Interdisciplinary Analysis of Plant Health Threats to Arable and Horticultural Crops in Scotland

Project Final Report

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Research Team:

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Sarah Gurr is a plant pathologist, with expertise in the molecular mechanisms underpinning pathogenesis and recent emphasis, with DB, on fungal infestations and in their global movement and control. She has authored or co-authored over 180 publications in this area, and with a contribution to the Government Foresight report on "Biological Hazards". She sits on the Scottish Government Advisory board (RESAS)

Alison Karley is an agroecologist with expertise in plant production and plant-insect interactions, focussing on improved crop performance under reduced inputs and a changing climate. Her research tests alternative cropping practices and pest control strategies to reduce reliance on external inputs and increase resilience to environmental stress. She uses participatory research and co-design with farmers and other agricultural stakeholders to trial innovative practices for agricultural sustainability. She leads research funded by RESAS, AHDB and other sources into pest epidemiology, plant-pest interactions, and IPM.

Luz-Maria Lozada-Ellison is a Socio-Economist trained in anthropology. She has carried out research with land managers and other stakeholders in different countries. She works with land managers in Scotland to elicit preferences and decision-making for uptake of environmental practices and cooperation for conservation, and in the adoption of agroecological principles. In collaboration with AK, she is consulting stakeholders to identify scenarios of future threats to agricultural production (RESAS project JHI-A1-2).

Tim Beale is a Senior Data Analyst in CABI's Digital Development team, steering the organisation's geospatial work from data collection to end-product delivery. Tim has over 16 years of expertise in resolving complex technical challenges within hydrological, agricultural, and environmental systems. Specialising in Geographic Information Systems (GIS), Tim's interests lie in spatial analysis and data visualisation, and he is responsible for maintaining CABI's geographic products such as the CABI Distribution Database, a collection of over one million pest and disease occurrence records.

Alex Gimenez Romero is a PhD student in Physics of Complex Systems at the Institute for Cross-Disciplinary Physics and Complex Systems in Mallorca, Spain under the supervision of Dr Manuel Matías. Alex conducted an internship with Prof. Bebber to implement the Pest or Pathogen Spread (PoPS) model for invasive insect pests. Alex has worked on modelling a range of ecological systems and has published global predictions for the risk of establishment of Pierce's disease of grapevines.

Content

1 List of Abbreviations

AHDB	Agriculture and Horticulture Development Board
BMU	Best Matching Unit
CABI	Centre for Agriculture and Bioscience International
CMIP	Coupled Model Intercomparison Project
CPB	Colorado Potato Beetle
DD	Degree Days
Defra	Department for Environment, Food & Rural Affairs
DoC	Drivers of Change
EFSA	European Food Safety Authority
EPPO	European and Mediterranean Plant Protection Organization
EWG	Expert Working Group
FAB	Fight Against Blight
GCM	General Circulation Model
GLAD	Global Land and Data
IPPC	International Plant Protection Convention
NPPO	National Plant Protection Organisation
PoPs	Pest or Pathogen Spread
PPD	Plant Pests and Diseases
PPO	Plant Protection Organisation
PRA	Pest Risk Analysis
P_S	Probability of Presence
RCP	Representative Concentration Pathway
R_{BIO}	Biophysical Risk
R_{TRD}	Risk from Trade of Crops and Live Plants
R_{TRV}	Risk from Importation by Overseas or Returning Tourists
SEI	Susceptible-Exposed-Infected
SI	Susceptible-Infected
SOM	Self-Organizing Map
SPAM	Spatial Production Allocation Model
SSP	Shared Socio-economic Pathway
STEEP	Social, Technological, Economic, Environmental and Political
UKCP18	United Kingdom Climate Projections 2018

2 Executive Summary

Background

Emerging plant pests and diseases (PPD) pose an escalating threat to global agriculture, horticulture, forestry, and ecosystems. PPD emergence stems from factors such as evolving virulence, resistance to pesticides, host jumps, trade and transport, climate change, and alterations in management practices. Despite limited empirical data on production losses, expert opinions estimate pre-harvest losses from PPDs at around one-fifth of potential crop yield. The global expenditure on plant breeding and agrochemical research and development, along with the pesticide market, underscores the economic significance of combating PPD. The arrival and establishment of novel PPDs can lead to transformative impacts on landscapes, economies, and society. Historical examples like the Great Famine in Ireland and the devastation of Sri Lanka's coffee export industry highlight the far-reaching consequences of PPD outbreaks. Recent incidents such as the re-emergence of wheat stem rust in the UK and the emergency eradication in 2023 of Colorado Potato Beetle (CPB) in England highlights the ongoing vulnerability of agriculture to biological threats. Addressing emerging PPDs requires concerted efforts in research, development, and management practices to safeguard agricultural productivity, biodiversity, and societal well-being against the evolving challenges posed by plant pests and diseases.

The interconnectedness of England, Wales, and Scotland, characterised by open land borders, similar climates, and shared cropping systems, underscores the common plant protection issues they face. Recent invasions, such as the spread of *Phytophthora* species and Ash Dieback across the UK, illustrate the risk of PPD introduction and establishment for Scotland. The scientific study of plant health in Scotland has roots tracing back to the devastating outbreaks of late blight of potato in Europe in 1845. Since then, numerous non-native pathogens have become established in Great Britain, with several first detections recorded in Scotland, impacting both forestry and agriculture. The arrival of the A2 mating type of *Phytophthora infestans* in 1983 was a critical event, because this enabled sexual recombination with the established A1 mating type, and the formation of long-lived oospores that can survive in soil for many years, with long-term consequences for disease management in potato production. Climate change is driving shifts in pest and disease dynamics, with growing incidences of nematode and insect pests, microbial diseases, and the re-emergence of formerly important pathogens. The spread of PPDs is facilitated by climate change-induced alterations in geographical distributions, affecting both PPDs and their host plants. In summary, ongoing vigilance, monitoring, and adaptation strategies are crucial for mitigating the risks posed by emerging PPDs and their impacts on Scottish agriculture and ecosystems in the face of changing environmental conditions.

Research questions

Here we present an interdisciplinary risk analysis for PPD in Scotland, to identify those that have high risk of arrival and establishment. We then co-designed plausible future scenarios for the arable and horticultural sector in Scotland and we tested the scenarios in relation to a selected subset of three PPDs, highlighted by the risk analysis, as example threats to the arable and horticulture sector (cereal, potato and soft fruit crops). We then applied a state-of-the-art invasion model to a particular case study to illustrate how such models can be used to understand the risk to Scotland under future climate change. Finally, we assessed knowledge gaps that should be addressed to improve the precision of Pest Risk Analysis (PRA) for Scotland.

Research undertaken

We employed the CABI Distribution Database for PPDs to analyse 171,481 distribution records of 9472 PPDs across 480 geographical units. We first conducted an ecological assemblage analysis to identify which geographical regions shared the most PPD with Scotland, then applied a machine learning algorithm known as a Self-Organizing Map (SOM) to estimate probabilities of invasion by PPDs currently absent from Scotland and the UK. We then used global climate matching and crop distributions to estimate biophysical risk ratings for absent PPD, focussing on the most important crops for Scotland (barley, wheat, oats, oilseed rape and potato). We used international imports of crop products and live plants into the UK to estimate the risk of arrival by trade, and international tourism data to estimate the risk of PPD arrival through travel. We co-designed with a diverse range of stakeholders (farmers, agronomists, crop breeders, scientists, policy advisors, regulatory bodies, and value chain actors) plausible future scenarios for Scotland's arable and horticulture sector and considered how risks from PPDs would differ among scenarios. The timeframe for the scenarios was set at 10 years. We elicited stakeholders' knowledge about potential future pest and disease issues to compare with model results. Finally, we employed the Pest or Pathogen Spread (PoPS) model to investigate how a PPD of particular interest, Colorado Potato Beetle, might invade the UK under a range of different climate scenarios, focussing on the risk of establishment in Scotland following an initial invasion into southern England.

Main findings

There were significant changes in crop cover in 2023 compared with previous years, particularly a large increase in oilseed rape and a decline in oat production. Climate change, as well as socioeconomic factors, are likely to change the composition and distribution of crop production in Scotland which is dominated by barley, wheat, potato, oilseed rape and oats, with soft fruit, grown over a smaller area, also contributing significantly to the Scottish economy. While some recent analyses have considered changing suitability for some individual crops across the UK and there is a predicted decrease in barley yields in Scotland, we are unaware of any comprehensive projections of the suitability of other crops for Scotland under climate change.

Our biophysical risk models identified a number of PPDs of greatest risk to Scotland. PPDs which emerged as being of particular concern included: Wheat thrip (*Haplothrips tritici*), corn earworm moth (*Helicoverpa armigera*), wheat common bunt (*Tilletia laevis*) and CPB (*Leptinotarsa decemlineata*).

Some of those identified had high unmitigated risk ratings in the Defra Plant Health Risk Register (PHRR), including: CPB, beet root weevil (*Asproparthenis punctiventris*), the disease vector *Hyalesthes obsoletus*, pea leafminer (*Liriomyza huidobrensis*), tarnished plant bug (*Lygus lineolaris*) and potato virus S.

The potato flea beetle (*Epitrix papa*) was identified as a risk through travel and has a high PHRR unmitigated risk rating.

Additionally, we consider as a potential threat to Scottish fruit production the blueberry rust pathogen (*Pucciniastrum minimum*, syn. *Thekopsora minima*), which was first reported in Scotland in 2021, and as a potential threat to cereal production the wheat stem rust pathogen (*Puccinia graminis* f.sp. *tritici*) due to its recent re-emergence in the UK and Ireland.

Summary of PPDs identified as of greatest risk from multi-model and interdisciplinary analyses (shown in alphabetical order):

Organism	Common name	Comments
Epitrix papa	Potato flea beetle	High travel introduction risk and Defra risk rating.
Eurygaster integriceps	Senn pest (shield bug)	Climate change increases risk.
Haplothrips tritici	Wheat thrip	Distributed across Eurasia.
Helicoverpa armigera	Cotton bollworm moth	Wide host range and global distribution.
Hyalesthes obsoletus	Hemipteran bug	Disease vector with high Defra risk rating
Leptinotarsa decemlineata	Colorado Potato Beetle	Recently intercepted in southern England.
Liriomyza huidobrensis	Pea leafminer fly	High Defra risk rating
Lygus lineolaris	Tarnished plant bug	High Defra risk rating
Meloidogyne javanica	Javanese root-knot nematode	Wide host range and high risk to glasshouse crops.
Potato virus S		High trade import and Defra risk rating.
Puccinia graminis f.sp. *tritici*	Wheat stem rust	Re-emerging throughout the UK.
Spodoptera frugiperda	Fall armyworm	Climate change increases risk.
Tilletia laevis	Common bunt of wheat	Global distribution, high trade import risk.

Several species are known migrants to southern UK and could become problematic in Scotland under climate change. Our PoPS dynamic model showed that a successful invasion of CPB into southern UK is likely to spread to Scotland within decades, assisted by climate warming which accelerates development time and promotes adult dispersal. Others, like wheat dwarf bunt, benefit from cold winter temperatures and may become less threatening. We were able to conduct detailed invasion and climate risk modelling for CPB because sufficient ecophysiological data (host range, life cycle, temperature-dependent development and dispersal parameters) are available for this species. For many other species, however, such information is either unavailable, incomplete, or outdated.

CABI and EPPO maintain the most comprehensive information on global PPD distributions. We found that these records can be incomplete for subnational regions like Scotland. While these databases continue to be updated and refined, it would be valuable for plant health management and risk analysis if responsible authorities maintained and published lists of established and emergent PPDs in Scotland. We also found that the Defra PHRR tends not to explicitly provide information on potential geographical distributions of invasive species within the UK. Indications of which UK regions are most at risk would be valuable.

Our analyses of PPD risks from trade and transport employed national-level data on trade and tourism flows along with CABI PPD distribution data. Defra has recently begun publishing data on interceptions of imported plants and associated harmful organisms (e.g. PPD), although the port of interception is not given.

We found that elicitation of PPDs by stakeholders as likely to cause future issues to the arable and horticulture sector showed little overlap with results from our biophysical risk analyses. This is likely because stakeholders focussed on species already present in the UK, e.g. marmorated stink bug in fruit and vegetable crops (*Halyomorpha halys*), cereal take-all (*Gaeumannomyces* spp.). CPB was highlighted by stakeholders as one of several pests of concern. The discrepancy of knowledge about PPD by stakeholders and modellers indicates the need for more co-production of new knowledge to mitigate pest and disease impacts to the arable and horticultural sector.

With stakeholders we co-designed two plausible scenarios which were tested against three example PPDs: CPD, emerging wheat stem rust, and recently arrived blueberry rust. These three PPDs were chosen as example threats to the potato, cereal and soft fruit industries, respectively, which represent economically important crops within the arable and horticulture sector in Scotland.

The scenarios present two plausible futures. These were entitled: “Scotland’s vision” and “Agriculture elsewhere”, reflecting different degrees of investment in the sector, international trade, technological innovation, governmental support and food consumption habits. PPD were considered to pose a greater threat to Scotland’s agricultural production under the “Agriculture elsewhere” scenario.

Likely impacts of focal PPDs in 10 years’ horizon differed between the two scenarios. Under the first “Scotland’s own vision” scenario, stakeholders highlighted that the government's precision and targeted farming programme, along with the resilience of the seed potato industry, mitigates the moderate impact of CPB. Precision farming practices improve PPD detection, allowing timely action and regulatory flexibility post-Brexit. Continuous research and development efforts help the cereal sector adapt to wheat stem rust, minimizing its small effect. Reduced wheat planting due to fertilizer constraints for achieving Net Zero emissions could further mitigate disease risks. Stakeholders predicted that blueberry rust’s permanent effect poses challenges that would be made worse by consumers' unwillingness to pay higher prices for locally produced blueberries. Despite increased production costs, local preference and potential disruptions in other countries could offer competitive advantages to Scottish producers.

Under a second “Agriculture elsewhere” scenario, stakeholders assessed that the permanent effect of CPB could severely undermine Scotland's potato industry, particularly without effective crop protection chemicals. The loss of prime arable land to CPB infestation could raise concerns about the industry's sustainability with potential repercussions for export markets. Stakeholders predicted that the major to permanent effect of wheat stem rust could pose significant challenges to Scotland's wheat sector, exacerbated by limited resistant wheat varieties and unpredictable weather conditions. While early-stage control measures are feasible, stakeholders proposed that technological and biological solutions are crucial for large-scale farms. The major to permanent effect of blueberry rust was assessed by stakeholders as a threat to Scotland's horticulture sector, necessitating technological innovation and potential pressure for fungicide use. Under this scenario, despite ongoing international trade, the disease would add further strain to the competitiveness of the blueberry industry. Overall, proactive research, targeted farming practices, and consumer preferences were felt by stakeholders to play crucial roles in managing and mitigating the impacts of PPD on Scotland's agricultural sector.

Recommendations

Here we list recommendations emerging from our data analyses, modelling and stakeholder engagement exercises.

Project recommendations and future research needs:

1. Conduct biophysical and socioeconomic modelling to understand potential future changes in Scotland’s crop production in coming decades, particularly to identify where and when novel crops may be cultivated.
2. Maintain and publish an active list of present and emerging PPD in Scotland or work with others (e.g. CABI) to do so.
3. Maintain and publish data on PPD interceptions at Scottish ports.
4. PPDs flagged as being of high risk by multiple methods in the present analysis should be prioritised for research into management and control methods.
5. Detailed life history and ecophysiological information for PPDs of interest should be collated from the literature or obtained via experiment to enable invasion modelling.
6. Consider emerging PPD as governmental agricultural support programmes are developed.
7. Conduct co-creation of knowledge for PPD management (research with stakeholders which translate into actions). The PPD listed as of concern by stakeholders did not

align with those identified by risk modelling, highlighting a need for knowledge exchange to raise awareness and continued dialogue.

Recommendations from stakeholder analysis of arable and horticultural sector future scenarios:

8. Conduct research and development on adapting the farming calendar for planting which could potentially help to adapt to the changing climate.
9. Adopt existing solutions, such as detection and application, in good time to mitigate PPD impacts.
10. Switch from monoculture to a more diverse cropping system, including resistant varieties and mixtures of landraces, to increase resilience.
11. Conduct research and development on agrobiodiversity to provide buffers against potential threats.
12. Promote crop production for food rather than non-food uses.
13. Improve weather driven PPD risk models ("decision support systems") to enable targeted control measures.
14. Analyse the economic implications of changing PPD management methods, e.g. switching from chemical to biological control or novel chemical control.
15. Improve border controls and inspections of plants and other products to reduce the risks of crop losses and costs of treatment.
16. Increase support for farmers or others to monitor fields in relation to PPD.
17. Provide government insurance and guarantee schemes for farmers to buffer losses and provide security.

3 Introduction

3.1 Emerging plant pests and diseases

Emerging plant pests and diseases (PPD) present a growing threat to global agriculture, horticulture, forestry and natural ecosystems (Bebber et al., 2014a; Fones et al., 2020; Guégan et al., 2023; Paini et al., 2016; Ristaino et al., 2021). A wide diversity of pathogenic and herbivorous species affect plants, including viruses, bacteria, fungi, oomycetes, invertebrates, molluscs and mammals. Weeds are also a major challenge to global agriculture (Morin et al., 2013). Emerging PPD are distinguished from those which are already established and endemic to a particular region (Ristaino et al., 2021). The causes of PPD emergence are diverse, but include evolution of virulence to resistant crop varieties, evolution of resistance to pesticides, host jumps to crop species, introductions through natural dispersal or trade and transport, shifts in suitable regions through climate change and alterations in management practices (Bebber, 2015; Brasier, 2008; Corredor-Moreno and Saunders, 2020; Hawkins et al., 2019; Stukenbrock and McDonald, 2008)

Though empirical data on production losses to these organisms are scarce, expert opinion suggests that around one fifth of potential crop yield is lost pre-harvest (Savary et al., 2019), with further post-harvest losses due to consumption and spoilage (Johns et al., 2022). Total global expenditure on plant breeding and agrochemical research and development stands at around US$ 6.5 billion per year (Nishimoto, 2019), while the global pesticide market reached approximately US$ 40 billion in 2020 (FAO, 2022). The emergence, or arrival and establishment, of a novel PPD can have transformative impacts on landscapes, economies and society. The wide-ranging impact of the Great Famine in Ireland in the mid-19th Century, caused by a combination of late blight (*Phytophthora infestans*) infection of potato crops and poor governance, is well known (Turner, 2005). The introduction of coffee leaf rust fungus (*Hemileia vastatrix*) to Sri Lanka (formerly Ceylon) from West Africa in the 1860s led to the demise of what was once the world's third largest coffee export industry (McCook, 2006). Sri Lanka is now the world's second largest tea exporter after China (Voora et al., 2019). More recently, the rapid spread of Ash Dieback (caused by the fungus *Hymenoscyphus fraxineus*) across Europe may lead to cascading biodiversity losses as forest ecosystems are destabilised by the loss of a keystone tree species (Hultberg et al., 2020). The re-emergence of wheat stem rust (*Puccinia graminis* f.sp. *tritici*) in the UK (Lewis et al., 2018), and emergency eradication of a small population of Colorado Potato Beetle (*Leptinotarsa decemlineata*, hereafter CPB) found in Kent, England in the summer of 2023 (DEFRA, 2023) illustrate the continued exposure of our plant resources to biological threats.

Here, we present an interdisciplinary analysis of plant health threats to Scotland, focussing on food crops in the arable and horticulture sector. We combine a suite of biophysical risk models with co-designing scenario planning with stakeholders to enable prioritization of actions to tackle new and emerging plant health threats.

3.2 Crop production in Scotland

The June Agricultural Census collates information on crop and livestock production from agricultural holdings in Scotland (Scottish Government, 2023). In 2023, Scotland's total agricultural area reached 5.33 million hectares, constituting 69 per cent of the country's total land. However, a significant portion of this agricultural land, particularly in hilly or mountainous regions, is used for rough grazing. The majority of cropland is found on the east coast, particularly Moray, Aberdeenshire, Angus, Perth and Kinross, Fife, East Lothian and the Scottish Borders (Figure 1a). According to remote sensing estimates (Potapov et al., 2022), total cropland cover increased by around 13.6 per cent between 2003 and 2019 (Figure 1b). Only around 7.6 per cent of Scotland's total land area is under arable crop production or fallow (Table 1). Nevertheless, agriculturally derived exports (particularly whisky) make an important contribution to the economy.

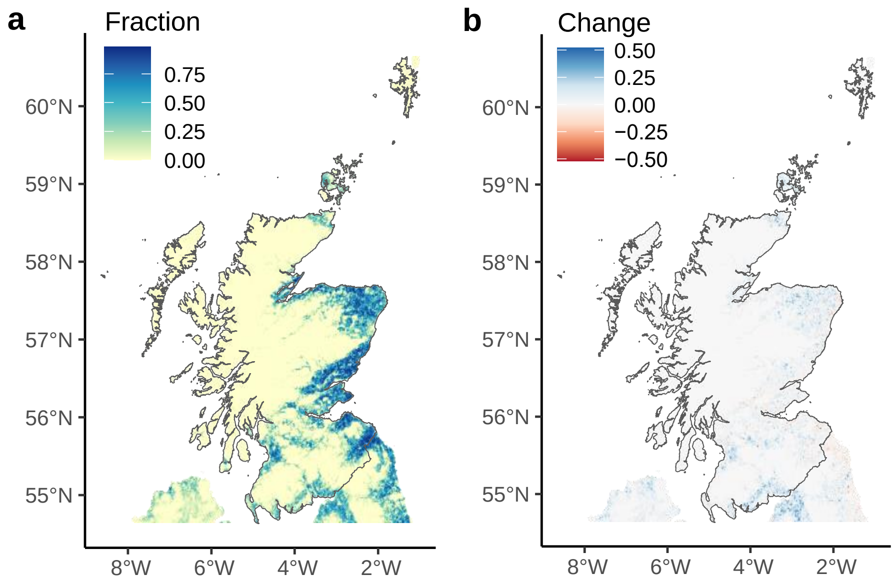

Figure 1. a. Crop area fraction in Scotland, 2019. b. Change in crop area fraction between 2003 and 2019. Cropland fraction from the Global Land and Data (GLAD) product aggregated to 1 km resolution.

Out of the holdings with arable land, 85 per cent (3,600) engaged in general crop rotation, covering at least 75 per cent of their land, totalling 562,700 hectares. Winter planted crops expanded slightly, primarily driven by an increase in winter wheat cultivation, covering approximately 107,200 hectares. Conversely, spring planting decreased slightly compared to the five-year average, largely due to a significant 27 per cent reduction in the area allocated to spring oats. In 2023, the cultivation area for cereals and oilseeds amounted to 477,000 hectares, a slight increase from the five-year average of 468,000 hectares. Barley and wheat, crucial crops for the whisky industry, accounted for 62 per cent and 23 per cent of the total area, respectively, mirroring the five-year averages. However, oat cultivation witnessed a 20 per cent decline compared to the five-year average, while oilseed cultivation increased by 25 per cent. Other minor crops such as rye and triticale collectively occupied around 7,500 hectares in 2023. Year-to-year variation in production is normal given seasonal variation in weather and prices – so for example the increase in oilseed rape reflects higher market prices for this commodity in the year of survey. The total area dedicated to potato cultivation was 26,600 hectares in 2023, marking a six per cent decrease from the five-year average of 28,400 hectares. This decline was attributed to reductions in both seed (down by five per cent) and ware potatoes (down by seven per cent). The cultivation of vegetables intended for human consumption (excluding potatoes) expanded by seven per cent, reaching 21,500 hectares in 2023. Conversely, the area designated for vegetables for animal feed decreased by five per cent, totalling 15,800 hectares.

Soft fruit cultivation areas, including blackcurrants, blueberries, and strawberries, experienced a seven per cent decline in 2023 compared to the five-year average. The estimated total soft fruit area in June 2023 was around 2,000 hectares, with strawberries, although the most popular fruit, decreasing by 11 per cent to 1,000 hectares compared to the five-year average of 1,100 hectares. The area used to grow raspberries continued to decline, to 200 ha in total. Blackcurrants and blueberries, on the other hand, saw increases in cultivation area to 381 ha and 241 ha, respectively. Approximately 69 per cent of soft fruit cultivation occurs under cover, utilizing either glasshouses or poly-tunnels.

Table 1. Crop production area in Scotland from the June Agricultural Census 2023 (Scottish Government, 2023).

Crop/Land use	Area (ha) 2017-2021 mean	Area (ha) 2023	Change (%)
Wheat	102,971	107,166	4.1%
Triticale	596	258	-56.6%
Winter barley	44,038	46,358	5.3%
Spring barley	248,805	249,462	0.3%
Barley Total	*292,843*	*295,820*	*1.0%*
Winter oats	9,118	8,785	-3.6%
Spring oats	23,756	17,397	-26.8%
Oats Total	*32,874*	*26,182*	*-20.4%*
Rye	5,889	7,197	22.2%
Mixed grain - not on the dataset	23	21	-10.0%
Total cereals	***435,192***	***436,644***	***0.3%***
Winter oilseed rape	32,167	40,484	25.9%
Spring oilseed rape	376	257	-31.7%
Linseed	119	49	-58.4%
Total oilseeds	***32,614***	***40,790***	***25.1%***
Protein peas	483	440	-9.0%
Field beans	2,204	2,654	20.4%
Seed potatoes	12,384	11,743	-5.2%
Ware potatoes	15,985	14,851	-7.1%
Total potatoes	*28,370*	*26,594*	*-6.3%*
Turnips/swedes	3,728	3,026	-18.8%
Kale/cabbage	2,025	1,961	-3.1%
Maize	952	1,460	53.3%
Oilseed rape	2,124	1,768	-16.8%
Fodder beet	964	1,041	8.0%
Lupins	15	11	-28.8%
Other crops for stockfeeding	6,868	6,517	-5.1%
Total crops for stockfeeding	***16,670***	***15,784***	***-5.3%***
Vegetables for human consumption	19,982	21,467	7.4%
Orchard fruit	131	160	22.1%
Soft fruit	2,098	1,961	-6.5%
Other crops	11,206	11,489	2.5%
Fallow - under 5 years	29,399	23,117	-21.4%
Fallow - 5th year & over	4,874	5,508	13.0%
Total Fallow	***34,273***	***28,624***	***-16.5%***
Total crops, fallow, and set-aside	***583,227***	***586,702***	***0.6%***

3.3 Plant Pests and Diseases in Scotland

Open land borders, similar climate and shared cropping systems mean that England, Wales and Scotland face many of the same plant protection issues. Indeed, the Defra Plant Health Risk Register (PHRR) which assesses PPD for potential invasion risk and impact considers the UK as a whole (Baker et al., 2014). Recent invasions of plant pathogens, such as *Phytophthora* spp. (Tracy, 2009) and Ash Dieback (Wylder et al., 2018), have spread rapidly across the UK. Thus, arrival and establishment of a PPD of a particular crop in any part of the UK poses a potential threat to production of that crop in Scotland.

The origin of scientific study of plant health has been linked to the devastating outbreaks of late blight of potato across Europe, including Scotland, in 1845 (Bourke, 1964; Ristaino, 2002). Indeed, one of the earliest studies of late blight was published in 1845 in Edinburgh by agricultural chemist and co-founder of the British Association for the Advancement of Science, J. F. W. Johnston (cited by Bourke, 1964). In the first half of the 20th Century, over 100 new records of plant pathogenic viruses, bacteria and fungi were recorded in Scotland (Foister, 1961).

Between 1970 and 2004, 234 non-native pathogens became established in Great Britain (Jones and Baker, 2007). The majority of these were fungi, with smaller numbers of oomycetes, bacteria and viruses. Just over half were found on ornamental crops, illustrating the importance of the live plant trade as a risk factor for plant disease import (Brasier, 2008). Where recorded, the South East of England was the most common region for the location of the first detection, but several pathogens were first recorded in Scotland. A substantial number of the first reports from Scotland are forestry pathogens, including *Anthosomella* spp. and *Ramichloridium pini* affecting pines, *Ceratocystis laricicola* affecting larch, *Clasterosporium flexum* and *Kabatina thujae* affecting Lawson's cypress, and *Septoria betulae* causing leaf spot of downy birch. However, several important horticultural and agricultural pathogens were also first recorded in Scotland. *Phytophthora fragariae* var. *rubi* and *P. idaei* causing root rot of raspberry were first reported in 1987 and have since become important pathogens of this soft fruit crop (The James Hutton Institute, 2023). Other soft fruit pathogens include *Conythyrium fragariae* causing crown necrosis of strawberry, first recorded in 1972, and Hawaiian Rubus leaf curl virus affecting blackberry, recorded in 2003. For field crops the most important new arrival was the A2 mating type of *P. infestans*, in 1983 and the first diagnosis of *Ramularia collo-cygni* as the causal pathogen of leaf spot of barley in 1998. Arrival of the A2 mating type of *P. infestans* was a critical event because this enabled sexual recombination with the established A1 mating type (Cooke et al., 2003), and the formation of long-lived oospores that can survive in soil for many years (Torro-Galiana et al., 2023).

The legacy of the arrival of the A2 mating type has been investigated in a recent study of spatiotemporal diversity of non-clonal outbreaks of *P. infestans* across the UK between 2006 and 2018 (Torro-Galiana et al., 2023). This study employed data collected by the Fight Against Blight (FAB) campaign, funded by the Agriculture and Horticulture Development Board (AHDB), which has tracked *P. infestans* populations across the UK since 2003. The research identified a significant cluster of such outbreaks in the north-east of Scotland, indicating a clear geographic separation in pathogen biology between northern and southern potato production areas in Scotland. The presence of non-clonal outbreaks may lead to greater pathogen diversity, impacting disease management practices in the potato industry. Factors influencing these outbreaks include climatological conditions favouring oospore formation, survival, and germination. The study emphasises the importance of considering oospores in soil as a source of primary inoculum and understanding their distribution for effective disease control. Despite the risk posed by the high incidence of non-clonal outbreaks in the north-east of Scotland, there is limited evidence of significant spread to other regions. The research highlights the need for continued good practices in late blight control, including regulated rotations for seed crops. Gardens and allotments are identified as potential sources of high pathogen diversity, suggesting the necessity for more intensive monitoring in non-commercial potato areas.

The two decades prior to 2006 saw growing incidences of a range of nematode and insect pests, as well as microbial diseases (Davies et al., 2007). Cabbage stem flee beetle (*Psylliodes chrysocephala*) and rape winter stem beetle (*Ceutorhynchus picitarsis*) were noted for the first time as problems for winter oilseed rape growers, possibly as a result of warming temperatures. Climate change may also have driven increases in the population of wheat bulb fly (*Delia coarctata*) and nematodes such as *Pratylenchus* spp. and *Trichodorus* spp., as well as infection risk from brown rust (*Puccinia triticina*). Changes in other factors such as evolution of resistance to pesticides, virulence against formerly resistant crop varieties, introduction of new resistant varieties and changes in agrochemical usage have also influenced the shifting importance of different PPD to Scottish agriculture (Davies et al., 2007). Recent re-emergences of formerly important pathogens, for example wheat stem rust caused by *Puccinia graminis* f. sp. *tritici* (Tsushima et al., 2022), and new reports of hitherto absent pathogens, such as blueberry rust caused by *Pucciniastrum minimum* detected in 2021 in Perthshire (Latham et al., 2022), demonstrate the continued risk from emerging PPD. Globally, PPDs have yet to reach all areas where they would find suitable host crops, but they are being rapidly disseminated (Bebber et al., 2014a, 2014b). Climate change is inexorably altering the geographical distributions of suitable areas for PPD (Bebber, 2015; Bebber et al., 2013) and their host plants (Beck, 2013), and will continue to do so (Chaloner et al., 2021).

3.4 Pest Risk Assessment

Pest Risk Assessment (PRA, also known as Pest Risk Analysis) is the process of estimating the probabilities of arrival and establishment of exotic PPD in a particular region of interest, the subsequent potential damage to assets (e.g. crop yields), and the options available for reducing risks and impacts (Jeger et al., 2018). PRA has a long history, dating back to the early 20th Century when climate was used to assess the potential distributions of insect pests in the USA (Sutherst, 2014). PRA tends to incorporate both quantitative analyses developed from statistical or mechanistic models of risk (Robinet et al., 2012) and qualitive analyses such as expert knowledge elicitation (Jeger et al., 2018).

PRA is undertaken or commissioned by national and international plant protection organizations (PPO) globally, based on frameworks developed by the International Plant Protection Convention (IPPC). Europe has two complementary PRA systems (EPPO, 2019; Jeger et al., 2018). The European and Mediterranean Plant Protection Organization (EPPO) addresses the challenge of new and emerging PPD by maintaining an Alert List, initiated in the 1990s (EPPO, 2019). This list aims to alert EPPO member countries to potential threats, enabling early warnings and facilitating PRA. The EPPO Secretariat selects PPD for the Alert List based on literature, suggestions from member countries' National Plant Protection Organizations (NPPOs), and recommendations from expert panels. The list includes PPD that could pose a phytosanitary risk to the EPPO region, such as those new to science, causing new outbreaks, or spreading rapidly. For PPD other than plants, prioritization for PRA relies on expert judgment, with the EPPO Alert List being a crucial reference. The process considers factors like geographical distribution, crop importance, spread speed, potential pathways, impact, and data availability. Expert Working Groups (EWGs), involving experts from both EPPO and non-EPPO countries, have been formed since 2006 to conduct PRAs, initially following EPPO Standard PM 5/3 and later adopting the PM 5/5 Decision-Support Scheme for Express Pest Risk Analysis. The EPPO also conducts pathway analyses to identify risks associated with specific commodities, such as live plants, fruit, and wood commodities. These analyses aim to identify potential PPD that could be introduced with commodities, though they do not include risk management sections. National PRAs have been utilized since 2000 to support EPPO recommendations, with a review process in place. Although a large number of data sources have been collated to support PRA, EPPO faces challenges in obtaining detailed information on industry practices and the role of current practices in PPD management. While the EPPO emphasises the importance of pathway analysis, the development of a commodity PRA scheme has not been prioritised. The new EU Regulation 2016/2031 allows the prohibition of high-risk commodities based on a preliminary assessment. Work on identifying high-risk pathways is ongoing in many EU countries, with a recommendation to allocate more resources to the Global Database for pathway analysis. The European Food Safety Authority (EFSA) is designated to perform commodity risk assessment for EU countries, and there is an agreement to share commodity PRAs via the EPPO Platform on PRAs.

The European Commission tasked the European Food Safety Authority (EFSA) with assessing the status of certain plant PPD listed in Council Directive 2000/29/EC for future plant health regulations (Jeger et al., 2018). The assessment involves a two-phase approach: pest categorisation to determine quarantine or regulated non-quarantine status in the EU, followed by a pest risk assessment for selected PPD. The EFSA Panel on Plant Health developed a methodological framework, emphasising quantitative risk assessment to enhance clarity in risk management decisions. This guidance focuses on the second phase of assessment, aligning with international standards and EFSA documents. It advises assessors on risk assessment design, stressing interaction with decision-makers and proposing a two-tiered approach involving expert knowledge elicitation and modelling. The guidance provides a flexible framework adaptable to available resources and supports the production of quantitative PRA, aligning with IPPC standards. It addresses risk communication and emphasises transparency and iterative processes in data interpretation. The document includes templates, examples, and tools for both phases, and concludes by recommending regular reviews to incorporate feedback and evolving needs. The aim is to inform risk managers about PPD entry, establishment, spread, and impact, facilitating effective risk management decisions.

The UK is no longer a member of the EU and hence PRA has proceeded somewhat independently. Defra established the PHRR in April 2013, following publicity around emerging PPD triggered by Ash Dieback (Baker et al., 2014). The PHRR relies heavily on EPPO data and PRA results, but there are certain differences in approach and analysis. For example, the PHRR includes assessments of the risk of entry, establishment and spread and the value of asset at risk, under unmitigated or mitigated scenarios, on a simple 1–5 scale. In contrast EPPO PRAs provide ordinal risk estimates without consideration of mitigation scenarios. Our approach is to conduct quantitative horizon-scanning to identify those PPDs that are not yet present in Scotland but that have high risk of arrival and establishment. We then select a subset of these for qualitative appraisal through expert knowledge elicitation to understand how key stakeholders view the risk from PPDs identified as a priority by our quantitative models. We then conduct detailed quantitative modelling for a particular case study to illustrate how state-of-the-art PPD dispersal models can be used to assess risk invasion risk. Finally, we assess knowledge gaps that should be addressed to improve the precision of PRA for Scotland.

4 Data Sources

4.1 *PPD geographical distributions*

Sources for all data utilized in this analysis are given in Table 2.

PPD distributions at subnational resolution were obtained with permission from CABI. We term this the *CABI dataset*. The organization CABI has compiled data on PPD distributions from reports in the academic literature and other published sources over many decades (Pasiecznik et al., 2005). This compendium is continually updated with new observations. We excluded non-PPD invasive species (e.g. weeds) from our analysis. Our version was obtained in February 2023 and contains 171,481 records of 9472 PPDs across 480 geographical units, of which 192 are countries, 198 are subnational divisions (e.g. US States, China Provinces), and the remainder are variously islands (e.g. Borneo), territories (e.g. American Samoa), historical regions (e.g. Czechoslovakia) or non-official subnational divisions (e.g. Southern Russia, Central Russia). Scotland is classed as a first-level political division (ADM1) of the United Kingdom. Among the PPDs are 437 species and subspecies of fungi, 286 species of beetle, 263 species of moths and butterflies, 257 bugs (Insecta: Hemiptera), 226 viruses and smaller numbers of other taxonomic groups of animals (including nematodes) and microbes. Notes on known extent (e.g. localized, widespread) are available for a subset of PPDs. Host range (plant species known to be affected by each PPD) was obtained from CABI. Although the CABI distribution data are the most comprehensive available, there are issues of reporting bias which must be taken into account when using them in analyses (Bebber et al., 2019, 2014b). Additional information on recent PPD invasions was obtained from ProMED-mail and the CABI PlantwisePlus Knowledge Bank pest alerts service.

4.2 *DEFRA Plant Health Risk Register*

We obtained PRA for the United Kingdom from the Defra PHRR (Baker et al., 2014), downloaded in December 2023. We term this the PHRR dataset. PHRR provides qualitative and quantitative risk assessments for 1423 PPDs comprising 783 insects, 201 viruses or viroids, 192 fungi, 82 nematodes and various other groups including some weeds. PHRR currently shares 766 PPD with the CABI dataset (assuming synonymy in taxonomic names). PHRR is continually updated with new PRAs. PHRR contains information on global distributions at country level but does not differentiate Scotland from the United Kingdom. However, presence in Scotland is mentioned in comments for a small number of PPDs, namely *Chryseococcus arecae*, *Dendroctonus micans, Dendrolimus pini, Dothistroma septosporum* and European mountain ash ringspot associated virus. The bacterium *Dickeya solani*, causing blackleg disease of potato, is flagged as a particular threat to potato production in Scotland. PHRR provides mitigated and unmitigated risk ratings for each PPD in three categories: Likelihood of establishment and spread, Impact, and Value at risk. Ratings are ordinal and run from 1 (low risk) to 5 (high risk), with an Overall UK risk rating (from 1 to 125) given as the product of these three components. Unmitigated ratings assume no plant health controls, while mitigated ratings consider the effectiveness of current mitigations (such as import prohibitions on live host plants). PHRR also provides known geographical distributions, plant host range, major hosts, uncertainties in understanding risk, current mitigations and proposed actions. For many PPDs, a detailed risk assessment document is also available.

4.3 *Climate data*

4.3.1 *Global bioclimatic variables*

We obtained historical (1970–2000 mean) global bioclimatic data from WorldClim v2.1 downscaled to 10 arc minute resolution, or approximately 1 km resolution at 55° latitude (Fick and Hijmans, 2017). Bioclimatic variables, often referred to as bioclimatic indices, are a set of climatic parameters that are used to characterise and classify the climate of a particular region.

These variables are commonly employed in ecological and biogeographical studies to assess the environmental conditions and their suitability for species' population persistence.

One widely used set of bioclimatic variables is the BIOCLIM system, which includes 19 variables derived from temperature and precipitation data (Booth, 2018). The 19 BIOCLIM variables are: BIO1 Annual mean temperature; BIO2 Mean diurnal range (mean of monthly maximum - minimum temperature); BIO3 Isothermality (BIO2/BIO7); BIO4); BIO4 Temperature seasonality (standard deviation of mean monthly temperatures); BIO5 Maximum temperature of warmest month; BIO6 Minimum temperature of coldest month; BIO7 Annual temperature range (BIO5 - BIO6); BIO8 Mean temperature of wettest quarter; BIO9 Mean temperature of driest quarter; BIO10 Mean temperature of warmest quarter; BIO11 Mean temperature of coldest quarter; BIO12 Annual precipitation; BIO13 Precipitation of wettest month; BIO14 Precipitation of driest month; BIO15 Precipitation seasonality (coefficient of variation among months); BIO16 Precipitation of wettest quarter; BIO17 Precipitation of wettest quarter; BIO18 Precipitation of warmest quarter; BIO19 Precipitation of coldest quarter.

We also obtained bioclimatic data for future near-term climate projections (2021–2040) from WorldClim. We chose Shared Socio-economic Pathway (SSP) 2-4.5 which is considered a 'middle of the road' scenario in which socioeconomic and technological trends remain similar to historical patterns, and atmospheric CO_2 concentration levels off at 600 ppm by the year 2090 resulting in a mean global temperature rise of around 2.5°C (O'Neill et al., 2016). SSP2-4.5 projections were available for 12 General Circulation Models (GCMs) which are part of the Coupled Model Intercomparison Project 6 (CMIP6) (Fan et al., 2020). These GCMs were ACCESS-CM2, CMCC-ESM2, EC-Earth3-Veg, FIO-ESM-2-0, GISS-E2-1-G, HadGEM3-GC31-LL, INM-CM5-0, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL. We generated ensemble average projected bioclimatic variables by taking the mean value across the 12 GCMs. Although a simple mean does not consider non-independence among GCMs (due, for example, to shared model architecture), previous analysis of CMIP3 and CMIP5 projections suggests that treating each ensemble member as independent does not result in large biases (Sanderson et al., 2015). Generating an unbiased model average is beyond the scope of the present analysis.

4.3.2 UK climate variables

For spatiotemporal modelling of PPD invasion we used temperatures from the CHESS-SCAPE dataset (Robinson et al., 2023), a high-resolution climate projection dataset for the United Kingdom, derived from downscaled United Kingdom Climate Projections 2018 (UKCP18) regional climate model output (Murphy et al., 2018). The dataset contains 11 near-surface meteorological variables such as mean, maximum and minimum daily temperature at a 1 km spatial resolution. In addition to downscaling, CHESSS-SCAPE implements bias correction to ensure consistency with historical climate data. The variables are available at several time resolutions, from daily to decadal means, for the years 1980–2080. The dataset provides projections for four Representative Concentration Pathway (RCP) scenarios: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (van Vuuren et al., 2011). The RCPs were superseded by SSPs for CMIP6, but represent similar ranges of greenhouse gas emissions trajectories (O'Neill et al., 2016). For each scenario, four ensemble members were chosen to span the range of temperature and precipitation change in the UKCP18 ensemble, representing the ensemble climate model uncertainty.

4.4 Crop production

We obtained global cropland area at 3km resolution for the year 2019 from the Global Land Analysis and Discovery project (Hansen et al., 2022). The data were aggregated to fractional cover of 10 arc minute resolution grid cells to match the WorldClim bioclimatic data for further analysis. For matching global crop distributions to Scotland's production we used the Spatial Production Allocation Model (SPAM 2010) at 5 arc minute resolution (Yu et al., 2020). For some crops (oats, oilseed rape) not reported in SPAM we used an alternative dataset

(Monfreda et al., 2008). Estimates of individual crop production areas at very high (10 m) resolution for the year 2018 were obtained from the EUROCROPMAP project (d'Andrimont et al., 2021). EUROCROPMAP estimates distributions of 9 different cereals, potatoes, sugar beet, other root crops, and various other food crops, grasslands, forests and other land use types. Total production area of different crops in Scotland from 2011 to 2021 was obtained from the Agricultural Census of Scotland.

4.5 Trade and transport

Agricultural commodity and live plant trade data were obtained from the UK Government's UK Trade Info regional trade database. We obtained UK import quantities (tonnes) from all available countries (in some cases minor import sources were grouped, e.g. some sub-Saharan African countries) from 2018 to 2021 for the following agricultural commodities: Cereals and cereal preparations, vegetables and fruit, live plants and cut flowers, oil seeds and oleaginous fruit, cork and wood.

International tourism traffic to and from the UK was obtained from the Office for National Statistics. The average of visits in 2018 and 2019 was used to avoid anomalies resulting from the COVID pandemic. UK-wide tourism data, rather than for Scotland specifically, was used in these analyses because imports of PPDs to any part of the UK could result in spread to Scotland.

Table 2. Datasets used in the analysis and their sources.

Data	Source
CABI Distribution Database	Available on request from CABI
ProMED-mail first reports	https://promedmail.org/
CABI PlantwisePlus Knowledge Bank pest alerts	https://plantwiseplusknowledgebank.org/
Defra Plant Health Risk Register	https://planthealthportal.defra.gov.uk/
WorldClim v2.1 bioclimatic variables (1970-2000)	https://www.worldclim.org/
CMIP6 SSP2-4.5 bioclimatic variables (2021-2040)	https://www.worldclim.org/
CHESS-SCAPE downscaled UKCP18 climate projections for the UK	https://catalogue.ceda.ac.uk/
GLAD global cropland cover	https://glad.umd.edu/
SPAM global crop cover	https://mapspam.info/
Farming The Planet crop cover	https://earthstat.org/
EUCROPMAP Europe crop cover	http://data.europa.eu/89h/15f86c84-eae1-4723-8e00-c1b35c8f56b9
Scottish Agricultural Census: June 2023	https://www.gov.scot/publications/results-scottish-agricultural-census-june-2023/
UK Trade Info agricultural commodity and live plant trade	https://www.uktradeinfo.com/
Estimates of overseas residents' visits and spending in the UK	https://www.ons.gov.uk/peoplepopulationandcommunity/leisureandtourism/
Estimates of UK residents' visits and spending abroad	https://www.ons.gov.uk/peoplepopulationandcommunity/leisureandtourism/

5 Methods

5.1 PPD assemblage matching

The shared presence of PPDs can indicate that geographical regions are biogeographically and agronomically similar, and so could be mutual sources of invasion risk. All PPDs in the CABI distribution dataset Treating the CABI presence-absence data as an ecological community matrix of m species in n locations, we calculated the Jaccard dissimilarity coeffient D_J between each pair of locations a and b:

$$D_J = \frac{A + B}{A + B + C}$$

where A is the number of PPDs exclusively in region a, B is the number exclusively in b, and C is the number of PPDs jointly in a and b (Legendre and Legendre, 2012).

An artificial neural network algorithm known as a Self-Organizing Map (SOM) has used this principle to predict occurrence risk of currently-absent PPDs from patterns of shared PPDs across geographical areas (Paini et al., 2010; Worner and Gevrey, 2006). The SOM is a clustering algorithm that organizes high dimensional input data into a smaller two-dimensional grid with p nodes or 'neurons', such that geographical units with shared species are placed in the same neuron, and neighbouring grid cells have more similar compositions than distant ones. The SOM algorithm can be visualized as follows. Each of the n data points occupies a position in m-dimensional space. The p neurons are randomly allocated a position in the m dimensional space. One of the n data points is selected at random, and the neuron closest to it (in this case, using Euclidean distance) is called the Best Matching Unit (BMU). The location of the BMU in m-space is adjusted to move toward the data point, and the other neurons also move toward it by an amount that decreases with distance from the data point. A second data point is then randomly selected, and the process repeated. The movements of the neurons through m-space decrease over a number of cycles (in this case, 100). The algorithm ensures that the neurons end up representing the distribution of the data as closely as possible.

At the end of the learning process, each data point is assigned to its nearest neuron creating p clusters. Given the stochastic elements of the algorithm (initial neuron weights, order of data presentation), the SOM can converge on different solutions. We therefore ran the algorithm 100 times to obtain a distribution of results. The SOM yields two pieces of useful information. The first is the location (known as the weight vector) of each neuron in m-space, which in the case of PPD distributions can be interpreted as a vector of probabilities of finding each PPD in members of that cluster (Worner and Gevrey, 2006). The second is the membership of each neuron cluster, which indicates which data points, or geographical units, have similar PPD compositions. We can therefore determine which countries have PPD compositions most similar to Scotland, and the probabilities of each PPD occurrence in Scotland. This is particularly useful for identifying PPDs that have not yet been recorded in Scotland but are most likely to arrive.

5.2 Biophysical risk assessment

We estimated relative biophysical risk (R_{BIO}) for PPDs currently absent from the UK and Scotland by considering presence in potential source regions, production of host crops in source regions, bioclimatic similarity of source regions to Scotland's crop production area, and physical proximity to Scotland:

$$R_{BIO} = \sum_{n=1}^{N} A_n \times C_n \times D_n$$

where A is the scaled area of host crop production in the nth potential source region (estimated from SPAM crop area), C is the scaled bioclimatic similarity with Scotland D is the scaled physical closeness (i.e. negative of distance). Both A and C were calculated for subnational regions where available. For countries with subnational data (e.g. United States), national-level data were excluded from the analysis. Risks were summed over the N source regions in which the PPD is known to be present. The minimum N is 1 because in our dataset we only included PPDs which could affect Scottish agriculture and are absent from Scotland but present in at least one other region. We were unable to assign *a priori* weightings to the relative contributions of crop area and climate similarity to risk, therefore A, C and D were scaled to the interval [0,1]. Host area was included in our model as a proxy for potential population size of a PPD in the region of origin (Bebber et al., 2014b), bioclimatic similarity as a measure of climatic suitability for a PPD (Kriticos, 2012), and distance because nearby regions tend to have similar PPD assemblages (Bebber et al., 2014a).

We included the most important arable and horticulture crops in Scotland by production area (Table 1): barley, wheat, oats, oilseed rape, and potatoes. A was calculated by dividing the area of a particular crop in a particular region by the maximum production area in a source region across all crops. This allowed relative risk to be compared across PPDs affecting different hosts. For PPDs affecting multiple hosts, areas for each host were summed, therefore A could exceed 1.

The distributions and impacts of PPDs are strongly determined by climate, hence matching the climate of a region of interest (in this case, Scotland) with that of other countries can indicate areas that might be the source of future biosecurity threats (Kriticos, 2012). We estimated climate similarities between cropland in Scotland and other countries globally using historical (1970–2000) and future projection (SSP2-45, 2021–2040) bioclimatic variables. Use of bioclimatic variables provides a more nuanced description of climatic conditions than categorical systems such as the Köppen–Geiger climate classification (Beck et al., 2018) that is sometimes used for PRA (MacLeod and Korycinska, 2019). The 19 bioclimatic variables were centred to mean zero and scaled to unit variance. The crop area-weighted mean of each scaled bioclimatic variable was estimated from all grid cells in Scotland, using the GLAD cropland cover data. We then calculated Euclidean distance of all global grid cells to this Scotland crop mean. We identified regions with similar climates to Scottish croplands as being a potential source of invasive PPDs. Bioclimatic distances were calculated independently for historical and future climates. For risk modelling, we converted distance to climate similarity S_c by normalizing the distance to interval [0,1] and subtracting this from 1 (Legendre and Legendre, 2012 p. 270).

5.3 *Trade and travel risk assessment*

International trade and travel data were available at national level only, hence risk assessment from this source was conducted separately to biophysical risk. The combined risk from trade (R_{TRD}) was calculated as:

$$R_{TRD} = \sum_{n=1}^{N} V_{L,n} + V_{C,n}$$

where V_L is the volume of live plant imports (UK) and V_C is the volume of crop imports (UK Trade Info data) for the nth of N countries with the PPD present, each scaled to interval [0,1]. The average volumes for 2019, 2021 and 2022 were used in the calculations.

The risk from international travel (R_{TRV}) was calculated as:

$$R_{TRV} = \sum_{n=1}^{N} V_{I,n} + V_{O,n}$$

where V_I is the volume of inbound tourism to the UK, V_O is the volume of outbound tourism, both scaled to interval [0,1]. We again used equal weightings in the absence of *a priori* information on the relative importance of each potential mode of entry. The average volumes for 2018 and 2019 were used in the calculations.

5.4 Stakeholder perspectives on threats from CPPs

The objectives of the stakeholder engagement exercise were:

i. Characterise key threats to the sustainability of key Scottish production sectors.
ii. Co-design of plausible scenarios with stakeholders.
iii. Elicit stakeholders' knowledge about likely future PPD issues.
iv. Test scenario resilience to specific pest and pathogens and identify solutions (technology, regulatory, knowledge) for safeguarding the cereal, fruit and potato sectors against future PPD risks.
v. Transfer knowledge to plant-health experts and practical guidance for growers.

The first objective, completed in March 2023 (Lozada and Karley, 2023) involved working with stakeholders to characterise and prioritise key threats to the sustainability of the arable and horticulture sector. Information was gathered using an online survey distributed to agricultural stakeholders (farmers, agronomists, crop breeders, scientists, policy advisors, regulatory bodies, and value chain actors) supplemented by face-to-face discussion groups at relevant stakeholder events. The second, third and fourth objectives involve developing plausible scenarios by eliciting stakeholders' knowledge in the cereal, fruit and potato sectors and identifying mitigating actions. Through a series of workshops, we achieved these objectives, and gathered additional insights into stakeholders' perceptions of future PPD threats to Scottish arable and horticulture sector.

Scenario planning in this research is a *set of narratives describing different alternative futures, constructed with an iterative approach based on the uncertainties of the context, with the aim to raise awareness of plausible futures and increase performance of the organisation* (Cordova-Pozo and Rouwette, 2023). Scenario planning followed established methods (Boden et al., 2015; Duckett et al., 2022). Our process integrated the six components identified by Cordova-Pozo and Rouwette (2023) as being oriented to the future (1), concerning with external contexts (2) and following a narrative form (3); they are plausible (4) and part of a systemised set (5) of meaningfully different alternatives, raising awareness and increasing performance in the future based on the strategy adapted in the present (6). To develop the scenarios with stakeholders it was important to have balanced representation from the arable and horticulture sector in Scotland. We recruited 16 participants representing farmers, researchers, agro-industry organisations, and regulators. Detailed information about the recruitment strategy can be requested from the authors.

We conducted two one-day in-person workshops in June and September 2023 and two half-day online workshops in December 2023. Scenario planning is the creation of plausible scenarios. The future, however, is unpredictable and uncertain. What we know is what has happened in the past and what is happening in the present. To develop the scenarios, we used existing knowledge to guide creative thinking to develop narratives for the future. This information helped stakeholders to identify drivers of change, critical uncertainties and their assumptions to finally develop the narratives. The scenarios were almost entirely developed by stakeholders and to achieve this aim we ensured that they had clear instructions and guidance to develop each activity in the workshops. Workshops progressed as follows:

1. Review past and present events.
2. Identify drivers of change (STEEP).
3. Identify critical uncertainties and assumptions.
4. Morphological boxes.
5. Scenario narratives.

To develop the exploratory scenarios, we followed a focal question and used the five STEEP factors (Social, Technological, Economic, Environmental and Political) to comprehensively analyse past events, present processes and to construct plausible futures. Our focal question was: *What will the Scottish arable and horticulture sector look like in X years time and how resilient will it be to pests and diseases?*

Participants then decided the timeframe they wanted to work with for past events and develop scenarios. To be able to compare the scenarios across the two workshops we standardised the timeline to 10 years. Using the same focal question and five colour coded sets of sticky notes we asked participants about past events (Figure 2). The colour coding corresponded to each of the five factors of STEEP. The review of past events asked a slightly different question: *What **has happened** to the Scottish Arable and horticulture sector in the past X years and how resilient **has it been** to pests and diseases?*

Figure 2. Timeline developed by stakeholders, workshop at Battleby, June 2023. The timeline from one of the scenario planning workshops where drivers of change were summarised for the previous 30 years. Sticky notes were colour-coded accordingly to the five factors of STEEP analysis.

Stakeholders highlighted various past events that have influenced the sector and its resilience to PPD. The most frequently repeated events were related to:

- **Social:** Food; Dietary changes (obesity problems); Mobility of people; farm demographics.
- **Technological:** Information; related innovations in land and food; PPD.
- **Economic:** Food system changes; economic damage to agricultural system by PPD and weather events; also, opportunities.
- **Environmental:** Land use and management changes; PPD events and changes in rules and regulations; public awareness.
- **Political:** EU-CAP land use policy trade-offs for biodiversity, Net Zero and food security; Brexit; State responses.

This process primed participants for the next step, which aimed to identify critical uncertainties for the agricultural sector in each of the drivers of change using the five STEEP factors. Flip charts, one per STEEP factor, were used to collect information about drivers of change (DoC) which participants identified by adding coloured coded sticky notes (Figure 3).

Figure 3. Drivers of Change identified by stakeholders at workshops.

Through the carousel method, participants were asked to agree collectively and select five critical uncertainties, one per category, for constructing the scenarios. Critical uncertainties refer to drivers that have major impact and the outcome is highly uncertain. These were developed using morphological boxes to describe the links between uncertainties in each STEEP category. With the selected critical uncertainties, participants were asked the "what if" question which helped them to develop the assumptions to build the morphological boxes and subsequently the narratives of the exploratory scenarios. The morphological boxes were used as the basis for drafting narratives describing two scenarios – "better not best" and "worse not worst" case scenarios for the future (Table 3).

Table 3. An example of the assumptions made by participants in relation to critical uncertainties within the five STEEP factors. The resulting morphological box was used to develop the narratives of two scenarios. Columns left to right show three levels of assumption from 'better' to 'worse' case scenarios. Purple coloured assumptions were used for the scenario "Scotland's own vision" and light green coloured assumptions were used for the scenario "Agriculture elsewhere".

	Critical uncertainty	**"Better"**	**"Intermediate"**	**"Worse"**
Social	Food production. Disconnection between people and land farming.	Strong connection between people and food production (i.e. through local markets). Willingness to pay for higher quality food. Willingness to pay for surveillance. More diverse crops. More resilience		Total disconnection between people and food production. If people don't care where their food comes from or what they eat, then there is no interest in PPD. Perception of food (i.e. difficult to accept changes in food habits). Low influence on food policy.
Social	Diets and consumer education	High awareness of food production and more demand for healthy food and better quality is demanded.	Consumers education on diets and food production is fragmented and lack of understanding	Consumers are not interested in food production. Complete lack of education.
Technological	Precision Agriculture. AI Tools	Increase in the use of precision targeted farming. Controlled use of pesticides prevents resistance developing in PPD	No change from current circumstances If continued use of pesticides = resistance development.	
Technological	Gene editing	GE is accepted in Scotland.	GE continues to be in state of uncertainty.	GE is banned and does not represent an option in Scotland.
Economic	Changes in Food prices & Food Affordability	Costs of living and production are very cheap. More home grown food and more control with less PPD. Higher standards.	Costs of living/production food is affordable. Consumers have a choice to think of quality = less pests, land management to help reduce pressure. Differences between cereals and fruit = reduced inputs may not cause a diminution of crops.	High cost of living/production. Food is expensive. Reliance on imports. With more exposure to PPD. Costs of production are high; market shrinks and more need to rely on food imports.
Economic	Farmers profitability. Economic instability.	Farmers are economically fragile, but slow reversal of profitability declines from 2020s starts to improve farmers' economic resilience.	Farmers are economically fragile and decline from 2020s continues at the same rate	Farmers are economically fragile and farm decline from 2020s accelerates creating a very vulnerable farming sector.
Environmental	Extreme weather events & Climate warming, weather unpredictability	Weather becomes warmer and drier. Longer period of exposure/ crop damage. Less pressure from slugs, rust, fungus – with warmer, drier weather. Ability to grow a wider variety of crops = more resilience. Invasive species from continent. Opportunity to learn from other countries.	More extreme events, flooding, drought. Longer periods of exposure/crop damage More difficult to manage unpredictability Difficult to predict crop drought and floodings. Sudden PPD infestations.	Weather becomes warmer and wetter. Range of new PPD. Wet weather may make it harder to control PPD. Longer periods of attack/ crop damage.
Environmental	Weather annual variation	Better systems in place to predict weather extreme events, creating a more resilient system.	Extreme weather events higher frequency but more predictability.	Weather event unpredictability is extremely high.
Political	International trade. Geopolitics (Brexit, EU/UK policy divergence, other parts of the world)	Protection regime/restriction increased. Fewer PPD and better information if system is effective. Less use of chemicals Different impact on food quality, higher prices. More diversification.	UK has some limited restriction/protection, Scotland could voluntarily introduce restrictions. Divergence between Scotland and the rest of the UK (with threats and opportunities). Fewer PPD.	UK has no restrictions / protection regime. Risk of entry of non-native/ new PPD. More pressure to remove controls here to minimise production costs. Pressure to aim for commodity/low quality market. More PPD = increase pesticide use.
Political	Net zero targets 2045	Targets set for reduction of pesticides, GHGs, fertilisers and other targets are achieved at 50%		Targets set in reduction of pesticides, GHGs, fertilisers and other targets are missed, and none are achieved.

The narratives for six scenarios were developed by stakeholders in the two one-day in-person workshops. Four of these scenarios were expanded by the investigators with further description and enhanced with additional contextual information in terms of new or anticipated policy developments, global events, sectoral developments etc. A further two half-day online workshops were conducted with the same group of stakeholders (with four absences). The objective of these online workshops was to test the resilience of the scenarios to specific PPD, elicit stakeholders' knowledge and awareness of PPD, and develop a set of recommendations to create a more resilient sector. In the online workshop, the participants were asked to review and confirm or adjust the scenarios they had developed to ensure they were realistic and feasible.

Participants were asked to list and discuss the PPD they anticipated becoming problematic in the future. The questions they responded to were:

1. Which pests and pathogens do you know?
2. What are their characteristics and behaviour?
3. How likely do you think these are to occur in Scotland in the next 10 years?

Afterwards, participants were presented with three PPDs predicted to become more prevalent by modelling (CPB), have recently arrived in Scotland (blueberry rust) or identified as a potential threat by other research (wheat stem rust) (Figure 4). These three examples were chosen as representative threats to the key economically important arable and horticultural crop types in Scotland (i.e. (seed) potato, cereal, soft fruit).

To test the robustness of the future scenarios against potentially emerging PPD threats, participants were asked to imagine that each PPD threat is well established in Scotland in 2033 and answer the question "*How severely would your scenario be impacted?*". The responses were gathered by taking notes about what the outcomes would be in each scenario, and how severe the impact would be, using an ordinal scale (from negligible impact to permanent change). Finally, stakeholders were asked to recommend actions that could be taken now to mitigate the severity of the impact of these PPD in the future.

Colorado potato beetle

- Larvae and adults feed on several cultivated and wild members of the Solanaceae (potato, tomato, aubergine, and pepper)
- Each female can lay ~2000 eggs
- Feeding defoliates the plant causing up to 50% yield losses
- Can spread potato diseases (bacterial wilts)
- Outbreaks managed by crop/weed destruction (herbicide), insect eradication (insecticide) and soil/tuber incineration

Management:

- Biocontrol (natural enemies) is considered ineffective
- Chemical control using chlorpyrifos (no longer approved for use on potatoes in the UK) and thiacloprid
- GM (Bt toxin) effective but growers reluctant to use
- Resistance breeding lines derived from wild relatives (deterrent chemistry)
  - Resistance management necessary
- Cultural control using rotation, trapping and early planting to avoid second generation within one season

Not predicted:
Wheat stem rust appears to be re-invading the UK

- Recently re-emerged in Europe as environmental conditions have become more conducive (last epidemic was in 1955)
- Caused by the fungal pathogen *Puccinia graminis* f. sp. *tritici*
- New supervirulent wheat stem rust isolates have emerged (Ug99 race group in Africa)
- Complex life cycle involving another host (barberry, *Berberis* spp.) which is increasingly grown in arable areas
  - can enhance the pathogen's genetic diversity and provide a seasonal bridge
- The disease can cause crop devastation
- Infected wheat plant found in southern UK in 2013
- Detected on barberry in a cereal hedgerow in 2017
- Only 20% of UK wheat varieties are resistant
- Good control relies on early application of rust-active azole fungicides (e.g. tebuconazole)

Blueberry rust

- Caused by the fungus *Thekopsora minima*
- Attacks a range of plants in the Ericaceae family
- Second host required to complete the life cycle (conifer, *Tsuga* species)
- Infection leads to premature leaf drop, reducing plant vigour, yield, and flower production the following year
- Predicted to have a serious impact on the commercial production of cultivated North American blueberry species from crop losses and increased pest control costs
- Potentially high environmental and social impact if *T. minima* attacks wild European *Vaccinium* species if this pest hybridised with the closely related native *Naohidemyces vaccinii* rust and led to a new virulent type (uncertain)

Management:

- Crop husbandry (pruning to increase air circulation and remove disease inoculum)
- Remove diseased plants
- No approved fungicides currently available in UK

Figure 4. Information about three selected PPD presented to stakeholders in the scenario testing online workshops.

5.5 *Modelling invasion by the Colorado Potato Beetle (CPB)*

5.5.1 *CPB Life Cycle*

The recent discovery of CPB in southern England (DEFRA, 2023), along with high PHRR risk scores and results of our analyses, suggest that CPB could become an important pest of UK potato production in the near future. Though the small population in England appears to have been eradicated, further invasions could occur and so the possibility of further spread and establishment must be investigated.

CPB is thought to be native to mountainous regions of southwestern USA and Mexico, becoming a pest of potato production in the 19th Century (Hare, 1990). CPB arrived in France in 1922 and spread rapidly across Europe and Asia through the 20th Century (Grapputo et al., 2005), entering China via Kazakhstan in the 1990s (Li et al., 2014). The CPB life cycle begins with the adult female beetle depositing clusters of yellow-orange eggs beneath the foliage of potato plants and other Solanaceae family members like tomatoes (Hare, 1990). This egg-laying phase can span several weeks, with a single beetle capable of laying hundreds of eggs. Upon hatching, the larvae emerge, characterised by their reddish-brown bodies and black heads. The larvae undergo four growth stages, consuming host plant foliage. This causes significant agricultural damage. The larvae then descend into the soil to pupate, a transformation phase where they stay for one to three weeks, emerging as adult beetles adorned with striking yellow-orange hues and ten black stripes on their wings. Post-emergence, these adults not only resume feeding on plant leaves but also begin the reproductive process, perpetuating the cycle. In colder climates, the beetles overwinter in the soil or under plant debris, entering diapause when days become shorter and re-emerging with the arrival of warmer spring weather. The life cycle, from egg to adult, can be as brief as four weeks in favourable conditions, allowing for several generations in a single growing season. This rapid reproduction, coupled with their ability to quickly develop resistance to pesticides, renders CPB a significant agricultural pest.

Temperature is a strong determinant of CPB life cycle process rates (Hare, 1990; Jönsson et al., 2013; Pulatov et al., 2016). Thermal time models have been developed using developmental thresholds of 10 or 12 ˚C, and a minimum temperature sum of 411 degree days (DD) comprising 60-90 DD for emergence after hibernation, 51-70 DD for feeding, mating and egg laying, and 300 DD for development from egg to adult (Jönsson et al., 2013). Under the high-emissions Representative Concentration Pathway climate change projection RCP8.5, CPB could complete at least one generation in Scotland from the middle of the 21st Century when using the 10 ˚C developmental threshold (Pulatov et al., 2016). Temperature also governs long distance dispersal by CPB adults. Flight is initiated when air temperature is at least 15 ˚C, and mass flight occurs at a daily maximum temperature of 25–28 ˚C (Jönsson et al., 2013). CPB has demonstrated remarkable climate adaptation during its invasion of Eurasia. Comparison of larval behaviour found that those from CPB populations in the native range (Mexico) climbed out of soil during winter and died due to cold temperatures, while those from Eurasian populations burrowed deeper to avoid the cold (Izzo et al., 2014). This adaptation had a dramatic impact on the validity of an earlier attempt (Sutherst et al., 1991) to model the invasion of CPB into Asia based on thermal tolerances of the native population (Bebber, 2015).

5.5.2 *Pest or Pathogen Spread (PoPS) Model*

PoPS is a spatially-explicit discrete-time stochastic model that simulates the reproduction, dispersal, and establishment of pests or pathogens modulated by climatic variables such as temperature or precipitation (Jones et al., 2021). It incorporates various options for infection dynamics such as Susceptible-Infected (SI) or Susceptible-Exposed-Infected (SEI) schemes that contain modules for mortality, dispersal, and treatment interventions. Dispersal is controlled by a kernel that describes the spatial spread with different options for its functional form (e.g. Gaussian, exponential, Cauchy), including both natural short-scale dispersal (i.e. flight) and anthropogenic long-range dispersal (i.e.

hitchhiking on vehicles). The model was originally developed to model the spread of sudden oak death in California in the 1990-2030 period, showing promising results (Meentemeyer et al., 2011).

The basic equation determining the number (or fraction) of infested hosts Ψ in cell j as a result of spread from another cell i at time step t is:

$$\psi_{ijt} = [\beta X_{it} P_{it} T_{it} I_{it}] \times [K(d_{ij}; \alpha_1, \alpha_2, \gamma, D(\varpi, \kappa))] \times \left[\frac{X_{jt} P_{jt} T_{jt} S_{jt}}{N_j}\right]$$

where the three terms in square brackets represent reproduction, dispersal and establishment, respectively. We used the SI scheme and applied the model to dispersal from an initial population in Kent, using monthly time steps and a 1 km spatial grid across the UK.

For **Reproduction**, β is the number of beetles that disperse from a single host under optimal environmental conditions. The monthly transmission rate of the beetles was set to β = 10, based on the annual reproduction rate of r = 30 (Valosaari et al., 2008) and considering that only about 3 months are available for transmission in our model. β is modified by a series of environmental factors. X is a seasonality term and P a precipitation term, both of which were ignored. T is a temperature-dependent term, in this case combining development and flight (see below). I is the number (in this case, fraction) of hosts in a grid cell infested at time t, dependent on previous dispersal and establishment.

We used the daily CHESS-SCAPE 1km climate projections for the UK to estimate thermal time for CPB development and subsequent adult dispersal. The model was run for the four emissions scenarios in CHESS-SCAPE. Accumulated degree days for the Nth day of the year were estimated from the mean of daily maximum and minimum temperatures (T_{max}, T_{min}) using the 10 °C threshold temperature:

$$DD_N = \sum_{d=1}^{N} \frac{T_{max,d} + T_{min,d}}{2} - 10$$

where d is each day of the year up to N. We computed the monthly dispersal rate as the fraction of days per month suitable for dispersal, i.e. days when $T_{max} \geq 15$ °C. Because a day length threshold of < 15 h induces diapause of CPB in Europe (Sutherst et al., 1991), no emergence was assumed in cells not reaching the 411 DD conditions before mid-August and thus not considered vulnerable to CPB establishment.

Dispersal was implemented with a Cauchy kernel K:

$$K(d; \alpha_1, \alpha_1, \gamma) = \frac{\gamma}{1 + (d/\alpha_1)^2} + \frac{1 - \gamma}{1 + (d/\alpha_2)^2}$$

where d is distance from the centre of a grid cell from which beetles are dispersing, $\alpha 1$ = 10 km and $\alpha 2$ = 50 km and control the typical dispersal ranges of natural (flight) and anthropogenic (hitch-hiking on vehicles) dispersal ranges, and γ = 0.95 controls the fraction of dispersal events which are short-range. PoPS draws a stochastic realization of dispersal from the kernel for each dispersal event. We ran PoPS 500 times to obtain a range of possible invasion outcomes.

Establishment is a function of the density of susceptible hosts per grid cell, where S is the number (or area) of susceptible hosts and N is the number (or area) of all species, and environmental influences. We ignored seasonality, precipitation and temperature, and used the fraction of grid cells with potato in the EUCROPMAP dataset.

6 Results

6.1 *PPD presence in Scotland*

The CABI distribution database currently lists 141 PPDs as present in Scotland. A further 584 PPDs are listed as present in the United Kingdom but are not specifically listed as present in Scotland. Observations of PPDs are not necessarily complete and can suffer from severe observational biases (Bebber et al., 2019), therefore we cannot conclude that those PPDs listed as present in the UK but not specifically in Scotland are truly absent from Scotland – in fact, many are known to be present. The CABI Plantwise Knowledge Bank pest alert system flagged no new PPD in Scotland between 2021 and 2023, though a new pest of *Acer* spp. trees, the sawfly *Pristiphora depressa*, was recorded in England in 2021 (Gibbs, 2022). The ProMED mail alert service flagged the first report of blueberry rust, *Pucciniastrum minimum* in Scotland in January 2022 (Latham et al., 2022).

6.2 *PPD assemblage matching*

6.2.1 *PPD assemblage similarity to Scotland*

Other than immediate UK neighbours, Scotland is most likely to share PPD with Central Europe, though some regions of North America are also relatively similar (Figure 5). Unsurprisingly, England was found to be closest in PPD assemblage. In order of similarity, Ireland, Northern Ireland, Belarus, Denmark, Central Russia, Latvia, Prince Edward Island (Canada), Belgium, Norway, Serbia, the Channel Islands, Finland, Estonia, Switzerland, Nova Scotia (Canada), the Netherlands, Sweden, Oregon (USA), European Russia, Lithuania and Ukraine shared a relatively large number of PPDs with Scotland. Wales was not particularly close to Scotland in terms of shared PPDs but this may be due to a lack of specific reporting for Wales in the CABI database, which only includes 34 records.

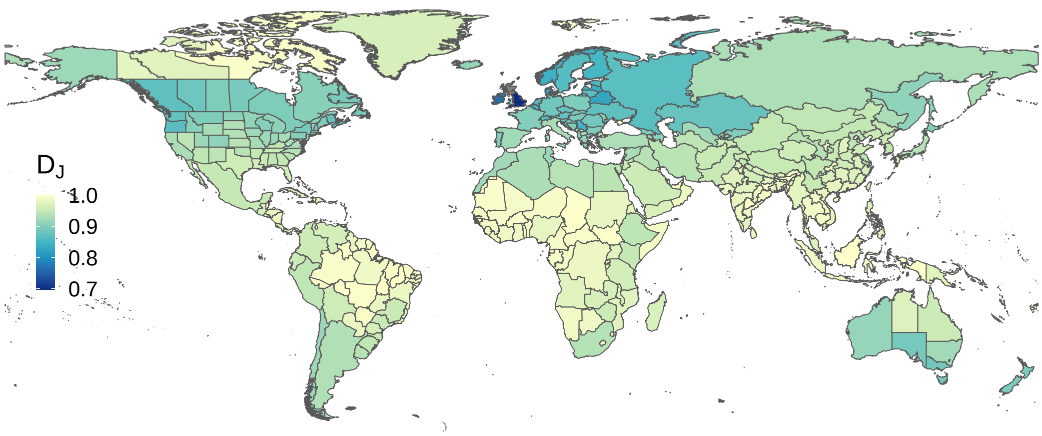

Figure 5. PPD assemblage Jaccard dissimilarity (D_J) to Scotland. Darker colours indicate a larger number of shared PPDs with Scotland. Values for countries with subdivisions are not shown.

The SOM algorithm grouped Scotland most often with Luxembourg (89 %), England (88 %), Siberia (84 %), European Russia (84 %), the Channel Islands (80 %), Northern Russia (79 %), Mongolia (75 %), Eastern Siberia (72 %), Alaska (63 %), Iceland (58 %), Newfoundland and Labrador (58 %) and Ireland (52 %). Countries in Central Europe with similar PPD assemblages were allocated a separate group from Scotland, hence the results should not be interpreted as indicating a different result from the ecological dissimilarity analysis. Rather, the classifier enforced a distinction between sets of closely linked regions.

6.2.2 *Probability of PPD presence in Scotland*

The mean probability of presence in Scotland over the 100 SOM runs (P_S), interpreted from the multidimensional distance of the Scotland cluster neuron to each PPD, varied according to whether the PPD was listed as present in the UK or Scotland in the CABI dataset (Figure 6a). Comparison of currently absent with currently present PPDs enables the relative risk of presence for absent PPDs to be gauged. Thus, the median P_S for PPDs recorded in Scotland is 0.2. This indicates a high degree of uncertainty in the model. P_S was zero for 67 % of PPDs. P_S was generally greater for PPDs recorded in the PHRR than for those not in the PHRR (Figure 6b).

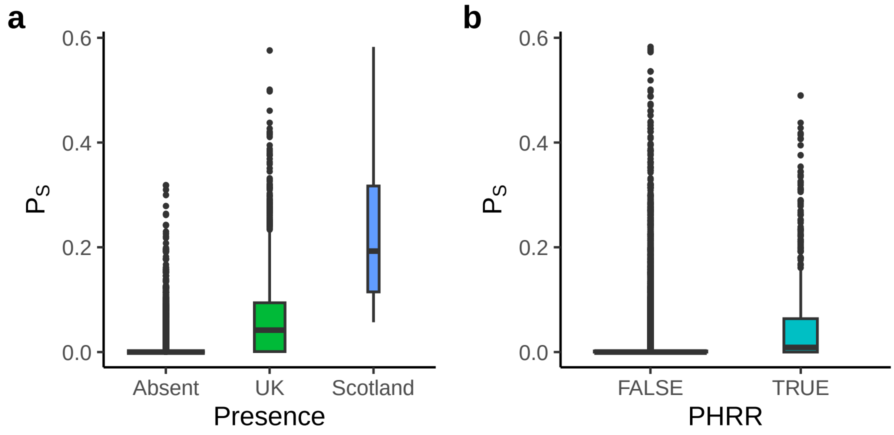

Figure 6. a) SOM probability boxplots of PPD presence in Scotland for PPDs currently absent from the UK, present in the UK but not specifically recorded in Scotland, and specifically recorded in Scotland. b) Presence probability for PPDs absent or present in the DEFRA PHRR. Box widths are proportional to the number of PPDs in each category. Boxes show interquartile range and median. Whiskers extend to 1.5 IQR. Points show outliers. Presence probabilities are zero for the majority of PPDs.

We first inspected risk to Scotland from PPDs currently listed as present in the UK but not specifically in Scotland (Table 4). For several of these, the absence of a specific listing for Scotland is simply because the UK listing indicates listing across the UK as a whole. Several others are moths which are either migrants to the UK or are localized to south-east England. The convolvulus hawk moth is a rare migrant to Scotland, most recently spotted in Perthshire for the first time in over a century (Robertson, 2021). This moth would not be considered a pest in the UK. The clover cutworm moth is known as a major pest of sugar beet in eastern Europe, though the larvae are polyphagous and could have significant impacts on oilseed rape (CABI, 2021). Climate warming is likely to cause northward encroachment into Scotland by many of the species currently limited to southern England.

Perhaps of greatest concern is the high presence probability for CPB. This extremely problematic pest was discovered in potato fields in southern England in the summer of 2023 (DEFRA, 2023). Eradication efforts appear to have been successful, hence the listing as present in the UK appears to be premature. The DEFRA PHRR lists the unmitigated likelihood of arrival as 4/5, spread as 3/5, impact as 3/5 and value at risk as 5/5, giving a combined relative risk rating of 60/125 which is considered high. The mitigated risk rating is just 20/125, because eradication and control measures are considered to be effective. CPB is known to be highly invasive (Grapputo et al., 2005). CPB was first detected in Europe in France in 1921, rapidly spreading eastward through the 20th Century and entering China, the world's largest potato producer, in the 1990s (Li et al., 2014). Evolution of burrowing behaviour by larvae to avoid cold winter temperatures was key to invasion success in Central Asia and China (Bebber, 2015; Izzo et al., 2014). Climate warming is likely to increase the probability of invasion into Scotland, by reducing development time and increasing adult dispersal (Pulatov et al., 2016). We evaluate the risk of CPB invasion into Scotland in detail below.

Table 4. Top ten PPDs currently present in UK but not specifically noted as present in Scotland according to CABI distribution data. PPDs are ordered by mean P_S. PHRR is the Defra unmitigated relative risk rating. Notes on status in Scotland obtained from the scientific literature and other sources (see text for discussion).

Organism	Common name	Major host	P_S	PHRR	Notes
Blumeria graminis	Powdery mildew	Cereals	0.58	NA	Present in Scotland
Hadula trifolii	Clover cutworm moth	Oilseed rape	0.50	NA	Localized in UK
Agrius convolvuli	Convolvulus hawk-moth	None in UK	0.50	NA	Southern UK visitor
Derocera laeve	Marsh slug	Omnivore	0.46	NA	Present in Scotland
Sitobion avenae	English grain aphid	Cereals	0.44	NA	Present in Scotland
Hylotrupes bajulus	House longhorn beetle	Conifers	0.43	NA	Localized SE England
Lymantria dispar	Gypsy moth	Broadleaf trees	0.42	30	Localized SE England
Leptinotarsa decemlineata	Colorado Potato Beetle	Potato	0.42	60	Recent invasive (see text)
Agrotis ipsilon	Black cutworm moth	Polyphagous	0.40	NA	Migrant
Acronicta rumicis	Knot grass moth	Strawberry	0.39	NA	Rare in Scotland

We next inspected PPD currently listed as absent from the UK with the highest P_S (Table 5). Several of these are forestry pests and will not be considered further. Of those remaining, two could affect wheat, one of the most important crops in Scotland. Wheat thrip can be an important pest in eastern Europe, central Asia and China (CABI, 2023). Dwarf bunt of wheat caused by the smut fungus *Tilletia controversa* affects both winter wheat and barley, but not spring wheat. It is found across North America, and from central Europe to far eastern Russia (CABI, 2022a). Climate change is likely to reduce the impact of dwarf bunt because germination of teliospores and subsequent infection require low temperatures (Jia et al., 2013). Long periods of snow cover in particular encourage increase the risk of serious disease outbreaks.

Table 5. Top ten PPDs currently absent from the UK according to the CABI Distribution Database. PPDs are ordered by mean P_S. Primary host refers to the most important host plant. PHRR is the Defra unmitigated relative risk rating. Notes from the scientific literature and other sources.

Organism	Common name	Primary host	P_S	PHRR	Notes
Monochamus galloprovincialis	Pine sawyer beetle	Pine	0.32	45	Vector of pine wood nematode
Haplothrips tritici	Wheat thrip	Wheat	0.32	NA	
Rhagoletis cerasi	European cherry fruit fly	Cherry	0.32	24	
Aporia crataegi	Black-veined white butterfly	Hawthorn	0.3	NA	
Asproparthenis punctiventris	Beet root weevil	Sugarbeet	0.28	45	
Monochamus urussovii	White mottled sawyer beetle	Conifers	0.26	NA	
Helicoverpa armigera	Corn earworm moth	None in UK	0.26	32	Migrant to southern UK
Chrysomphalus dictyospermi	Dictyospermum scale bug	None in UK	0.24	NA	
Tilletia controversa	Dwarf bunt of wheat	Wheat	0.24	NA	
Ips duplicatus	Northern bark beetle	Conifers	0.24	75	

6.2.3 Probability of PPD presence for major crops in Scotland

To focus on PPDs most likely to be invasive in Scotland, we selected those known to affect major crops (barley, wheat, oilseed rape, oats and potato) and which had $P_S > 0.1$ (Table 6). This cut-off is approximately equal to the lower quartile of P_S for PPD already present in Scotland (0.11) and therefore gives some confidence that these PPDs could establish. *H. tritici* (wheat thrip), *H. armigera* (cotton bollworm or corn earworm moth) and *T. controversa* (wheat dwarf bunt) were among those with the highest P_S. Though *H. armigera* is primarily a pest of cotton and other crops not widely grown in Scotland, it has been recorded as a minor pest of all five major Scottish crops. The shield bug *Eurygaster integriceps* is an important pest of wheat in the Middle East, parts of Europe and Russia (Critchley, 1998). Risk modelling using the CLIMEX ecological niche model suggests that, while the UK is currently unsuitable for *E. integriceps*, the climate of England and parts of Scotland will become suitable by the end of the 21st Century (Aljaryian et al., 2016). The root-knot nematode *Meloidogyne javanica* is currently most damaging in the tropics and subtropics, or in protected agriculture (greenhouses) in cooler climates (CABI, 2022b). Though the optimal hatching temperature for *M. javanica* is around 30 ˚C some hatching does occur even at 15 ˚C (Bird and Wallace, 1965), suggesting that this nematode could become a minor pest of field crops in Scotland as temperatures rise. The host range of *M. javanica* is very wide, including many crops grown under glass (e.g. strawberry, tomato, cucumber). Hence, this nematode could become a pest of protected cultivation, as it has in parts of Europe (Talavera et al., 2012).

In summary, SOM analysis suggests that several PPDs which are currently absent from Scotland and the UK have probabilities of presence in line with those PPDs already present in Scotland. Among the most concerning are CPB, wheat thrip, corn earworm moth and dwarf bunt. Several are currently summer migrants to the UK or restricted to countries with warmer climates, suggesting that climate change could increase risk of invasion in future. In contrast, dwarf bunt requires cold winter temperatures and therefore risk of invasion could decline in future.

Table 6. Probability of occurrence for PPDs which are potential pests of major field crops in Scotland. All are absent from the UK according to CABI distribution data. PPDs are ordered by mean P_S. Host gives the major crops known to be affected, whether these are major or minor hosts. PHRR is the Defra unmitigated relative risk rating. Notes from the scientific literature and other sources (see text for discussion).

Organism	Common name	Host	P_S	PHRR	Notes
Haplothrips tritici	Wheat thrip	Barley, oats, wheat	0.32	NA	
Helicoverpa armigera	Corn earworm moth	Barley, oilseed rape, oats, potato, wheat,	0.26	32	Migrant
Tilletia controversa	Dwarf bunt fungus	Barley, wheat	0.24	NA	
Eurygaster integriceps	Senn pest (shield bug)	Barley, oats, wheat	0.22	30	
Meloidogyne javanica	Javanese root-knot nematode	Potato	0.21	30	
Loxostege sticticalis	Beet webworm moth	Oats, potato, wheat	0.20	NA	Migrant
Tilletia laevis	Common bunt fungus	Wheat	0.19	NA	
Dociostaurus maroccanus	Moroccan locust	Barley, oats	0.18	NA	
Diuraphis noxia	Russian wheat aphid	Barley, oats, wheat	0.15	20	
Pseudomonas syringae pv. tabaci	Wildfire	Oats, potato	0.15	NA	
Sesamia cretica	Corn stem borer moth	Wheat	0.14	NA	
Xiphinema index		Potato	0.14		
Oxycarenus hyalinipennis	Cotton seed bug	Wheat	0.12	NA	
Hyalesthes obsoletus		Potato	0.12	60	Disease vector
Phytophthora capsici	Pepper blight	Potato	0.12	NA	
Citrus exocortis viroid		Potato	0.11	18	
Mythimna separata	Paddy armyworm moth	Barley, oats, wheat	0.10	NA	
Liriomyza huidobrensis	Pea leafminer fly	Oilseed rape, potato	0.10	48	

6.2.4 Blueberry Rust

We now turn to an example which illustrates that surprises are possible, and PRA cannot guard against all potential PPD threats. Blueberry Rust, caused by the basidiomycete fungus *Pucciniastrum minimum* (syn. *Thekopsora minima*), was first reported in Scotland in September 2021, on a locally-grown blueberry plant (*Vaccinium corymbosum* cv. 'Liberty') in a nursery in Perthshire (Latham et al., 2022). Phylogenetic analysis based on ITS sequences determined that the UK isolate is an outgroup to isolates from Brazil and Germany, hence it is not possible to establish whence the UK isolate originated. Blueberry Rust has a wide distribution in North America, South America, Australasia, South Africa, China, Japan and Europe. However, the probability of establishment in Scotland, as estimated by SOM, was only 6 %. Blueberry rust is not listed in the DEFRA PHRR. The disease is primarily a problem for commercial blueberry production, but *P. minimum* is also able to affect rhododendron in the uredinial stage, while the aecial stage has been found on hemlock (*Tsuga* spp.) (Anderson, 2022).

6.3 *Biophysical risk assessment*

6.3.1 *Biophysical metrics*

Biophysical risk (R_{BIO}) for each PPD was the product of bioclimatic similarity to Scotland for crop-growing areas in potential source regions, the area of host crop under production, and the physical distance from the source region to Scotland. Bioclimatic similarity largely followed a latitudinal gradient (Figure 7). Newfoundland was an outlier, due to the presence of only a single cropland pixel in this region which resulted in an anomalous value. Europe had the most similar climate, though some parts of North America and Australasia were also relatively close. Greenland and northern Canada have no cropland so are excluded from the analysis.

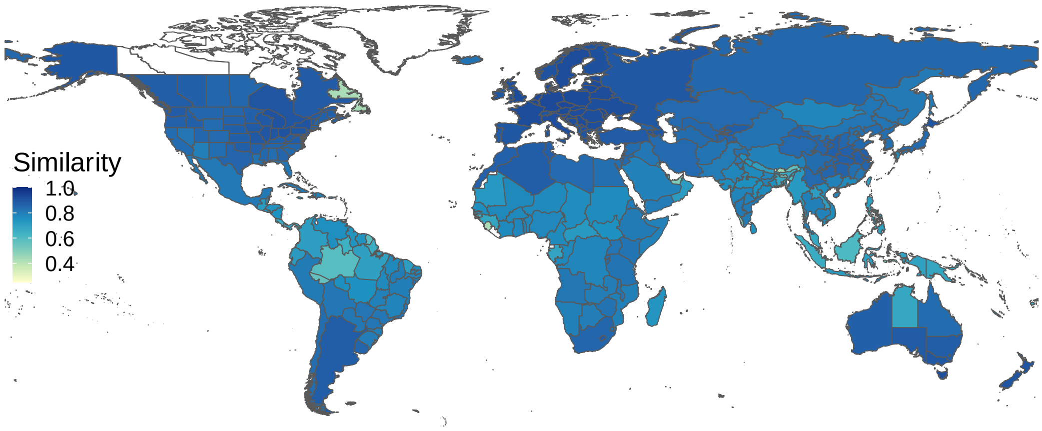

Figure 7. Bioclimatic similarity to Scotland, based on recent historical (1970-2000) average climate. Values are weighted to cropland area within each region.

Temperature and precipitation patterns across the UK are projected to change somewhat between the historical period and the near future (2021-2040) under the SSP2-4.5 climate change scenario (Figure 8). Summer temperatures increase by 1.0–1.5 ˚C in Scotland, with larger increases in the south of England. Winter temperatures are projected to increase by a smaller amount. There is very little change in summer or winter precipitation between the two periods, with only summer precipitation in the west of Scotland showing a substantial increase. There is no indication of major changes in precipitation in the crop-growing areas of Scotland.

We focussed on PPDs of the five major field crops of Scotland, barley, wheat, oats, rapeseed and potato (in order of area under production, Table 1). Barley is produced primarily in Canada, Europe, Ukraine, Russia and Australia; wheat has a similar distribution, but the USA, Brazil and China are also major producers. Oats are produced mainly in Canada, eastern Europe and Russia; rapeseed in Canada, central Europe, northern India, China and Australia; potato in eastern Europe, Russia and China.

6.3.2 *Biophysical risk score*

Considering all PPD, including those already recorded as present in the UK, the biophysical risk assessment listed wheat stem rust (*Puccinia graminis*) as the most likely cereal PPD to establish in the UK, followed by wheat aphid (*Sitobion avenae*), root and foot rot fungus (*Cochliobus sativus*) and yellow rust (*Puccinia striiformis*). Though wheat stem rust was largely eradicated in the UK through removal of the alternative host, barberry, there is growing concern that this major pathogen is re-emerging as a serious threat to cereal production (Lewis et al., 2018; Saunders et al., 2019).

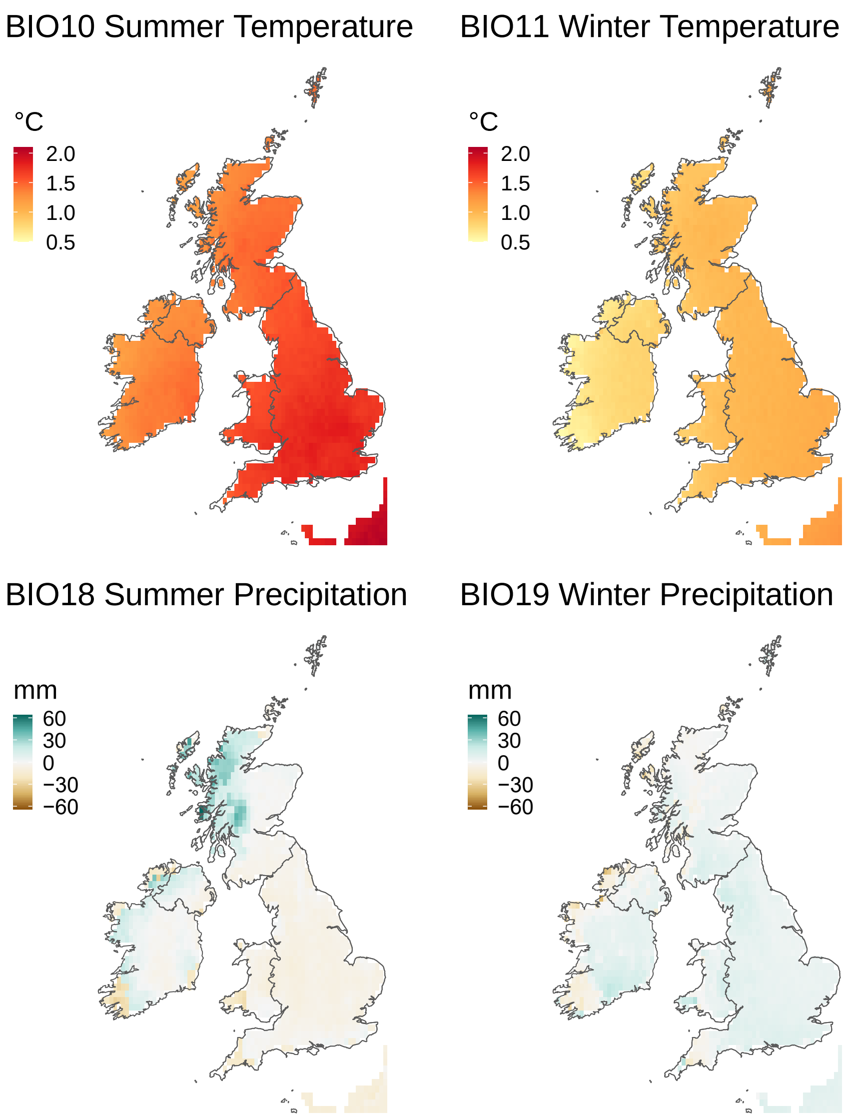

Figure 8. Changes in key bioclimatic variables across the UK between recent historical averages (1970–2000) and near future projection (2021–2040) under the SSP2-4.5 climate change scenario. Climate data were downscaled to 10 arc minute resolution for analysis.

Considering only those PPDs currently listed as absent from the UK (but also CPB, which is erroneously listed as present in the CABI Distribution Database), the biophysical risk assessment identified many of the same PPDs as were found most likely to occur in Scotland by the machine learning algorithm (Table 7). For the most important crops, wheat thrip, corn earworm moth, CPB and common bunt fungus were among the top five most likely to establish in Scotland, in agreement with the SOM results. Several of these (CPB, fall armyworm, pea leaf miner and tarnish plant bug) received medium to high-risk scores in the DEFRA PHRR. For context, the R_{BIO} for wheat stem rust was 4.6, in comparison with 3.5 for common bunt fungus. Variation in scores among crops for the same PPD reflects the differing area under production in potential source areas.

Table 7. Top five PPDs per major host by biophysical risk (R_{BIO}) score. Host refers to one of the five major crops by area in Scotland. PHRR is the current UK Relative Risk Rating where available. Listed PPDs are thought to be absent from the UK.

Host	Organism	Common Name	R_{BIO}	PHRR
Barley	*Haplothrips tritici*	Wheat thrip	3.5	NA
	Diuraphis noxia	Russian wheat aphid	3.3	20
	Helicoverpa armigera	Corn earworm moth	2.7	32
	Sitotraga cerealella	Angoumois grain moth	2.6	NA
	Athelia rolfsii	Southern blight	2.6	NA
Oats	*Pseudomonas syringae pv. tabaci*	Wildfire disease	2.0	NA
	Haplothrips tritici	Wheat thrip	1.9	NA
	Maize dwarf mosaic virus		1.7	NA
	Haplothrips aculeatus	Grass thrip	1.7	NA
	Diuraphis noxia	Russian wheat aphid	1.7	20
Potato	*Pseudomonas syringae pv. tabaci*	Wildfire disease	2.8	NA
	Helicoverpa armigera	Corn earworm moth	2.6	32
	Leptinotarsa decemlineata	Colorado Potato Beetle	2.2	60
	Athelia rolfsii	Southern blight fungus	2.1	NA
	Potato virus S		2.1	45
Rapeseed	*Helicoverpa armigera*	Corn earworm moth	2.9	32
	Spodoptera frugiperda	Fall armyworm	2.6	60
	Liriomyza huidobrensis	Pea leaf miner fly	2.0	48
	Rhizobium rhizogenes	Hairy root disease	1.8	NA
	Lygus lineolaris	Tarnished plant bug	1.3	45
Wheat	*Tilletia laevis*	Common bunt fungus	3.5	NA
	Diuraphis noxia	Russian wheat aphid	3.2	20
	Haplothrips tritici	Wheat thrip	3.0	NA
	Athelia rolfsii	Southern blight fungus	2.8	NA
	Magnaporthe oryzae	Rice blast	2.6	30

Recalculating R_{BIO} using bioclimatic similarity derived from future climate projections made no appreciable difference to the results. This is because the regions most climatically similar to Scotland are projected to change climate in similar ways to the UK, thereby their contribution to R_{BIO} does not change. However, the continuing warming is likely to make Scotland's agricultural areas more suitable for warm-weather species currently found as migrants or visitors in southern England, for example CPB (see Section 6.6). General latitudinal shifts in PPD distributions have been observed and are predicted to continue in future (Bebber et al., 2013; Chaloner et al., 2021).

6.4 Trade and Travel Risk Assessment

6.4.1 Trade

We estimated risk from trade of crops and live plants into the UK (R_{TRD}) and risk from importation by overseas or returning tourists (R_{TRV}) for all PPDs not currently listed as present in the UK (Table 8,

Table 9). In some cases, further searches of the literature and online sources (e.g. CABI Compendium, EPPO) indicated that PPDs listed as absent from the UK were actually present, and these were omitted from further analysis. The most likely PPD to be imported via trade was common bunt fungus, which was also identified as high risk via PPD assemblage analysis and biophysical risk analysis. Another fungal pathogen, southern blight, was also likely to be imported via trade and had a relatively high R_{BIO} score. However, this soilborne pathogen is currently limited to warm regions and is unlikely to become a problem in northern Europe in the near future (Manici et al., 2012). Several of the PPDs likely to be imported are pests of potato, including CPB which is given a high relative risk rating in the PHRR. Other PPDs with high PHRR scores include pepino mosaic virus, the American serpentine leafminer, potato virus S and the pea leaf miner.

Table 8. Top 10 PPDs by trade risk (R_{TRD}) score. Major hosts lists which of the major host crops in Scotland are hosts. If none, then any other relevant major hosts are listed. Listed PPDs are thought to be absent from the UK.

Organism	Common name	Major hosts	R_{TRD}	PHRR
Tilletia laevis	Common bunt fungus	Wheat	6.9	NA
Athelia rolfsii	Southern blight fungus	Barley, wheat, potato	6.7	NA
Pepino mosaic virus		Potato	6.2	36
Citrus exocortis viroid		Potato	6.2	18
Alternaria longipes	Tobacco brown spot	Potato	5.9	NA
Leptinotarsa decemlineata	Colorado Potato Beetle	Potato	5.9	60
Liriomyza trifolii	American serpentine leafminer	Barley, oats, potato	5.9	36
Potato virus S		Potato	5.9	45
Sitona cylindricollis	Sweetclover weavil	None (clover, other legumes)	5.8	NA
Liriomyza huidobrensis	Pea leaf miner fly	Rapeseed	5.6	48

6.4.2 Travel

The list of PPDs most likely to arrive via international travel was very different to that generated by the other methods we employed (

Table 9). This is partly because R_{TRV} could not be calculated for many PPDs, since UK government tourism data are only provided for 50 countries. This left 380 PPDs with R_{TRV} scores, which were highly correlated ($r = 0.83$) with R_{TRD} scores (Figure 9).

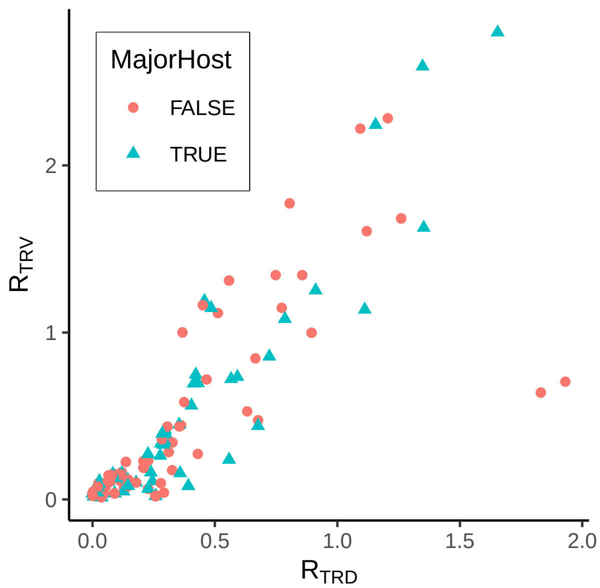

Figure 9. Travel risk (R_{TRV}) vs. trade risk (R_{TRD}) for 380 PPDs for which R_{TRV} could be calculated. Colour indicates whether PPDs affect major crops in Scotland. Figure includes PPDs thought to be absent from the UK.

Maize rough dwarf virus is a planthopper vector-borne *Fijivirus* which primarily affects maize in Europe, although it can affect most major cereal crops (Jones, 2020). The vector, *Laodelphax striatellus*, has a global distribution and is found throughout Europe including the UK (National Biodiversity Atlas). However, there are no records of this species in Scotland. Climate change models suggest that this *L. striatellus*, which also vectors rice stripe virus in Asia, could show northwards range shifts in future (Yamamura and Yokozawa, 2002). Therefore, maize rough dwarf virus could threaten Scotland's cereal production in coming decades.

The only PPD with a high R_{TRV} listed in the PHRR is the potato flea beetle (*Epitrix papa*). This beetle is thought to be native to North America, and was recently detected in Spain and Portugal (EPPO, 2017). Analyses of development times in relation to temperature suggest that *E. papa* can complete several generations within one growing season in central Portugal, the second of which is most damaging to maturing tubers (Boavida et al., 2019). Although formal modelling of potential distributions in Europe has not yet been undertaken, it is likely that climate change will increase the risk of this PPD establishing in the UK. The PHRR lists import on fruit and vegetables as the likely route of entry to the UK, rather than accidental import by tourists. Our analysis found that R_{TRD} is very low (0.5) for *E. papa*. This is because the global distribution is poorly understood and only Spain and Portugal are listed in the CABI Distribution Database. Once the full distribution is identified, the risk from international trade can be more reliably assessed.

Table 9. Top 10 PPDs by travel risk (R_{TRV}) score. Major hosts lists which of the major crops in Scotland are hosts. If none, then any other relevant major hosts are listed. Listed PPDs are thought to be absent from the UK.

Organism	Common name	Major hosts in Scotland	R_{TRV}	PHRR
Maize rough dwarf virus		Barley, oats, wheat	2.8	NA
Agromyza megalopsis	Barley miner fly	Barley, wheat	2.6	NA
Conorhynchus mendicus	Beet weevil	None (sugar beet)	2.3	NA
Parietaria mottle virus		None	2.2	NA
Nysius niger	False chinch bug	None (millet)	1.6	NA
Tetranychus neocaledonicus	Vegetable spider mite	Many	1.3	NA
Phaeocytostroma ambiguum	Stalk rot of maize fungus	None (maize)	1.3	NA
Acremonium maydis	Black bundle disease	None (maize)	1.3	NA
Soil-borne cereal mosaic virus		Barley, wheat	1.3	NA
Epitrix papa	Potato flea beetle	Potato	1.2	60

6.5 *Stakeholder perspectives on threats from CPPs*

Exploratory scenarios are narratives for plausible futures and a vehicle to raise awareness of these complexities and tenable future developments. The two narratives presented below should be read as a tool to explore plausible future threats and opportunities in the arable and horticultural sector and its resilience to PPD on a 10-year horizon. The benefit of these processes is to picture these plausible futures and think about recommendations that could work under various "futures".

6.5.1 Narrative 1: Scotland's own vision

Under this scenario Scotland diverges from the rest of the UK and can implement its own vision of trade and policies, allowing the arable and horticulture sector to be strong and growing with fairer market prices.

Scenario

The world continues to be unstable politically and economically (extension of current trends). However, with Russia's war on Ukraine ended and an easing of geopolitical tensions between China and the US, the global economy overall maintains a path towards free trade although adapting to some new protectionist tendencies. Grain exports from Ukraine and Russia return to patterns roughly similar to the pre-2022 patterns, which renders acceptable the UK's continued dependence on imports for a significant proportion of its food.

The UK continues to increase its international trade with other countries and improves its economic and political relations. The UK manages to keep out of international conflicts and crises but internal political instability adds to the country's fragmentation. In this context Scotland manages to agree with the rest of the UK to have a higher degree of devolution, some more economic autonomy (including less dependence on the UK food-system supply chain) and gets closer to the EU approach of more protection through environmental and quality standards. Exports and imports of an important proportion of Scottish products allows stability and room for planning, improving and protecting the agricultural sector. Scotland could voluntarily introduce restrictions on some practices. This divergence between Scotland and the rest of the UK presents both threats and opportunities.

Following the UK's withdrawal from the EU and the conclusion of the Trade and Cooperation agreement in 2021 Scotland develops and achieves to a certain degree its own vision for trade. The government does so by applying its five principles of inclusive growth, well-being, sustainability and 'just transition' to net zero, and good governance to Scotland's economy, Scotland's People, and the planet. Successive government achieves the aim of reducing carbon emissions by 32% by 2032 (as initially established in the 2021 Scotland Climate Smart Agriculture Framework).

Scotland achieves a moderate autonomy from the UK agro-food supply chain and, therefore, is able to implement some limited restrictions, having external control and avoiding dynamics of "race-to-the-bottom" between nations. UK devolves to Scotland a limited number of trade-agreements with the EU, which warrants a degree of economic stability and allows the farming industry to maintain and promote good practices. Scottish producers receive fairer market returns, enabling them to invest in research and development and newer and potentially more expensive practices that make production more resilient (and reduces the externalisation of costs). The farming industry remains in good shape allowing new entrants and more diversified (size and demographics) arable and horticulture farms with variation of farm sizes. The horticultural sector recovers from the continued decline it experienced in the early 2020s.

Weather becomes more unpredictable, but warmer and wetter, affecting different parts of the industry differently every year. Markets are more often resilient, with faster reaction time to implement strategies to adapt. In Scotland, the Government develops a programme to establish precision and targeted farming practices, which is adopted by much of the sector, allowing the industry to adapt and mitigate some of the shocks and allowing strategies to be implemented that prevent the sector from stronger shocks. Controlled use of pesticides prevents resistance developing in PPD. New crops and crop rotations are under examination to test their resilience - including against PPD.

The Scottish government successfully implements interventions that allow stronger connections between people and food provenance (e.g. local markets). Consumers are willing to pay more for healthy and locally produced food. This continuous support to the arable and horticulture sectors helps to deal with major economic and political instability internationally.

Pests and Diseases under 'Scotland's own vision' scenario

CPB – Moderate effect. Government has developed a programme to establish precision and target farming and it is adopted by much of the sector, allowing the industry to adapt and mitigate some of the shocks and allowing strategies to be implemented to prevent the sector from stronger shocks. The seed potato industry is the most important part of the potato industry in Scotland and as the CPB is not yet affecting it, therefore its impact is not as problematic as aphid pests. Precision and targeted farming practices would improve PPD detection and allow growers to take action accordingly, including easing regulatory rules if necessary. This is also possible because of Brexit. People are well prepared because their systems are more diversified. Being pest free is important for Scotland, and this is an incentive to support research and development of mitigating actions if there was an outbreak.

Wheat Stem Rust – Small effect. Continuous research and development allow the sector to adapt and compensates for the low responsive actions of farmers in the cereal sector. Wheat is the second most important cereal grown in Scotland, used in distilling and animal feed, although it does not have the importance of barley for the whisky industry. The crop needs high fertiliser use to attain high yields. If there are no alternatives and fertiliser allowance is reduced to achieve Net Zero, the risks of disease outbreak would become lower if the area planted with wheat is reduced.

Blueberry Rust – Permanent effect. The disease is difficult to control. Consumers' unwillingness to pay more for blueberries produced in Scotland would have a major impact as costs of production will increase. This would also imply that supermarkets are willing to sell locally produced fruit even though it is not cost competitive compared with other countries like Chile. However, if other countries are affected by PPD, then it could represent a competitive advantage to Scotland.

Recommendations from 'Scotland's own vision' scenario

Stakeholders discussed the scenarios under the three PPD risks and proposed a set of recommendations, quoted below:

"Do this and do more!" Consider invasive PPD as agricultural support programmes are developed. Incentivise uptake of programme adoption through agricultural policy - relating to CPD / advisory / KE - and possibly through 'conditionality' measures to receive support payments by farmers.

More research and development about adapting the farming calendar for planting which could potentially help to adapt to the changing climate. Bringing the season forward could potentially help to cope with some of the diseases. Invest in research which helps to understand what measures are needed in addition to other strategies such as relying on cultural management.

Adopting existing solutions in good time, such as detection and application, was mentioned as part of the recommendation to reduce the negative effects of the PPD on the sector.

The economic system was also discussed as being dysfunctional and weak by being based on monoculture and therefore acting as petri dish for evolution of diseases of all kinds of PPD (when they are not under control). Participants argued that the degree of production being under monoculture was unnecessary. They suggested this system to be changed to a more diverse system growing varieties that have resistance. And they recommended particular mixtures of crop landraces where there is a buffering effect from the genetic diversity that is built into these kinds of cropping and that will only happen if new drivers are provided for farmers to shift towards those kind of diversified cropping approaches. A shift of production system where farmers grow more food for people rather than for vehicles or alcohol production.

Weather predictions are central to cope with PPD since the damage can be accelerated and devastating if the right weather conditions are there.

More research and development in crop diversity and blends was mentioned, highlighting intercropping for instance for potato or blueberry with other crop types.

Also discussed was the idea of letting the system find its own way of "fighting" PPD by creating more diverse environments. As opposed to developing research in silos, which, although it may be suited to good control of individual pathogens, could create problems or miss targets elsewhere within the system. More research and development on the principle of diversity creating the natural system to provide buffers against potential threats and understand how best to grow crops under those conditions which are also good for providing nutritionally healthy and economically viable food.

6.5.2 Narrative 2: Agriculture elsewhere

Under this scenario Scotland follows the same trend as the rest of the UK. International trade is oriented towards free-market trade and the arable and horticultural sector concentrates into large exporting farms reducing public investment in the sector and pushing agricultural production elsewhere when it is not competitive at home.

Scenario

After overcoming major geopolitical tensions and a lessening of trade-wars, the international system has regained some stability. Yet the global economy, which is again strongly oriented towards free trade, is subjected to new threats and weaknesses, especially in the face of climate crises. The UK and Scotland continue to increase their international trade with other countries and strengthen their economic and political relations. However, this is jeopardized by accelerating climate change. The dominant trend of favouring market-based solutions (i.e. carbon credits etc.) to address climate action has proven to be insufficient and Net Zero targets remain unreachable. Extreme weather events intensify and are more and more unpredictable, and this has direct economic impacts on agriculture in the UK and Scotland.

Farms continue to become less profitable and an increasing number are becoming economically inactive (so-called Zombie Farms); incomes are squeezed, and farms are more likely to amalgamate with other farms thus reducing the number of holdings. Large commercial farm operations become the rule. This goes hand in hand with failure to achieve targets (Net Zero) and reduces sector resilience. Successive Scottish governments fail to achieve the aim of reducing carbon emissions by 32% by 2032 (as initially established in the 2021 Scotland Climate Smart Agriculture Framework).

Reduced farm income and less support to the sector reduces investment in technology and science (e.g. using gene editing for crop improvement), increasing uncertainty about new available technologies for most farmers. Only the most profitable have access to high tech. Technology and information (data) are privatised and only some can access these in the UK. Investment in farm infrastructure is also reduced affecting the possibility of developing knowledge and innovation in agriculture.

Food is generally affordable for consumers but only thanks to imports. Agricultural production in Scotland is mainly for international markets (e.g whisky industry) and production for local food markets is expensive. On top of the higher dependency on food imports, there is a growing 2-tier tendency in society, with only the better-off being able to afford nutrient-rich, fresh, sustainably-produced food while for most of the population food is largely imported given comparative advantages, especially for production costs.

Scottish government fails in its efforts to increase awareness about food provenance and the lack of awareness in the population leads to less political pressure for change in food production (i.e. increasing healthy local food grown sustainably), decreasing demand for local, Scottish produce. In addition to larger commercial operations, farmers are more likely to move to rewilding, carbon offsetting and provision of leisure activities. Lack of diversity makes the few crops grown in Scotland more vulnerable to PPD.

Pests and Diseases under 'Agriculture elsewhere' scenario

CPB – Permanent effect. Scotland has a premium product and high plant health safeguards in relation to seed and ware potato production. However, the industry would weaken very quickly in this scenario, unless there are crop protection chemicals to defend against CPB. There are more than ~26 000 ha of seed and ware potato in Scotland in prime agricultural land, all of that would become fair game to these beetles if the pest was to become established and there were no effective controls. If government wants to stop CPB getting in, what would they choose? Major changes to the whole industry? Prime arable land could no longer be used for potato growing. Would the permanent effect change the entire industry because we would lose all our export markets?

Wheat Stem Rust – Major to Permanent effect. With only 20% of the wheat varieties being resistant to wheat stem rust and weather being increasingly unpredictable, this pathogen could have a major to permanent effect and further strain the already fragile sector. On one hand weather conditions are favourable to the pathogen and with more land under rewilding the risk of increasing the availability of alternative host plants increases the chances for the pest to survive. However, control is possible at early stages. Technologies for improved crop husbandry and PPD control could be applied on large scale cereal farms which are the principal types to be affected. Along the same line, biological controls could represent a viable option if the availability of chemical solutions was a barrier.

Blueberry Rust – Major to Permanent effect. Assuming commercial horticulture production survives in this scenario, this pathogen would have major to permanent effects. Investing in technological innovation by businesses would give them the chances to survive or by pressuring for the use of fungicides to be used if the disease becomes established. Because international trade continues the same in this scenario it would be hard for the blueberry sector to continue competing with additional pressures such as this disease.

Recommendations from 'Agriculture elsewhere' scenario

Discussion about the recommendations under this scenario was about the reconciliation between available plant protection products, fungicides and pesticides and existing cropping practices. Stakeholders questioned what the costs for the industry would be if these protection products are not available and what the farming best practices should be. They also mentioned risk analysis on chemical and biological control products available to halt PPD and the impact of losing them (or not developing new ones) on the economy of the arable and horticulture sector, rural economy and rural communities.

Stakeholders highlighted the need for better border controls and inspections of plants and other products to reduce the risks of PPD introduction and subsequent crop losses and costs of treatment which are borne by the business. Recommendations were also about increasing support for farmers to monitor fields in relation to PPD, referring to economic support but also training to detect PPD before they become a threat. Importantly they emphasised the need for increased resources, and research and development, to aid substitution of chemical means of crop protection. This highlights the fact that pesticides are being withdrawn but alternatives are still to be developed. One concern expressed was that many alternative pesticides have the same chemical properties as previous ones and so are also deemed as at risk of withdrawal.

Maintaining biodiversity in the fields, agrobiodiversity, intercropping etc. was important for stakeholders specifically for this scenario. Schemes that buffer the losses of farmers and insurance schemes which help to buffer crop losses might be one option to aid financial sustainability in the face of these PPD risks.

Stakeholders also mentioned that in addition to insurance schemes, there is a need for government guarantee schemes. If government does not want to regulate markets, then they should develop assurance schemes for farmers to borrow the money they need to establish their crops and to run the business. In particular, stakeholders felt that there was a need to look at how best to share risk and consider the combination of banks' vulnerability and risks that farming businesses bear.

6.5.3 Stakeholders' knowledge elicitation about pests and diseases

Pest and pathogen threats highlighted by stakeholders

The PPD threats identified by stakeholders are summarised in Table 10. The reasons given for selecting these PPD included i) changing climatic conditions (e.g. wetter conditions favouring slug damage and fungal disease incidence; milder winters increasing overwinter persistence of insect pests, including new species from warmer climates); ii) appearance of new insect pests (e.g. CPB) or fungal pathogen strains from overseas or through rapid evolution of new strains locally due to agronomy and climate, resulting in breakdown of crop resistance, iii) loss of pesticides, iv) changing farming practices (e.g. more trash-borne diseases due to direct drilling; cover crops acting as green bridges between seasons; wildflower strips providing refugia to PPD), v) new crops or changing crop rotations bringing new PPD threats or exacerbating existing threats (e.g. expansion of sugar beet growing could lead to beet nematode incidence increases).

Comparison with pest and pathogen threats identified by modelling.

In terms of predicted risk based on proximity to other counties with shared PPD assemblages, three of the PPD identified by stakeholders are listed as present in the UK but not specifically noted in Scotland according to CABI distribution data: mildew, slugs, and CPB (Table 4), with the latter not yet established in the UK. The English Grain aphid is also known to be present on cereal crops in Scotland. PPD which have a high probability of arriving in Scotland (P_S >0.24) were not identified by stakeholders (Table 5, Table 6). PPD with a moderate probability of arriving in Scotland (P_S >0.1) and likely to be problematic for major Scottish crops were largely absent from the list selected by stakeholders, although the identification of general threats from aphids and nematodes was expressed by stakeholders (Diuraphis noxia and Meloidogyne javanica, respectively). In terms of bioclimatic similarity, only cereal aphids, rusts, CPB and potato blight were highlighted by stakeholders and modelling (Table 7), with many other PPD identified as potential risks by modelling. Blight and CPB were the only threats identified as a trade risk (Table 8) that were also identified by stakeholders, and none of the PPD predicted to pose a risk through travel (

Table 9) were highlighted by stakeholders.

Table 10. Pest and disease threats anticipated by stakeholders to become more problematic in future Scottish agricultural systems.

Type	**Cereals**	**Fruit**	**Potato**	**Vegetables**
Fungal/oomycete pathogens	*Septoria* (wheat) *Rhynchosporium* (barley) *Ramularia* (barley) eyespot (cereals) *Gaeumannomyces tritici* (take-all of wheat and barley) *Gaeumannomyces avenae* (take-all of barley) Rusts Ergot	Mildew *Botrytis* *Monolinia* *Phytophthora* *Sclerotinia*	Blight	
Arthropods	Aphids Leatherjackets	Aphids Spotted wing Drosophila Marmorated stinkbug *Xylella*	Aphids CPB Wireworms	Cabbage stem flea beetle Pollen beetle Bean weevil Beet nematode Beet moths Cabbage stem weevil Carrot fly
Nematodes			Potato cyst nematode Other free-living nematodes	
Bacteria			Zebra Chip Brown rot *Pectobacterium* Storage diseases	
Viruses			Aphid-vectored viruses (PLRV)	Turnip yellows
Other	Slugs Rabbits Pigeons Geese New Zealand flatworm			

6.6 *Modelling invasion by the Colorado Potato Beetle (CPB)*

Our biophysical analyses and stakeholder discussions suggested CPB as a potential threat to Scotland. For the most recent year for which gridded temperature data were available at the time of writing, 2022, we found significant vulnerability of UK, including Scottish, potato production (Figure 10). For the major potato production areas in Scotland, concentrated on the east coast around Edinburgh and Dundee, a new generation of adult beetles would emerge several weeks before autumn diapause. Hence, CPB is potentially an immediate threat to Scotland's potato growers.

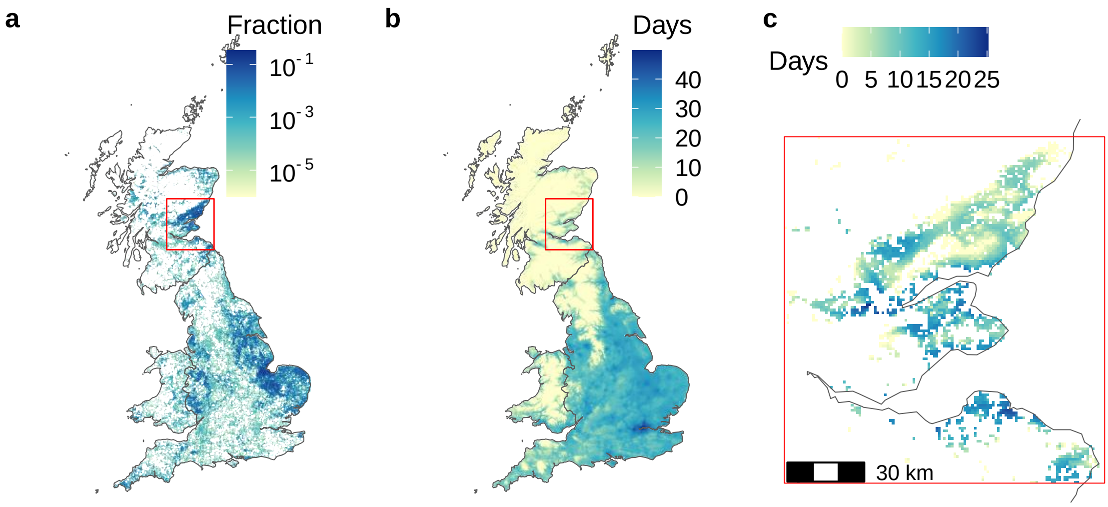

Figure 10. a. Fraction of 1 km grid cells with potato production, EUCROPMAP 2019 data. Major production region in Scotland outlined in red. b. Predicted number of days between emergence (at $DD_{10} \geq 411$) and diapause (day length < 15 h), in 2022. c. Predicted number of days between emergence and diapause within major production region in Scotland, for grid cells with ≥1 ha potato production.

CPB was recently detected in southern England, hence we modelled its potential spread northward across the UK as climate warms. In common with other analyses (Jönsson et al., 2013; Pulatov et al., 2016), our analyses showed that climate change will greatly increase the risk of CPB invasion in the UK. The date of first emergence of adult beetles (based on the thermal time calculation of 411 DD above 10 °C) increased with latitude for all RCPs (Figure 11). By 2060, first emergence in southeast England is projected to occur around the middle of July under RCP2.6 and around the end of June under RCP8.5. In contrast, first emergence in the crop-growing regions of eastern Scotland occurs in early August under RCP2.6, and in large areas does not occur before the diapause threshold of mid-August. Under RCP8.5, first emergence occurs in July, giving enough time for beetles to enter diapause.

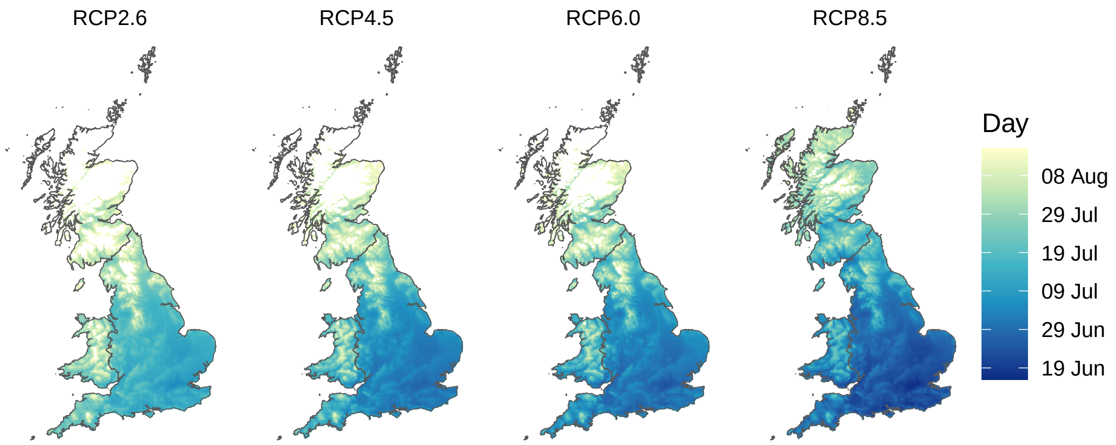

Figure 11. Date of first emergence of CPB ($DD_{10} \geq 411$) in 2060 under four RCPs.

The number of dispersal events (days when $T_{max} \geq 15$ °C) also varied with latitude (Figure 12). By 2060, most of England and eastern Scotland experience sufficiently high temperatures to trigger several dispersals, even under RCP2.6.

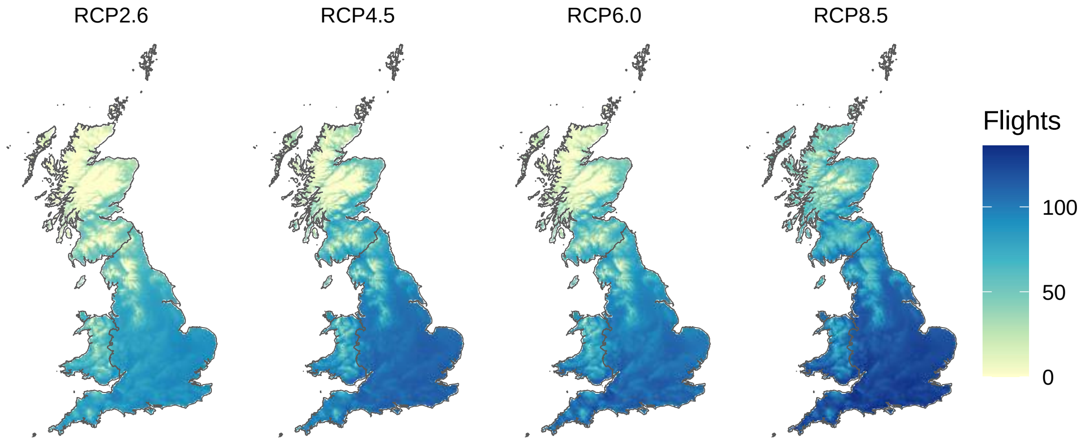

Figure 12. Number of potential dispersal events ($T_{max} \geq 15$ °C) in 2060 under four RCPs.

We ran the PoPS simulation 500 times to obtain probabilities of establishment of CPB across all 1 km grid cells currently growing potato, from an initial invasion in Kent. Even under RCP8.5, the risk of establishment in Scotland remains low until the late 21st Century (Figure 13). CPB remains limited to southeast England until around 2040 when populations become established in East Anglia and the East Midlands. By 2060 the whole potato-producing region of England has been invaded. Not until 2079 does CPB become established in Tayside, though the probability of invasion remains at only around 50 %. These simulations suggest that Scotland is likely to remain free of CPB for several decades, barring local adaptation of CPB populations to Scotland's climate.

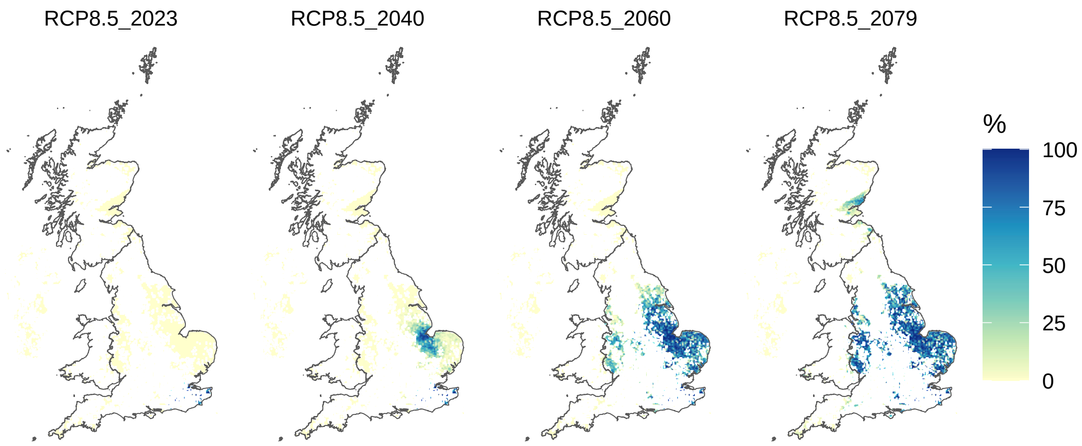

Figure 13. Probability of establishment of CPB in potato-growing regions of the UK under RCP8.5, from an initial population in Kent.

7 Conclusions

We have combined a range of mathematical and statistical models with stakeholder scenario planning to provide an interdisciplinary analysis of plant health threats to the arable and horticulture sector in Scotland. Our numerical analyses considered the global distributions of PPDs, climate, crop distributions, PPD host range, pest ecophysiology and behaviour, trade, travel and transport. Our stakeholder engagement exercise employed online surveys and workshops to co-develop plausible future scenarios for Scotland's arable and horticulture sector, focussing on the threat from three example PPDs, representing threats to economically-important crop types (cereal, potato and soft fruit) and differing in their biology, ecology and perceived threat to crop production. Here, we summarize our findings and make recommendations regarding avenues for further research to improve the resilience of Scotland's arable and horticulture sector to future threats from emerging PPD.

Scotland's crop production. Crop area in Scotland is dominated by barley, wheat, potato, oilseed rape and oats. Although covering a small area, soft fruit production also contributes significantly to the Scottish economy. Climate change, as well as socioeconomic factors, are likely to change the composition and distribution of arable and horticultural crop production in Scotland. While some recent analyses have considered changing suitability for some individual crops across the UK (e.g. Coleman et al., 2021). Rivington et al., 2022 project a reduction in barley yields under the most likely climate projections but aside from this, we are unaware of any **comprehensive projections of crop suitability for Scotland under climate change**. A recent technical report does not incorporate results from crop models and lacks crop-specific detail (Jenkins et al., 2023). Hence, we recommend that such an analysis, considering both bioclimatic and socioeconomic factors, is undertaken.

Plant pest and disease distributions. CABI and EPPO maintain the most comprehensive information on global PPD distributions. We found that these records can be incomplete for subnational regions like Scotland. While these databases continue to be updated and refined, it would be valuable for plant health management and risk analysis if **responsible authorities (Scottish Government) maintained and published lists of established and emergent PPDs specifically in Scotland, or worked with EPPO or CABI to make such data available**. We also found that the Defra PHRR tends not to explicitly provide information on potential geographical distributions of invasive species within the UK. Indications of which UK regions are most at risk would be valuable.

Routes of entry. Our analyses of PPD risks from trade and transport employed national-level data on trade and tourism flows along with CABI PPD distribution data. Defra has recently begun publishing data on interceptions of imported plants and associated harmful organisms (e.g. PPD), although the port of interception is not given. **Analyses of these interceptions will improve understanding of invasion risk**.

PPD risk to Scotland. Our biophysical risk models identified a number of PPDs of greatest risk to Scotland. PPDs which emerged as being of particular concern included wheat thrip (*Haplothrips tritici*), corn earworm moth (*Helicoverpa armigera*), common bunt (*Tilletia laevis*) and CPB (*Leptinotarsa decemlineata*). Some of those identified had high unmitigated risk ratings in the PHRR, including CPB, beet root weevil (*Asproparthenis punctiventris*), the disease vector *Hyalesthes obsoletus*, pea leafminer (*Liriomyza huidobrensis*), tarnished plant bug (*Lygus lineolaris*) and potato virus S. The potato flea beetle (*Epitrix papa*) was identified as a risk through travel, and has a high PHRR unmitigated risk rating. Additionally we consider wheat stem rust (*Puccinia graminis* f.sp. *tritici*) as a potential threat to Scotland due to its recent re-emergence in the UK and Ireland (Saunders et al., 2019; Tsushima et al., 2022). **PPDs flagged as being of high risk by multiple methods should be prioritised for research into management and control methods**.

Climate change and PPD risk. Several species are known migrants to southern UK and could become problematic in Scotland under climate change. Our PoPS dynamic model showed that a successful invasion of CPB into southern UK is likely to spread to Scotland within decades, assisted by climate warming which accelerates development time and promotes adult dispersal. Others, like dwarf bunt, benefit from cold winter temperatures and may become less threatening. We were able to conduct detailed invasion and climate risk modelling for CPB because sufficient ecophysiological data (host range, life cycle, temperature-dependent development and dispersal parameters) are available for this species. For many other species, however, such information is either unavailable, incomplete or outdated. **Detailed life history and ecophysiological information for PPDs of interest should be collated from the literature or obtained via experiment** to enable invasion modelling.

We now turn to results from our **stakeholder engagement exercise**. PPDs listed by stakeholders as likely to be threats to future crop production showed little overlap with results from our biophysical risk analyses. This is likely because stakeholders focussed on species already present in the UK, e.g. marmorated stink bug (*Halyomorpha halys*), take-all (*Gaeumannomyces* spp.). CPB was highlighted as a concern by stakeholders, and we asked them to consider this beetle along with emerging wheat stem rust and recently arrived blueberry rust as example PPD threats across different economically important cropping systems (cereals, potato, soft fruit). The aim was to analyse the robustness of future scenarios for the Scottish arable and horticulture sector to emerging PPD threats.

Stakeholders co-designed two plausible scenarios for the future, over a ten-year timespan. Under the *Scotland's own vision* scenario where Scotland has greater autonomy and control of agriculture, stakeholders envisaged that despite some protectionist tendencies, the global economy largely maintains a trajectory towards free trade. Under this scenario the UK, increasing international trade is coupled with internal political instability, particularly in Scotland, which negotiates greater autonomy and economic ties with the EU. Scotland's focus on inclusive growth, sustainability, and good governance leads to reductions in carbon emissions and a moderate independence from the UK's agro-food supply chain. The government implements interventions to strengthen connections between people and food provenance, supporting local markets and fostering consumer willingness to pay more for healthy, locally produced food.

Concerns about pests and diseases (PPD) in this scenario affect crop types and agricultural actors differently, with recommendations from stakeholders including increased use of precision farming practices, early PPD detection, and investing in crop diversity to mitigate risks. Stakeholders propose shifting away from monoculture towards more diverse cropping systems to enhance resilience. Weather predictions play a crucial role in managing PPD risks, prompting calls for more research and development into crop diversity and blends, as well as letting natural systems evolve diverse environments to combat threats effectively. In this scenario, a potato industry pest threat such as CPB has a moderate effect on Scotland's potato industry, but precision farming programs help mitigate its impact by allowing growers to adapt and prevent stronger shocks. The seed potato industry remains unaffected, incentivising research and development for pest mitigation. A cereal pathogen such as wheat stem rust has a small effect due to continuous research and development compensating for farmers' low responsiveness. However, reduced fertiliser allowances for Net Zero goals may lower disease risks due to decreased wheat planting. A soft fruit pathogen such as blueberry rust poses a permanent challenge, impacting production costs, but consumer willingness to pay more for locally produced fruit could offset this. Additionally, if other countries face similar PPD issues, Scotland may gain a competitive advantage.

Under a second *Agriculture elsewhere* narrative, stakeholders projected that after overcoming geopolitical tensions and trade conflicts, the global economy has reverted to a focus on free trade but faces new challenges from climate crises. In the UK and Scotland, efforts to strengthen international trade and relations are hindered by accelerating climate change. The failure to meet emission reduction targets impacts farming, leading to decreased profitability, farm closures, and reliance on large commercial operations, undermining sector resilience. Reduced investment in technology and science exacerbates uncertainty among farmers, with only the most profitable accessing high-tech solutions. Food affordability relies heavily on imports, contributing to a societal divide where only the wealthy can afford locally produced, sustainably grown food. The lack of awareness about food provenance dampens demand for Scottish produce, while farmers increasingly turn land over to rewilding and leisure activities.

PPD pose significant threats, with recommendations from stakeholders focusing on reconciling available crop protection products with cropping practices, improving border controls, investing in research and development for chemical substitution, maintaining biodiversity, and implementing insurance schemes to buffer crop losses and guarantee schemes to provide security. Under this scenario, a potato pest such as CPB poses a permanent threat to Scotland's premium seed and ware potato production, potentially devastating the industry without effective crop protection chemicals. With a large area of prime agricultural land at risk, the government faces critical decisions to prevent CPB establishment and preserve export markets. A cereal pathogen such as wheat stem rust presents a major to permanent threat, exacerbated by unpredictable weather and increasing land under rewilding, potentially impacting the already fragile wheat sector. However, early-stage control measures and technological innovations offer potential solutions, particularly for large-scale cereal farms. A soft fruit pathogen such as blueberry rust also poses a major to permanent threat, potentially undermining the survival of commercial horticulture production. Investments in technological innovation and the use of fungicides may offer some resilience, but competing in international trade amidst disease pressures remains challenging for the blueberry sector.

Stakeholder recommendations

Stakeholders proposed several recommendations to address pest and disease (PPD) challenges in agriculture:

1. Consider invasive PPD as agricultural support programmes are developed.
2. Conduct research and development on adapting the farming calendar for planting which could potentially help to adapt to the changing climate.
3. Adopt existing solutions, such as detection and application, in good time to mitigate PPD impacts.
4. Switch from monoculture to a more diverse cropping system, including resistant varieties and mixtures of landraces, to increase resilience.
5. Conduct research and development on agrobiodiversity to provide buffers against potential threats.
6. Promote crop production for food rather than non-food uses.
7. Improve weather-driven PPD risk models ("decision support systems") to enable targeted control measures.
8. Analyse the economic implications of changing PPD management methods, e.g. switching from chemical to biological control or novel chemical control.
9. Improve border controls and inspections of plants and other products to reduce the risks of crop losses and costs of treatment.
10. Increase support for farmers to monitor fields in relation to PPD.
11. Provide government insurance and assurance schemes for farmers to buffer losses and provide security.

These recommendations aim to address the challenges posed by PPDs and promote sustainable and resilient agricultural practices.

Final Conclusions and recommendations

Project recommendations are summarised in terms of the target audience, and take into account the recommendations from stakeholder analysis of future scenarios for Scottish arable and horticultal production.

For policy advice and regulation, these include:

1. Maintain and publish an active list of present and emerging PPD in Scotland, or work with others e.g. CABI to do so.
2. Maintain and publish data on PPD interceptions at Scottish ports.
3. Consider emerging PPD as governmental agricultural support programmes are developed, including support for PPD monitoring and government insurance and assurance schemes.

For farmers, agronomists and other agricultural practitioners:

1. PPDs flagged as being of high risk by multiple methods in the present analysis should be prioritised for early detection and management, using existing solutions in good time to mitigate PPD impacts.
2. Consider diversifying crop production systems to increase resilience, including use of resistant crop varieties, intercropping, mixtures of landraces, diverse uncropped vegetation, and modifying or adapting crop rotations.

For research and development:

4. Conduct a biophysical and socioeconomic modelling to understand potential future changes in Scotland's crop production in coming decades, particularly to identify where and when novel crops may be cultivated.
5. Detailed life history and ecophysiological information for PPDs of interest should be collated from the literature or obtained via experiment to enable invasion modelling.
6. Improve decision support to enable targeted control measures, including research into the implications of changing PPD management methods (e.g. switching from chemical to biological control or novel chemical control)
7. Conduct co-creation of knowledge for PPD management (research with stakeholders which translate into actions).

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