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The potential of ecological and epidemiological models to inform assessment and mitigation of biosecurity risks arising from large scale planting

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Content

1 Executive Summary

Exotic pests and pathogens (P&P) are introduced to new regions primarily through human movements of plants and plant products, with devastating consequences for individual host species, ecosystem function and society. Large scale planting projects linked to infra-structure such as transport networks and major housing projects or to planting for environmental benefits (e.g. urban greening, woodland restoration) pose high biosecurity risks due to the high number and types of plants involved. This report focusses on whether and how ecological and epidemiological model frameworks can inform assessment and mitigation of biosecurity risks from large scale planting using a combination of literature review and stakeholder engagement. Through two participatory multi-stakeholder workshops, stakeholders across sectors were asked to experiment with example risk models for P&P and reflect on their utility to inform decision making around planting and biosecurity in Scotland. Stakeholders spanned horticulture, agriculture, forestry and natural environment sectors, and included policy makers and practitioners. Through this process, **we aimed to identify priority steps to develop more useful models and tools for assessing biosecurity risks from planting in the future**.

The literature review reveals that a wide range of ecological and epidemiological models have been developed to understand biosecurity risks from planting at specific stages of P&P invasions. Modelling approaches linking new P&P detections to international and domestic plant trade networks are of particular value for predicting P&P introduction and spread risk. Models that predict establishment and spread at land-scape scales can estimate P&P responses to environmental (e.g. climate suitability for occurrence and growth), ecological (e.g. host susceptibility, availability and diversity, natural spread pathways) and social risk factors (e.g. proximity to planting, man-made spread pathways). Models have informed policy decision-making. In Europe, P&P distribution models have been integrated into pest risk assessments and subsequent listing of threats for quarantine regulation. At the national level in the UK, models that identify establishment risk across the landscape have been used to guide quarantine pest surveillance by both Forestry and Natural Environment sectors (e.g. for *Phytophthora ramorum* in Scotland).

At the workshops, stakeholders identified promising ways for models to inform decision making around planting and for their integration into existing plant health tools. In the **horticultural sector**, this includes supporting nursery managers to comply with the Plant Health Management Standard (planthealthy.org.uk) by adapting models and databases of P&P arrival, source areas and host-pest interactions. For **forestry managers**, it was suggested that modelled risks from priority P&P could be integrated into existing tools such as the Ecological Site Classification (ESC) tool (Forest Research) that predicts survival and yield of different tree hosts under current and future climate conditions. Stakeholders in the **agricultural sectors,** in particular, felt that further work was required to integrate biosecurity risks for farmers into the models, with agricultural advisers potentially acting as key points of liaison. A key opportunity in mitigating biosecurity risks around planting was highlighted in the **landscaping sector**, where planting practices are perceived to be particularly high risk and it can be difficult to communicate risks to practitioners.

Challenges were highlighted around the sourcing and interpretation of information on biosecurity risks. Workshop participants called for a balance between prioritising and predicting impacts across multiple P&P threats versus detailed modelling of individual high impact species. Accounting for these findings, we make the following recommendations:

1. Modellers co-produce, frame and tailor models of biosecurity risks from planting with specific groups of stakeholders across sectors and roles, cognisant of the different ways these groups (e.g. practitioners and policy-makers; different sectors; different scales) access and interpret information.
2. For stakeholder groups that currently use decision-making tools, models of biosecurity risks will be more effective if developed to integrate with these existing tools, particularly sources of information provided by the Scottish or UK government, for example the UK Plant Health Risk Register.
3. Two priority avenues for linking models to decision making should be explored through inter-disciplinary partnerships between modellers, plant pathologists, inspectors and decision makers, namely:
    a. addition of risk models of priority P&P to tools for Forestry site managers such as the Ecological Site Classification (ESC).
    b. adaptation of risk models of priority P&P to inform robust pest risk analysis by nursery managers sourcing and supplying plants, as part of compliance with the Plant Health standard.
4. The particular challenges of mitigating and monitoring biosecurity risks in the landscaping sector, given the lag time between P&P arrival and recorded impact or outbreaks, may be worthy of review by policy makers across sectors.
5. Centralised cross-sectoral databases should be developed at national to regional and global levels, encompassing P&P occurrence, traits and behaviour across different ecosystems, so that models can better capture and predict the origins and processes of arrival, spread and impact between sectors.
6. Data on historical and current planting behaviour and locations (e.g. from the landscape and environmental sectors and on local to regional trade networks and supply chains) would be particularly beneficial to inform predictions of biosecurity risks from planting.
7. Further empirical studies of processes including hybridisation, enemy release, pathogen dispersal and acquisition of new traits, and host susceptibility are required to improve our predictions of the behaviour and impacts of P&P arriving in new regions.

2 Introduction

Movements of plants and plant products by human activity is the primary pathway by which exotic pathogens and pests (P&P) are introduced to new regions with devastating consequences for individual plant host species, economies and ecosystem function (Brasier 2008; Roy *et al.* 2014). Global and continental scale studies indicate that new P&P arrive at a higher rate in countries with greater levels of total imports (or GDP as a proxy for trade, (Liebhold *et al.* 2012; Santini *et al.* 2013; Roy *et al.* 2014), and higher levels of trade in specific commodities with pest source countries (Chapman *et al.* 2017), particularly for agricultural and horticultural commodities (Santini *et al.* 2018). Frequently, P&P have been intercepted arriving with plants that are imported into nurseries (Moralejo *et al.* 2009; Jung *et al.* 2016) or plantations, in raw log imports or other wood products (Aukema *et al.* 2011) and causing outbreaks in the wider environment. For example, in the US, the Sudden Oak Death pathogen, *Phytophthora ramorum* was dispersed from California to 1200 locations in 39 other states via infected *Camelia* sp. shipped from a wholesale nursery (Pautasso *et al.* 2010) and also spread rapidly from horticultural nurseries into UK forests (Goss *et al.* 2011). Similarly, the importation of over 5 million ash saplings between 2003 to 2011 is implicated in the spread of ash dieback from mainland Europe to the UK (Smith *et al.* 2013). Alongside these observational data, population genetic data on pathogens also implicate large scale movement and planting of live material in spreading plant pathogens (Goss *et al.* 2011; Andjic *et al.* 2011), with the probability of invasion increasing with the volume and frequency of plants being introduced (Roy *et al.* 2014).

Planting projects linked either to large scale infra-structure such as transport networks and major housing projects or to planting for environmental benefits such as urban greening or woodland restoration thus pose high biosecurity risks due to the high number and type of plants involved (Brasier 2008; Tubby & Webber 2010). Landscaping projects may involve transport of whole large semi-mature "rooted" trees and shrubs (up to 10m, with large root balls) to create instant woody landscapes with the risk that P&P may be transported on soil around the roots, the crown and stem of the plants (Brasier 2008; Tubby & Webber 2010) or in associated woody packaging material. For example, alder saplings imported from other European countries for landscaping and shelter belts are the most probable pathway by which the hybrid alter *Phytophthora x alni* arrived in the UK (Gibbs, van Dijk & Webber 2003). Moreover, landscaping projects often face significant cost pressures since they make up a small component of the overall infrastructure, which coupled with the small scale of domestic production can favour low cost, large scale imports from intensive nursery producers in Europe and elsewhere rather than UK or Scottish grown material with associated risks of P&P introduction. Regarding plant species selected, urban greening schemes, for example, which increasingly source drought tolerant exotic species (Tubby & Webber 2010), increase the likelihood of introducing exotic pathogens. The growing evidence of the increased biosecurity risks from "Plants for Planting" (plant material grown abroad then imported as living material), particularly for large scale projects, has gained international attention, e.g. recent reviews of the knowledge gaps and regulation of this pathway by the International Plant Protection Convention, the US Department of Homeland Security, and the International Union of Forest Organisations.

Sourcing native plants of local provenance can also pose a biosecurity threat if those plants are produced in nurseries. Investigation of failed restoration sites in California identified a novel pathogen, *Phytophthora tentaculata,* as the cause of widespread mortality of a locally endemic host planted as part of a large-scale restoration project (Rooney-Latham & Blomquist 2014). The pathogen was detected in the native plant nurseries producing and supplying stock to the project (Rooney-Latham *et al.* 2015). Subsequent detection of more than 30 *Phytophthora* taxa on a breadth of host species in three restoration projects in the San Francisco Bay area, led to the suspension of restoration planting and the piloting of an accreditation scheme involving best management practices for nursery restoration stock (Frankel *et al.* 2020). For several nurseries, this increased biosecurity resulted in no *Phytophthora* detections in over two years (Frankel *et al.* 2020).

A risk-based approach to plant health aims to assign a relative or absolute risk value to a given threat to prioritise biosecurity actions (Spence, Hill & Morris 2020). However, microbial diversity is vastly under-described worldwide (Roy *et al.* 2016) and therefore P&P are often unknown to science at the point of emergence (Brasier, 2008). Thus, a major limitation in predicting and regulating biosecurity risks from "Plants for Planting", is that organisms can only be recognised as a potential threat after they have escaped from their area of origin to a region where native plants may have little resistance or there may be an absence of natural enemies. (Brasier, 2008). Once recognised as a potential threat, the decision to regulate or list P&Ps is often based on a Pest Risk Assessment (PRA), which summarises current risk information, knowledge gaps and potential interventions (Brasier, 2008). For example, the International Standards for Phytosanitary Measures (ISPM11) guidelines for PRA identify traits relating to life-cycle, dispersal mechanism, survival and reproductive strategy as potentially informative about risk of transport, transfer to a suitable host and probability of establishment (FAO 2017). Given that PRAs are largely reactive and cannot encompass organisms that are yet to show impact or account for data gaps, such as dispersal rates of invasive pathogens, they have been combined more recently with horizon scanning exercises. These identify and rank future threats from different species, often involving expert elicitation and consensus building (Roy et al. 2016), as a tool to prevent invasions before they occur and can inform national and regional risk registers and lists of notifiable P&P (Pheloung, Williams & Halloy 1999; Baker *et al.* 2014). For example, the European Food Standards Agency (EFSA) recommend a two-stage approach in which P&Ps undergo preliminary screening to prioritise whether a full PRA is required, encompassing life-history traits that may influence risk (EFSA Panel on Plant Health (PLH) *et al.* 2018)

In parallel with the development of national and regional level regulation and risk assessment and horizon scanning protocols, there has been substantial progress in quantitative modelling and prediction of the processes by which exotic plant pathogens arrive, establish, spread and have impact in new regions (Cunniffe *et al.* 2015). These include models of the behaviour and control of individual high impact introduced species (White *et al.* 2017, 2020), and comparisons of invasion success between P&P species with different biological characteristics ("traits"), such as spore shape and size (Philibert *et al.* 2011) or cold-tolerance (Barwell *et al.* 2020). A key gap in quantitative models of the behaviour and spread of introduced pathogens is the role of human activities in introducing P&P and the number and frequency of individuals arriving (Cunniffe et al. 2015). Risk frameworks have a predictive component, where risk factors in a specific region are related to disease patterns or spread, using current or historical data, and then these relationships are used to estimate risks within new regions or timeframes (EFSA Panel on Plant Health (PLH) *et al.* 2018). This could include the potential extent of a recently introduced pest in a new region or the potential economic impacts of a disease outbreak (Robinet *et al.* 2012; Cunniffe *et al.* 2015). Tools for risk assessment represent the interface between a model (or other source of information) and the user. This requires an accessible interface and translation of the model outputs into useful knowledge that meets the needs of the end-user. This translation, along with policy maker engagement, may be crucial to ensure available knowledge is acted upon and used to inform decisions about plant health (Sutherland and Freckleton 2012).

This report assesses the potential of current ecological and epidemiological modelling approaches to inform biosecurity risks from large scale planting projects, identifying which models are applicable to different planting pathways and stages of invasion (Blackburn *et al.* 2011; Redondo *et al.* 2018) (Fig. 1). Using a mixed method approach combining literature review of existing models and participatory stakeholder engagement around potential models, we address whether ecological and epidemiological models can and do inform strategic decision-making about the species, locations and sources of plants for planting across multiple sectors (horticulture, agriculture, forestry, natural environment, and plant health inspection and policy) to reduce biosecurity risks. Since decision making structures can vary between large-scale planting projects (Bate *et al.* 2016; Dunn, Marzano & Finger 2021; Karlsdóttir *et al.* 2021), it is important to identify which actors and decisions concerning planting and biosecurity could be informed by models at each stage of the planting process. The roles and responsibilities of those making or influencing decisions about large-scale planting are many and varied and may be categorised as vectors, governors, managers, monitors and networkers (Dandy *et al.* 2017; White *et al.* 2018). Furthermore, a recent study exploring how information is accessed and informs plant health decision-making, indicated that use of available information depended on trust in the information source as well other contextual factors (Creissen *et al.* 2019). It highlighted the need to translate academic knowledge and build trust in order for practitioners to be able to access them (Boden & McKendrick 2017). We expected this need to apply equally when tailoring models of biosecurity risks from planting to key actors and decision-makers. Our study therefore focussed on the following specific questions:

(a) What key model types and frameworks are already available that have been or could be applied to understand biosecurity risks from planting?
(b) How important are models and risk assessment tools currently in informing decision making around biosecurity risks from planting in different sectors?
(c) For which decision makers, at which stages of the planting process, might different models and tools be most useful for mitigating biosecurity risks from planting?
(d) How could models and frameworks be better tailored to relevant biosecurity risks for the UK and for Scottish plant health in particular?
(e) What are the priority steps and knowledge gaps that would enable more useful models and risk assessment frameworks to be developed for biosecurity risks from planting in the future?

Our methods included a literature review of the use of models in biosecurity decision making and two stakeholder workshops to test existing models and explore the additional research questions. In Section 2, we describe the methods and results of the literature review. In Section 3, we explain and analyse the process and outcomes of the workshop, including details of the models and tools presented. In Section 4, we synthesise the work in a general discussion and conclusions.

3 Literature review of ecological and epidemiological models for plant pests and pathogens

3.1 Methods

The literature search utilised the Web of Science Core Collection, using the search terms given in Table 1. The abstracts of all 149 papers returned were reviewed to determine whether they included; (i) epidemiological evidence of links between planting and biosecurity risks; (ii) information on risk assessment or horizon scanning frameworks; (iii) information on quantitative ecological or epidemiological models or risk frameworks for biosecurity risks from plant trade or planting. Quantitative models were defined as having data-driven, statistical or mathematical, deterministic estimation of parameters describing the relationships between environmental, ecological or social drivers and P&P populations or biosecurity outcomes. This definition excluded conceptual models that identify, but do not quantify, important relationships. From the initial list of 149 papers, 52 were excluded as irrelevant on this basis. A further 109 relevant papers were then added from the 354 citations of Brasier (2008) as the primary paper identifying the plant trade as the route by which most plant P&P are introduced to new areas. These papers were read to determine the key model types and risk frameworks available at each stage of invasion through the planting process that have been or could be applied to understand biosecurity risks. They were scanned for evidence that model outputs already feed into decision making around planting or into risk assessment or horizon scanning processes of different actors across sectors and also to understand the key knowledge gaps that are limiting modelling and prediction of biosecurity risks from planting particularly for Scotland and the UK.

***Table 1**. Search terms for the literature review of ecological and epidemiological models, together with the number of references (hits) returned for each search.*

Search Terms	No. hits from the Web of Science Core Collection
Biosecurity AND planting AND model	140
Biosecurity AND planting AND model AND risk	93 (all duplicates of above)
large-scale AND planting AND biosecurity risk	9
Landscaping AND biosecurity risk	0
Citations of Brasier 2008	354/109 relevant

3.2 *Key model types and frameworks that are available to understand biosecurity risks from planting and potential impacts on decision-making*

Our review is structured around the use of statistical and mathematical models to address risks at different stages of the invasion pathway. Statistical models match patterns in P&P with patterns in potential risk factors, to understand the importance of risk factors and predict patterns in P&P over space or time. Mechanistic models instead mathematically represent disease and invasion processes such as growth, dispersal and survival through equations in order to predict and explain P&P patterns and impacts of interventions. Current key model types and risk assessment frameworks that could inform decision making at different stages of the invasion pathway are shown in Figure 1 in relation to the invasion pathways associated with plant trade and planting. This is an adaptation of the invasion framework used in invasive species management (Blackburn *et al.* 2011; Redondo *et al.* 2018) which we have now applied to threats to plant health. Plant P&P are severely underrepresented in the literature on invasion ecology (Paap *et al.* 2020). We now highlight the different modelling approaches (Table 2) that have been used to address risks at each of these invasion stages in turn.

Table 2: Modelling approaches and their use at different stages of prediction, introduction, invasion management and control of pests and pathogens (P&P).

Modelling approach	**Approach description**	**Main use in P&P invasion stage risk identification**
Horizon-scanning	Often limited data, experts and consensus building used to assess potential future threats and likelihoods	Identifying future threats by P&P
Global network models	Links existing data on global networks such as trade patterns with parameters such as climate	Risk of introduction of P&P
Ecological niche models	Use understanding of host biological characteristics or environmental parameters such as climate and habitat	Risk of establishment of P&P
Network analyses	Links nodes in a network, such as clusters of P&P outbreak or trade networks	Risk of spread and impact of P&P
Epidemiological models	Assesses risk through understanding host plant susceptibility, and P&P and disease characteristics	Risk of spread and impact of P&P
Socio-ecological models	Combines ecological or epidemiological data with socio-economic data such as trade, management or land use; can be any of the above modelling approaches adapted	Any stage of invasion

3.2.1 *Horizon-scanning: identifying future threats*

Horizon scanning is the identification and ranking of future threats and has become an important component of invasive species management because of the recognition that prevention of invasions is preferable to managing invasions at later stages. Expert knowledge and consensus building are at the core of horizon-scanning exercises because of the paucity of data on new and emerging threats (Roy *et al.* 2016), but cross-species ecological modelling approaches have the potential to feed into this process and support improved decision-making on what are lesser and greater threats. Horizon-scanning has the potential to inform national risk registers and lists of notifiable P&P (Baker *et al.* 2014).

It has been proposed that the degree to which host species are related (genetically) may predict which pathogens can cause infection and disease in these hosts. Within bacteria, fungi, oomycetes, insects, molluscs and nematode groups (but not viruses), the probability that two hosts share a pest or pathogen is significantly greater if those hosts are closely related (Gilbert *et al.* 2012). For example, two host species in the same genus would be more likely to share a pathogen than two hosts in different genera (Gilbert, Briggs & Magarey 2015).

Shared biological traits might explain why closely related hosts tend to be attacked by similar communities of pathogens or pest herbivores, because closely related hosts (and P&P) tend to have more similar characteristics than unrelated species. These biological or "functional" traits are defined as measures of growth (e.g. hyphal expansion rates), survival (e.g. thermal tolerance range) and reproductive performance (e.g. fecundity) (Laughlin & Messier, 2015). These life-history processes determine the outcome of biotic and abiotic interactions (fitness), implying a central role for traits in predicting potential invasiveness (Moravcová, Pyšek, Jarošík, & Pergl, 2015) and, for P&P, impacts on their hosts (Crowther *et al.* 2014).

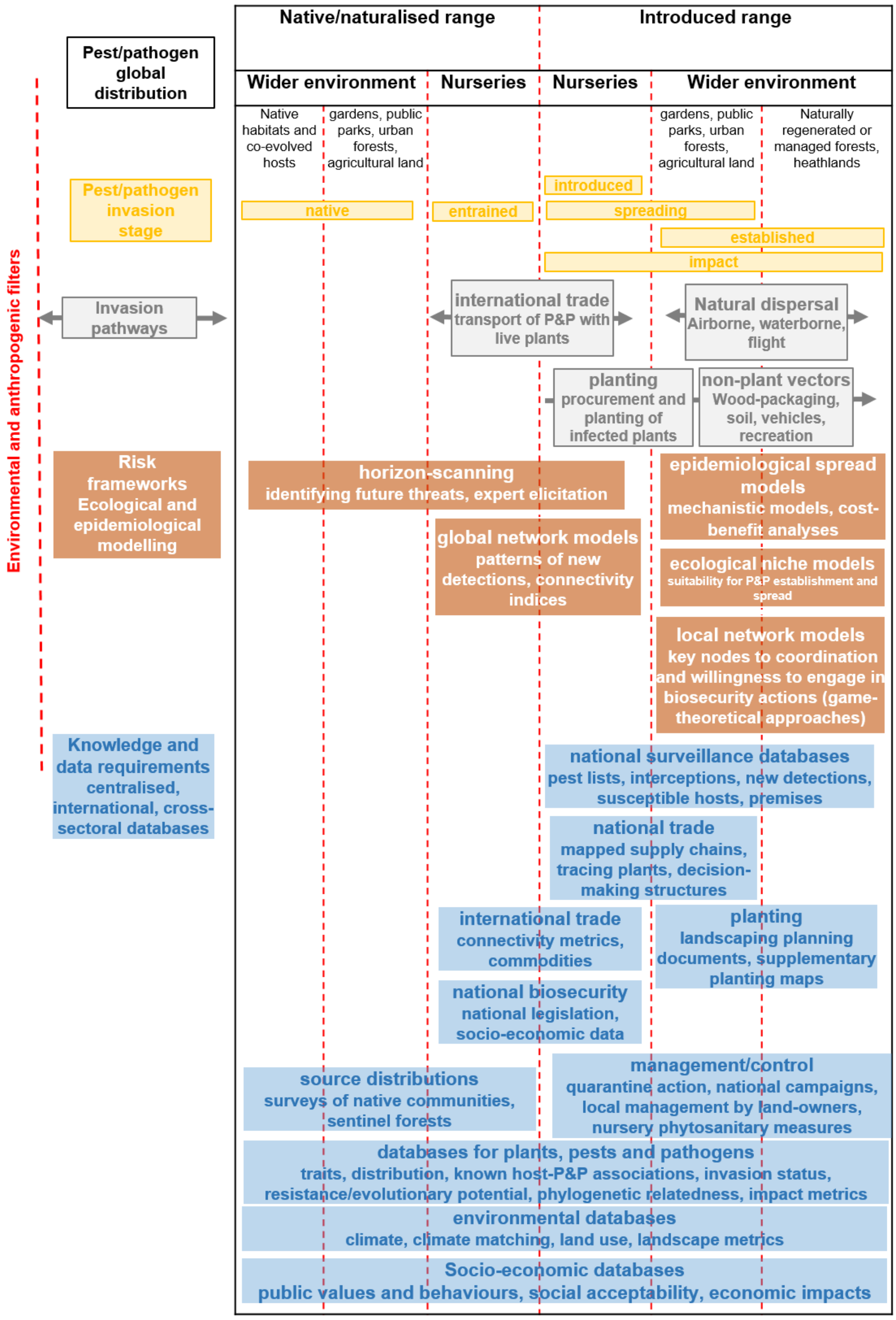

Figure 1. *A framework mapping different classes of ecological model to the invasion stages at which they can address risks from plant and plant product movement in large-scale planting. Invasion pathways move pests and pathogens globally and locally, facilitating progression to the next invasion stage (native → entrained → introduced → spreading → established → impact).* ***International trade*** *is the primary pathway for transporting plant pests and pathogens to new regions. The purchasing of infected nursery stock for large-scale infrastructure and environmental* ***planting*** *can transfer introduced pests and pathogens from national trade networks into the wider environment, such as forests and heathlands, potentially leading to outbreaks of plant pests and diseases, through* ***natural dispersal*** *and accidental transport with other* ***non-plant vectors****. Data and informatics that are used to develop models addressing biosecurity risks at different invasion stages. Ecological models draw on data and informatics from diverse sources to identify and quantify risks to plant health at different invasion stages. These risk frameworks can inform decision-making about the species, locations and sources of plants-for-planting in large-scale environmental and landscaping projects. The figure is based on the invasion framework of (Blackburn et al. 2011) and its adaptation to pathogens by (Redondo et al. 2018).*

Trait-based approaches that link invasion success (in different phases) to biological traits of P&P help to prioritise future threats to plant health. For example, models classifying invasion success among forest pathogenic fungi performed better when traits were included in classification rules. Important traits discriminating invasion success were spore shape and size, optimum temperature for growth, the ability to disperse long distances and the ability to reproduce both sexually and asexually as important trait predictors of invasion success (Philibert *et al.* 2011). The ability to attack both forest and ornamental hosts and species of hybrid origin was also linked, statistically, to higher spread rates (Santini *et al.* 2013). Statistical analyses of functional diversity indices identified cold-tolerance and the ability to form asexual survival structures (Redondo, Boberg, Stenlid, & Oliva, 2018) as potentially important predictors of pathogen invasiveness. Combining phylogenetic and trait-based approaches may offer additional insights. For *Phytophthoras*, such models, accounting for levels of knowledge about species (time since description), have been used to identify newly described species that could potentially achieve broad host ranges or geographic spread, based on shared traits or evolutionary history with well-known high impact species (Barwell *et al.* 2020).

Direct integration of horizon-scanning models into policy is so far limited. However, screening of threats and pest risk assessments at the European and International levels does encompass biological traits relating to life cycle, dispersal mechanism, survival and reproductive strategy (see introduction). The Australian Weed Risk Assessment framework (Pheloung, Williams & Halloy 1999) uses invasive attributes to rapidly assess and blacklist non-native species posing an unacceptable risk and has performed well in identifying threats across different regions and taxa (Baker et al., 2008).

Knowledge gaps that hamper the wider application of trait-based or phylogenetic approaches for horizon scanning of plant health threats are the paucity of trait data available, particularly for pathogens (Aguilar-Trigueros *et al.* 2014). For pathogens, we need to understand how traits reflect alternative life-history strategies (e.g. obligate versus facultative pathogens) and trade-off and interact with each other. These evolutionary processes acting on traits could make single trait measurements less meaningful than trait combinations when predicting invasion success (Aguilar-Trigueros *et al.* 2015). More-over, native and non-native ranges of P&P are often poorly documented, highlighting the potential value of international and cross-sectoral collaborations to provide centralised databases on pathogen distributions, traits, and invasion to support horizon scanning within plant health.

3.2.2 Risk of introduction: global network models

Previous ***global network models*** have addressed the risk of introduction for P&Ps by linking global trade networks and other metrics of connectivity (spatial proximity, climate similarity) to predict the rate of new detections of P&Ps. Live plant imports from nearby source countries was the best predictor of the frequency of recent invasions among 173 insect pests, 166 pathogens and 83 weeds at national level (Chapman *et al.* 2017). Examining interactions between pests and different commodity types or comparing model performance based on trade in different commodities can help to identify high-risk pathways for particular P&P taxa indirectly (Chapman et al. 2017). A large proportion of global pathogen diversity is undescribed (Roy et al., 2016), and global potential source areas for pathogens are consequently uncertain. This significantly hampers estimation of the risk of novel pathogen introductions. Modelling observed *Phytophthora* diversity at the national scale as a function of socio-economic (gross national income, travel, imports, human population) and environmental (vascular plant richness and land use) variables was used to estimate national data deficits in the number of pathogens reported (Scott *et al.* 2019). Such approaches can improve estimates of risk associated with trade connectivity to source regions. Modelling arrival rates in relation to trade and transport connectivity has also provided evidence of the efficacy of biosecurity measures in New Zealand. Using records of 466 fungal pathogens on 131 non- native host plants, pathogen arrival rates were modelled as a function of time (Sikes *et al.* 2018). The overall trend in arrivals has slowed since 1980, despite increases in import volumes and air travel, but varies considerably among sectors: strengthened biosecurity in agricultural sector appears to have slowed arrival rates, while they continue to rise in the forest/orchard sector.

Knowledge gaps that limit the application of global network models for P&Ps are the lack of access to i) global interception data at ports of entry and ii) inspection data from within trade. Without documenting both successful and unsuccessful invasions it is difficult to understand why some P&P are transient arrivals, but others spread rapidly and widely within and beyond the trade network. Interpreting interception and inspection data for modelling will require support from plant health inspectors and plant pathologists with knowledge of how inspections are conducted and potential biases in the detectability of P&Ps. Given the strong explanatory power of global trade networks in the introduction of new P&Ps, these global network models have the potential to predict future risks under changing global trade (Bradley *et al.* 2012) and biosecurity effort (Early *et al.* 2016). However, this predictive modelling will require interdisciplinary effort involving economists and social scientists to develop realistic future trade scenarios and integrate behaviour related to biosecurity.

3.2.3 Risk of establishment: ecological niche models

Ecological niche models can predict the potential distributions of P&P by finding statistical associations between climate variables and the known occurrences of the species. Land-use and socio-economic variables can also be incorporated to understand the importance of different risk factors. When projected onto geographic space, they can provide spatial risk maps for invasive P&P, identifying regions that would be strongly suited for P&P but which have yet to be reached.

A major challenge in modelling establishment risk for threats to plant health is that many P&P have yet to occupy their full potential global range, and the limits of their niche tolerances may be underestimated by matching known occurrences to climate and other risk factors. Accounting for the invasion process is an important step in improving predictions (Václavík & Meentemeyer 2009; Venette *et al.* 2010). Incorporating dispersal constraints and biological information (e.g. thermal tolerance) can help to identify areas that are not yet accessible, but may be suitable, to improve estimates of species potential distributions. This has proved successful for improving predictions for invasive non-native plants (*Humulus scandens*, *Lygodium japonicum*, *Lespedeza cuneata*, *Triadica sebifera* and *Cinnamomum camphora*) within Europe (Chapman *et al.* 2019).

Risk of establishment is further constrained by the distributions of suitable hosts, which is problematic when the host-associations are not fully known. Moreover, novel host-associations may arise in the invaded range through encounters with new plants species (Ghelardini *et al.* 2016). Incorporating phylogenetic information into spatially explicit risk maps for 20 beetle species and 235 plant genera, models were used to identify locations where pest distributions may intersect with those of potentially vulnerable hosts (Robles-Fernández & Lira-Noriega 2017).

When coupled with future climate scenarios, ecological niche models are a promising tool for predicting novel interactions arising from the survival of P&P that would not have been adapted to the historical climate (Pautasso *et al.* 2010; Bebber, Ramotowski & Gurr 2013), along with the selection of alternative plants that may be better suited to the changing climate (Ennos *et al.* 2019). Global niche models of *Phytophthora ramorum* (Ireland, Hardy, & Kriticos, 2013) and *Phytophthora cinnamomi* (Burgess *et al.* 2017) have predicted the potential distributions of the pathogens under current and future climate scenarios, highlighting key regions that may still be at risk of invasion and the environmental factors (e.g. cold-stress) that may limit the distributions of these pathogens. The predicted potential range includes regions that are now known to encompass the native range of *P. ramorum* (Jung *et al.* 2021), suggesting these global models could have a role in assessing high risk source regions for importation of host plants. Ecological niche model approaches can also be applied to multiple species simultaneously to understand the relationships between environmental predictors and pathogen diversity (Burgess *et al.* 2019). Coupled with trait-based approaches, these cross-species ecological niche models may also be valuable for identifying shared responses of P&P to climate (or other factors) and providing information about which other P&P are likely to behave similarly to high impact P&P.

A limitation of ecological niche models is the lack of information on the frequency of P&P introduction events and the number of individuals introduced at each event: This "propagule pressure" is expected to have a strong influence on successful invasion of an environmentally suitable region, but it remains a challenge to quantify (Wonham *et al.* 2013). Models of P&P establishment locations in US forests identified high densities of ports and roads as useful proxies for propagule pressure (Ward, Fei & Liebhold 2019). Mapped trade networks can also be integrated into ecological niche models. Chapman *et al.* (Chapman *et al.* 2017) analysed connectivity of nurseries to international and domestic trade networks to measure local propagule pressure and incorporated this alongside climatic suitability in models of P&P establishment risk.

Though niche modelling can give accurate estimates of areas that are suitable for establishment, a major challenge is that P&P tend to suffer from fairly incomplete and biased recording, limiting the species for which niche models can be developed (Purse & Golding 2015). Among published CLIMEX models (a software package originally designed to predict species distributions for the purpose of quarantine, biological control and pest management (Sutherst 1985)), pathogens were less than half as likely as plant insect pests to be modelled (Ireland & Kriticos 2019). Global cross-sectoral databases of P&P occurrence are a prerequisite for developing robust niche models for predicting suitable habitats for these species in their invaded range. Such databases are being built for some taxa (e.g. a Global Database of Alien Pathogenic Fungi incorporating traits is under development at the University of Vienna). Data for non-pathogen invasive alien species is much better than for pathogens at present so there is increasing potential to apply the approaches to other priority P&P.

There are clear examples in the literature where establishment risk maps have informed decision-making and biosecurity policy. For example, at European Union level, European suitability maps developed for non-native species by Chapman *et al.* 2019, fed directly into Pest Risk Assessments for the European Plant Protection Organisation (EPPO) region. These Pest Risk Assessments in turn informed whether species were added to the EPPO A2 List of pests recommended for regulation as quarantine pests (e.g. https://gd.eppo.int/download/doc/1424_pra_exp_AMBTR.pdf). Following the arrival of *Phytophthora ramorum* and *P. kernoviae*, risk frameworks were developed for Scotland that incorporated habitat suitability for hosts (Purse *et al.* 2013), climate suitability for pathogen growth, and proximity to spread pathways (rivers, roads) and to nurseries and large gardens as potential sources of infection. Initially focussing on *Rhododendron ponticum* as a key sporulating host, these frameworks were later adapted to account for the pathogens' shift to Larch, and informed Forestry Commission and Scottish Natural Heritage about key vulnerable habitats to target for surveillance (Purse *et al.* 2016; Searle *et al.* 2016). Such risk frameworks could be adapted for the establishment of other newly arriving P&P species relatively easily, given equivalent data on host occurrence, sources of infection and spread pathways.

3.2.4 Risk of spread and impact: Network analyses and local spread processes

Network models comprise nodes connected by links. The effect of network structure on disease spread can be described by attributing properties to nodes (e.g. biosecurity measures at nurseries in the supply chain) and links (e.g. trade flows through supply chains). By manipulating the network properties, it is possible to explore the effect of different scenarios on disease outbreaks, typically at the landscape scale, though these models have potential to be applied at multiple geographic scales (Moslonka-Lefebvre *et al.* 2011; Pautasso & Jeger 2014). Network models have mapped trade networks within the UK to investigate the efficacy of plant inspection policy for the containment of *Phytophthora ramorum* and *Phytophthora kernoviae* under different scenarios of introduction pressure and susceptible areas in the wider environment (Harwood *et al.* 2009).

Epidemiological models classify a host population as susceptible, infected or removed (SIR) with the spread rate proportional to the size of the susceptible and infected populations (Kleczkowski, Hoyle & McMenemy 2019). Spread rates at different stages of disease life-cycle, asymptomatic period and time to host plant death were estimated from field-scale data for *Xylella fastidiosa* (White *et al.* 2020). Coupled with risk maps and dispersal estimates, they have been used to predict the probability that a location will become infected and to explore optimal management (buffer zones and surveillance activities) options (White *et al.* 2017). Epidemiological models have also explored how the observed spread of *Phytophthora ramorum* in the US relates to the production of inoculum at a given site, the probability that inoculum is dispersed and the probability of infection for susceptible host vegetation, allowing estimates of spread under different climate scenarios (Meentemeyer *et al.* 2011). By adjusting these epidemiological parameters to reflect the effects of management, it is possible to estimate the efficacy of different management options, both current and retrospective for *Phytophthora ramorum* (Cunniffe *et al.* 2016) and Dutch elm disease (Harwood *et al.* 2011; Potter *et al.* 2011). The effects of climate change on emergence and spread of plant and tree pests and diseases in forestry or agriculture settings (*including Xylella fastidiosa, Candidatus Liberibacter solanacearum* and *Ips typographus*) has been modelled by combining epidemiological (derived from literature) and economic (market and non-market values of affected hosts) data (Kleczkowski *et al.* 2018). This approach allows end-users to explore the cost-benefit of management options by experimenting with different epidemiological parameters affected by the management approach (and is one of the modelling tools presented in the stakeholder workshop).

Integrating networks with epidemiological SIR models is at the forefront of ecological modelling (Shaw & Pautasso 2014; Kleczkowski, Hoyle & McMenemy 2019) and provides a flexible framework for addressing the complexity of interactions and socio-economic drivers that affect biosecurity risks from planting (Garrett *et al.* 2018). A key knowledge gap is the poor resolution of domestic plant supply chains. Stronger engagement with stakeholders is needed to understand the factors driving biosecurity awareness and decision making for different stakeholder groups (e.g. landscaping) and sections of the supply chain (Bate *et al.* 2016; Dunn, Marzano & Finger 2021; Karlsdóttir *et al.* 2021). Integrating these data into epidemiological network models can address how the coordination of biosecurity actions and willingness of the actors to engage can influence the spread of P&P within trade networks and into the wider environment (Mills *et al.* 2011).

3.3 Key findings, knowledge gaps and next steps: Towards more informative models to mitigate biosecurity risks around planting across sectors

Our review identified a wide range of ecological and epidemiological models that are applicable to understanding biosecurity risks from planting. Particularly valuable are:

- models that predict arrival and spread of P&P through plant importation and trade networks between nurseries and other premises;
- landscape level models that predict the likelihood of P&P establishment and spread in relation to additional environmental (e.g. climate suitability for occurrence and growth), ecological (e.g. host susceptibility, availability and diversity, natural spread pathways) and social (e.g. proximity to planting, man-made spread pathways) factors (Purse *et al.* 2016; Searle *et al.* 2016).

The area in which the linkages between decision making and models are currently strongest is at the policy level. At *regional scales*, P&P distribution models have been integrated into pest risk assessments and subsequent listing of P&P threats for quarantine regulation (Chapman *et al.* 2015, 2019). At *national scales*, models have been used to understand the likely extent of spread of newly arriving species through nursery networks (Harwood *et al.* 2009; Cunniffe *et al.* 2015).

Other models map hotspots for establishment by scoring the *landscape level* risk factors for establishment, e.g. habitat and climate suitability and proximity to nurseries or plantings as sources of infection, and have been used to guide quarantine pest surveillance by both Forestry and Natural Environment sectors (e.g. for *Phytophthora ramorum* in Scotland) (Purse *et al.* 2016; Searle *et al.* 2016).

Most models have examined the introduction and establishment phases, whilst fewer have focussed on P&P horizon scanning prior to introduction or on predicting onward spread and impact. Approximately half the models attempted to predict spatial or temporal patterns of pathogen risk.

Alongside the roles of international trade and planting in introducing P&P to new areas, a wide range of additional factors encourage introduction, establishment and spread some of which have been incorporated in predictions of risks from planting. These include climate change, hybridization, a hypervirulent or previously unknown species, the appearance of novel biological traits or characteristics (e.g. extended latency period for pathogens), novel vector-pathogen associations and intensive management of plantations comprising non-native host species or populations with low genetic diversity (Ghelardini *et al.* 2016). Predicting the relative risk of planting particular species in particular locations in the UK may require socio-ecological risk frameworks, incorporating vulnerable hosts and habitats, local management, biological and phylogenetic information about hosts, P&P, and socio-economic factors affecting trade flows and biosecurity behaviour.

4 Stakeholder engagement around models for plant health

4.1 Multi-stakeholder workshops on tools for assessing plant health risks

Two workshops entitled "Feedback on tools for assessing plant health risks" were held on 18th and 21st September 2020, attended by 14 stakeholders (identified as key informants) from multiple sectors including horticulture, agriculture, forestry and natural environment, as well as policy makers and practitioners (see Appendix 1 for workshop itinerary). There were representatives from inspection, NGOs, national agencies, nurseries and associated networks. In addition, seven researchers from the natural and social sciences participated.

The workshop objectives were:

i) to understand how knowledge is acquired and acted upon by plant health stakeholders to inform tailoring of and engagement around models,

ii) to identify key knowledge gaps around plant health and biosecurity that affect decision-making

iii) to explore which maps and tools are already used to guide planting and biosecurity decision making and

iv) to test the modelling tools presented for different stages of the invasion through planting process, suggest improvements and identify how they might best be adapted for additional P&P, contexts and decision-making.

A pre-workshop questionnaire, plenary discussion and assessment of an online interactive toolset of existing models were used to engage these stakeholders in a discussion on how models can inform knowledge and action in relation to plant health. Details of these processes are described along with analysis of the results below.

A pre-workshop questionnaire was circulated to participants to enable the modelling team to understand how they acquire knowledge on plant health and through which channels and sources, and how this knowledge is applied in strategic decision-making (Appendix 2). Five participants completed this questionnaire and the participants were asked to reflect in open discussion on the results.

4.2 Introducing and exploring the online interactive toolset

A prototype online interactive toolset and accompanying questionnaires were developed for use with the workshop participants (https://loubar.github.io/PHC-plant-health-biosecurity-risks-Scotland/). The tools were designed as an example of how existing models could be translated for use by practitioners and policy-makers and are not intended to provide current predictions for risk assessment. They are not maintained and the underlying databases are not updated. The online tools were used to explore the ways in which ecological models and databases could be used to help support biosecurity risk assessment and decision-making when choosing and procuring plants for planting in the wider environment. They are based on models and databases created under a number of different plant health projects. The tools and their contexts are briefly described in Table 3 and outlined in more detail below.

Table 3*. Models/Tools explored in the workshops.*

Model/ Tool	Development context
a) Risk modelling - *Phytophthora* risk factors	UKCEH/Forest Research https://www.forestresearch.gov.uk/research/global-threats-from-phytophthora-spp/
b) Ecological niches - *Phytophthora* suitability maps	UKCEH/Forest Research https://www.forestresearch.gov.uk/research/global-threats-from-phytophthora-spp/
c) Horizon scanning - Databases of known associations between host plants and their pests and pathogens	UKCEH/Forest Research https://www.forestresearch.gov.uk/research/global-threats-from-phytophthora-spp/
d) Mapping juniper and *Phytophthora austrocedri* for environmental schemes	PhD https://www.ceh.ac.uk/staff/flora-donald
e) To assess the effects of climate change on spread of pests and pathogens	Supported by PHC https://www.planthealthcentre.scot/projects/impact-climate-change-spread-pests-and-diseases-scotland

A team of ecological modellers demonstrated the online tools in a series of presentations to participants, and described the background and methods used for the underlying models and datasets. Each of the tools presented allows the participants to interact with the outputs from a model or dataset. The tools presented to the stakeholders address a breadth of P&P or represent case studies of focal pathogen taxa (e.g. *Phytophthora*) with potential to be extended to other P&P taxa. The tools are designed to enable users to visualise risk factors at different invasion stages (arrival, establishment, spread and impacts), including introduction pathways, national biosecurity effort, climate and land-use. The tools also provide access to information about the hosts and regions impacted by P&P. Scenarios for management and mitigation of the economic consequences of specific P&P outbreaks can also be explored. Each of the tools presented is described in more detail below.

Time was allocated for experiential learning, i.e. for participants to explore and interact with each of the tools in the presence of the modellers who developed them, and to ask specific questions. In the first workshop, this was run as an interactive plenary. In the second workshop, this was run as parallel breakout rooms. Following these interactions with the tools, the participants were asked to complete a short questionnaire to evaluate whether, and how, the tools could be useful to participants in their different roles and sectors, and to identify how the tools could be developed to better meet their plant health needs (Appendix 3). These questions were also used to structure subsequent open discussions within breakout groups and the plenary session.

4.2.1 Where are new pests and pathogens coming from? Global network models of import and export risk

4.2.1.1 Background

Previous modelling has estimated arrival risk factors by linking global trade networks and other metrics of connectivity (spatial proximity, climate similarity) to new detections of P&P

(Chapman *et al.* 2017). In this analysis, live plant imports from nearby source countries provided the best explanation of recent invasions among 173 insect pests, 166 pathogens and 83 weeds (Chapman et al. 2017).

4.2.1.2 Aim of model

To prioritise future threats from *Phytophthora* pathogens and to assess risk factors for arrival including trade, climate similarity (between exporting pathogen sources areas and importing countries) and pathogen characteristics.

4.2.1.3 Description of tool and proposed uses

We presented stakeholders with a global dataset from this analysis, in the form of an interactive map of the known number of plant P&P per country that are non-native within the EPPO (European Plant Protection Organisation) region to visualise potential source distributions for new P&P invasions. The maps also provided species lists for each country and information about whether the P&P is already present in the UK and whether it is on the UK Plant Health Risk Register.

We also presented a case-study for pathogens within the genus *Phytophthora*, from the Phytothreats project that adapts the approaches used in Chapman et al. (2017) to predict risk factors for *Phytophthora* introductions to the UK. The potential source range for each pathogen was defined as countries where the *Phytophthora* species was already present prior to 2000. Then after 2000, any new detections outside of the source distribution were interpreted as new pathogen arrivals. The connectivity between source regions and importing countries was measured in terms of volumes of live plants being imported and was used to predict global patterns of arrivals and non-arrivals at national-scale resolution. The models estimated the role of climate matching, export country biosecurity and plant health surveillance on new detections of *Phytophthora* species and assessed whether pathogen traits affect how well different pathogen species move through global trade networks.

The interactive global map allows users to explore these risk factors as individual layers, or to visualise a composite risk estimate of a new pathogen arriving from different source countries, when all risk factors are considered together. The map also has functions to explore whether this export risk is greater for some species than for others. For each species reported in the source country, there is information about whether that species is already present in the UK and if it is on the UK Plant Health Risk Register (Fig. 2a). For the species that are not yet present in the UK, there is an estimate of arrival risk, based on the import risk factors adjusted for the biological traits of that species, indicating whether that species may be more or less likely to be transported with live plants. The workshops allowed stakeholders to explore whether these models could be useful for identifying which countries may represent higher risk source regions from which to import live plants, based on the risk factors for transporting plant P&P.

4.2.1.4 Caveats and limitations

The global distributions of individual organisms are under reported. The models attempt to account for this using national P&P reporting activity, which does not capture threats from species that are not considered pests or pathogenic in their native range or may even be undescribed. Assessing risks at the national scale lacks resolution to understand sub-national variation biosecurity risk. The underlying databases and the online tools are not maintained nor intended to provide current estimates of risk.

4.2.2 Which areas of the UK are at risk from pest or pathogen species? Global niche models

4.2.2.1 Background

Ecological niche models have been used as part of risk assessment frameworks to understand environmental risk factors for establishment and how environmental suitability may influence the potential extent of a species that has yet to arrive or been recently introduced to a new region.

4.2.2.2 Aim of models

A proof-of-concept exercise to test whether the global distributions and environmental risk factors for individual *Phytophthora* species can be used to predict the suitability and known distributions of pathogens within the UK, to inform the prioritisation of future threats from P&P yet to arrive.

4.2.2.3 Description of tool and proposed uses

As a case study, we presented to stakeholders the predicted suitability maps from global niche models, again from Phytothreats, which integrate global environmental risk factors and indicate how much of the UK might be at risk from different *Phytophthora* species. The approach was validated using UK distribution data for 9 *Phytophthora* species that are already present and well-recorded globally (*P. ramorum*, *P. cinnamomi*, *P. lacustris*, *P. plurivora*, *P. cryptogea*, *P. gonapodyides*, *P. x alni, P. cactorum* and *P. cambivora*). The records used in validation were those from natural and outdoor managed environments only excluding nurseries and other primary premises in which *Phytophthoras* may arrive. For P&P species, these models may be useful for predicting the locations, extent and severity of outbreaks in the wider environment, to help inform the choice of species and the locations for planting. The tools developed allowed stakeholders to explore relative predicted suitability for each of the different *Phytophthora* pathogens in 10km squares across the UK, with predictions based on environmental risk factors such as summer temperature, winter temperature, precipitation seasonality, moisture index, forest cover, urban cover and agricultural cover. This information indicates whether a particular site for planting might be more or less favourable for particular pathogens and disease outbreaks. These maps were overlaid with known locations of outbreaks in the wider environment (in 10km cells) so users can also consider whether a proposed planting scheme is close to other sites with known outbreaks (Fig. 5b).

In the workshop, we explored with stakeholders whether these approaches could inform decisions and should be extended to other P&P and, if so, what priority the taxa would be.

4.2.2.4 Caveats and limitations

Though accuracy measures were reasonable for 8 of the 9 *Phytophthora* species, suggesting global environmental niche models can provide useful risk maps for *Phytophthora* species establishment in new regions, a major challenge is that biological recording of P&P is highly incomplete and biased (Purse & Golding 2015), limiting the species for which niche models can be developed. The underlying databases and the online tools are not maintained nor intended to provide current estimates of risk.

4.2.3 *Which pathogen and pest species are plants and trees susceptible to? Databases of known associations between host plants and their pests and pathogens.*

4.2.3.1 Background

Cross-sectoral databases of associations between plants and P&P can be analysed to understand host resilience and P&P traits favouring invasion (Barwell *et al.* 2020). They can be used to identify plant health risks associated with nursery stock and plant species selected for planting schemes.

4.2.3.2 Aim of model

To test whether the ecological traits of P&P can be used to predict their known host ranges to support horizon-scanning for new and emerging P&P.

4.2.3.3 Description of tool and proposed uses

We presented stakeholders with a table of known interactions between plant hosts and P&P and the geographical origin of these associations (Fig. 1c). The data were collated during the Phytothreats project and were sourced from the EPPO Global database, the USDA fungal-host database, CABI databases, national plant health surveillance data, references in the literature and personal databases shared by a global network of pathologists (Barwell et al. 2020). Stakeholders were able to search the host-pest/pathogen records by plant host, by pest, pathogen or by country. We also presented the outputs of horizon-scanning models developed during the Phytothreats project, which link the pathogen traits to their known host breadth (number of plant host families attacked) and global range. These models predicted that pathogens with faster growth rates and thicker-walled resting spores were more likely to attack a broader range of host plant families (Barwell et al. 2020). The models identified newly described and emerging species which are not yet known to have impacted many hosts but that share similar biological traits or are closely related to already impactful species. The model outputs were presented as a ranked list of *Phytophthora* species described in the last 10 years.

4.2.3.4 Caveats and limitations

Trait databases for P&P are scarce, limiting the potential for these methods to be applied across a broad range of taxa. The distributions and host ranges of P&P are under reported, increasing the uncertainty around prioritising future threats. The underlying databases and the online tools are not maintained nor intended to provide current estimates of risk.

4.2.4 *Risk assessing wider environment planting schemes: juniper case study*

4.2.4.1 Background

Juniper (*Juniperus communis*) planting has been both advocated and funded by statutory agencies and conservation charities for the past twenty years to re-invigorate dwindling, native populations (Forestry Commssion Scotland (FCS) 2009). However, the introduced plant pathogen, *P. austrocedri,* is now causing widespread mortality in juniper populations across Scotland and England and juniper planting is a potential pathway by which the pathogen may have been introduced or spread. Juniper management guidance issued by DEFRA in 2017 (DEFRA 2017) included a decision tree to help assess the population vulnerability and suitability of sites for supplementary planting.

4.2.4.2 *Aim of model*

Part of Flora Donald's PhD project, funded by the Scottish Forestry Trust, Scottish Forestry, Forest Research, NatureScot, the Royal Botanic Garden Edinburgh and UKCEH and registered at the University of Cambridge Plant Science Department, is to use statistical models to understand environmental and land-use factors promoting *P. austrocedri* spread and to communicate these risk factors to stakeholders who manage juniper. The workshop participants were, therefore, asked how the decision tree could better inform juniper conservation strategies and if decision trees are a useful tool that could be used to assess pest and disease risks associated with other host plant species (results not shown).

4.2.4.3 *Description of tool and proposed uses*

An interactive map was presented showing the national distribution of positive *P. austrocedri* detections (1km grid cells from Forest Research, Forestry Commission, FERA and APHA) in relation to native juniper (2km grid cells provided by the Botanical Society of Britain and Ireland (BSBI)) and juniper planting events carried out per decade from 1960-2019 (2km grid cells, from the BSBI, monitoring reports and data provided by organisations). Participants were encouraged to use the maps to explore the distribution of *P. austrocedri* outbreaks in relation to juniper planting in geographical locations of interest and to provide feedback on whether these maps would complement steps in the decision tree and how they could be improved to aid risk assessment of planting projects

4.2.4.4 *Caveats and limitations*

The distribution maps and proposed models are unlikely to show a causal link between juniper planting and presence of *P. austrocedri* because the pathogen was probably introduced to the UK decades before first detection (Riddell *et al.* 2020), during which time it may have spread naturally or via vectors such as vehicles and livestock to new locations. Records of juniper are most often collected at 2km resolution and the maps could only be updated to include field or land-holding information at locations where higher resolution data are available with the express permission of the data owner. Information about the species composition of planting projects granted government funding by the previous Scottish Rural Development Programme and the current Forestry grant scheme is not recorded and while juniper is likely in only a small component of most applications, the volume and distribution of missing data is uncertain. Similarly, intention to plant juniper cannot readily be retrieved from planning applications so locations are missing from the dataset unless incidentally recorded by other means (e.g. BSBI records). Planting events will be duplicated at locations where insufficient information was provided with a record to distinguish year of observation from year of planting.

4.2.5 *A decision support framework for assessing climate change impact on tree and plant pests and diseases*

4.2.5.1 *Background*

Epidemiological models classify a host population as susceptible, infected or removed (SIR) with the infection rate proportional to the size of the susceptible and infected populations (Kleczkowski, Hoyle & McMenemy 2019). In order to explore the outcome of an epidemic under different scenarios, SIR models can incorporate the effect of management on the division of the host population among these groups.

4.2.5.2 Aim of model

To illustrate the effects of climate change on spread of P&P, how the key processes and parameters are expected to vary with climate change and explore the epidemiological and economic outcomes for selected P&P in the period up to 2050.

4.2.5.3 Description and proposed uses of tool

The final modelling tool presented to participants was developed during a previous PHC project (https://www.planthealthcentre.scot/projects/impact-climate-change-spread-pests-and-diseases-scotland). This novel modelling framework combines epidemiological and economic modelling, with epidemiological and economic parameters (both market and non-market) from the literature for the selected pests and hosts, and is implemented in a user-friendly online app (Fig. 2e). Future climate change scenarios (over approximately the next 30 years) have been incorporated together with the impact of increased temperature on P&P. The app can be used to study predictions of spread and economic impact of P&P in forestry or agriculture settings under alternative scenarios. Plants can be susceptible or infected and there is an option for treatment to affect infection rates, for example through vaccination, spraying, culling and planting resistant varieties.

4.2.5.4 Caveats and limitations

The model assumes there is no spatial heterogeneity in spread and damage or costs and the population age structure is assumed to be constant. The predictions are strongly dependent on the size of the initial outbreak. Demographic stochasticity is not accounted for, meaning the model may perform better when host populations are larger. Only the temperature aspect of climate is used to predict spread.

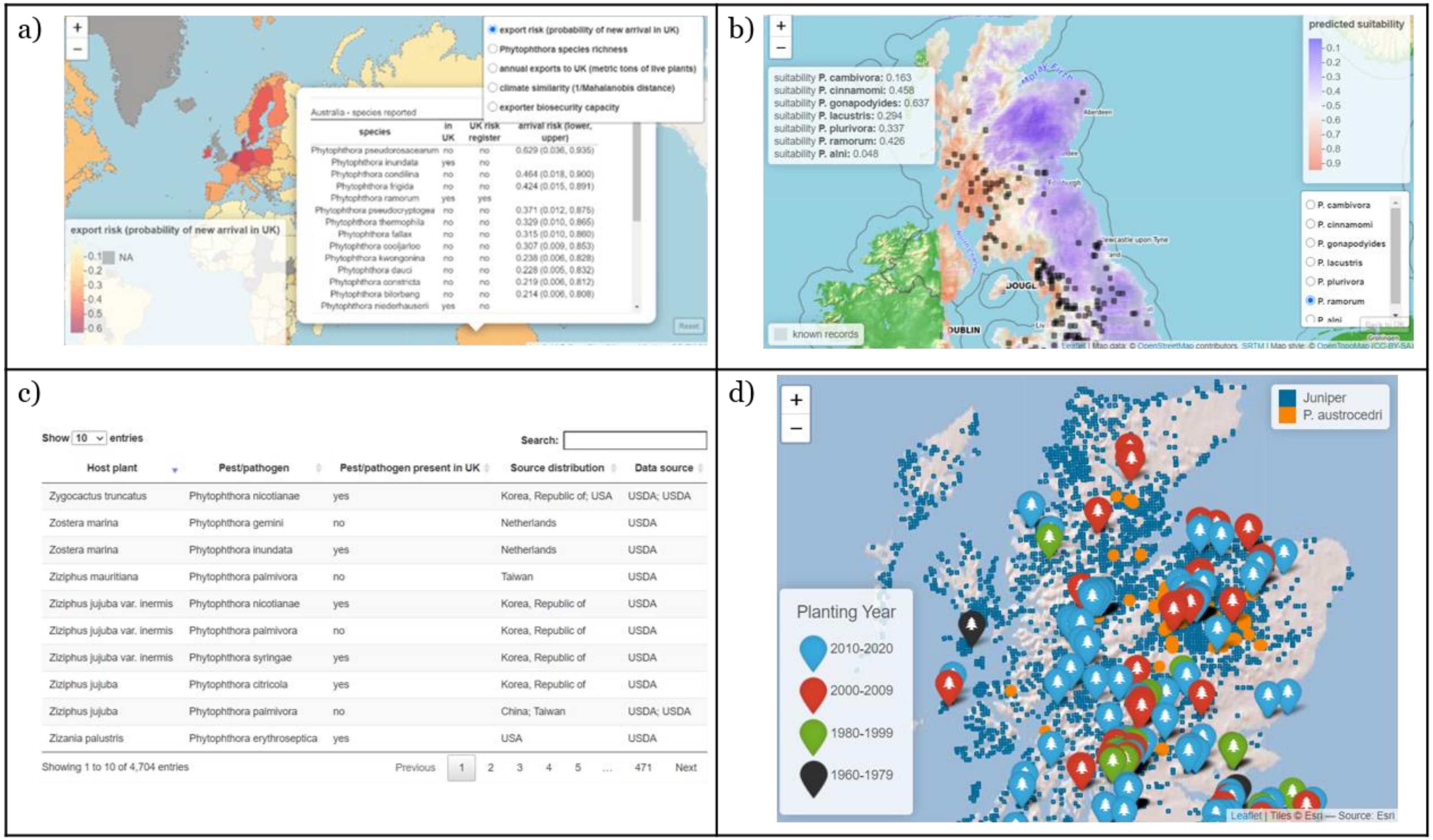

Figure 2 *Example screenshots from four ecological modelling and informatics tools presented during two workshops with key stakeholders involved in large-scale landscaping or environmental planting. The models were designed to allow stakeholders to interactively explore a) Where do new pests and pathogens come from? b) Which areas of the UK are at risk from pest or pathogen species? c) Which pathogen and pest species are plants and trees susceptible to? d) Risk assessing wider environment planting schemes: juniper case study. The full set of interactive tools and associated questionnaires for stakeholders can be accessed at https://loubar.github.io/PHC-plant-health-biosecurity-risks-Scotland/.*

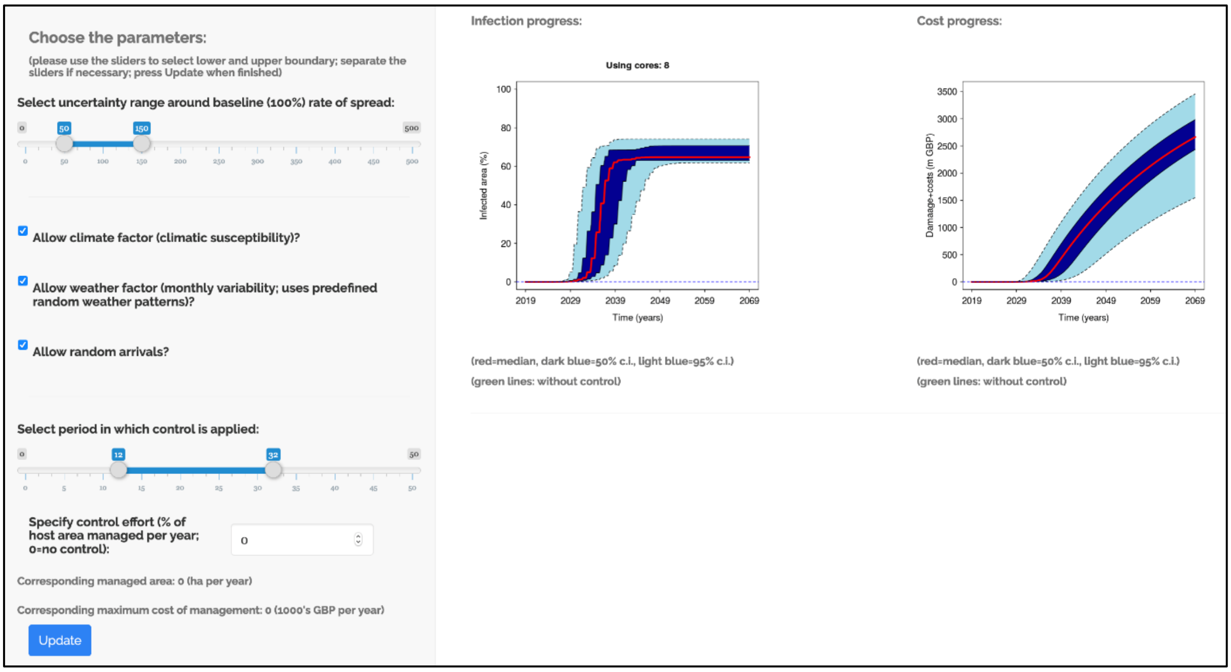

Figure 3 *Example output from a decision support tool for assessing climate change impact on tree and plant pests and diseases, presented during two workshops with key stakeholders involved in large-scale landscaping or environmental planting.*

4.3 Stakeholder perspectives on online tools

When presented with models for *Phytophthora* introduction risk, incorporating known areas of origin and global trade networks, from the Phytothreats project (Fig. 2a), stakeholders from the horticultural sector were interested in how they could be adapted to support an ornamental nursery or plant retail manager to carry out a robust P&P risk analysis for the plants that they intend to source and supply on their sites. For the Plant Health standard, nursery managers are expected to do a full risk assessment on every house plant that they stock for the Plant Health standard. This is a big task as they may stock over 200 plant species, and source them from a range of national and international supplies. It was suggested to reconfigure the tool so that it can be queried primarily for hosts and to encompass a wider range of P&P threatening the UK than *Phytophthoras* (e.g. *Xylella*).

Stakeholders suggested that the models as presented would be *"useful for the people developing the plant health standard but there is too much detail in there for your average person"* and they would be suitable for *"policy advocacy and developing schemes for trade"*. However, they commented that *"you need some knowledge before using it"*. This highlights the importance of experimenting with prototype tools and outputs with different groups of end-users to ensure that the tools are interpretable.

Key sensitivities and mismatches were highlighted around the geographical resolution of the information displayed. For example, one participant commented that: "*It might be important to not portray a country as bad because some countries have good and bad suppliers. Country wide might be too broad – e.g. in Italy there are different departments and plant suppliers who are managed quite differently and who therefore represent different risk*". In terms of priority P&P taxa to which similar approaches might be applied, emerald ash borer was mentioned. Other stakeholders questioned whether there was good knowledge sharing on

P&P from areas like the Netherlands where "*plants are being pushed through the supply chain rapidly*" to integrate into the models and whether the models could be applied at county level (not possible at present). Overall, the value of combining data across forestry, horticulture and agriculture sectors to provide "*centralised information on pathogen behaviour*" was felt to be high.

Stakeholders were presented in workshops with maps of predicted suitability, identifying which parts of the UK were suitable for occurrence and establishment of different P&P species, overlaid with P&P occurrence and planting locations in the wide environment. The potential impacts of these tools and outputs on decision making were not clearly defined. Though the map was developed from publicly available data, often from institutes that are generally transparent about the pathogens present on their land, concerns were raised about identifying 10km grid cells containing outbreaks. At this small scale, it would be possible to identify an estate or other premises and there might be potential negative impacts on trade. Some stakeholders indicated, however, that large areas owned by National Trust or RSPB and other such organisations have to publicly declare pathogens and so it would be no different for them. It was also suggested that perhaps nurseries should be required to make information on P&P present in their premises available to allow others to assess local biosecurity risks. Moreover, stakeholders pointed out that interpretation of the importance of proximity to outbreaks or potentially infected plantings was problematic given the knowledge gaps around how and over what distances pathogens spread. One participant asked: "*Would seeing a dot on the map lead to a greater chance of visiting a site or not visiting a site? E.g. it [guidelines] might say to not plant anything within 200m of a juniper planting. Juniper is currently surveyed at distance ....they try to leave it alone as much as possible*". Referring to juniper and *Phytophthora austrocedri*, stakeholders also pointed out potential conflicts in management responsibilities and statutory obligations. In one case a stakeholder was managing juniper on their estate but also managing juniper SSSIs which have *P. austrocedri*, meaning possible conflicts that could lead to spread of the pathogen, and so they should not visit potential infected sites and then potential clean sites.

Stakeholders were presented with a decision support framework for assessing climate change impacts on the spread and economic impacts of tree and plant pests. This tool has been used for horizon scanning (e.g. by DEFRA) for individual pest species such as the Oak processionary moth. For this species, the model could not predict exactly how many new sites of infection would occur or where, but it did predict that there would be multiple infections. The predictive ability/sensitivity of such models is increased if past outbreak data is available to refine the model parameters. It did thus seem to work, although it was not sensitive enough to predict where outbreaks might occur. Past outbreaks might be used to parameterise the model more and increase sensitivity. This is a relatively more complex model, with sometimes wide distributions of predicted spread and economic losses under different scenarios.

The presentation of this model triggered questions from stakeholders around the validity of model assumptions and the input data integrated into the model. There were sources of uncertainty such as species responses to climate change, or vagaries of trade ("*In the trade you are hostage to fortune and prediction is very difficult")*. Stakeholders were also interested in which P&P the tool was more useful for (e.g. P&P at early stages of invasion) and how much flexibility there was to accommodate different assumptions about the biology and impacts of different P&P species (e.g "*How does it work on species which are wind borne, such as*

Chalara?") or to accommodate current and future climates. They were also interested in whether the models could be extended beyond biosecurity risks, to identify opportunities and trade-offs. It might be more useful for some P&P or at early stages of invasion.

Advantages agreed about this model included the ability to parameterise the settings to, for example, set it to exponential growth rate or time to double area, which can mimic the effects of different P&P. This model was appreciated by stakeholders for the ability to estimate expected intrusion events per year and to run current and predicted climate details. As climate changes, we will thus see more events as the beetle for example spreads. This kind of sophisticated model adjustment requires knowledge of the biology of P&P as well as an understanding of the context of other variables but means that decision makers can use it to understand potential scenarios.

4.3.1 Knowledge sources and tools utilised by stakeholders across sectors to assess biosecurity risks: further insights to tailor and translate models

When exploring the value of modelling to plant health decision-making, it is important to understand where and how knowledge about plant health is currently accessed (White et al. 2018). Pre-workshop questionnaires (from five participants including both policy makers and practitioners) and the subsequent open discussion indicated that stakeholders in plant health access a wide range of sources of information. The most used sources varied between participants, with some using academic papers, some conferences and others professional magazines. The stakeholders described how different communication mechanisms are useful for reaching different stakeholder groups. This is important to account for when translating and tailoring models. One horticultural stakeholder indicated that magazines and conferences are "*for the converted*" but commented that in the trade sector it is hard to communicate key plant health messages to all practitioners. It was suggested that peer reviewed papers need to be interpreted or translated so that those working at all levels of the plant trade can use them. For example, it is difficult for practitioners to understand the dynamic state of knowledge around *Xylella* from academic papers alone. One stakeholder commented that a "One-stop" shop or reference point for information on biosecurity risks would be helpful, particularly for plant trade stakeholders. This stakeholder expressed concern that access to critical information might be opportunistic, for example, from magazines. Generally, it was felt that the media is unreliable in providing plant health information. Key events such as horticultural week were thought to be useful to promote plant health messages. Conferences and trade fairs reach many people. The Horticultural Trade Association was perceived to be "*good at sending relevant information*" to practitioners. The emerging plant health portal would also be useful. However, information should possibly be available from multiple doors to permit wider access.

Some stakeholders already used tools and models in their work and there was an existing appreciation of basic maps of species distributions and risk. Those working for government departments or agencies tended to use government supported and approved tools such as the UK Plant Health Risk Register. This implies that future models and tools will be most useful to policy makers if they can be linked to these existing tools. People in trade do not use the UK plant health risk register much but it was felt to give important messages. The stakeholders responsible for the register indicated that it would be useful to understand how people can be encouraged to use it more and how it can be improved. One stakeholder commented: "*Possibly the Plant Health Risk Register is so full of information that it is overwhelming. It has over*

1000 species in it and it is not really user friendly for someone who is not experienced or knowledgeable".

Overall, the candidate models presented were perceived to be useful for decision making at the policy level, but concerns were raised over whether the modelling outputs would be accessible and applicable to practitioners. The participants did suggest that there is an appetite amongst practitioners for information on biosecurity risks, but they identified challenges in learning how to use model outputs and tools. Despite these challenges, both policy and practice level forms of advice are required, but both the information and level of detail are likely to be different, indicating a need to tailor models and risk frameworks to specific sectors and scales. Further stakeholder suggestions on relevance and tailoring of risk models to different sectoral groups are itemised below.

A need was expressed for balance in the focus of modelling between identification of key priorities across multiple P&P threats and recognising and addressing complex processes for individual P&P species. Across the sectors represented, there was a need for both priority actions for specific P&P, but also general good practices to support plant health and protect against multiple threats. One proposed possible solution to the problem of assessing and mitigating risks from individual P&P versus multiple P&P described above was to focus attention on *Xylella*, since good nursery practices against *Xylella* may protect against a wide range of plant P&P. There was a request for a model to include risks from emerald ash borer. Modellers indicated that it would be useful to have a list of priority P&P for which to develop models.

There was discussion over the extent to which people used decision trees in making planting or detection decisions. Decision trees were considered useful to provoke questions, but difficult to use when qualitative answers were required within them (e.g. vulnerability).

Models are composed of assumptions and have to deal with high levels of uncertainty in some instances. It was commented by modellers that predictions from the climate change model combined climate uncertainties along with P&P uncertainties. Models not only provide information but also need to be trusted to promote plant health behaviours. Perhaps practitioners and the public have become more aware of plant health issues due to the frequent discussion of the Covid-19 pandemic. It was also suggested that models could link more with other issues; for example, linking the climate change model to biodiversity conservation planning.

4.3.2 Plant nurseries

As indicated above (in "Risk of introduction") stakeholders in the horticultural sector were particularly interested in adapting models predicting the arrival of different P&P (from trade connections to source areas, climate suitability and pathogen traits). They also wanted host-pest databases to support an ornamental nursery or plant retail manager carry out a robust P&P risk analysis for the plants that they intend to source and supply on their sites, as part of compliance with the Plant Health standard. Supply chains were perceived to be high risk pathways for new P&P to enter the UK or are spread further within the UK. The model outputs were seen to be potential means of transmitting the key messages to nurseries to be more careful about plant sourcing. It was suggested that models in future may need to not only focus on source of plants for import, but also to consider where we might export our clean stock more.

4.3.3 Landscape architects and contractors, and other small links in the supply chain

Practitioners are diverse and include not only reputable nurseries but also small-scale individual businesses such as landscape contractor businesses, which can be tiny e.g. one man and a white van. Such individuals may have a lot of experience but often do not have a lot of formal education: "*especially given that fifteen years ago there was not a plant health module in the landscape architecture courses*". Such a component needs to be "brought into" such degree programmes as highlighted by one participant below:
"There is a disconnect between recent theory and knowledge and the boots on the ground. It will require concerted effort to make professionals, lay people and the public aware of biosecurity risks and then to act in ways that promote plant health. The people who plant and maintain are very important and may sometimes be the missing link in the chain. The tools used here are visual and interactive and could better inform landscaping practice but it would wholly depend on other concerns ongoing at the time. It depends on the level of apparent and acceptable risk. There is a clear need to flag priorities."

4.3.4 Gardeners

There was discussion of how gardeners (such as enthusiastic amateurs or professionals with responsibility for public or private gardens) might use information derived from models. For gardeners, it was felt that resources that could provide information about species susceptibility to P&P would be helpful. One participant said: *"At the sharp end you have the gardener who might put dead plants on a bonfire or in a skip. Where do they get the resource or knowledge to tell them what the biosecurity risks are? Any information about species susceptibility for growers and gardeners is helpful. We also need to prevent jumps to the natural environment – there is an artificial boundary between horticulture and the natural environment."*

4.3.5 Forestry

Existing tools such as the Ecological Site Classification (ESC) tool produced by Forest Research for Forestry site managers were highlighted, that are often based on yield and whether a tree will grow under current and future soil and climate conditions but do not yet integrate biological threats. It was suggested that variable risks from P&P from the models could be integrated into such existing forestry tools. Moreover, stakeholders reported conflicts or *"false dichotomy between woodland management and forestry organisations"* around issues such as resilience, provenance and sourcing of trees to mitigate climate change that complicate assessment and communication of biosecurity risks.

"The more complex climate change model of economic and epidemiological impacts seemed to work very well for pest risk analysis at scale. It might have other applications across Forestry to help them understand cost benefit, especially by the Forest Estate."

4.3.6 Agriculture

Overall, representatives from the agricultural sector were less clear on how the tools could inform decision making by farmers or large land owners in their current form. It was recognised that farmers currently have many issues to contend with, including P&P, but that targeting key gatekeepers rather than all farmers might be a more effective way to link model outputs to decision making in agriculture. One participant said: *"It is key that these tools also function for the agricultural community. In every [training] session people asked who the audience was, and it was never the farmer or large landowners. These stakeholders recognise plant health but currently have more pressing concerns elsewhere. Farmers are moving into different areas now which means new species. Farmers rely on people to interpret the tools for them and highlight relevant topics. We need to work with agricultural advisers to deliver information to the farmers e.g. at colleges where it is connected to payment schemes. The advisory community and colleges and advisory consultants are key for agriculture."*

4.3.7 Over all sectors

Stakeholder engagement and experimentation with candidate models focussing on different invasion stages revealed further promising avenues for linking models to decision making around biosecurity risks from planting. For example, nursery managers must conduct a **robust P&P risk analysis** for the plants that source and supply on their sites, as part of compliance with the Plant Health standard. Thus, stakeholders in the horticultural sector were particularly interested in **adapting models predicting the arrival of different P&P** (from trade connections to source areas, climate suitability and pathogen traits) and host-pest/pathogen databases to support this process. They suggested **reconfiguring the outputs to be queried by host**, rather than by pest or pest pathogen, and indicated a preference for a **"One-stop" shop for information on biosecurity risks**. For forestry managers, it was suggested that variability in risk of priority P&P predicted from models could be **integrated into existing tools** such as the Ecological Site Classification (ESC) tool (Forest Research) that predict survival and yield of different tree hosts under current and future climate conditions.

Overall, it was felt that **additional models and tools of biosecurity risks would be most effective if they can be linked to existing tools**. Stakeholders in the agricultural sectors in particular felt that further work was required to integrate biosecurity risks to farmers into the models, with **agricultural advisers** potentially acting as key gate keepers. Indeed, work on risks from *Phytophthora* plant pathogens has indicated that collating and linking data on pathogen occurrence across the agriculture, horticulture and environmental sectors can improve predictions of pathogen behaviour and host ranges (Barwell et al. 2020). Overall, models were felt to be useful not only for providing predictions but also bringing wider awareness of risks and understanding of systems and processes.

Key general challenges were highlighted around the **sourcing and interpretation of information on biosecurity risks**, particularly by practitioners. It was highlighted that policy decision makers and practitioners need to be engaged in different ways. Whilst government stakeholders used government approved tools such as the UK Plant Health Risk Register and were generally conversant with model types and outputs, **substantial tailoring of risk models and peer-reviewed papers were needed for interpretation** by other groups, suggesting that **co-development models and tools with specific end users across sectors will be beneficial, including framing, knowledge integration and experimentation**. Indeed, the principles set out by Boden and McKendrick for delivering models to inform Public Health policy makers of independence, transparency (being transparent about model assumptions and inputs), beneficence (models must be better than existing tools) and justice can be equally applied by modellers aspiring to inform plant health decision making. The need was expressed for **balance** in the focus of both modelling and risk assessment tools such as the UK Plant Health Risk Register between horizon scanning, prioritising and predicting impacts of multiple P&P threats and recognising and addressing complex processes driving impacts of individual species. Tools that mapped host-pest/pathogen interactions and P&P source areas or predicted arrivals were generally thought to be more useful if they can incorporate the majority of major current threats in one framework.

A **key gap in mitigating in biosecurity risks around planting was perceived in the landscaping sector**. Biosecurity and plant health is not covered in the education programmes for landscapers. There can be a lag of two to three years in the appearance of host symptoms and outbreaks of P&P following arrival in a site through planting (Brasier, 2008). Landscaping project sites can change ownership and responsibilities rapidly between project initiation and completion (within 12 months) and sites are not monitored for P&P following planting meaning that subsequent outbreaks are less likely to be detected and mitigated early in the spread process. Moreover, stock planted is often of higher risk, of exotic host species or from low cost, high through put nursery operations with weaker biosecurity practices (Brasier, 2008). Finally, landscaping operations can be small scale (single individuals) and consequently hard to reach with risk communication messages and outputs.

4.4 Synthesis points from the discussion of models

- *Most models will be useful mainly for policy makers and key decision makers; some knowledge is required to be able to use and interpret them*
- *Models need to balance user-friendly and accessibility aspects with appropriate detail, such as recognition of different supplier reliability within countries*
- *Cross-sectoral information and model capabilities are required, to reflect ecological realities and to enhance joined up planning and practice*
- *Scale and confidentiality are potential conflicting issues when locating infection or clear zones on maps*
- *Potential for models for **plant trade in horticulture** included: models focused on host rather than P&P; tools with supplier reliability as well as country risks; potential export as well as import information*
- *To be useful to **landscape contractors**, more training on P&P needed to be included in landscaping education and professional development and links/responsibility clarified within this diverse profession; this was a key risk area identified*
- *For **forestry**, models should link to existing models used such as the Ecological Site Classification tool, and there should be applicability to commercial forestry and woodland management*
- *The development and use of models with agricultural advisers would be an effective way to support plant healthy practices in **agriculture***

Overall, the following needs were identified:

- *We need a balance between identification of priorities (e.g. particular P&P) and recognising and addressing the complexity*

- *We need information to support both specific priority actions and P&P specific responses but also general pro-plant health good practices*
- *We need both policy and practice level advice; this will probably require either different models or models that can be adjusted or translated by academics and policy makers for use in practice.*
- *We need co-production and piloting of models for plant health facilitated between modellers and stakeholder groups*

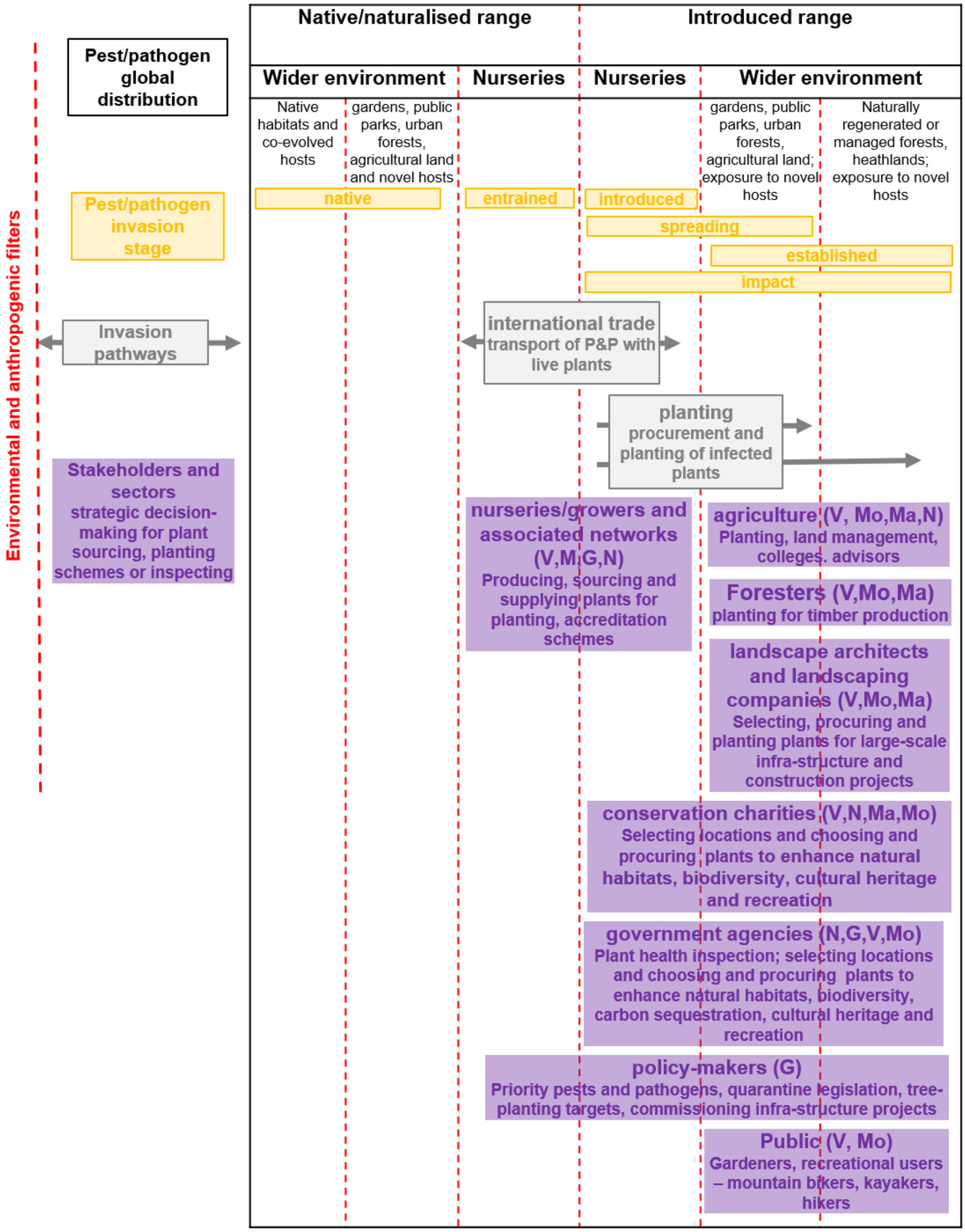

Figure 4 *A framework mapping stakeholder groups in multiple sectors to plant health threats at different invasion stages (see Fig. 1 for models corresponding to different invasion stages). Stakeholders make decisions about the species, locations and sources of plants for large-scale environmental and landscaping projects. We attempt to map onto the invasion stages, the key actors and the types of decisions about plantings that could be, or already are being, informed by model outputs and risk assessment frameworks. The stakeholders span multiple sectors (natural environment, agriculture, horticulture and government), but can also be categorised by their roles and responsibilities including vectors (V), Governors (G), managers (Ma), Monitors (Mo) or Networkers (N).*

5 General discussion and conclusions

We have described a suite of socio-ecological and epidemiological models available to address risks from planting at different stages along the invasion pathway. We identify key knowledge gaps that are limiting further development and application of these models, including in Scotland and the UK (Table 3, Fig. 1). The participants identified both specific feedback on each of the modelling tools and more general insights into the value of modelling and informatics in different sectors (Section 3). Using a framework adapted from invasion biology, we highlight where the literature review or stakeholder workshops have indicated that models can inform decision-making about the species, locations and sources of plants-for-planting across multiple sectors (Fig. 4).

Our literature review of knowledge gaps that are limiting the development of modelling and interactions with key informant stakeholders in multiple sectors has highlighted the need to strengthen the links between modelling, tools and decision-making in plant health. The literature review and the feedback from stakeholders identified a common appreciation in the modelling community and among key informant stakeholders that models address risks at specific scales, both spatially (e.g. local, national, regional) and taxonomically (e.g. single species, cross-species). Moreover, the level of translation required to be of value would vary significantly between roles, organisations and sectors (e.g. policy-maker or landscape gardener), which may account for the greater uptake of models at policy level compared to other levels of responsibility. Together these findings highlight the need to co-produce models and tools working closely with different groups and sub-groups of stakeholders to understand their specific needs.

The literature review also highlighted a mismatch between the breadth of models available for assessing biosecurity risks from planting and the use of models in decision-making. The discussion around knowledge flows in the workshop highlighted a potential reason for this. Stakeholders suggested different preferences (and in some cases rules or guidance) among the sectors, organisations and groups they represented in terms of the sources used to access information about plant health. One approach, to improve the links between risk models and decision-making around planting, is to integrate them better with well-used and recognised sources of plant health information such as the UK Plant Health Risk Register.

There were also notable differences in the knowledge gaps identified and prioritised by modellers (based on our review of published models) compared to those identified by participants in the stakeholder workshop. Whilst there was some overlap in perceived knowledge gaps (e.g. the complexity of supply chains), modellers identified a much larger body of missing information that could inform risk assessment from large-scale planting. One interpretation of this is a need for modellers to better engage multiple stakeholder groups to communicate the full potential of models to address multiple risks and the knowledge gaps that limit this. There is an opportunity to highlight to stakeholders the value of accessing their knowledge for improving models of biosecurity risks. For example, specific feedback from stakeholders on the global trade network tool presented in the workshop challenged the validity of model assumptions about the how informative trade flows can be at the national level.

The principles set out by (Boden & McKendrick 2017) for delivering models to inform Public Health policy makers are independence, transparency (being transparent about model assumptions and inputs), beneficence (models must be better than existing tools) and justice. These principles can be equally applied by modellers aspiring to inform plant health decision-making at all levels from policy maker to practitioner. It may be beneficial to develop a framework for the co-production of models and tools by ecological modellers and plant health stakeholders. Such a framework would be designed to enable the formation of partnerships between modellers and stakeholders. Stakeholder groups, such as government policy makers, inspectors, plant trade organisations or conservation agencies, could shape models to address their specific needs at a much earlier stage in the model development process. Where models are available that are relevant to decision making in specific roles and sectors, assistance from modellers in finding and translating these tools may be valuable. Improving knowledge exchange could also enable stakeholders to identify where they may have data and/or knowledge of value for informing the development of modelling approaches.

The Plant Health Centre is well positioned to create opportunities and channels for knowledge exchange and engagement between ecological modellers and key stakeholder groups involved not only in large-scale planting in Scotland, but plant health more widely. As a knowledge broker and point of contact for multiple stakeholder groups, the PHC is in a unique position to link modellers with stakeholder networks and facilitate the co-production of modelling tools for risk assessing threats to plant health in Scotland.

***Table 4**. Priority knowledge gap to improve models of biosecurity risks associated with planting*

Invasion phase	Priority knowledge gap	Source
Horizon-scanning and establishment	Improve trait data and conceptual and empirical links between traits and invasiveness, including through development of cross-sectoral databases of pest and pathogen occurrence, traits and behaviour across different ecosystems	Barwell et al. 2020
Introduction and spread	Improve records and understanding (through population genetics) of global pathogen and pest source distributions, particularly in countries with less intensive prior research effort and across sectors within countries.	Jung *et al.* 2021
Introduction and spread	Improve data on locations of historical and current planting in the landscape as sources of infection, particularly for the landscaping sector	Dunn et al. 2021, Karlsdóttir 2021
Introduction and spread	Improve understanding and mapping of complex supply chains and trade networks from local to global scales	Dunn et al. 2021, Karlsdóttir *et al.* 2021,Workshop
Introduction and spread	Develop future trade and biosecurity scenarios through inter-disciplinary collaboration with economists and policy-makers, stakeholders and growers with knowledge of trends in the market	Bradley *et al.* 2012
Establishment	Lack of monitoring of landscaping, infrastructure or environmental plantings	Workshop

Establishment	Improve distribution records and centralised databases across sectors for pests and pathogens in their native and invaded ranges for developing models of environmental conditions favouring establishment	Barwell et al. 2020
Establishment, spread and impact	To increase predictability of pathogen and pest behaviour in the introduced range, through empirical study of processes including hybridisation, enemy release, pathogen dispersal, acquisition of new traits, host susceptibility	Brasier 2008, Roy et al. 2014

Accounting for these findings, we make the following recommendations:

1. Modellers co-produce, frame and tailor models of biosecurity risks from planting with specific groups of stakeholders across sectors and roles, cognisant of the different ways these groups (e.g. practitioners and policy-makers) access and interpret information.
2. For stakeholder groups that use existing decision-making tools, models of biosecurity risks will be more effective if developed to integrate with these tools, particularly sources of information provided by the Scottish or UK government, for example the UK Plant Health Risk Register.
3. Two priority avenues for linking models to decision making should be explored through inter-disciplinary partnerships between modellers, plant pathologists, inspectors and decision makers, namely:

    a. addition of risk models of priority P&P to tools for Forestry site managers such as the Ecological Site Classification (ESC)
    b. adaptation of risk models of priority P&P to inform robust pest risk analysis by nursery managers sourcing and supplying plants, as part of compliance with the Plant Health standard

4. The particular challenges of mitigating and monitoring biosecurity risks in the landscaping sector, given the lag time between P&P arrival and recorded impact or outbreaks, may be worthy of review by policy makers across sectors.
5. Centralised cross-sectoral databases should be developed at national to regional and global levels, encompassing P&P occurrence, traits and behaviour across different ecosystems, so that models can better capture and predict the origins and processes of arrival, spread and impact between sectors.
6. Data on historical and current planting behaviour and locations (e.g. from the landscape and environmental sectors and on local to regional trade networks and supply chains) would be particularly beneficial and should be compiled and shared across sectors and integrated into models where-ever possible to improve predictions of biosecurity risks from planting
7. Further empirical studies of processes including hybridisation, enemy release, pathogen dispersal and acquisition of new traits, and host susceptibility are required to improve our predictions of the behaviour and impacts of P&P arriving in new region

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7 Appendices

7.1 *Appendix 1 Agenda for key informant stakeholder workshops (18th and 21st September 2020): Feedback on tools for assessing plant health risks*

10.00 – 10.05	**Introductions**	
10.05 – 10.10	**Overview of the Plant Health Centre Projects and the objectives of the workshop**	Louise Barwell
10.10 – 10.15	**Summary results of questionnaire on knowledge acquisition and application in strategic decision-making**	Rehema White
10.15 – 10.25	**Discussion of knowledge gaps and tools required**	
10.25 – 11.00	**Introduction to the interactive online tools**	
10.25	***a)* Where are new pests and pathogens coming from?** Risk factors for import: Pest and pathogen source regions, global trade networks, climate-matching, exporter biosecurity and pathogen traits	Louise Barwell
10.30	***b)* Which areas of the UK are at risk from pest or pathogen species?** Environmental risk factors for establishment, UK suitability and outbreaks in the wider environment: a case study with nine *Phytophthora* species	Louise Barwell
10.35	***c)* Which pathogen and pest species are plants and trees susceptible to?** Known host-pathogen/pest associations and their geographic origin, future threats and horizon-scanning	Louise Barwell
10.40	***d)* Risk assessing wider environment planting schemes and decision trees: juniper case study** Supplementary juniper planting as a potential pathway by which a pathogen could be introduced or spread.	Flora Donald
10.50	***e)* A decision support framework for assessing climate change impact on tree and plant pests and diseases**	Adam Kleczkowski
11.00 – 11.10	**Comfort break**	
11.10 – 12.25	**Experiential learning in breakout rooms** An opportunity to trial each interactive tool with the support of an ecological modeller and provide feedback for future development. Groups will move between rooms.	
Room 1	**Global threats, horizon scanning and risk assessment tools (a, b, c)**	Louise Barwell and Daniel Chapman

Room 2	**Risk assessing wider environment planting schemes and decision tree (d)**	Flora Donald and Bethan Purse
Room 3	**A decision support framework for assessing climate change impact on tree and plant pests and diseases (e)**	Adam Kleczkowski
12.25 – 12.35	**Comfort break**	
12.35 – 12.55	**Plenary Discussion** Do these kinds of tools influence your decision making? At what point in decision-making are such tools useful? Do you trust these tools? Does the tool need facilitation by a scientist?	
12.55	**Concluding remarks**	

7.2 *Appendix 2 Pre-workshop questionnaire*

Participants were asked to answer the following questions to establish their role in plant health decision-making and the sources of information they access to support these decisions (https://forms.gle/XzpfT6HWey8B53VB9).

1. Can you describe your role and which organisation you work for?

2. Can you describe your (or your organisation's) contribution to plant health? Does it have responsibility for sourcing, planting or inspecting, for example?

3. Where do you get most knowledge about plant health? Please rank from most important (1) to least important (10)

Academic Papers
Conferences
Professional Workshops
Professional Magazines
Informal with Peers
Email Bulletins
Twitter
Websites
Policy Briefs
Other
If other, please state

4. How do you use knowledge to make strategic decisions for plant sourcing, planting or inspecting within your organisation?

5. Do you use existing models, maps or tools to inform decision-making processes in your role or organisation?

Yes/No

6. If yes to question 5, can you describe which tools you use?

7. How might you incorporate models or tools into the decision-making process?

8. What models, maps or tools do you think might be useful for you and your organisation? For what species or contexts?
9. Does your role include juniper or *Phytophthora austrocedri* management?

Yes/No

10. Are you involved in juniper planting?

Yes/No

7.3 Appendix 3 Questions used to gather feedback from workshop participants on modelling tools and informatics

This set of questions was used to structure discussions around each of the tools available at https://loubar.github.io/PHC-plant-health-biosecurity-risks-Scotland, The questions were designed to help the modelling team understand for which pests and pathogens and in which environmental and decision-making contexts such tools are required?

1. How likely would you, or your organisation, be to use a tool like this in your work? Please select one.

2. If you answered very likely or likely, please explain how you would use the tool in your work?

3. If you answered unlikely or very unlikely, please explain why you would not use the tool?

4. Is there additional functionality or features you would like to see in such a tool?

5. How would these additional features help you in your work?

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