk scoring accuracy. Some suggested using spatial modelling (a data-driven approach) of current disease patterns and comparing predictions with actual distribution data in the wider environment. Additionally, while not explicitly linked in the discussions, the suggestion by some participants to consider both the likelihood of occurrence and severity of impact in risk assessment was seen to offer a degree of inherent validation.

Indeed, as discussed in the risk factor identification, these elements were directly or indirectly reflected as highly important in risk scoring discussions. For instance, most participants saw the primacy of climate hazard (from suitability models) and host as high key factors to be considered in risk scoring (Table 2). For others, the importance of water-related factors was particularly emphasised for specific pathogens, such as those affecting alder. In terms of weighting these various factors, participants suggested using climate suitability and host distribution as baseline elements, with other factors serving as modifiers.

Other participants also (indirectly) suggested interactive tools that would allow users to change risk factor weightings and explore different scenarios. For instance, while stakeholder inputs to risk scoring were not mentioned directly in the discussion or Miro boards, participants in the earlier discussion on risk factor identification noted the importance of incorporating expert knowledge, level of management in an area and stakeholder inputs in risks and risk weightings. This was similarly linked to participants' significant interest in developing flexible risk scoring tools that can be adjusted based on new information or changing conditions or factors.

However, as highlighted in the discussions on risk factors, participants also acknowledged the challenges in developing a consistent risk scoring system. As was noted in Group 2, factors such as the complexity of the disease triangle – involving the pathogen, host, and environment – makes it difficult to develop a one-size-fits-all approach.

Table A20 – Extracted relationship between risk factors and importance/ considerations for risk scoring and weighting.

Risk Factor	**Importance in Scoring**[3]	**Illustrative quotes/ extracted comments**
Climate Suitability	High	"*primacy to climate hazard (from suitability models) then look at how other risk factors modulated the hazard/risk*" – Group 1
Water-related factors	Important for specific pathogens	"*presence of water/waterlogging is necessary for disease development*" (for species affecting alder) – Group 2
Host distribution and susceptibility	Important	"*where disease hosts are present then whether they are terminal or sporulating hosts will determine their importance in terms of priority*" – Group 2
Other factors: land use changes, recreation, trade, connectivity, Forest management practices etc	Mentioned, but importance not explicitly ranked	• "*Trade is one of the most obvious ones, which is probably the most difficult to quantify*" – Group 1

[3] The relative importance of risk factors for scoring was inferred from the frequency and emphasis of mentions in the workshop discussions. However, it should be noted that a formal ranking exercise was not conducted, and the perceived importance of factors may vary among participants.

		• Suggestion to use Strava data for assessing footfall in forests – Group 2
Climate Change	Important for future risk	Suggestion to incorporate "*climate prediction / forecasting - 5 - 10 - 50 years - to aid future planning/ mgt*" – Group 2

7.8.3.3 Potential uses and communication strategies for risk framework outputs

7.8.3.3.1 Application of outputs (risk models) for decision making

Participants identified several potential applications for risk frameworks including surveillance planning and resource allocation policy. In terms of surveillance planning, participants saw potential in using the frameworks to guide monitoring efforts. While they might not significantly change surveillance for regulated species, the frameworks could help target resources for non-regulated species in the wider environment. This was seen as particularly valuable given limited resources for widespread monitoring.

Several participants noted that the frameworks or risk maps could help prioritise where to focus limited resources for *Phytophthora* management. This was seen as particularly important for addressing emerging threats or managing diseases in non-commercial settings. Others also viewed risk maps as tools for future-proofing. For instance, in the discussion, participants discussed how risk assessments could inform species selection for new plantings, helping create more resilient landscapes in the face of climate change and evolving disease pressures.

While not extensively discussed, there were suggestions that the risk frameworks could contribute to broader policy decisions related to land use, forestry practices, and biodiversity conservation. Some participants suggested using simplified versions of the risk assessments in public education campaigns. This could help increase general awareness of plant health issues and promote responsible behaviour in natural areas. To some, these would be useful in guiding and convincing higher-level actors such as 'steering committees' in decision-making and advocacy purposes.

7.8.3.3.2 Dissemination and stakeholder engagement strategies

Related to the above, participants emphasised the need for accessible, tailored outputs to ensure that risk assessment information reaches and is understood by diverse audiences.
A key finding was the importance of simplifying complex risk data for broader use. Participants across both groups stressed that risk information should be presented in easily accessible formats. For instance, several workshop participants advocated for the creation of simple, visually appealing maps that could be readily shared and understood by non-specialists. This approach was seen as particularly important for engaging policymakers and the general public.

The discussions also highlighted the need to tailor communication strategies for different stakeholder groups. Participants recognised that risk information relevant to forest managers will differ from details to policymakers or the public. They suggested developing a range of outputs, from detailed technical reports to simplified summaries, to meet the needs of various audiences. For some, leveraging existing communication channels was identified as an effective way to disseminate risk information. Participants in both groups mentioned several potential platforms, including the UK Plant Health Information Portal, professional events for arboriculturists and conservationists, and established networks within the forestry and horticulture sectors. These channels were seen as valuable for reaching key stakeholders efficiently. Others also noted using interactive tools and, pest and disease databases to understand risks to vulnerable plants and priority habitats (e.g. Aaspen, species rich grasslands) and to help stakeholders engage with risk data.

7.8.4 Conclusions and next steps

Key next steps for the project team, integrating the workshop findings (Table 1) are:

1. To agree between UKCEH and the SPHC Steering Group for how many of the priority combinations identified in the figure above, spatial risk frameworks will be delivered in the time available.
2. To rapidly follow up suggested data sources on key alternative hosts, pathways, host and habitat layers, occurrence data across trade and wider environment habitats for pathogen-host-habitat combination for which models will be developed.
3. Discuss how to balance the data processing required to project future climate suitability under alternative climate change scenarios against number of Phytophthoras for which "current day" spatial risk frameworks can be produced.
4. Implement the spatial risk frameworks based on decisions under 2 and 3.
5. Prepare other data summaries identified by participants as being of value for advocacy and decision making (e.g. maps of *Phytophthora* richness in each sector and databases of *Phytophthora* threats by habitat and key hosts).
6. To prepare the trade model outputs and host-*Phytophthora* association databases in different formats for stakeholder feedback in August/September ahead of the experimentation/validation at the final workshop in October.
7. Schedule and invite participants to the final workshop in October.
8. Contact relevant Forest Research teams about integration of risk outputs with the ESC tool and layers.

7.8.5 References

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7.8.6 Supporting information

7.8.6.1 S1 Pre-workshop survey results

Table S1 Percentages of survey respondents self-rating their knowledge of plant diseases

Knowledge about plant diseases	**n (%)**
Very knowledgeable	(7) 78%
Knowledgeable	(2) 22%

Table S2 Percentages of survey respondents rating Phytophthora species as an important threat

Importance of *Phytophthora* as a disease threat	**n (%)**
Very important	7(78%)
Important	2(22%)

Table S3 Ranked threats from Phytophthora species identified in the survey, representing unique combinations of Phytophthora species, host and/or habitat

***Phytophthora* (n=7, 78%)**	**Host (n=6, 67%)**	**Habitat (n=7, 78%)**	**Rank** 1= most serious, 4= serious	**Impact Status**
P. alni	Alder	Wet woodlands	1	Current
P. alni	Alder	Riparian	1	Current
P. austrocedri	Juniper	Native Caledonian woodland	1	Current
P. austrocedri	Juniper	Woodland	1	Current
P. cinnamomi	Oak species	Oak woodland	4	Anticipated
P. kernoviae	Oak species	Oak woodland	4	Anticipated

P. pinifolia	Scots Pine	Caledonian Pine Inventory sites	4	Anticipated
P. pseudosyringae	Oak species	Oak woodland	4	Anticipated
P. ramorum	Blaeberry	Heathland	4	Anticipated
P. ramorum	Blaeberry	Pinewoods	-	Anticipated
P. ramorum	Blaeberry	Woodlands with Larch and other sporulating species	1	Anticipated
P. ramorum	Larch	Forest	1	Current
P. ramorum	Oak species	Oak woodland	1	Anticipated

7.8.6.2 First workshop agenda

Timing	Session description	Team members and details
14.00	Welcome and introductions, objectives and agenda of workshop, SPHC project overview, housekeeping	Ruth Mitchell and Louise Barwell
14.15	Presentation: spatial risk frameworks mapping risks of *Phytophthora* to priority habitats and hosts	- Results of survey on your priority *Phytophthora* threats to Scotland's plant hosts and habitats - Prior risk frameworks for *Phytophthora ramorum* and *Phytophthora kernoviae* Beth Purse
14.30	Break out Discussion 1: priorities for new risk frameworks	**Guiding questions:** Do the species / hosts / habitats of focus for the modelling align with your priorities and why / why not? How should we select among these within the project time frame?
14.50	Plenary summary of Discussions	Led by Festus Asaaga & Godfred Amankwaa
14.55	Presentation continued: spatial risk frameworks mapping risks of *Phytophthora* to priority habitats and hosts	- Plans for new risk frameworks - Stakeholder inputs needed on data and risk factors for new risk frameworks
15.10	**COMFORT BREAK**	
15.20	Break out Discussion 2: risk factors, data inputs and risk scoring	**Guiding questions:** Concerning the planned new risk frameworks, are there additional risk factors or datasets that should be considered? Are there risk factors or data that seems unnecessary? Why? Looking at the potential method for scoring risk of *Phytophthora* establishment in each framework, how would you weight these risk factors?
16.00	Plenary summary of Discussions	Led by Festus Asaaga & Godfred Amankwaa

16.10	Break outs Discussion 3: How frameworks could inform decision making and risk assessment, communication and dissemination	**Guiding questions:** How could these spatial risk frameworks inform plant health decision making and risk assessment? (prompts: which actors, which decisions, how important to management) How can we ensure that the outputs and tools reach the people that need them?
16.50	Plenary summary of discussions	Led by Festus Asaaga & Godfred Amankwaa
17.00	**COMFORT BREAK**	
17.10	Wrap up and next steps	Beth Purse and Louise Barwell

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