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Quantitative horizon scanning to identify species with the potential to become plant pests in new regions

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Abstract

The international spread of emerging and novel plant pests is increasing rapidly due to the expansion of global trade and poses substantial economic, socio-cultural, and environmental risks across ecosystems worldwide. Horizon scanning offers a proactive means of identifying emerging pests before they establish in new regions, creating valuable opportunities for prevention and risk mitigation. However, current horizon scanning approaches are largely qualitative, relying on extensive literature reviews and expert consultation that are both time-consuming and resource intensive. The Euphresco project presented here aims to strengthen and accelerate traditional horizon scanning by introducing a quantitative, highly automated modelling framework capable of screening large numbers of potential plant pests and identifying and prioritising those posing the greatest risk. The approach integrates multiple analytical components, including automated data retrieval from databases and web sources, high-throughput climate-suitability and ecological modelling, machine learning-assisted screening and analysis for informing and quantifying risk criteria, quantitative prioritisation of species according to risk, and sensitivity analysis to test the robustness of the ranking. The new approach will support evidence-based triage, enabling the most concerning pests to be rapidly identified for formal pest risk assessment and targeted surveillance. Ultimately, the project seeks to develop an open-source, robust, and maintainable toolkit that enables efficient, scalable, and automated horizon scanning for any country or region, supporting more effective integration of quantitative risk intelligence into phytosanitary decision-making.

Key Words

biosecurity preparedness, climate matching, decision-support tool, emerging pests, machine learning, preventive measures, risk prediction, targeted surveillance

Introduction

Invasive alien species, in particular plant pests, can cause severe economic, socio-cultural and environmental damage in all types of ecosystems (e.g., Pimentel et al. 2005, Bradshaw et al. 2021, Moran et al. 2025, Turbelin et al. 2023). The frequency of species invasions has increased almost exponentially in recent times (Seebens et al., 2017) mainly due to the acceleration in global trade during the twentieth century (e.g., Yamamura and Katsumata 1999, Work et al. 2005, Jamieson et al. 2022) and is projected to increase by over a third by 2050 (Seebens et al. 2021). As international trade networks expand, the risk of introducing non-native pests into new regions continues to increase, making prevention and early detection a central challenge for biosecurity systems. Proactive identification of potential threats is critical to increase preparedness. In this context, horizon scanning has emerged as an important approach for anticipating biological invasions.

Horizon scanning can be broadly defined as a systematic and structured process aimed at identifying and prioritizing the species that are most likely to invade and impact a target area. The approach is based on the evaluation of the likelihood of entry, establishment and spread of the species, on the estimation of the magnitude of their ecological and socio-economic impacts and on the opportunities for mitigating these impacts. The main output is a list of potential high-risk species that will then be considered further and, if appropriate, undergo a full pest risk analysis to identify species posing the greatest risk. This information is extremely valuable for providing guidance to authorities for regulatory purposes, for guiding phytosanitary services for targeting surveillance and enabling early detection, as well as for field managers for planning preventive measures (Wintle et al. 2020; Nunes et al. 2025).

Traditionally, horizon scanning for biological invasions has relied largely on qualitative approaches. These typically involve extensive literature reviews to identify species of concern, followed by expert-based risk assessments and consensus-driven prioritization (e.g., Roy et al. 2014; Roy et al. 2019; Peyton et al. 2020; Kenis et al. 2022; Mulema et al. 2022; Dawson et al., 2023). While effective in many cases, these approaches are often

labour-intensive and time-consuming, which strongly limits the number of species that can be scanned. Furthermore, they can be limited in their ability to systematically incorporate multiple risk factors, leading to potential biases and inconsistencies across assessments (Pratt et al. 2025).

To address these limitations, several frameworks and tools have been developed to standardise and partially automate the different steps of a horizon scanning process. These include standardised impact classification schemes that enable consistent comparison of invasion impacts (e.g., Dick et al. 2017; Blackburn et al. 2014; Bacher et al. 2018; Antoniou et al. 2024), minimum standards for risk assessment (Roy et al. 2018), as well as structured scoring systems such as FinnPRIO (Heikkilä et al. 2016), which quantify uncertainty through probabilistic risk estimates. In addition, database-driven tools such as the CABI Horizon Scanning Tool (Kenis et al. 2022; CABI 2026) use large-scale species occurrence data to identify species absent from a target region but present in climatically or economically connected areas.

More recently, horizon scanning has increasingly shifted towards quantitative and data-driven approaches. A central component of many modern frameworks is *climate matching*, whereby the climatic conditions of a species' native and invaded ranges are compared with those of a target region to assess establishment potential. Climate matching approaches range from relatively simple comparisons using climate classification systems (frost maps, degree-days maps, Köppen–Geiger world climate classification, etc.; e.g. Baker 2002; New et al. 2002; Kottek et al. 2006; MacLeod & Korycinska 2019; Cui et al. 2021), to methods such as hierarchical clustering and principal component analyses (e.g. Duffy et al. 2021; Ivison et al. 2025), and further to more advanced techniques based on distance metrics in multidimensional climate space (e.g. Erickson et al. 2022; Hubbard et al. 2025) or species distribution models (e.g., Srivastava et al. 2019; Ivison et al. 2025).

In parallel, advances in artificial intelligence and machine learning are increasingly enabling the automation of key steps in the horizon scanning workflow. AI-based tools can systematically extract information from large and heterogeneous data sources,

including scientific literature, databases, and web content (Gougherty & Clipp, 2024). Machine learning algorithms analyse the collected data to identify relevant risk factors to then score and generate ranked lists of potential invasive species with improved efficiency and reproducibility (e.g., Rojas-Sandoval et al., 2025; Cornelius et al., 2025; Farell et al., 2022).

Despite these developments, current approaches remain limited by their strong reliance on climate matching as the primary quantitative component and often lack a more comprehensive integration of additional drivers of invasion risk, as well as explicit quantification of uncertainty across all stages, with the exception of a simplified approach by Stinziano et al. (in press). In this context, Euphresco Topic D-462 aims to develop a fully quantitative framework for horizon scanning of plant pests, integrating data-driven methods for risk assessment beyond high-throughput climate matching, with the goal to advance the field of quantitative horizon scanning by improving the robustness, transparency, and scalability of the approach and to support risk assessment and responses to phytosanitary risks and early warning systems.

The specific objectives of the project are to i) identify risk criteria that can be automatically assessed through open-source databases, ii) identify and source data to inform the scoring of these criteria, iii) develop a horizon scanning framework for aggregating risk and integrating models into an actionable list of priority pests, iv) develop open-source code and models to facilitate quantitative horizon scanning for any region of interest, v) make these frameworks and tools publicly available.

Project Area, Partnership, and Scope

This project focuses on plant pests, which include lineages of organisms that can pose a threat to plants including insects, pathogens and invasive plants. Selected taxonomic groups are used to evaluate the developed methodology and serve as a proof of concept of the horizon scanning framework. Taxonomic groups are selected based on a range of factors, including but not limited to: i) taxonomic groups with traits that are characteristic of invasiveness, ii) taxonomic groups including species already considered pests in other

jurisdictions or institutions, or iii) groups with species associated with a particular commodity. The selected taxonomic groups for this project span insects, plants and pathogens and include two insect orders, Coleoptera and Hemiptera, the plant order Poales and the oomycete genus *Phytophthora*, which includes numerous plant-pathogenic species.

Reasons for Selection

Coleoptera and Hemiptera

The selection of Coleoptera and Hemiptera is motivated by their disproportionate importance in plant health, high invasion potential, and well-documented involvement in major phytosanitary threats worldwide (Liebhold et al. 2016; Liebhold et al. 2024). Both orders are strongly represented among regulated and high-impact pest species. Coleoptera includes numerous destructive wood borers (e.g. bark beetles and cerambycids; Brockerhoff et al. 2006) and defoliators, while Hemiptera encompasses phloem-feeding taxa such as aphids, psyllids, whiteflies, and scale insects. Members of these groups exhibit key invasion-facilitating traits, including cryptic or concealed life stages, broad host ranges, and, particularly in Hemiptera, high reproductive capacity, all of which contribute to their establishment and spread (Liebhold et al., 2016). Furthermore, both orders include species that function as vectors of plant pathogens, thereby amplifying their impact through the transmission of economically important diseases.

Poales

Among flowering plants, Poales are one of the most important taxonomic groups globally (approximately 24,000 species, Elliott et al., 2024) and include numerous species with biological traits favouring invasion, such as rapid growth, high seed production, efficient wind dispersal, vegetative propagation through rhizomes, broad ecological tolerance and adaptation to disturbance (Randall, 2017). Grasses (Poaceae) are among the most successful invasive plants worldwide. Approximately one-fifth of grass species are currently catalogued as invasive and almost 38% are listed as naturalized (Pertierra et al.

2023). Many of these grass species are already regulated as invasive plants because they reduce crop yields, alter ecosystems, interfere with water managementand increase management costs. The movement of propagules through trade pathways is therefore a focus of phytosanitary inspection and risk analysis.

Phytophthora

The oomycete genus *Phytophthora* includes many plant pathogens causing important diseases affecting agriculture, horticulture, forests and natural ecosystems (e.g. Grünwald and Flier 2005; Grünwald et al. 2008; Burgess et al. 2017). *Phytophthora* is a large and diverse genus with 260 species already described (Green et al., 2021; Horta Jung et al., 2024; Jung et al. 2024). *Phytophthora* species have efficiently spread across countries and continents by the trade of living plants, and across hosts and sectors, which makes targeted surveillance more useful than reactive outbreak response (Green et al. 2021; Barwell et al, 2025). Many harmful Phytophthora-related diseases are recognized only after establishment, and prevention has the highest probability of success compared to eradication, which is rarely achieved (Marcot et al, 2023; Hansen, 2015). Horizon scanning helps prioritize which species deserve attention before they become obvious problems by combining trade information, climate matching, surveillance effort, phylogeny, and traits linked to invasion success (Barwell et al., 2020, 2025).

This project involves six European countries (Finland, Ireland, Italy, Sweden, Switzerland, United Kingdom), one North American country (Canada) and one South American country (Guyana). The work is being coordinated across six government organisations (Agroscope CH; Canadian Food Inspection Agency; GB Department for Environment, Food & Rural Affairs; Finnish Ministry of Agriculture and Forestry; Swedish Board of Agriculture), and nine other research institutions and universities (CABI; Edmund Mach Foundation; Finnish Food Authority; Queen Mary University of London; Royal Botanic Gardens, Kew; Swedish University of Agricultural Sciences; University College Dublin;

University of Guyana). The quantitative horizon scanning framework will be applied to the country of each partner of the consortium (target countries hereafter) to provide a country-specific list of potential pests.

Structure and Approach of the Project

The project is organized into a series of interconnected work packages (WPs) that collectively support the development of a quantitative and automated horizon scanning framework for invasive plant pests (Figure 1).

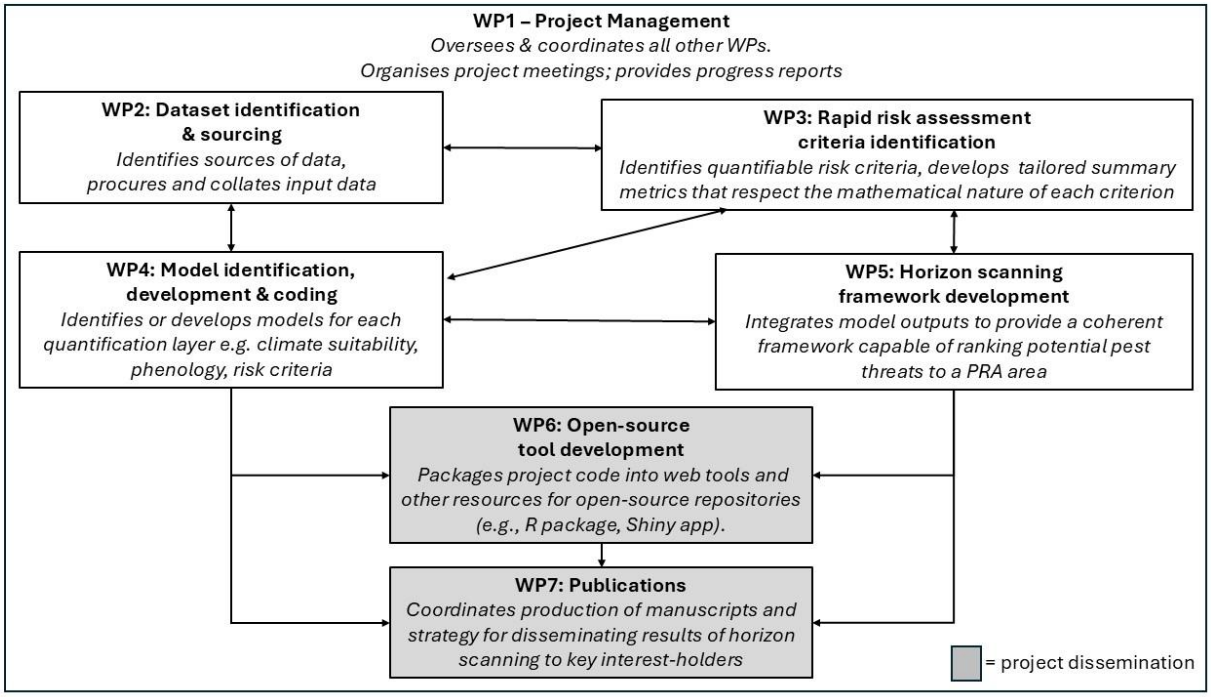

Figure 1. Structural relationships and functional linkages between project work packages supporting quantitative horizon scanning for plant pests

WP1: Project Management

Work package 1 deals with the management of the whole Euphresco Topic D-462 project including handling administrative tasks, fulfilling reporting responsibilities, and overseeing all other work packages. Most major tasks pertaining to WP1, such as solidifying project

membership, setting up collaboration spaces, etc., were completed at the outset of the project. The ongoing responsibilities within WP1 include organizing regular whole-project meetings every other month, delivering interim reports to the Euphresco office every six months, and coordinating work amongst the other work packages.

WP2: Dataset Identification and Sourcing

Work package 2 focuses on identifying and compiling datasets needed to support quantitative horizon scanning and rapid risk assessment of invasive plant pests. A broad range of publicly available and institutional datasets will be reviewed and catalogued, covering information relevant to climate suitability, species occurrence, host distributions, trade and transport pathways, pest regulatory status, species traits, and environmental and socio-economic impacts. Data sources will include international databases, national and regional repositories, biodiversity infrastructures, phytosanitary databases, trade datasets, and environmental data products. Priority will be given to publicly available datasets with broad geographic or taxonomic coverage and, where possible, automated access through Application Programming Interface (APIs) or other reproducible retrieval methods. For each dataset, information on accessibility, coverage, and potential use in risk assessment will be compiled.

To support integration with WP3, the datasets identified in WP2 will be linked to the rapid risk assessment criteria developed within the project. This will create a direct mapping between each criterion and the datasets that could support its quantification, allowing the feasibility and level of automation of different criteria to be evaluated. WP2 will also support the development of automated data extraction and processing workflows implemented in WP4, contributing to a scalable and reproducible quantitative horizon scanning framework by providing a central data curation node for accessing and processing the compiled datasets.

WP3: Rapid Risk Assessment Criteria Identification

Work package 3 focuses on identifying informative and quantifiable risk factors that can

be extracted, developed, or estimated on a high-throughput basis (i.e. for thousands of species at a time). The objective of compiling and defining these criteria is to facilitate an automated 'rapid risk assessment' as part of the horizon scan to prioritize and reduce the resultant list of potential pests, which may then be considered for formal risk assessments.

Factors that influence risk can include the presence of a species in a given region, the physical connectedness of that area to the potential area of entry, and trade flows between those areas (Hulme 2009, Banks et al. 2015). They can further result from the traits of a species, such as its dispersal ability, fecundity or association with humans (Williamson and Fitter 1996; Theoharides and Dukes 2007). The characteristics of the host, including its distribution, may also influence risk. Finally, documented impacts of the species, and where evidence is lacking, evidence from comparable pests, or closely related taxa can be considered (FAO, 2019). For those broad categories, specific criteria will be developed, the type of quantification evaluated (binary, categorical, etc.), and the availability of data checked. These criteria may include, but are not limited to: the current distribution of the assessed pests, the presence/absence of hosts and the extent of their distribution, trade volumes between regions where specific pests exist and the region of interest, whether species are considered pests in other jurisdictions, species traits that may be correlated with potential invasiveness, potential economic, environmental, and social impacts of pests. Criteria will also be differentiated according to the taxonomic group they are being applied to, as some criteria might not apply to all groups (e.g. plants versus insects).

WP4: Model Identification, Development, and Coding

Work package 4's activities focus on identifying existing or developing new models for each quantification layer (risk factor) of the horizon scan and writing the open-source code to apply the models in a high-throughput manner. In particular, WP4 will be responsible for developing modelling approaches for i) climate matching and species distribution modelling; ii) automating the extraction, curation and processing of relevant data to support risk assessment; iii) combining the components of the horizon scan to produce a priority list and a sensitivity analysis.

Climate matching and species distribution modelling

In the first step of the horizon scan, a climate-matching approach will be applied to identify the species for which the target areas have climatic conditions suitable for their establishment. Approaches for climate matching could range from something as simple as matching Köppen-Geiger climatic zones, to using measures of climatic distance between species' native areas and target areas (e.g. EUCLIMATCH, Hubbard et al. 2025). Climatic-distance approaches require the choice of a set of relevant climatic variables for defining the climatic space across which distances are measured. Common variables chosen to this end are bioclimatic variables derived from temperature and precipitation data through databases like WorldClim (Fick and Hijmans 2017) and CHELSA (Karger et al. 2017) that are relevant to the species' physiology (e.g. cold limits influencing overwintering survival), phenology and range limits (mean and seasonal temperature regime influencing the distribution and number of generations).

For species in step one that were identified to have the potential for establishment, a secondary step will develop high-resolution models that predicts their potential distribution within the target region. In addition, for species identified as potentially high-risk during the risk assessment, supplementary models (e.g. more complex habitat suitability models, phenological models, etc.) could be developed to support risk assessment.

Automated extraction, curation and processing of relevant data for risk assessment

A key component of the risk assessment is the process of summarizing a vast amount of data into information that can be used to quantify the risk a pest species poses. To automate the process of extracting, curating, and processing data identified by WP2 to inform the risk criteria compiled by WP3, this work package will create a modular and extensible pipeline written in the R language for statistical computing (R Core Team, 2026). Individual datasets are downloaded and, if required, combined with other datasets to inform the risk criteria. As an example, one risk criterion is the extent of the pest species' global distribution. Data used to inform this criterion will be assembled from a hierarchy of sources, prioritising authoritative, curated databases such as the European and Mediterranean Plant Protection Organization (EPPO) Global Database (EPPO, 2026)

and relevant taxon-specific resources, and supplementing these with quality-filtered occurrence data from sources such as the Global Biodiversity Information Facility (GBIF) for species for which curated distribution records are unavailable. The R code developed by this work package abstracts away the complexities of data extraction (e.g., retrieving data from APIs or other data sources), data curation (e.g. orchestrating the whole pipeline), and data processing (e.g. counting the number of countries within each pest species' distribution), so end users can simply execute a few simple commands to access the data required for risk assessment. However, since all code will be made open source, experienced users will also be able to customize or extend functions to suit their own needs.

Combination of the horizon scan's components to produce a priority list and a sensitivity analysis

WP4 will also be responsible for executing the full horizon scan and prioritisation pipeline for the selected species according to the framework developed by WP5. This process includes the integration of data identified and sourced in WP2, a structured screening and analysis to retrieve relevant data for informing and quantifying risk criteria identified by WP3, the incorporation of additional risk criteria if needed, and the prioritisation of species according to their risk score. The pipeline will be applied consistently across all taxonomic groups to ensure comparability, with outputs validated through consortium review and model performance assessments, including sensitivity analysis. A sensitivity analysis will be carried out to systematically test the robustness of the horizon scanning pipeline by rerunning the framework with varying combinations of the quantification layers (risk factors) selected in WP5. The outputs of this analysis will be compared to identify which layers most strongly influence rankings or classifications, identifying any potential bias or sensitivity in the pipeline. The expected findings will provide additional information for decision-makers on the sensitivity of pest species rankings to individual risk factors and may yield recommendations for improving methodological robustness in future applications.

WP5: Horizon Scanning Framework Development

Work package 5 will focus on developing the heuristic framework for conducting quantitative horizon scans over a medium-term time horizon, including the necessary quantification layers, and the methods for combining the quantification layers into a coherent output. These outputs may include ranked lists of pests, categories of pests, or lists or categories of commodities based on cumulative pest risk for each target country within a horizon scan.

The primary objective of this work package is to design and implement a quantitative horizon scanning framework that can operate effectively at both global and country-level scales. This dual applicability is essential, as invasive species risks often emerge from global pathways but manifest differently depending on ecological, climatic, and regulatory contexts of different countries. The framework will therefore be constructed to accommodate varying data availability and needs of particular countries, spatial resolutions, and taxonomic considerations, all while maintaining methodological consistency across scales.

A second objective is to develop a proof-of-concept application of the framework using selected taxonomic groups included in the project. This demonstration will serve to validate the operational workflow, highlight the adaptability of the framework to different biological systems, and identify any taxon-specific requirements that may need to be incorporated into the final design. The proof of concept will also provide an early indication of the framework's capacity to support prioritisation and decision-making processes.

To meet these objectives, WP5 will first identify the core components that constitute a quantitative horizon scan. These components represent the essential analytical elements that are broadly applicable across taxonomic groups and spatial contexts. They include, for example, the mechanisms for integrating risk criteria, the data structures required to support quantitative assessments, and the computational processes that enable reproducibility and scalability.

In parallel, the work package will identify auxiliary components whose relevance depends on the biological characteristics of the taxonomic group under consideration or the specific scope of the scan. Such components may include environmental variables that influence establishment potential (e.g., soil composition for invasive plants), ecological interactions (e.g., presence of animal vectors for pathogens), or host availability. Cataloguing these auxiliary elements will support the development of a modular framework in which users can select only those components relevant to their particular assessment.

Building on this foundation, the work package will develop a heuristic to guide the selection of modules within the framework. This heuristic will provide a structure that helps users determine which components are required for a given horizon scan, based on factors such as taxonomic group, geographic scope, data availability, and the intended use of the results. The heuristic will ensure that the framework remains flexible while still promoting methodological coherence.

Finally, the work package will review existing semi-quantitative prioritization schemes to inform how individual risk elements or criteria can be combined within the project. This review will examine approaches used in related risk assessments, with particular attention to transparency, reproducibility, and the balance between expert judgment and quantitative evidence. Insights from this review will guide the development of a robust and defensible method for integrating diverse risk criteria into a unified prioritization output.

WP6: Open-Source Tool Development

Work package 6 involves the development of software packages, tools, and web applications that will enable users across the globe to perform quantitative horizon scanning. The source code for all products will be stored on GitHub and made publicly available so that all users can inspect the code, provide feedback, and customize the codebase.

At a minimum, the code for all components of quantitative horizon scanning (e.g. downloading data, performing climate matching analyses, etc.) will be bundled into one or more software packages for the R programming language and published to the Comprehensive R Archive Network (CRAN), the most common package repository for R.

While interfacing directly with software packages will be a comfortable experience for seasoned R users, other users may prefer an interactive, no-code, web-based workflow for quantitative horizon scanning. To this end, a web application built with Shiny will be developed and hosted on GitHub so that users can download and launch the application locally or deploy it themselves on a sufficiently powerful server.

WP7: Scientific Publications

Work package 7 will focus on the coordination, writing, and submission of the research outputs of the research consortium - mainly under the form of scientific publications but also reports - and the strategy for disseminating the horizon scan outputs to regulators and other stakeholders that can act upon the results of the horizon scan.

Preliminary Results

The consortium has so far completed the first main task, which is the conceptualisation and definition of the different components of the horizon scanning framework. The framework and relative components are described hereafter.

Quantitative Horizon Scanning Framework

The quantitative horizon scanning framework has four potential components, including preliminary screening, rapid risk assessment, prioritisation, and regulatory review (Figure 2).

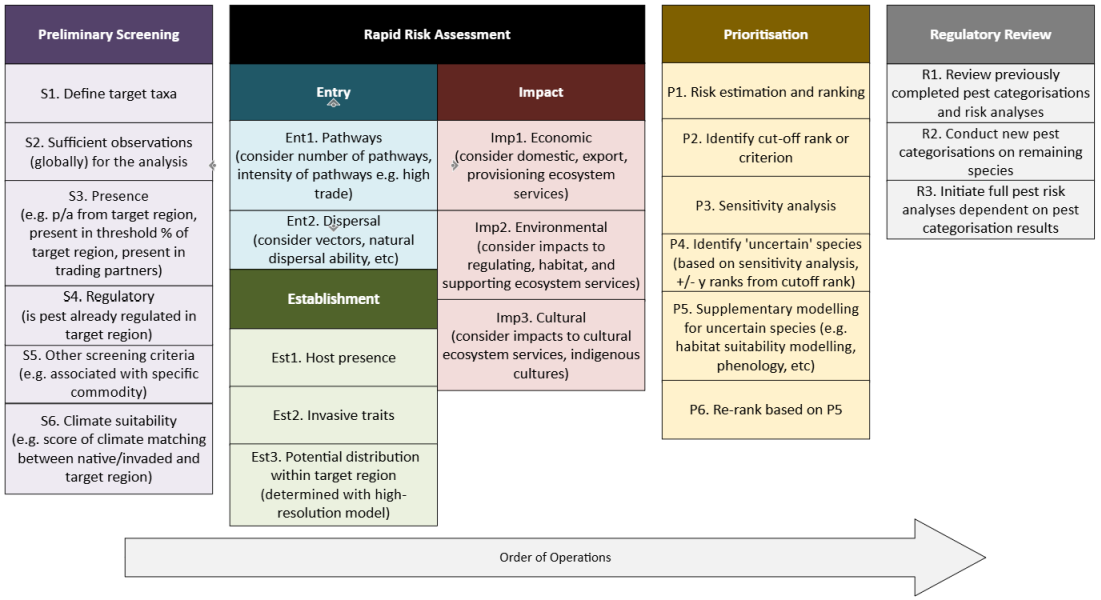

Figure 2. The quantitative horizon scanning framework has four primary components: preliminary screening, rapid risk assessment, prioritization, and regulatory review. The framework here presents sub-components that identify the range of what can be considered in a quantitative horizon scan. For some taxa, some of the sub-components may not be relevant, e.g. host presence for certain plants, invasive traits for some types of pathogens, environmental impacts for specialized agricultural pests.

Preliminary Screening

The goal of the preliminary screening is to reduce the pool of species as much as possible. First, the taxonomic group of interest for the scan is defined (**S1**). This may be based on high-risk families or orders, or on another criterion such as a common host. Then follows a series of checks to determine whether i) there are sufficient observations for statistical analysis / modelling based on a pre-defined threshold (**S2**), ii) the scan should only consider species absent or present in a portion only of the target region, or present in trading partners (**S3**) and iii) to include or exclude species already regulated in the target region (**S4**). Note however, that for validation purposes, it is best to also include species already regulated and species already present in the target region. Additionally, some species are regulated at the genus level, and a scan may seek to identify exceptions or specific species to highlight from regulated genera. Other screening criteria, such as whether the species are associated with specific commodities, pathways, vectors, etc., can also be used to select the species relevant for a particular purpose (**S5**). As a last step of the preliminary screening, the climate suitability of the target area for the species

will be estimated with climate matching approaches providing maps with scores of suitability for each pixel of the territory (**S6**).

Rapid Risk Assessment

The preliminary screening is followed by rapid risk assessments with the goal of quantifying the likelihood of a species entering, establishing, spreading within, and impacting the target region.

In the subcomponent **Entry** the likelihood that the species will enter the target region is estimated. Interception data from NPPOs would support quantification of the likelihood of entry for some species, as well as identifying potential pathways. Relevant pathways are considered and estimates of the rates of species entry are made **(Ent1).** For example, total imports of a commodity could be used as a proxy for species entry via that pathway. The dispersal potential of the species is assessed, particularly with respect to natural spread **(Ent2).** The presence of known vectors, proximity to source regions, and mechanisms of dispersal can all be considered here.

In the subcomponent **Establishment** the ability of the species to establish and spread within the target region is assessed. First, the presence of suitable hosts for establishment is considered **(Est1).** Note that for invasive plant taxa in particular, this criterion should be replaced by the presence of suitable habitats or soil characteristics (except in the case of parasitic plants). Furthermore, traits that make a species invasive are considered (**Est2**)**.** Note that this is highly variable depending on the taxonomic group, and for some groups may be irrelevant. For quantifying the area over which a species could establish, a high-resolution model with projections of the species' potential distribution in the target region now and in the future is developed (**Est3).** This may be a simple climatic correlative or (semi)-mechanistic distribution model (e.g. MAXENT, Phillips et al. 2006; CLIMEX, Sutherst and Maywald 1985; Proto4, Kim et al. 2023), or a more sophisticated habitat suitability model possibly incorporating variables other than climate (e.g. land use, host presence, soil characteristics, etc.).

In the subcomponent **Impact** the consequences of a species invasion in the target area are assessed. The economic consequences of a species invasion could include impacts to international trade (i.e. exports), domestic economic impacts, and provisioning ecosystem services, such as food, crops, livestock, capture fisheries, aquaculture, wild foods, timber and other wood products, biomass for fuel, and biochemical and medicinal resources (**Imp1**). The environmental consequences of a species invasion could include impacts on native biodiversity, on regulating services such as air-quality regulation, carbon sequestration, water-flow regulation, erosion regulation, pollination, and natural hazard regulation, as well as supporting and habitat services, such as soil formation, primary production, nutrient and water cycling, and habitat (**Imp2**). The cultural (i.e. human) impacts of a species invasion could include impacts on cultural identity and heritage, recreation and ecotourism, and impacts on Indigenous cultures (**Imp3**).

The rapid risk assessment is followed by a **Prioritisation** step which involves estimating and refining risk values, and ranking species for regulatory review. First, the information compiled in the rapid risk assessment, along with additional data as needed, is used to obtain a risk estimate within a risk prioritisation schema (**P1**). Risk prioritisation schema, such as the FinnPRIO risk ranking model (Heikkilä et al. 2016), or the USDA Weed Risk Analysis framework (Koop et al. 2012), could be used followed by ranking based on the risk estimates for each species. Second, a cut-off rank or criterion is identified (**P2**). Third, a sensitivity analysis is performed which could include using an ensemble of risk prioritisation schema to assess rank-stability for each species across schema, or reweighting components of the rapid risk assessment within a given schema (**P3**). This could be done using i) a statistical analysis of the rank-risk score relationship, ii) a type of categorisation criterion from a risk prioritisation schema such as the probability of being a major invader from Koop et al. (2012), or iii) a simple threshold number based on the downstream capacity for regulatory review. The sensitivity analysis should be considered in identifying an uncertainty range for the cut-off rank. Based on the rank cut-off uncertainty from the sensitivity analysis, species whose ranks fall within the window of uncertainty of the rank cut-off are identified for additional modelling scrutiny (**P4**). For uncertain species identified in P4, supplementary models are run (**P5**). This modelling

step may include models based on phenology, infection suitability, or other biological parameters. Part of this exercise includes identifying species for which there may be insufficient information to run a more detailed model. Finally, the species are re-ranked taking into account the P5 outcome, and species for which there was insufficient information for more detailed modelling flagged, as regulatory review may be necessary (**P6**).

Regulatory Review

The final component of the framework involves reviewing a short list of species to determine whether regulatory action could and should be taken against any of the species using the following stepwise procedure. Ranked species that have recently been assessed or categorized but remain unregulated may be omitted from further analysis (**R1**). An initial review of existing databases within the NPPO can quickly identify species for which no further review is required. For each remaining species, a pest categorisation is conducted to determine which species are potential quarantine pests within the target area (**R2**). For species identified as potential quarantine pests, the PRA process continues with further assessment of introduction, spread and potential consequences, as technically justified by the circumstances (**R3**). In cases where there is new information available that could influence whether a species receives regulatory review, the relevant risk criteria could be updated and the analysis could be re-run starting at the prioritization step.

Outlook

The Euphresco Topic D-462 project seeks to advance horizon scanning from a predominantly qualitative and expert-driven process towards a more scalable, transparent, and reproducible quantitative framework for identifying plant pests that may threaten new regions. By combining climate matching, species distribution modelling, automated data acquisition, machine learning approaches, and rapid risk assessment criteria, the project aims to provide plant health authorities with a practical means of screening large numbers of potential pest species more efficiently than using existing conventional approaches.

A major anticipated outcome of the project is the development of open-source tools and workflows that can be readily adapted to different countries, regions, and taxonomic groups, as well as compiled datasets that support and underlie these tools and workflows. Although the current proof-of-concept focuses on selected insect, plant, and pathogen taxa, the framework has been designed to be modular and extensible, enabling future incorporation of additional pest groups, pathways, datasets, and analytical components as new information becomes available. This flexibility is particularly important in a rapidly changing biosecurity landscape characterized by increasing trade connectivity, emerging pathways for pest entry, and shifting climatic suitability for pest establishment.

The project will also contribute to improving the integration of quantitative evidence into phytosanitary decision-making. Horizon scanning outputs are intended to support regulatory review, prioritization of pest risk analyses, targeting of surveillance activities, and strategic allocation of biosecurity resources. As NPPOs face growing numbers of potential threats and limited assessment capacity, quantitative approaches may help focus attention on species and pathways that warrant further investigation while also providing greater transparency regarding uncertainty and prioritization decisions.

Several scientific and operational challenges remain. Opportunities exist to expand the use of artificial intelligence and automated knowledge extraction to improve the speed and consistency of data acquisition and risk assessment. Data availability and quality vary considerably among taxonomic groups, geographic regions, and impact categories, and many potentially important risk factors remain poorly documented. Future work will therefore need to further refine methods for handling uncertainty, develop approaches for taxa with limited biological information, and evaluate the predictive performance of quantitative horizon scanning through retrospective and prospective validation exercises. In this respect, in a side project conducted in Switzerland, horizon scans to prioritise potential plant pests likely to threaten Switzerland and Europe are being conducted based on expert opinion, using a conventional method based on the CABI horizon scanning tool (CABI 2026) and mini pest risk assessment protocols, as described in Kenis et al. (2022)

and Mulema et al. (2022). In the last phase of the project, new horizon scanning and prioritization exercises will be conducted for Switzerland using the quantitative and automated tools developed by the Euphresco project. Comparisons will be made between the results of the prioritizations obtained using the conventional method and the new quantitative approaches. Conclusions will be drawn regarding the utility of the new tools, and recommendations will be made for future horizon scanning activities to the relevant plant health authorities.

Beyond the lifetime of the current project, the consortium intends that the datasets, workflows, models, and software developed within the framework will continue to evolve through open-source development and international collaboration. Continued integration of new datasets, risk factors, modelling approaches, and user feedback will help ensure that the framework remains relevant and effective as emerging plant health threats, environmental conditions, and phytosanitary priorities change over time.

Ultimately, the project aims to contribute to the development of next-generation early-warning systems for plant health. By enabling more comprehensive and proactive identification of potential pest threats, quantitative horizon scanning has the potential to strengthen national and international biosecurity preparedness, support evidence-based phytosanitary policy, and improve the protection of agricultural production, forestry, biodiversity, and ecosystem services from future biological invasions.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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Data Availability

All data produced in this preliminary phase of the project are available in the main text.

References

Antoniou A, Abergel M, Akrivou A, Beale T, Day R, Fielder H. et al. (2024) Horizon scanning: Tools to identify emerging threats to plant health in a changing world. EPPO Bulletin, 54(Suppl. 1): 73–88. https://doi.org/10.1111/epp.12988

Bacher S, Blackburn T M, Essl F, Genovesi P, Heikkilä J, Jeschke J M,.... Kumschick S, (2018) Socio-economic impact classification of alien taxa (SEICAT). Methods in Ecology and Evolution 9(1): 159–168. https://doi.org/10.1111/2041–210X.12844

Baker R H A (2002) Predicting the limits to the potential distribution of alien crop pests. In: Invasive Arthropods in Agriculture. Problems and Solutions, (Eds Hallman G J & Schwalbe C P), pp. 207–241. Science Publishers Inc., Enfield (USA).

Banks N C, Paini D R, Bayliss K L and Hodda M (2015) The role of global trade and transport network topology in the human-mediated dispersal of alien species. Ecology letters 18: 188–199. https://doi.org/10.1111/ele.12397

Barwell L J, Pérez-Sierra A, Henricot B, Harris A, Burgess T, Hardy G, Scott P, Williams N, Cooke D, Green S, Chapman DS, Purse B (2020) Evolutionary trait-based approaches for predicting future global impacts of plant pathogens in the genus Phytophthora. The Journal of Applied Ecology, 58: 718–730. https://doi.org/10.1111/1365–2664.13820

Barwell L J, Purse B, Green S, Hardy G, Scott P M, Williams N, Cooke D E L, Pérez-Sierra A, Burgess T I, Chapman D (2025) Trait-mediated filtering of Phytophthora pathogen invasions through global horticultural trade networks. The New Phytologist, 248: 2480–2497. https://doi.org/10.1111/nph.70587

Blackburn T M, Essl F, Evans T, Hulme P E, Jeschke J M, Kühn I,... Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS biology 12(5), e1001850. https://doi.org/10.1371/journal.pbio.1001850

Bradshaw C J A, Hoskins A J, Haubrock P J, Cuthbert R N, Diagne C, Leroy B, Andrews L, Page B, Cassey P, Sheppard A W, Courchamp F (2021) Detailed assessment of the reported economic costs of invasive species in Australia. In: Zenni RD, McDermott S, García-Berthou E, Essl F (Eds) The economic costs of biological invasions around the world. NeoBiota 67: 511–550. https://doi.org/10.3897/neobiota.67.58834

Brockerhoff E G, Bain J, Kimberley M, Knížek M (2006) Interception frequency of exotic bark and ambrosia beetles (Coleoptera: Scolytinae) and relationship with establishment in New Zealand and worldwide. Canadian Journal of Forest Research 36: 289–298.

Burgess T I, Scott J K, Mcdougall K L, Stukely M J C, Crane C, Dunstan W A, Brigg F, Andjic V, White D, Rudman T, Arentz F, Ota N, Hardy G E S J (2017) Current and projected global distribution of Phytophthora cinnamomi, one of the world's worst plant pathogens. Glob Change Biol, 23: 1661–1674. https://doi.org/10.1111/gcb.13492

CABI (2026) Horizon Scanning Tool. CABI Compendium. Wallingford, UK: CAB International. https://www.cabi.org/HorizonScanningTool

Cui D Liang S Wang D Liu Z (2021) A 1 km global dataset of historical (1979–2013) and future (2020–2100) Köppen–Geiger climate classification and bioclimatic variables. Earth Syst Sci Data 13(11):5087–114. https://doi.org/10.5194/essd–13–5087–2021

Cornelius J, Detering H, Lithgow-Serrano O, Agosti D, Rinaldi F, Waterhouse R M (2025) From literature to biodiversity data: mining arthropod organismal traits with machine learning. Biodiversity Data Journal, 13. https://doi.org/10.3897/bdj.13.e153070

Dawson W, Peyton J M, Pescott O L, Adriaens T, Cottier-Cook E J, Frohlich D S, Key G, Malumphy C, Martinou A F, Minchin D, Moore N, Rabitsch W, Rorke S L, Tricarico E, Turvey K M A, Winfield I J, Barnes, D K A, Baum D, Bensusan K, … Roy H E (2023) Horizon scanning for potential invasive non-native species across the United Kingdom Overseas Territories. Conservation Letters 16: e12928. https://doi.org/10.1111/conl.12928

Dick J T A, Laverty C, Lennon J J, Barrios-O'Neill D, Mensink P J, Robert Britton J, Médoc V, Boets P, Alexander M E, Taylor N G, Dunn A M, Hatcher M J, Rosewarne P J, Crookes S, MacIsaac H J, Xu M, Ricciardi A, Wasserman R J, Ellender B R, Weyl O L F, Lucy F E, Banks P B, Dodd J A, MacNeil C, Penk M R, Aldridge D C and Caffrey J M (2017) Invader Relative Impact Potential: a new metric to understand and predict the ecological impacts of existing, emerging and future invasive alien species. J Appl Ecol 54: 1259–1267. https://doi.org/10.1111/1365–2664.12849

Duffy C, Tuffen MG, Fealy R, Griffin CT (2021) Application of hierarchical clustering to identify high risk pests to Sitka spruce: Ireland as a case study. Forestry: An International Journal of Forest Research 94: 86–101. https://doi.org/10.1093/forestry/cpaa014

Elliott T L, Spalink D, Larridon I, Zuntini A R, Escudero M, Hackel J, Barrett R L, Martín-Bravo S, Márquez-Corro J I, Granados Mendoza C, Mashau A C, Romero-Soler K J,

Zhigila D A, Gehrke B, Andrino C O, Crayn D M, Vorontsova M S, Forest F, Baker W J, Wilson K L, Simpson D A, Muasya A M (2024) Global analysis of Poales diversification – parallel evolution in space and time into open and closed habitats. New Phytol, 242: 727–743. https://doi.org/10.1111/nph.19421

EPPO (2026) EPPO Data Services. Paris, France: European and Mediterranean Plant Protection Organization. https://data.eppo.int/ui/#/auth/login

Erickson R A, Engelstad P S, Jarnevich C S, Sofaer H R, Daniel W M (2022) Climate matching with the climatchR R package. Environmental Modelling & Software 157:105510. https://doi.org/10.1016/j.envsoft.2022.105510

FAO (2019) ISPM 11. Pest risk analysis for quarantine pests. International Standards for Phytosanitary Measures No. 11. Secretariat of the International Plant Protection Convention, FAO, Rome, Italy.

Farrell M, Brierley L, Willoughby A, Yates A, Mideo N (2022) Past and future uses of text mining in ecology and evolution. Proceedings of the Royal Society B: Biological Sciences, 289. https://doi.org/10.1098/rspb.2021.2721

Fick S E, Hijmans R J (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37: 4302–4315. https://doi.org/10.1002/joc.5086

Gougherty A V, Clipp H (2024) Testing the reliability of an AI-based large language model to extract ecological information from the scientific literature. npj Biodiversity, 3. https://doi.org/10.1038/s44185–024–00043–9

Green S, Cooke D E L, Dunn M, Barwell L, Purse B, Chapman D S, Valatin G, Schlenzig A, Barbrook J, Pettitt T, Price C, Pérez-Sierra A, Frederickson-Matika D, Pritchard L, Thorpe P, Cock P J A, Randall E, Keillor B, Marzano M (2021) PHYTO-THREATS: Addressing Threats to UK Forests and Woodlands from Phytophthora; Identifying Risks of Spread in Trade and Methods for Mitigation. Forests, 12(12): 1617. https://doi.org/10.3390/f12121617

Grünwald N J, Flier W G (2005) The biology of Phytophthora infestans at its center of origin. Annu. Rev. Phytopathol. 43(1): 171–190.

759 Grünwald N J, Goss E M, Press, C M (2008) Phytophthora ramorum: a pathogen with a
760 remarkably wide host range causing sudden oak death on oaks and ramorum blight on
761 woody ornamentals. Molecular Plant Pathology 9(6): 729–740.
762
763 Hansen, E (2015) Phytophthora Species Emerging as Pathogens of Forest Trees.
764 Current Forestry Reports 1: 16–24. https://doi.org/10.1007/s40725–015–0007–7
765 Heikkilä J, Tuomola J, Pouta E et al (2016) FinnPRIO: a model for ranking invasive plant
766 pests based on risk. Biol Invasions 18: 1827–1842. https://doi.org/10.1007/s10530–016–
767 1123–4
768
769 Horta Jung M, Maia C, Mora-Sala B, Abad-Campos P, Schena L, Mosca S, Carella G,
770 Moricca S, Nechwatal J, Dionísio L, Cravador A, Jung T (2024) High diversity of
771 Phytophthora species in natural ecosystems and nurseries of Portugal: Detrimental side
772 effect of plant introductions from the age of discovery to modern globalization. Plant
773 Pathology. https://doi.org/10.1111/ppa.14022
774
775 Hubbard JAG, Andrew R, Drake D, Mandrak NE (2025) ‘Euclimatch': an R package for
776 climate matching with Euclidean distance metrics. Ecography 2025: e07614.
777 https://doi.org/10.1111/ecog.07614
778
779 Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in
780 an era of globalization. Journal of Applied Ecology 46: 10–18.
781 https://doi.org/10.1111/j.1365–2664.2008.01600.x
782
783 Ivison K, Howard C, Baldini L., Essl F, Pyšek P, Dawson W and Speed JDM (2025)
784 Horizon scanning of potential invasive alien plant species and their distribution in Norway
785 under a changing climate. Ecography 2025: e07604. https://doi.org/10.1002/ecog.07604
786
787 Jamieson LE, Woodberry O, Mascaro S, Meurisse N, Jaksons R, Brown SDJ and Ormsby
788 M (2022) An Integrated Biosecurity Risk Assessment Model (IBRAM) For Evaluating the
789 Risk of Import Pathways for the Establishment of Invasive Species. Risk Analysis 42:
790 1325–1345. https://doi.org/10.1111/risa.13861
791
792 Jung T, Milenković I, Balci Y, Janoušek J, Kudláček T, Nagy ZÁ, Baharuddin B, Bakonyi
793 J, Broders KD, Cacciola SO, Chang TT, Chi NM, Corcobado T, Cravador A, Đorđević B,
794 Durán A, Ferreira M, Fu CH, Garcia L, Hieno A, Ho HH, Hong C, Junaid M, Kageyama K,
795 Kuswinanti T, Maia C, Májek T, Masuya H, Magnano di San Lio G, Mendieta-Araica B,
796 Nasri N, Oliveira LSS, Pane A, Pérez-Sierra A, Rosmana A, Sanfuentes von Stowasser
797 E, Scanu B, Singh R, Stanivuković Z, Tarigan M, Thu PQ, Tomić Z, Tomšovský M,
798 Uematsu S, Webber JF, Zeng HC, Zheng FC, Brasier CM, Horta Jung M (2024)

Worldwide forest surveys reveal forty-three new species in Phytophthora major Clade 2 with fundamental implications for the evolution and biogeography of the genus and global plant biosecurity. Studies in Mycology, 107(1): 251–389. https://doi.org/10.3114/sim.2024.107.04

Karger DN, Conrad O, Böhner J, Kawohl T, Kreft H, Soria-Auza RW, Zimmermann NE, Linder HP, Kessler M (2017) Climatologies at high resolution for the earth's land surface areas. Scientific Data 4: 170122 (2017) https://doi.org/10.1038/sdata.2017.122

Kenis M, Agboyi LK, Adu-Acheampong R, Ansong M, Arthur S, Attipoe PT, Mahamud Baba A-S, Beseh P, Clottey VA, Combey R, Dzomeku I, Eddy-Doh MA, Fening KO, Frimpong-Anin K, Hevi W, Lekete-Lawson E, Nboyine JA, Ohene-Mensah G, Oppong-Mensah B, Nuamah ASA, van der Puije G, Mulema J (2022) Horizon scanning for prioritizing invasive alien species with potential to threaten agriculture and biodiversity in Ghana. Neobiota 71: 129–148. https://doi.org/10.3897/neobiota.71.72577

Kim S, Koop A, Fowler G, Israel K, Takeuchi Y, Lieurance D (2023) Addition of finer scale data and uncertainty analysis increases precision of geospatial suitability model for non-native plants in the US. Ecological Modelling, 484: 110458. https://doi.org/10.1016/j.ecolmodel.2023.110458

Koop A L, Fowler L, Newton L P, Caton B P (2012) Development and validation of a weed screening tool for the United States. Biological Invasions 14: 273–294. https://doi.org/10.1007/s10530–011–0061–4

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15: 259–263. https://doi.org/10.1127/0941–2948/2006/0130

Liebhold A M, Yamanaka T, Roques A et al. (2016) Global compositional variation among native and non-native regional insect assemblages emphasizes the importance of pathways. Biological Invasions 18: 893–905. https://doi.org/10.1007/s10530–016–1079–4

Liebhold A M, Turner R M, Bartlett C R, Bertelsmeier C, Blake R E, Brockerhoff E G, Causton C E, Matsunaga J N, McKamey S H, Nahrung H F, Owen C L, Pureswaran D S, Roques A, Schneider S A, Sanborn A F, Yamanaka T (2024) Why so many Hemiptera invasions? Diversity and Distributions, 30: e13911. https://doi.org/10.1111/ddi.13911

Marcot B G, Scott P, Burgess T I (2023) Multivariate Bayesian analysis to predict invasiveness of Phytophthora pathogens. Ecosphere 14(6): e4573. https://doi.org/10.1002/ecs2.4573

MacLeod A and Korycinska A (2019) Detailing Köppen-Geiger climate zones at a country and regional level: a resource for pest risk analysis. EPPO Bulletin 49 (1): 73–82. https://doi.org/10.1111/epp.12549

Moran N P, Wang Lu-Yi, Hanea A M, Kompas, T (2025) An invasive species cost review for New South Wales, Australia, highlights key drivers and limitations of economic cost estimates. NeoBiota 104: 319–337. https://doi.org/10.3897/neobiota.104.157434

Mulema J, Day R, Nunda W, Akutse KS, Bruce AY, Gachamba S, Haukeland S, Kahuthia-Gathu R, Kibet S, Koech A, Kosiom T, Miano DW, Momanyi G, Murungi LK, Muthomi JW, Mwangi J, Mwangi M, Mwendo N, Nderitu JH, Nyasani J, Otipa M, Wambugu S, Were E, Makale F, Doughty L, Edgington S, Rwomushana I, Kenis M (2022) Prioritization of invasive alien species with the potential to threaten agriculture and biodiversity in Kenya through horizon scanning. Biological Invasions 24: 2933 – 2949. https://doi.org/10.1007/s10530–022–02824–4

New M, Lister D, Hulme M & Makin I (2002) A high-resolution data set of surface climate over global land areas. Climate Research 21: 1–25. https://doi.org/10.3354/cr021001

Nunes A L, Venter T S, Adriaens T, Bond G M, Costello K E, Delva S, Gospodinov K, Novoa A, Peyton J, Pyšek P, Rabitsch W, Roy H E, Scalera R, Smith K E, Tricarico E, Aldridge D, Altamirano M, Bellotto V, Bertolino S, Brundu G, Cardoso AC, Cavadino I, Dawson W, Demetriou J, Devisscher S, D'hondt B, Essl F, Evans T, Everts T, Gallardo B, García-Berthou E, Groom Q, Hillaert J, Jacobs A, Katsanevakis S, Marchante E, Marchini A, Oficialdegui F J, Olenin S, O'Riordan R M, Pattison Z, Petersen F, Preda C, Rebelo R, Reniers J, Scheers K, Skuhrovec J, Solarz W, Steen F, Strubbe D, Van Landuyt W, van Valkenburg J, Verëll V, Verhelst P, Verreycken H (2025) Invasive Alien Species Horizon Scanning in support of implementation of Regulation 1143/2014 - Final Study Report. Prepared under Service contract 09.0201/2023/907919/SER/ENV.D2 for the European Commission.

Pertierra LR, Martínez PA, Rubalcaba JG, Richardson DM, Olalla-Tárraga MA (2023) Contrasting patterns in phylogenetic and biogeographic factories of invasive grasses (Poaceae) across the globe. npj biodiversity 2: 11. https://doi.org/10.1038/s44185–023–00016–4

878 Peyton JM, Martinou AF, Adriaens T, Chartosia N, Karachle PK, Rabitsch W, et al. (2020)
879 Horizon Scanning to Predict and Prioritize Invasive Alien Species With the Potential to
880 Threaten Human Health and Economies on Cyprus. Frontiers in Ecology and Evolution
881 8–2020. https://doi.org/10.3389/fevo.2020.566281
882
883 Phillips S J, Anderson R P and Schapire R E (2006) Maximum entropy modeling of
884 species geographic distributions. Ecological Modelling 190: 231–259.
885 https://doi.org/10.1016/j.ecolmodel.2005.03.026
886
887 Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic
888 costs associated with alien-invasive species in the United States. Ecological Economics
889 52(3): 273–288. https://doi.org/10.1016/j.ecolecon.2004.10.002
890
891 Pratt C J, Ashworth E C, DiBacco C, Kingsbury S (2025) Balancing efficiency and rigour
892 in horizon scanning: an application to the management of invasive non-indigenous
893 species in the marine waters of Eastern Canada. Management of Biological Invasions 16:
894 749–785. https://doi.org/10.3391/mbi.2025.16.3.09
895
896 R Core Team (2026) R: A Language and Environment for Statistical Computing. R
897 Foundation for Statistical Computing, Vienna, Austria.
898 https://doi.org/10.32614/R.manuals. https://www.R-project.org/
899
900 Randall R P (2017) A Global Compendium of Weeds, 3rd edn. R G and F J Richardson,
901 Perth, Australia.
902
903 Rojas-Sandoval, J., Anglés-Alcázar, D., Willig, M (2025) Machine learning for biosecurity:
904 A probabilistic framework for invasive species management. Journal of Applied Ecology
905 62(11): 3194–3206. https://doi.org/10.1111/1365–2664.70164
906
907 Roy H E, Bacher S, Essl F, et al. (2019) Developing a list of invasive alien species likely
908 to threaten biodiversity and ecosystems in the European Union. Global Change Biology
909 25(3): 1032–1048. https://doi.org/10.1111/gcb.14527
910
911 Roy H E, Peyton J, Aldridge D C, Bantock T, Blackburn TM, Britton R, Clark P, Cook E,
912 Dehnen-Schmutz K, Dines T, Dobson M, Edwards F, Harrower C, Harvey MC, Minchin
913 D, Noble DG, Parrott D, Pocock MJ, Preston C D, Roy S, Salisbury A, Schönrogge K,
914 Sewell J, Shaw RH, Stebbing P, Stewart AJ, Walker KJ (2014) Horizon scanning for
915 invasive alien species with the potential to threaten biodiversity in Great Britain. Global
916 Change Biology 20(12):3859–3871. https://doi.org/10.1111/gcb.12603
917

Roy H E, Rabitsch W, Scalera R, et al. (2018) Developing a framework of minimum standards for the risk assessment of alien species. Journal of Applied Ecology 55(2): 526–538. https://doi.org/10.1111/1365–2664.13025

Seebens H, Blackburn T M, Dyer E E, Genovesi P, Hulme P E, et al. (2017) No saturation in the accumulation of alien species worldwide. Nature Communications 8: 14435. https://doi.org/10.1038/ncomms14435

Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, Genovesi P, Hulme PE, Van Kleunen M, Kühn I, Jeschke JM, Lenzner B, Liebhold AM, Pattison Z, Pergl J, Pyšek P, Winter M, Essl F (2021) Projecting the continental accumulation of alien species through to 2050. Global Change Biology 27(5): 970–982. https://doi.org/10.1111/gcb.15333

Sutherst R W, Maywald G F (1985) A computerised system for matching climates in ecology. Agriculture, Ecosystems & Environment 13(3):281–299. https://doi.org/10.1016/0167–8809(85)90016–7

Srivastava V, Lafond V, Griess VC (2019) Species distribution models (SDM): applications, benefits and challenges in invasive species management. CABI Reviews 2019: 1–13. https://doi.org/10.1079/PAVSNNR201914020

Theoharides K A, Dukes J S (2007) Plant invasion across space and time: factors affecting nonindigenous species success during four stages of invasion. New Phytologist 176(2): 256–273. https://doi.org/10.1111/j.1469–8137.2007.02207.x

Turbelin A J, Cuthbert R N, Essl F, Haubrock P J, Ricciardi A, Courchamp F (2023) Biological invasions are as costly as natural hazards. Perspectives in Ecology and Conservation 21(2): 143–150, https://doi.org/10.1016/j.pecon.2023.03.002

Williamson M H, Fitter A (1996) The characters of successful invaders. Biological Conservation 78(1–2): 163–170. https://doi.org/10.1016/0006–3207(96)00025–0

Wintle B C, Kennicutt II M C, Sutherland W J (2020) Scanning horizons in research, policy and practice. In: Sutherland W J, Brotherton P N M, Davies Z G, Ockendon N, Pettorelli N, Vickery J A, eds. Conservation Research, Policy and Practice. Ecological Reviews. Cambridge University Press; 2020:29–47. https://doi.org/10.1017/9781108638210.003

Work T T, McCullough D G, Cavey JF, Komsa R (2005) Arrival rate of nonindigenous insect species into the United States through foreign trade. Biological Invasions 7: 323–332. https://doi.org/10.1007/s10530–004–1663-x

Yamamura K, Katsumata H (1999) Estimation of the probability of insect pest introduction through imported commodities. Population Ecology 41: 275–282. https://doi.org/10.1007/s101440050032