Biosecurity for plant health: better justification of precautionary measures

Project Final Report

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Content

1 Executive summary

This research report focusses on an exploration of the drivers of and barriers to the adoption of precautionary plant health and biosecurity measures by practitioners across agriculture, horticulture, forestry, and natural environment management sectors in Scotland. Precautionary measures are likely beneficial if introduction or spread of a plant pest will lead to significant negative ecological, economic, or social impacts.

The research aims to better understand how practitioners make decisions relating to plant health and biosecurity; when reacting to a pest event, or when planning for potential future events. Such understanding can help design interventions which can encourage greater precautionary decision-making.

We conducted rapid evidence reviews to identify drivers for and barriers of adopting precautionary measures and to assess how economic cost benefit calculations are made for evaluating plant health interventions. We then conducted interviews with individuals in each of the four sectors of interest and held a stakeholder workshop to discuss the findings of the reviews as well as attitudes to risk and the use of case studies to communicate the advantages of precautionary measures.

Research conclusions:

- Important system factors which impact practitioner decision-making about plant health and biosecurity include: individual knowledge and awareness of plant pests and possible precautionary measures, self-identity, and self-efficacy to make the right decisions; community networks and social norms of those within their sector and with information providers; and wider system availability of plant health information and market forces. These system factors are generally applicable to decisions regarding many types of plant health or biosecurity measures, not just those which are precautionary.
- Practitioner perceptions of risk, cost benefit, and uncertainty are potentially mediated by how far into the future the practitioner was willing or able to 1) forecast, and 2) apply that forecast to aid decision-making in the present. Precautionary measures are more likely to be preferential when considering the long term.
- Pest risk assessment is an area which practitioners find information hard to interpret and apply due to complexity and individual context. Needing to think longer term for precautionary measures, adds to this complexity. Trusted advisors / information gatekeepers to help translate complex information for decision making are lacking.
- Practitioners often make decisions at a smaller scale (farm, woodland, catchment) than are considered in cost benefit analyses which compare precautionary action with no action. Analyses were therefore of limited use for individual decision-making; however, they were useful to justify decisions to others (e.g. large scale landowners) who are more likely to give credence to models predicting financial impacts.
- Precautionary measures for plant health are often calculated as more beneficial when including public benefits (e.g., potential damage to the natural environment) as well as individual benefits, but the latter are more relevant to individual practitioner decision making. Considering a longer timeframe or lower discount rate in cost benefit calculations will often tip the balance in favour of precautionary measures but changes in the wider system over that time mean longer forecasts maybe less reliable and may decrease trust in advisors who choose to use them.

- Perceptions of the uncertainties which were found to be important when making plant health decisions included practical effectiveness of measures and impact on productivity of precautionary measures, as well as market forces, climate change, and policy priorities. Uncertainty may be perceived to increase the further into the future is considered, or conversely a longer timeframe may be perceived as advantageous to even out shorter-term volatility for a more predictable outcome.
- Successfully using case studies to justify adoption of precautionary measures and persuade practitioners to adopt, should have relevant content clearly applicable to the context of the practitioner, and be delivered by a trusted and genuine advisor (individual or organisation).

Practical recommendations:

- A wider range of opportunities should be made available for practitioners to connect to each other, on their own terms. The heterogeneity of individuals in all sectors, sites, and of personal experiences means an onus should be on creating the environment for collective action to emerge.
- Pest information gatekeepers have previously been identified as crucial actors in transfer and interpretation of information. The dearth of such people who effectively interpret the high-quality information and advice already available on precautionary measures and their benefit should be addressed.
- A suite of sector-relevant case studies should be developed to highlight the range of benefits of precautionary measures applied at the individual, community, and wider system scales. Case studies would include discussion of factors identified by this project as impacting decision-making, including how complex risk and cost-benefit information was applied, and actions taken to deal with uncertainties, particularly those associated with managing for longer timeframes.

Future research areas:

- We recommend investigation into what characteristics of collective action are successful in which contexts (across sector, location, plant, pest), how rules, incentives and consequences are developed and communicated, and how social learning could be successfully applied.
- Our findings suggest that their effectiveness may rely on gatekeeper characteristics such as interpersonal relationships (e.g., trust), personal / organisation objectives, and pressures faced by the gatekeepers themselves. The way these characteristics are perceived by practitioners themselves may also impact such effectiveness. Further research in this area is warranted.
- Risk, uncertainties, and cost benefit calculations change when considering longer time frames. The perceptions practitioners have of risk, uncertainties and cost benefit analyse also change with the longer-term thinking required when considering precautionary measures. There is a need for longitudinal (both new and retrospective) social and economic studies to evaluate accuracy and usefulness of forecasting.

2 Introduction

2.1 Background

The introduction and spread of pests and pathogens of plants (hereafter 'plant pests') are a serious issue to be considered in the management of agriculture, horticulture, forestry, and the natural environment in Scotland. Therefore, land managers including farmers, foresters and conservationists are constantly making decisions regarding if or how to respond to current and future plant pest threats. Measures available to aid in tackling plant pest threats can be broadly categorised as either precautionary or reactionary (Table 1). Both precautionary and reactionary measures are key to good plant health and biosecurity, and land managers must choose how to mix the adoption of preventative and curative actions. These approaches align with the concepts of mitigation and adaptation strategies, which have become familiar in debate and action on climate change and other environmental threats.

Table 1 - Precautionary and reactionary measures for plant health and biosecurity

Type of measures	Description	Example measures
Precautionary / mitigation	Actions taken **before** introduction or spread to reduce the likelihood or impact of a plant pest event occurring	Crop rotation; choice of species and variety to plant; controls of movement of plants (e.g., at borders); clean supply chains; onsite phytosanitary measures (e.g., boot washing, vehicle washing, limited access, quarantine area, removing disease- and pest-ridden plants/plant materials); pest monitoring networks; prophylactic use of agrochemicals
Reactionary / adaptation	Actions taken **after** introduction or spread to reduce or mitigate the impact of the plant pest event or to eradicate the pest	Use of agrochemicals to remove pest after detection; removal / destruction of affected or potentially affected plants; ban on plant movements

In many cases, prevention is seen as better than cure. For example, this is more likely if introduction or spread of a plant pest will lead to significant negative impacts before it can be managed or eradicated, or if a plant pest once present is impossible to remove. There can also be socio-economic benefits arising from smaller precautionary investments in mitigation measures rather than managing larger financial or societal impacts after pest outbreaks. For this reason, it is important to understand how stakeholders such as land managers justify their decisions to adopt precautionary measures or reactionary measures.

A key tool in precautionary decision-making around plant health and biosecurity are risk assessments. Risk assessments consider the likelihood of a risk and the potential magnitude of consequences as well as strategies that can be taken to reduce or minimise likelihood of an event occurring. Structured pest risk assessments which can be conducted at any scale (from site to global), formalising the process of evaluating the likelihood and impacts of a pest outbreak to aid prioritisation and decision making. A major source of information available to stakeholders is the UK government's Pest Risk Analyses (PRAs) (https://planthealthportal.defra.gov.uk/pests-and-diseases/pest-risk-analyses/defras-approach-to-pest-risk-analysis/) which follows international standards on assessing risk, and individual pest analyses can include details on the likelihood of a pest event occurring, the potential impacts, and the estimated costs and benefits of measures needed to prevent entry to an area (introduction or spread) and to manage or eradicate a pest outbreak. PRAs are available publicly on the UK Plant health Risk Register (https://planthealthportal.defra.gov.uk/pests-and-diseases/uk-plant-health-risk-register/). Plant health is a devolved matter in the UK, however all UK nations have representation on the technical groups involved with Pest Risk Analyses as part of a coordinated approach. Scotland can take a differing approach to a specific pest should there be seen to be mitigating circumstances. If and how practitioners use plant health risk assessment tools will likely impact their understanding of plant pest risks, and therefore play a part in whether they choose to adopt precautionary measures or not.

A challenge for precautionary action is that the potential likelihood or magnitude of a plant pest threat or the consequences of particular actions are not always understood. This may be because of uncertainty deriving from a lack of scientific research on the pest or context, a lack of information easily available or a lack of awareness despite available information.

Part of the process of risk assessment and decision making, when information is available, includes comparing the costs of any plant health measures against the potential savings or losses. Cost benefit analyses for precautionary measures attempt to estimate the overall costs of implementing a precautionary measure and compare these to the estimated benefits (often through avoided costs) of implementing these measures. This is achieved by comparing a scenario where one or more precautionary methods is implemented to prevent an outbreak, with a scenario where no intervention takes place, (business-as-usual). From here it is possible for the benefits of the precautionary method to be estimated by calculating the difference in the damage caused in the business-as-usual scenario with when the precautionary method is implemented. This avoided damage can then be regarded as the benefit of the precautionary method. These benefits must also account for the probability of the outbreak event happening, and therefore benefits must be multiplied by this probability to give an 'expected benefit'. Given that precautionary measures occur before an outbreak happens, cost benefits analyses of this type are often strongly reliant on projections and may suffer from uncertainty in the probability of an outbreak and the way it may spread.

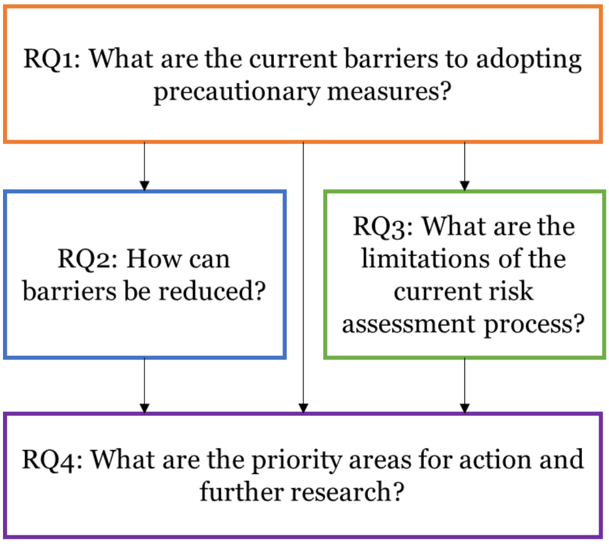
This project addresses the research questions below, and provides recommendations relevant to government, industry, third-sector, or other interested parties regarding practitioner adoption of precautionary measures for plant health.

- RQ1 – What are the current barriers to adopting precautionary measures?
- RQ2 – How can barriers be reduced?
- RQ3 – What are the limitations in risk assessment?
- RQ4 – What are future research priorities?

2.2 Research approach

It is not the aim of this project to detail the technical aspects of precautionary measures and thus what barriers or risks are associated with adopting a particular measure for a particular pest threat. Rather we approach the problem from a social science perspective. We focus on studying the attitudes and behaviours of people who make plant health and biosecurity decisions and assess risks, to which they will apply technical detail as available.

The project addresses the four research questions using stakeholder mapping, rapid evidence assessments, semi-structured interviews, and a discussion workshop (Figure 1). The outputs of each activity feed into those that follow.



Activities & topics

Expanded stakeholder map
- Cross-sectoral mapping (RQ1)

Evidence review
- Trade-offs of existing measures (RQ1)
- Valuation of pest impacts (RQ1)
- Encouraging behaviour change (RQ2)
- Use of case studies for justification (RQ2)

Semi-structured interview
- Trade-offs (RQ1)
- Perceived / actual economic costs (RQ1)
- Failures / successes (RQ2)
- Use of and attitudes towards risk assessment (RQ3)

Workshop
- Discuss findings and prioritise next steps (RQ4)

Figure 1 - Research approach: tasks and activities aligned with research questions.

3 Methods

3.1 *Rapid evidence assessments*

Three searches were performed to rapidly assess evidence on: description of existing precautionary measures for plant health, to identify potential trade-offs of adoption; drivers of and barriers to practitioners adopting environmental practices; the economic value of adopting precautionary measures. The project lead and the wider participatory team, provided advice, feedback and further literature recommendations throughout the search-term identification and inclusion process. Research timelines meant that search terms were also adapted, and screening criteria applied where needed to reduce the number of results to a manageable volume (see details in Appendix 1 – Rapid assessment search terms). Additional papers identified by snowballing from search responses and any suggested by the wider research team were also considered for inclusion if not already returned via search. All final searches were performed in Scopus. A total of 75 articles were included over all three rapid assessments.

3.2 *Semi-structured interviews*

Participants

Nine participants across key sectors were recruited for interview (Table 2). A long list of potential participants was compiled through research team contacts, internet searches, and recommendations following contact with an organisation. Participants were then approached for interview to get a spread of views from across target sectors. Microsoft Teams was used to conduct the interviews online, with an average interview time of 47 minutes. Participants completed a consent form prior to the interview, complying to SERG Code of Ethics, which included a brief explanation of the project, and consent questions, including questions around anonymity, confidentiality, and data use. Furthermore, participants who were themselves practitioners (rather than representatives or researchers) were also asked to complete a survey (N=9) which included questions around the economic aspects of the project (see Appendix 2 – Economic survey for practitioners). The economic survey yielded zero responses, and therefore no economic data was collected. Participants did not receive any compensation for their time.

Table 2 - Semi-structured interview participants

Sector	Role
Agriculture	Agronomist
Agriculture	Policy Manager
Horticulture	Programme Manager - biosecurity
Forestry	Harvesting Contracts Manager
Forestry	Head of Forestry
Forestry	Senior Woodland Officer
Forestry	Stewardship Forester
Natural Environment	Site Officer
Natural Environment	Social Scientist

Interviews

Semi-structured interviews included questions around background information of the participants, experiences of precautionary measures (e.g., positive, negative, precautionary vs. reactive measures, scales, and barriers to adoption), economic barriers, mechanisms to encourage adoption of precautionary measures (including case studies), risk perceptions and assessment, and pest and pathogen resources needed by participants. The interview schedule (Appendix 3 – Semi-structured interview schedule) along with the economic survey, were both shared with the wider project team, where feedback was received, edits were agreed among the team members and final edits were made, prior to the interviews and the distribution of the economic survey.

Analysis

Interviews were automatically transcribed in real time using the transcription function of MS Teams and subsequently checked for errors by the researcher who conducted the interview. Transcriptions were coded initially using the question framework to allow each question response to be compared between respondents and eliminate superfluous text from the analysis. Responses were then collated by research question (see intro), and any additional emerging themes noted for potential inclusion in the subsequent Discussion Workshop.

3.3 Discussion workshop

Participants and Procedure

Eight participants (and four facilitators) across various sectors, participated in the study (Table 3). Microsoft Teams was used to conduct the workshop online, which lasted approximately 2 hours. Participants were recruited through email or phone communication, where a brief explanation of the project was given, and acceptance of the invitation to take part in the workshop was received. Initially, participants were presented with the objective of the research and the workshop aim. Background information of the project were given, as well as key outputs/summary results from the rapid evidence assessments (behaviours & economics) and the interviews contacted prior to the workshop.

Key themes which emerged from the rapid evidence assessment and interviews were presented and discussed with participants. For each discussion theme/topic, a Padlet board (https://padlet.com) was used as a visual aid by the facilitators to prompt discussion among participants, who recorded participants' answers or the participant's added their answers themselves. Questions to stimulate discussion on the themes are shown in Table 4.

Table 3 - Workshop participants

Sector	**Role**
Agriculture	Agricultural Consultant
Agriculture	Agricultural Consultant
Agriculture	Director of Operations
Horticulture	Independent Consultant
Forestry	Biosecurity Officer
Forestry	Biosecurity Officer and Tree Health Champion
Forestry/Natural Environment	Head of Woodlands
Natural Environment	Plant Health and Biosecurity Scientist

Table 4 - Workshop discussion themes and associated questions

Themes	Questions
Collective Action	Are collective actions always necessary for plant health? Differences / synergies between communities of place and of practice How/when do these groups work well/poorly with policy, research, etc
Long-term thinking	What timescales do people work to and how does this impact plant health?
Relationships with risk	What are the potential outcomes of interactions between specificity of precautionary measures (specific to general) and formality of risk assessments (informal / experiential to formal / process driven

4 Results

4.1 *Summary of drivers, barriers, and potential actions for encouraging precautionary behaviours*

A wide range of drivers for adopting precautionary measures, as well as barriers to uptake and potential actions to take for increased uptake were present in the reviewed literature and from the semi-structured interviews. These elements can be broadly categorised by scale into those relating to the individual, community, and wider system (
Figure 2).

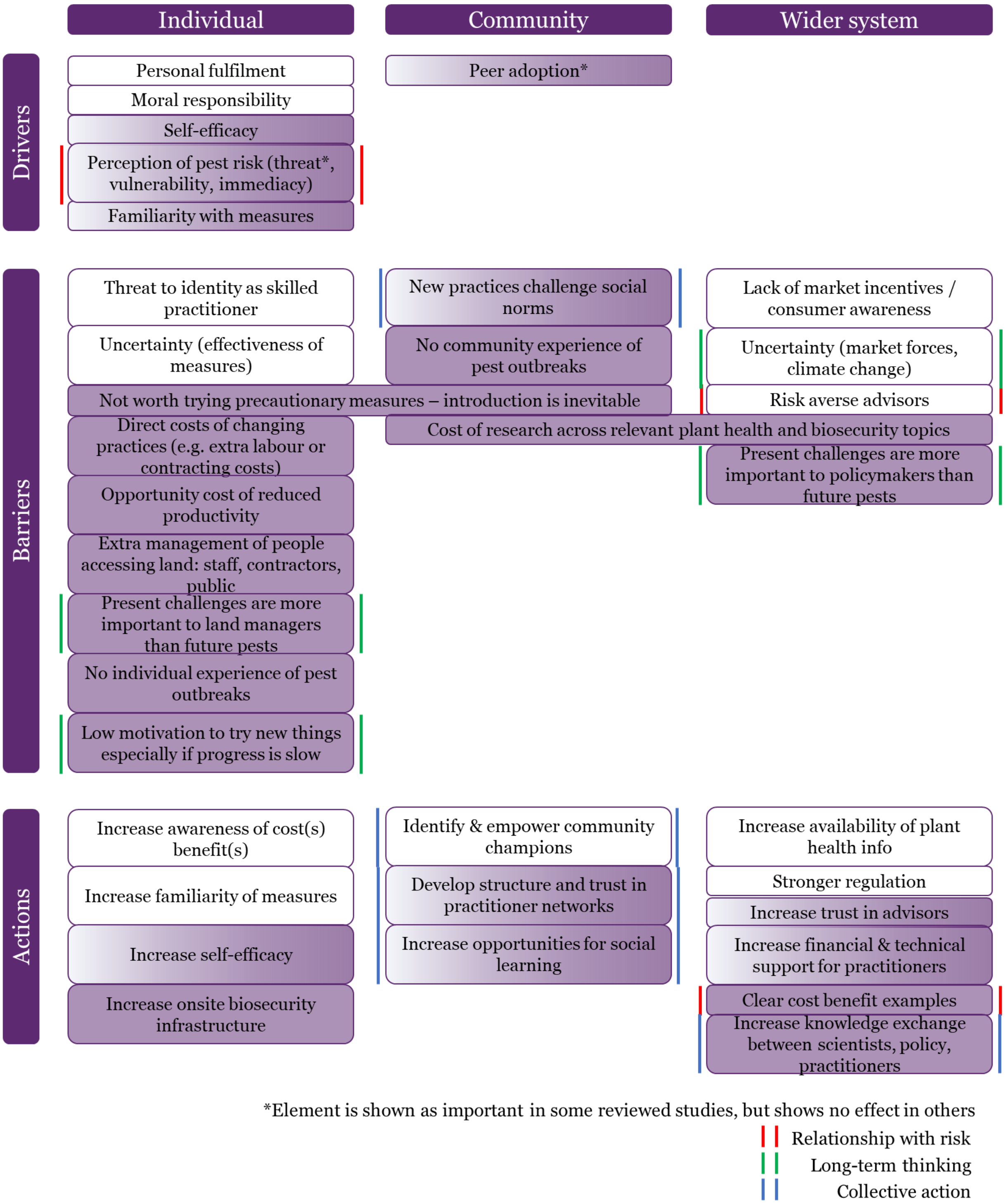


Figure 2 - Drivers for adopting precautionary measures, barriers to uptake and potential actions to increase uptake. Elements are categorised by individual, community, or wider system. White boxes are elements derived from the rapid review, purple boxes from semi-structured interviews, mixed white/purple boxes are elements occurring in both review and interviews. Three recurring themes of Relationship with risk, Long-term thinking, and Collective action are highlighted in red, green, and blue respectively.

4.2 Rapid evidence assessments

Published papers and reports were sought to provide evidence on the drivers for and barriers to adopting precautionary measures, and on potential interventions to overcome those barriers. The scope was limited to land managers in agriculture, horticulture, forestry, and environmental management, in Europe (including UK), North America, Australia and New Zealand.

Drivers and/or barriers to adoption of precautionary measures

Perceived threat of pest introduction and response costs are not drivers of biosecurity actions with respect to banana farmers in Australia, with self-efficacy, intrinsic reward (e.g., fulfilment and personal satisfaction from protecting the farm), and extrinsic reward (e.g., peer approval - especially when not taking part has negative connotations) correlating more strongly with adoption (Mankad, Zhang, and Curnock 2019). Self-efficacy, moral responsibility to the environment, and peer adoption correlate with pesticide reduction action by farmers in Netherlands (Bakker et al. 2021).Threat appraisal (perception of vulnerability and severity) is a factor indicative of intention to adopt pest management strategies in vegetable growers in Australia, alongside self-efficacy and efficacy of response (Mankad, Loechel, and Measham 2017). UK livestock farmers adopting animal health measures is related to their perception of risk (disease incidence, risk of adoption, timelines) (Gilbert and Rushton 2018). Perceived high risk can be directly associated with perceived high cost of implementation (Adamson et al. 2020). Timescales are also important, with land managers under pressure to respond to immediate issues (reactive) rather than act for longer term benefits (precautionary) (Irwin et al. 2016).

In a survey of UK and Ireland farmers regarding uptake of integrated pest management (IPM) actions, including preventative (precautionary) measures, Creissen et al. (2021) showed that significant drivers of uptake were: familiarity with IPM; number of factors considered when planning pest management programmes; perceived importance of biological pest control methods; and attitudes towards recommendations from crop advisors. Farm size and location (England, Northern Ireland, Scotland, Wales, and Ireland) were also predictors of IPM actions. The barriers associated with preventative IPM measures, were seen as lower than for other IPM measures.

Linder and Campbell-Arvai (2021) highlight that while proactive (rather than reactive) adaptations to climate risks by fruit farmers in the US such as crop diversification, planting new varieties, and improving soil health will be necessary to increase farm resilience in the future, growers were unable to justify making these changes due to their uncertainty about future climate changes. The study found that subjective norms (actions of other practitioners) did not correlate with proactive decision-making. Advisors can also be risk averse in their information provision (Barnes et al. 2021).

Financial barriers described came from practitioner perceptions of: direct costs of (or lack of available funding for) implementation (Barnes et al. 2021; Kaler and Ruston 2019; Mankad et al. 2017; Snyder et al. 2022); market forces and the power of customers (Barnes et al. 2021; Snyder et al. 2022); lack of mechanisms of direct payment for behaviour change (Blicharska et al. 2016); and uncertainty surrounding of cost-effectiveness of action (Barnes et al. 2021; Blicharska et al. 2016; Speksnijder and Wagenaar 2018). Uncertainty of estimating the cost-effectiveness of mitigation efforts can increase due to variations in the wider situational context, for example trade volume fluctuations caused by changes in international policies unrelated to pest legislation (Adams et al. 2020). The source of cost-effectiveness calculations lack transparency and may not be seen as trusted, for example if supplied by advisors linked to commercial companies (Barnes et al. 2021).

Adoption of new methods in animal health can threaten identity held as a skilled practitioner, particularly if those new methods seek to reduce hands-on interactions with livestock. Similarly, perceptions of whether implementation of an action puts the health of livestock at risk, and any resulting negative impact on reputation as a stockman, drive wariness of change (Doidge et al. 2020). Experts (such as veterinarians) have a collaborative role in changing practices, with frequency of contact and alignment of expert-practitioner goals impacting adoption of animal health practices (Redfern, Sinclair, and Robinson 2021; Skjølstrup et al. 2021; Weary, Ventura, and Von Keyserlingk 2015). Collaboration between farmers and veterinarians as experts operates in a wider context of government legislation, available technology (e.g., diagnostics), consumer awareness, and media awareness (Skjølstrup et al. 2021).

Actions to encourage adoption of precautionary measures

In some cases, increasing practitioners' awareness of costs and benefits, and direct and indirect consequences of on-farm behaviours correlate with behaviour change (Mankad et al. 2017), as do levels of skill and ability of the practitioner and environmental constraints (Price and Leviston 2014), and familiarity with the desired actions or system (Creissen et al. 2021). Operationalising community champions and value chain actors, greater dissemination of credible scientific evidence, increasing trust between neighbours, and trust in advocates have also been identified (Mankad et al. 2017).

In the absence of strong top-down regulations (and in some cases, in preference to them), self-efficacy of individuals to make their own decisions and put them into practice was identified by multiple authors as a key factor in adoption of new practices, including precautionary measures (Mankad and Loechel 2020; Mankad, Zhang, and Curnock 2019; Price and Leviston 2014; Speksnijder and Wagenaar 2018).

Creating conditions for social learning between farmers in preference to top-down schemes has been shown in surveys of farmers (Creissen et al. 2021; Price and Leviston 2014) and in agent based modelling studies which suggest that IPM actions passively diffusing through a population of farmers results in better adoption outcomes than active diffusion (Rebaudo and Dangles 2013). So-called passive adopters (who implement straightforward and less costly measures) are not willing to invest as much time and money as active adopters (who are proactive, innovative, and prioritise broader industry benefits) (Mankad and Curnock 2018). However, a combination of coercive and voluntary change can also be preferential for promoting adoption of animal health practices (Speksnijder and Wagenaar 2018). One driver for voluntary action can be to avoid increased top-down environmental regulations (Mitchell et al. 2016), as social approval and peer comparisons may be stronger drivers than perceived threat or response costs, particularly if the intervention is new to participants (Mankad et al. 2019). Global farmer-to-farmer communications have been identified as a major factor on successful adoption of farmer pro-environmental actions (Mitchell et al. 2016), as has the presence of an effective community of value-chain actors (Mankad et al. 2017; Speksnijder and Wagenaar 2018).

Plant health can be framed as a collective action problem where choice and adoption of measures is driven by groups of practitioners working together, appropriately supported by government or other more formal institutions (Ervin and Jussaume 2014). Trust between individuals for example between neighbours who may be required to also take precautionary measures for success to be achieved or between practitioners and advocates, is a key factor in adopting measures (Gilbert and Rushton 2018; Mankad et al. 2017; Speksnijder and Wagenaar 2018). Co-design of novel precautionary measures between practitioners and other stakeholders (e.g., scientists, manufacturers) requires trust in order to be successful (Carter et al. 2021; Kaler and Ruston 2019).

Issues with prioritisation of short-term over longer-term thinking can be combatted in a number of ways: strategic framing of information to decrease psychological distance; use of decision structuring and multi-criteria decision analysis to facilitate intertemporal trade-offs; structural solutions impacting consequences (increasing the negative consequences of short-sighted behaviour or increasing the benefits of far-sighted behaviour) (Irwin et al. 2016); education and outreach should give growers information on how climate change will impact local agriculture, particularly long-term projections that help visualise climate risks affecting them and impact of "no-regrets" strategies (beneficial regardless of uncertainties) such as crop diversification & soil health (Linder and Campbell-Arvai 2021).

Research gaps identified in reviewed literature

The papers reviewed identified several research gaps for understanding how better to encourage adoption of precautionary measure, as summarised in Figure 3.

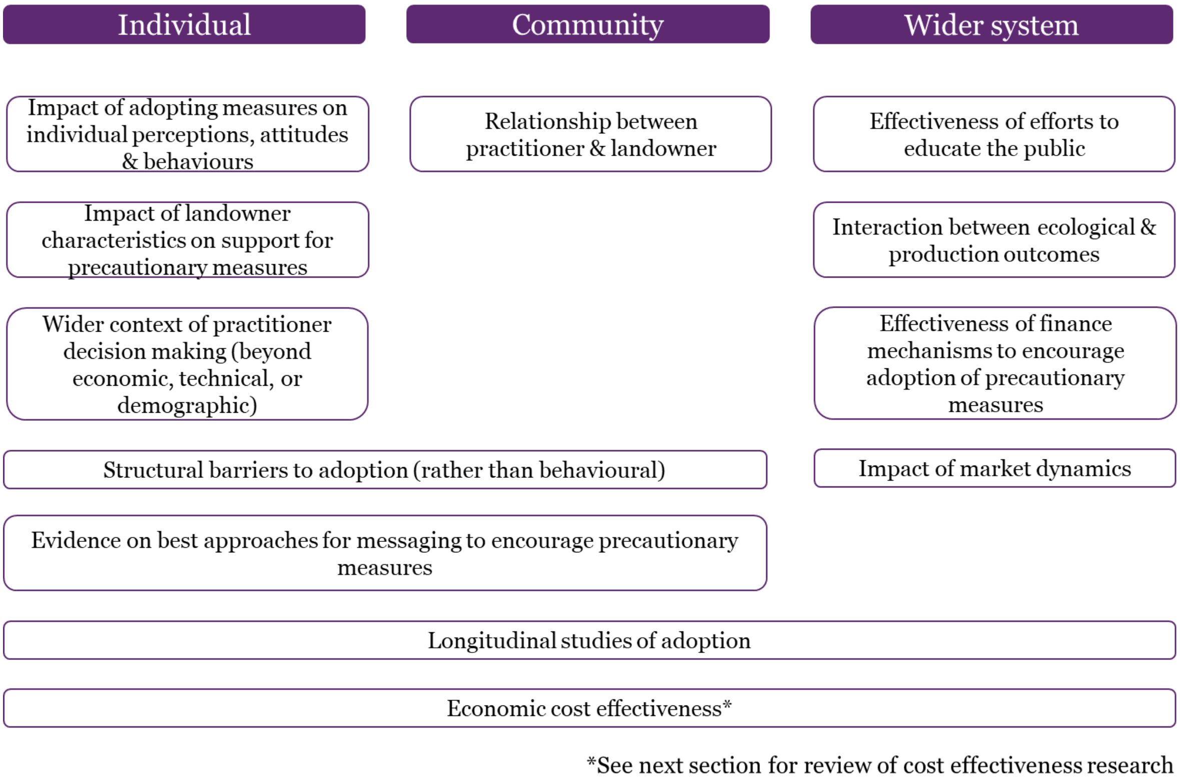


Figure 3 - Research gaps identified in the rapid review, categorised by scale at which research should be focussed; individual, community, and or wider system (Adamson et al. 2020; Blicharska et al. 2016; Ranjan et al. 2022; Weigel et al. 2021; Yoder et al. 2019).

4.2.1 The economic value of adopting precautionary measures

Included in this evidence assessment are studies that estimate the cost and benefits of intervening in an outbreak after the introduction of a pest, whilst this is not the direct focus of the evidence assessment such studies use broadly the same methodology and therefore still offer valuable information, especially those that are in the sectors of interest. A summary of findings is shown in Figure 4, with further details in the following sections: Cost and benefits estimates; Discount rate; Time horizon; Data used to calculate costs and benefits; and Key assumptions.

Benefits are more likely to outweigh costs when:

- Adopting precautionary measures offered protection against more than one threat
- Measures were targeted early in the supply chain
- Benefit calculations included more than just benefits accruing to an individual or single industry

Impact of temporal choices

- Choice of discount rate can impact whether benefits will outweigh costs over time, so sensitivity analyses should be included
- Most evaluations only included impacts 10 years into the future or less, although systems with a longer harvest cycle (forestry) had longer time horizons

Calculation estimations & assumptions

Benefits were estimated using:
- Historic market prices
- Previous estimations of non-market prices
- Views of industry experts

Costs were estimated using:
- Industry experts
- Previous studies (which also came from practitioners or experts)

Probabilities of introduction were estimated using:
- Historical data
- Modelling

Further assumptions:
- All practitioners act in the same way
- Interventions were highly effective

Figure 4 - Summary of rapid review of studies which calculate the cost benefit analysis of adopting precautionary measures.

Cost and benefit estimates

From the literature reviewed 13 of the 26 studies estimated both the cost of implementing a precautionary measure and the expected avoided costs (the benefit) associated with this measure, thus providing a full cost benefit analysis of precautionary measures. From these studies the most frequent finding was that the benefits of precautionary measures for plant health outweighed the costs, with 2 studies finding the opposite, with results ranging from (-)$0.21bn net present value (NPV) to $5.89bn NPV. The benefit to cost ratio (1:1 being an equal ratio of benefits to costs) ranged from 0.0001:1 to 172:1, though most estimates ranged between 2:1 and 6.4:1. Even within some studies the NPV and benefit to cost ratios varied widely depending on the assumptions and scope of benefits, with one study ranging from a

NPV of (–)€1.27m to €12.03m (Gatto et al. 2009) and another estimating a benefit to cost ratio of between 4:1 to 110: 1 (MacLeod, Head, and Gaunt 2004). One study found that the required reduction in outbreaks needed for the NPV to be positive was unrealistically high, however if the study included another disease that would also be prevented through the same measures, then the NPV would likely be positive over the same period (Valatin, Price, and Green 2022). Studies that found the highest NPV for precautionary measures were generally those implemented earliest in the supply chain, with interventions at the point of entry offering the highest NPV (Epanchin-Niell et al. 2014; Turner et al. 2004).

When considering studies that included only private costs and benefits the results of the economic viability of precautionary measures were more mixed compared to those that included wider benefits. Out of all studies included, six included only the costs to the individual or industry in question through loss of revenue and/or replanting with no inclusion of other benefits to society. Notably, the only two studies that found a negative NPV of precautionary measures were within this group, with the remaining three finding a positive NPV and one with mixed findings depending on how many outbreaks would be prevented in the period. This suggests that if we assume that the actors involved in the implementation of precautionary measures are largely self-interested then the studies included in the assessment give mixed results for economic viability and that in some cases economic viability may be a barrier, albeit these results are highly specific to the case in question.

Most studies included the expected impact of precautionary measures on wider society rather than just those affecting the organisation carrying out the precautionary measure and in all these instances the benefits of precautionary measures were found to outweigh the costs. Additional measures of benefits included carbon sequestration (Gatto et al. 2009; Hauer, Hanou, and Sivyer 2020; Valatin et al. 2022), recreation (Davis, Kragt, and Pannell 2015; Gatto et al. 2009), health (Gatto et al. 2009; Hauer et al. 2020), reduction in the loss of city trees (Epanchin-Niell et al. 2014), biodiversity (Davis et al. 2015), and property values (Hope et al. 2021). Perhaps unsurprisingly the expected NPV in these cases was often much greater than when looking only at private benefits, with the ratio of benefits to costs generally increasing in studies that included a wider range of benefits. For example in the study by Gatto et al. (2009) the NPV(€) for intervening increased from (-)1.27m when only including private costs and benefits, to 9.80m when also including carbon and health benefits, to 12.03m when including recreational benefits in addition to those already stated. Other studies noted that whilst they did not include all possible benefits and costs, if they had included these then they would have expected the NPV to be higher (Epanchin-Niell et al. 2014; Kriticos et al. 2013; Turner et al. 2004).

Discount rate

The discount rate used in cost benefit estimates indicates the value of future benefits of actions compared with the value of benefits today. The higher the discount rate, the more value is placed on present benefits than benefits received in the future, and thus the higher the future benefits must be to offset any upfront costs. The discount rate used in the studies varied between 2% and 10% with most studies using a discount rate of between 2% and 5%, the most frequently used discount rate was 2%. The choice of discount rate appears to be related to the country where the research was conducted, with studies in New Zealand and Australia generally using higher discount rates than those in Europe and North America, suggesting a cultural aspect to this choice. A notable exception to this is one of the two UK studies which used a discount rate of 6% (MacLeod et al. 2004), considerably higher than the UK government's recommended real discount rate of 3.5% for use in cost benefit analysis as outlined in The Green Book (HM Treasury 2022); the other UK study used this recommended discount rate (Valatin et al. 2022).

Given the wide range of possible discount rates that can be used in a cost-benefit analysis – with many different arguments on their use, especially regarding non-market costs and benefits – the sensitivity of overall results to the discount rate used was tested in some studies. Carnegie et al. (2018) and Epanchin-Niell and Liebhold (2015) found that their results were sensitive to changes in the discount rate, however Hope et al. (2021) found no significant change in the results. These results show that the choice of discount rate can have a notable impact on results, it is therefore recommended that a test for the sensitivity of results to this is included in any cost-benefit analysis for precautionary measures.

Time horizon

The time horizon covered in each study varied between 1 and 75, with horizons between 0 and 50 years more common than those greater than 50 years. The most common time horizon used was between 0 and 10 years suggesting that many projects did not account for the potential long-term impacts of the pest or disease and/or the precautionary measure or intervention. A possible reason for this is the difficulty in predicting the future with one study specifically stating that estimating costs and benefits more than 10 years would require "assumptions that are difficult to justify" (K. Kovacs et al. 2011). Often the horizon chosen appeared to be linked to the associated harvest cycle of the industry in question. For example, studies focused on forestry often used horizons of between 30 and 70 years (Bergseng et al. 2011; Kriticos et al. 2013; Liu et al. 2019; Turner et al. 2004) whereas the equivalent studies for nurseries and horticulture often used shorter timeframes of 10 years or less (MacLeod et al. 2004; Rodoni et al. 2006).

Data used to calculate costs and benefits

The estimation of benefits often used data on historic market prices (Bergseng et al. 2011; Epanchin-Niell et al. 2014; Hope et al. 2020, 2021; Watt, Bulman, and Palmer 2011), from previous studies where non-market values had been estimated (Epanchin-Niell et al. 2014; Hope et al. 2021), and estimates from industry experts (Davis et al. 2015). Estimating the costs of the precautionary measure itself more frequently relied upon industry expertise (Davis et al. 2015; Epanchin-Niell et al. 2014; Liu et al. 2019; MacLeod et al. 2004; Valatin et al. 2022) and estimates from previous studies (Davis et al. 2015; Gatto et al. 2009; Hope et al. 2021; Kriticos et al. 2013). Of those that used estimates from previous literature these included previous surveys of forest managers (Gatto et al. 2009), estimating labour costs using average wage and data provided by a regulatory body (Hope et al. 2021), and from surveys of forest managers in other countries converted to the domestic currency (Kriticos et al. 2013).

Whilst the estimated probability of introduction varied between studies, the overall economic viability of precautionary measures does not appear to be linked to this. Numerous studies that used a relatively low probability estimated a positive NPV whereas the two studies estimating a negative NPV used a relatively high probability of introduction. Estimates of the probability of introduction were either taken from historical data (Epanchin-Niell et al. 2014) or from previous studies (Turner et al. 2004), however in some cases there was little indication of where the estimate for probability came from. Results were found in some cases to be sensitive to the choice of probability estimate (Cook and Matheson 2008). The nature of spread and impact that the pest or disease had was often based on different methods within the studies assessed with some basing their estimates on historical data (Hauer et al. 2020; Watt et al. 2011) whereas others used more complex models of plant pest spread to determine which areas would be affected (K. F. Kovacs et al. 2011). In some studies where sensitivity analysis was performed by shifting the parameters used for the expected spread and damage this had a notable effect on the estimated NPV. For example in Carnegie et al. (2018) the authors found that increasing speed of spread from 1km/year to 2km/year increased the expected present value of damage from $6.9m to $21m, increasing the amount that could justifiably be spent on a given precautionary measure from $0.35m to $1.05m.

Key assumptions

In the studies included in the assessment a key assumption made is that the behaviour of managers remains the same in the face of an outbreak. In practice this may be unlikely, with previous evidence suggesting that management approaches are likely to change during such events (Petucco, Lobianco, and Caurla 2020). If this assumption is violated, then we may expect the nature of spread and the overall impact of an outbreak to differ from those predicted. It is possible this shift in behaviour may be something considered more by practitioners than in the studies included and may lead to different cost-benefit results if accounted for.

The effectiveness of an intervention was also a key assumption in the studies included in the assessment, with many studies assuming the intervention proposed was highly or 100% effective. In some cases this may be unrealistic given the exact effectiveness of intervention is often unknown (Johns et al. 2019) and empirically tested interventions have been found to vary depending on a number of factors (Epanchin-Niell and Liebhold 2015) including scale (K. F. Kovacs et al. 2011), and intensity of inspection (Hauer et al. 2020). If the effectiveness of an intervention were estimated to be lower this would have an impact on the expected NPV, with one study finding that the NPV was more sensitive to the effectiveness of the intervention than the rate of spread when these parameters were changed (Kriticos et al. 2013). If practitioners generally had less faith in the effectiveness of an intervention, then this may result in perceived cost-benefit estimates differing from those found in the literature.

4.3 Semi-structured interviews

4.3.1 Drivers of, barriers to, and actions to encourage precautionary thinking

Participants discussing precautionary thinking discussed a range of specific drivers and barriers. A summary of drivers, barriers, and actions is in

Figure 2 in section 4.1.

Participants mentioned a string of barriers founded on **financial and time cost**: costs associated directly with adopting new practices; cost of labour and contractors, particularly if asking for increased plant health measures such as washing of machinery; opportunity cost of land out of production due to crop rotation; costs associated with managing behaviour of those accessing the land (staff, public, contractors, customers); and costs for research across relevant plant health and biosecurity topics. Views on overcoming **material barriers** included: compensation for practitioners who lose crops to pests and pathogens despite taking recommended actions to support investment in precautionary measures; and building adequate infrastructure for practitioners and site visitors to undertake precautionary actions such as boot washing.

Economic valuations of potential pest or pathogen events compared to the cost of actions were seen as important to allow good decision-making, particularly communicating with senior colleagues or clients. However, experiences with such valuations were not always useful due to high uncertainty of a natural or semi-natural system, the assumptions in valuation models, the applicability to a local context, and the availability of high-quality data. Trust in the producers of the valuation was mentioned by one participant, particularly if a valuation was designed to promote sales. Recognising the value of precautionary measures was consistent across most of the participants interviewed, who were supportive in general of preparation where possible and frustrated by barriers. However, there were some participants who indicated they or others in their sector felt resigned to pests and pathogens being spread by wind or by other wildlife, so actions to try and prevent introduction were **not worth the effort**.

The certainty of current management challenges (plant health and otherwise) meant that taking precautionary measures against the threat of potential plant pest and pathogen events were seen as a **low priority**. Reducing current damage to plants (e.g., by existing pests such as deer) is simpler to justify to oneself or to a business owner in terms of cost, compared to precautionary measures, and practitioners are juggling many non-plant health challenges (both current and future) concurrently. One experienced horticulture researcher and communicator felt that practitioners were less likely to be encouraging of precautionary measures if they had no personal experience of a serious disease event or introduction. Lack of knowledge regarding pest and pathogen risks was rarely described as a barrier to adoption of precautionary measures by participants, but suggestions to encourage uptake of precautionary measures included in **increasing knowledge transfer** of good practices from researchers or government agencies to practitioners was discussed, as well as better formal planning for potential pest and pathogen events.

Precautionary measures involve **longer-term thinking** and planning ahead. Crop rotation may prevent building up of a soil pathogen for instance. Participants also discussed how preventative actions tailored to the site level require trying, reflecting, and altering to build up effective management techniques. The challenges of adopting a longer-term or practitioner research approach include having the time and space to experiment whilst still ensuring business viability. One participant noted the significant time lag between discovery and widespread implementation step: scientific research outputs, communication, early adopters, and more widespread adoption. Another participant suggested policymakers are more likely to support efforts for present or near-term threats, than longer-term threats. In the case of conservation management, one participant discussed how over the long-term, a particular pest or pathogen will inevitably arrive, and that rather than managers trying to control nature, the characteristics of the natural ecosystem should determine which plants die or survive resulting in a more resilient landscape.

Participants often talked about having the power or **self-efficacy to adopt precautionary measures**. There were several examples of participants lacking self-efficacy: difficulty in enforcing precautionary behaviours of site-visitors such as contractors (e.g., washing machine down, treating cut tree stumps) or the public (e.g., washing boots, mountain bikes) who do not wish to take action for time or cost reasons; power to make decisions residing with top-down management structures, meaning site-level staff or local communities affected by pests and pathogens or the measures used to prevent or treat pests and pathogens had little choice in what decisions were made and which actions taken; a lack of defined responsibility in organisations meaning precautionary measures did not align with anybody's role description; fragmentation within a sector with a resulting lack of opportunity/encouragement for various types of collective action (including creation of standards to follow, collaboration between managers of land nearby to each other or at distances appropriate to a particular pest or pathogen); and national borders as potentially porous for plant pests.

Where an individual did have the self-efficacy to make changes, many participants described those barriers associated with practitioner **motivation:** less willingness to try new practices, succumbing to fatigue if sufficient progress has not been made, and having management objectives (such as no chemical use on a conservation site) which may contradict the use of precautionary measures.

Existing **social norms** within land management were mentioned widely by participants as barriers to behaviour change. Having been trained to grow crops or trees in a particular system, having strong habits, and assessing by sight what a 'good' crop may look like in the field, can be uncomfortable to overcome if changing practices challenge these norms. Changing management actions could result in negative judgement from those who don't agree with the change, or just a reduction in the support available as fewer contacts have experience of desired practices. Participants variously suggested how environments should be created to help **spread new norms** amongst practitioners, firstly by highlighting changes in practice and allowing passive diffusion of actions, and secondly by increasing the opportunity for connections to be made between like-minded practitioners for active diffusion of actions. Two participants highlighted a need for greater creative, interdisciplinary, and collaborative innovation to be done between researchers, policymakers, practitioners, and communities to enable long-term sustained change.

4.3.2 Encouraging adoption of precautionary measures by using case studies

Practitioners discussed their experiences of **using case studies** to encourage the adoption of new practices. Aspects of effective case studies are shown in Table 5.

Table 5 - Aspects required to make effective plant health and biosecurity case study communications, based on experiences of interviewees

Case study content	Case study delivery
• A clear definition of the pest or pathogen problem • Detail on the risks of the pest or pathogen and the risks of adopting precautionary measures • Focussing on characteristics which make the pest a problem to a wide range of stakeholders rather than "just" a sector pest • Stories which highlight people making mistakes, which have then been rectified • Avoiding too many facts and figures • Focussing on impacts of plant pests and pathogens on people and their families • Health and safety implications • Case studies tailored to senior colleagues or clients as evidence towards justifying action • Key milestones to achieve change	• Including individuals who are genuine, relatable to the audience, and trusted • Strong images or videos • People visiting site / face-to-face discussion

4.3.3 Views on risk and risk assessments

Participants discussed how completing formal pest risk assessments was rare for themselves or in their sector, but that information on pest risks was of course welcome. Information was often sought via a third party which would help to curate the pest risk information appropriate to them / their sector and use it to make decisions.

Table 6 shows a summary of information sources used, and the concerns of practitioners when using information to make decisions.

Table 6 - Sources of information which practitioners use when judging pest risk, and concerns in how to use information and advice

Sources of information / advice used for judging pest risk	Key practitioner concerns
• **Government** (Science and Advice for Scottish Agriculture (SASA), Forestry Commission) • **Industry actors** (CONFOR, Institute of Chartered Foresters, Royal Scottish Forestry Society, Scottish Agronomy, Royal Forestry Society) • **Consultancies / advisors** (SAC Consulting, independent agronomists) • **Research agencies** (Forest Research) • **Non-profit / charity** (Woodland Trust, John Muir Trust, Trees for Life) • **Other individuals with similar practices** (e.g. online or in-person)	• Role of uncertainty in advice on judging potential impacts of risk (e.g., over long timeframes) • Lack of personal knowledge in how to reduce pest risk • Lack of sector / government impetus to reduce pest risk • Incorporation / consideration of pest risk alongside other sources of risk

There were various concerns with undertaking or applying pest risk assessments, and their utility. Several participants indicated **interpretation** of risk information to which they had access was difficult, particularly when judging if or how their site could be affected by the pest concerned. **Greater specificity** in scenario modelling was suggested by one participant, to aid application of pest risk assessments to practitioner context. Judging the **impact of uncertainty** was a common topic of discussion, including over long timescales in, for example, forestry. Those participants who indicated that they did not worry about plant pest events (as the testing of ecosystem resilience by pests would be beneficial in the very long term), were appreciative of pest risk information and assessment but rarely acted upon it.

A disconnect was described between understanding the risk (likelihood and impact) and **what could be done to reduce risk**. At the practitioner scale concern was a lack of knowledge ('what *can* I do about it?'), whereas at larger scale concern was expressed as a lack of collective impetus ('what *will* the sector / government do about it?').

Information on a specific pest risk was mentioned as being **difficult to incorporate with other information types and drivers of decision making** (other specific pest risks, non-pest risks, market forces, environmental obligations, and client/owner objectives). It was suggested that practitioners were unlikely to conduct their own formal risk assessments due to **competing time commitments**, and as such the role of third parties to help share and interpret pest risk information was vital and well trusted. However, there was concern about some third parties, particularly in agriculture or horticulture, who may be **profiting from risk mitigation advice** that was not impartial.

4.4 Stakeholder workshop

Three recurring themes emerged from the rapid evidence assessment and interviews (

Figure 2) which were then included for further discussion in the stakeholder workshop: collective action; long-term thinking; and relationships with risk.

4.4.1 Collective action

Overall, participants highlighted the importance of collaboration to tackle pests. The need for raising awareness was highlighted repeatedly across different participants from various sectors. A large amount of high-quality information is already available to tackle plant pests but getting it to practitioners in an effective way was seen as the ongoing challenge. Communicating via impactful stories was emphasised as important and critical to motivate and encourage others to collectively participate in personal onsite biosecurity. However, workshop participants felt that such motivation to engage in collective action to tackle pest and disease challenges is dependent on the individual and their perceptions and therefore requires highlighting of individual benefits. However, even though commitment is important to achieve such goals, people don't always act voluntarily, so regulation is a requirement for such actions, to achieve a level playing field. For example, in forestry, one participant noted how members of the public may not adhere to encouraged actions, which then makes it difficult to encourage contractors on the same site to take precautionary measures themselves. Equally individual walkers are very unlikely to demonstrate biosecurity behaviours. It was discussed how this might be the result of poor awareness, which was seen as a pre-requisite to get collective buy-in.

Participants mentioned that to achieve/drive compliance, consequences should be in place. For instance, individuals undertake health and safety requirements because of legalities but perceive less severe consequences from poor plant health behaviours. The importance of taking biosecurity measures and following such procedures (e.g., cleaning boots), should be pressed upon all parties (e.g., general public, contractors). Some individuals highlighted that there are cases where landowners are turning away contactors who arrive with unclean machines. This is often the case of landowners having direct experience of pests in the past. Increasing awareness, not working with people who are not committed to biosecurity, as well as placing the requirement of biosecurity measures and commitment in contracts may drive compliance. Creating a community and balancing with regulation were seen as very important. Communities within and across sectors which actively increase education and awareness were identified as examples of collective action. One example was discussed - Bee Connected (https://beeconnected.org.uk) which connects beekeepers with farmers to notify beekeepers when neighbouring farmers are applying insecticides to their crops, as spraying may present a risk to bees. Both formal communities such as the Plant Health Alliance, or less formal communities which emerge as individuals seek out others who are trying new practices, should be encouraged.

4.4.2 Long-term thinking

Participants discussed the importance of long-term thinking and planning but also the difficulty in calculating long-term consequences. For example, calculating the cost of losing ash trees and how this may affect individuals is challenging as there are many categories of impact to consider (e.g., ecological, social, economic, cultural). Equally it was felt that long-term awareness of biosecurity threats and plant pests is important because this will have direct impact on an individual's production (e.g., seed potato grower). Accounting for life cycle and length of rotation (e.g., forestry has relatively long crop rotation), the ramifications of a pest can be profound. Foresters need to plan economically far into the future judging long-term impacts preferably using cost benefit analyses. However, valuing and capturing the cost of tree species in the natural environment and the economic cost of a pest is challenging. Participants mentioned that it's important to incorporate resilience as a mechanism for tackling uncertainty, for example by matching species to sites and species diversification to reduce risk. Some participants promote ecological site classification tools, while focusing on outreach and engagement and helping those involved in woodland creation to engage in long-term thinking, including biosecurity and plant health. On the other hand, some other participants (e.g., natural environment and gardening) highlighted that people are not that good at long-term thinking, but instead are focusing on what affects them right now. There was agreement that there is a need for long-term planning and implementation of long-term strategies, such as integrated pest management. The benefits of some actions (e.g., changing rotations in arable farming), may provide immediate/short term effects which are fairly small, while they get larger benefits in the long-term.

Timescales are much longer in forestry than for agriculture. A community approach (e.g., landlords and potato farmer tenants), working together with the right tools (e.g., to put appropriate management in place, integrated pest management interventions, resistant varieties, rotation) should align with long-term thinking and an ongoing experimental approach to manage pest issues.

Public attitude was seen as a barrier to considering the long-term as priority, as people often consider their actions with respect to plant pests irrespective of future predictions of pest impact. The importance of proactive biosecurity measures, raising awareness and education, along with the government to set regulations and prevent pest arriving hold highest priority.

4.4.3 Relationship with risk

Participants highlighted the difficulty of being aware and knowledgeable of all the pests that are relevant to practitioners. Practitioners and land managers having such knowledge and being able to evaluate the relative risks of a range of pests is very important but overwhelming. Again, the need for education was widely supported. The importance of information gatekeepers (individuals or organisations who can control the flow of information between other actors) was highlighted (e.g., agricultural/horticultural advisers), but some sectors do not have them anymore. Being a gatekeeper (individual or organisation) comes with great challenges including to convey complex information to people regarding relative and actual pest risks. Furthermore, it was mentioned that horticulture is inherently a much more complex sector to be dealing with, with a higher number of more varied participants, compared to agriculture which tends towards monocultures.

It was highlighted that in the agricultural sector, risk is balanced with cost. If there is no payoff from taking actions when risk is involved, then those actions won't be taken. An increasing tolerance has been identified across farmers who are more tolerant of pest risk and less willing to spray for environmental reasons. In general, risk is defined partly by consequences/impacts. For example, the severe measures associated with detection of *Xylella fastidiosa* could result in the closure of nurseries which has provided motivation for adoption of better practices/actions.

A formalised process of risk assessment, as in the Plant Health Management Standard, makes people think carefully about risks associated with where materials (e.g., transport pallets) are coming from, their suppliers (including growing media), and their own biosecurity practices. Therefore, such companies want to improve, so their willingness to find out more about risk assessment increases. This may drive further risk reduction across the sector.

Finally, participants drew a parallel between plant health and that of the outbreak of coronavirus (COVID-19). The latter urged people to share responsibility (e.g., mask wearing), and promoted the benefits that can be accrued to the community by doing so.

5 A descriptive framework for research and intervention development

This study using a rapid evidence assessment, key interviews and a workshop cannot be seen as a complete and fully representative analysis of agriculture, horticulture, forestry, or management of the natural environment. However, the results align with the findings of previous researchers, as detailed in the rapid evidence assessment, whilst providing additional information and detail to support recommendations for encouraging individual behaviour and wider structure changes and to offer future research directions. A summary of the factors of influence relevant to the individual, community, and wider system and how perceptions of risk, cost benefit, and uncertainty relate to practitioner decision-making is show in Figure 5.

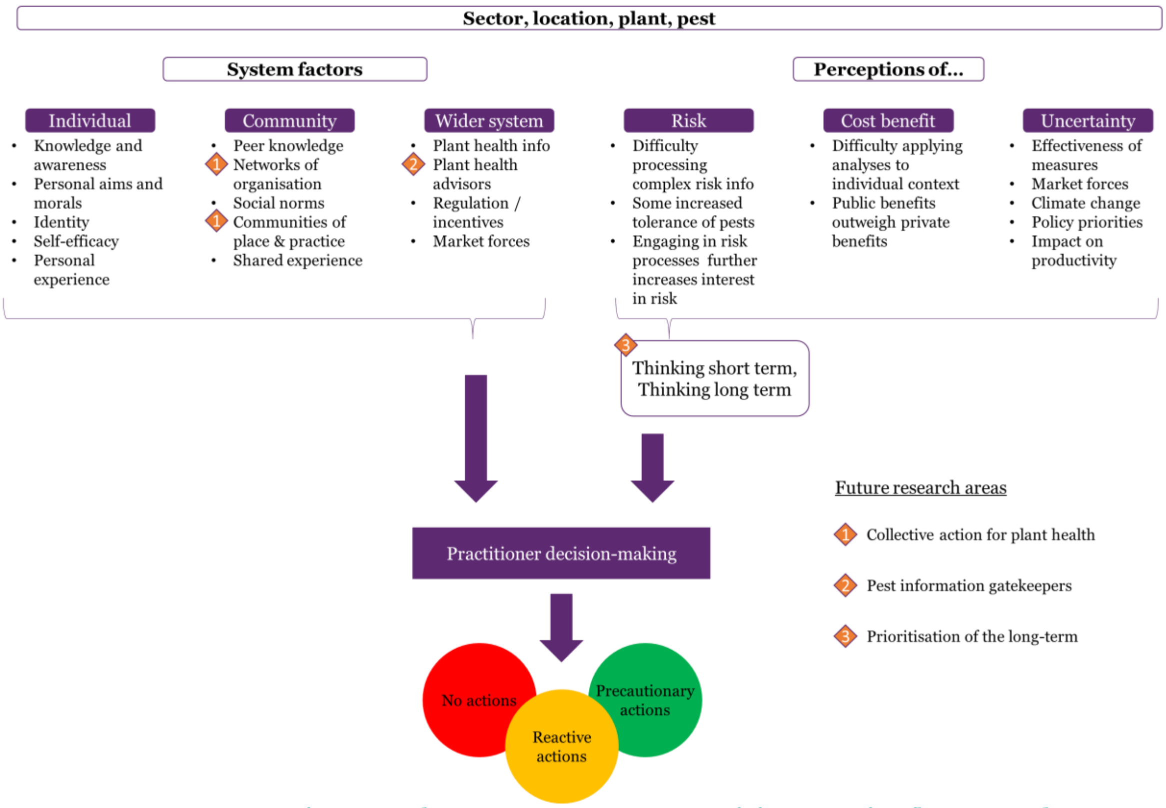


Figure 5 – Descriptive framework summarising impact of factors of influence and practitioner perceptions on decision-making and resulting pest management actions

The descriptive framework shows elements identified in the study which influence practitioners when they make decisions about how to deal with potential pest threats. The specific sector, location, plant, and pest should be considered for all instances of justifying precautionary measures as they will each influence the system factors and perceptions which drive decision-making. However, despite the importance of these specific characteristics, we have identified system factors and specific perceptions which are useful in thinking about potential interventions to encourage precautionary measures and areas for future research.

The system factors identified are categorised by scale (individual, community, or wider system) to focus thinking about interventions or as unit of analysis for future research. The system factors we identified here are more generally applicable to many types of plant health or biosecurity behaviours, not just those which are precautionary. For example, individual knowledge of a pest and the self-efficacy to be able to tackle it, community social norms of taking novel practical actions (precautionary or not), and the balance of policy regulation and incentive are all important determinants in wider plant health or biosecurity decision-making. However, perceptions of risk, cost benefit, and uncertainty, where generally important in plant health decision-making, hold significantly more importance when it comes to precautionary measures, due to a need for forecasting. Having to consider variables over the long-term to judge the worth of precautionary measures sways perceptions of risk, cost benefit, and uncertainty, making it more difficult for practitioners to determine their best course of action.

One key **perception of risk** is that, while information from trusted sources is always welcome, data or advice is often hard to interpret and apply in a real-life situation without extra help or resources. The combination of trusted sources and useful application of risk assessment to specific context are the main limitations of formal risk assessments currently. However once engaged in understanding pest risk, practitioners may perceive risk assessment to be more important than they had previously thought and increase their openness for formal risk assessment mechanisms. Changing perceptions of pest impact may emerge as tolerance for some pest risks in a trade-off for more environmentally friendly outcomes elsewhere (e.g., using fewer pesticides). Risk becomes even harder to usefully assess when considering longer timescales, which is required when opting for precautionary measures.

Similarly for **perceptions of cost benefit analyses**, application of examples is difficult to apply to practitioners' specific decision-making context. Among these difficulties are deciding preferences for individual and public benefits accrued from precautionary actions, finding agency to act at the most beneficial point in the supply chain, considering non-target pest impacts, both positive (e.g., measures which offer protection against multiple pests) and negative (e.g., opportunity cost of measures), and scrutinising model assumptions (e.g., that interventions are highly effective). Longer evaluation timescales often have an impact on the outcomes of the analyses themselves, as does the discount rate. Considering a longer timeframe or lower discount rate will often tip the balance in favour of precautionary measures but changes in the wider system over that time mean longer forecasts are less reliable and may decrease trust in advisors who chose to use them. Sensitivity analyses can help quantify the impact time will have on costs and benefits, but translation of analyses into applicable evidence for decision-making is the important step for practitioners.

Perceptions of the magnitude and relative **importance of uncertainties** affect practitioner decision-making. Uncertainties which practitioners perceive as important when making decisions around pest management are those surrounding: the effectiveness of measures and their impact on productivity; the impact of market forces and macro-economic drivers on their organisation or sector; impacts of climate change on the pest system; and how changes in policy priority may impact availability of resource or regulations surrounding pests and pathogens. When thinking long-term about uncertainties such as those listed above, the uncertainty may increase as further into the future is considered, or the longer timeframe may be perceived as advantageous to even out shorter-term volatility for a more predictable outcome. The advantages and disadvantages of the longer timeframe on these perceptions of uncertainty, and their resulting impacts on decision-making, should be considered when attempting to justify and encourage the use of precautionary measures.

All system factors and specific perceptions contain drivers for, and associated barriers to, encouraging precautionary measures, indicating multiple possible areas available for interventions to encourage adoption of precautionary measures. These areas are also areas in which future research would be. Knowledge gaps identified in the rapid evidence assessment are shown above in Figure 3, with three additional key themes for future research emerging from the primary research in this project are proposed in the next section: Collective action for plant health; pest information gatekeepers, and prioritisation of the long-term.

6 Practical recommendations and associated areas for further research

6.1 Practical recommendations

Perhaps unsurprisingly, rapid review, interviews, and workshop data all suggest that increased incentives and disincentives would help drive changes in individual practitioner behaviour. Support in the form of incentives to reflect the sector- and public-scale benefits as well as the long-term value of adopting precautionary measures would help overcome the financial and material barriers (both short term and long term) associated with required changes in practice, including experimentation. More stringent regulations for practitioners which are enforced with clear consequences would couple with incentives to act as carrot and stick. These are not novel conclusions, and although they feature strongly in interviews and the workshop, this study does point towards additional recommendations beyond these established policy levers.

6.1.1 Increasing opportunities for practitioner engagement

Practitioners should be actively engaged on their terms, by being offered a range of ways to connect with each other and with knowledge providers. Building and supporting appropriate communities could help with self-efficacy, motivation, positive social norms, and education and awareness of practices. This could take the form of suggested / recommended ways of connecting and working collectively, creating practical resources to enable collective action, or funding of facilitation organisations or roles. We have identified characteristics which have greater influence on decision-making in one sector than another. For example: agriculture was highlighted as potentially showing a higher tolerance for pests and disease in cases where there are other (non-financial) objectives such as pesticide reduction; horticulture was highlighted as having greater heterogeneity than other included sectors, resulting in challenges for sector-wide policymaking; forestry has much longer planning horizons; and managers of the natural environment may opt for minimal intervention as the default for land management. There is also heterogeneity within each of the sectors and as such, policies, and initiatives to provide the right environment for practitioners to lead or develop their own strategies may increase engagement in precautionary measures in addition to efforts to encourage measures directly.

6.1.2 Making information understandable, appropriate, and trusted

Beyond provision of up-to-date information (of which there is already a large amount, of a high quality), we have emphasised that interpretation of complex data into a form that is understandable, appropriate to practitioner context, and comes from a trusted source is required to encourage adoption of precautionary measures. Due to time pressures on practitioners, all three of these characteristics should be satisfied through one interaction. Greater emphasis should be placed on the role of pest and disease information gatekeepers as a diverse audience in their own right. Gatekeepers are already relied upon by some to reliably interpret advice and apply to the local context, but we show that there remains a need for gaps to be filled between information providers and practitioners. In the situations discussed, there were many occasions where a tool or self-service function could not make up for the lack of interaction with a trusted, knowledgeable, and experienced individual.

6.2 Areas for further research

To support the recommendations in section 6.1, greater knowledge is required. Here we suggest three areas for future research.

6.2.1 Characteristics of collective action

The rapid evidence assessment and our research highlighted system factors influencing practitioner decision-making related to how individuals work together. This includes the importance of networks of individuals and organisations, and of communities of people brought together by place or practice. Where incentives, or regulation/enforcement are not present or having effect, systems of collective action can emerge or be designed to help find alternative solutions. Such solutions can come in many forms (see Table 7 for an example typology), with various instances described in this study including communities of practitioners forming online for support and social learning, formal certification groups to define and authorise voluntary rules, and government initiatives. Further research is required to analyse existing types of collective action for plant health and biosecurity in Scotland, what characteristics (e.g. "type") are successful in which contexts (sector, location, plant, pest), how rules, incentives and consequences are developed and communicated, and how social learning could be applied to promote successful collective action in the future.

Table 7 - Example of a typology for collective environmental action amongst farmers. Adapted from (Uetake 2013)

Collective action type	Description
Type 1: Organisation-style collective action	Practitioners and other participants (e.g. NGO, government, researchers, publics) form organisations and act collectively as members. To manage members, rules and governance are very important.
Type 2: External agency-led collective action	External agencies gather and organise practitioners to act collectively, but practitioners don't necessarily work together, they just follow leadership or advice from the leading agency to all pull in the same direction.
Type 3: Non-organisation-style collective action	Practitioners collaborate with other practitioners (and non-practitioners), but don't form new organisations (such as with Type 1).
Type 4: Cooperation between external agency and practitioners	Combination of Type 2 and Type 3: external agencies lead and organise, but practitioners do work directly with each other.

6.2.2 Pest information gatekeepers and their impact on plant health and biosecurity decisions

Getting information from trusted sources who can interpret and communicate to practitioners given the latter's specific context, is a major barrier to making better biosecurity and plant health choices. Carter et al. (2021) highlight the role of trust in those individuals and institutions who are communicating pest control knowledge when mediating support for interventions. Those individuals who act as information gatekeepers for others (sometimes practitioners themselves sharing information with peers) can control flow of pest knowledge, information, and or advice. In positive instances discussed, trusted gatekeepers (individuals or organisations) would synthesise complicated evidence highlighting risks, trade-offs, uncertainties, assumptions behind modelling or predictions, and relevance to local context. In negative instances discussed, gatekeepers would pass on information without adequate explanation, or present advice skewed to promote their own (e.g., commercial) interests. The use of case studies as discussed by interviewees highlighted the potentially contradictory mix (e.g., focus on detail, but avoid facts and figures) which different audiences may require for genuine and prolonged engagement. Building on previous recommendations to develop engagement strategies and better understand knowledge flows to aid use of plant health and biosecurity information (e.g. Creissen et al. 2019), we additionally suggest focus on pest information gatekeeper individuals and organisations. Gatekeeper influence on knowledge transfer (one-way provision of information) and knowledge exchange (two-way sharing of information), the pressures on gatekeepers themselves (e.g., responsibility for decisions made by others and resulting attitude to risk), and the nature of trust (or other key interpersonal relationship characteristics) between practitioners and individual or institutional gatekeepers, all warrant further study.

6.2.3 Considering short- or long-term effects of precautionary measures

Precautionary measures specifically rely on looking forward to plan for an event with uncertain probability. It is apparent that uncertainties around the future value associated with precautionary measures are an important barrier to justifying action now. Cost-effectiveness calculations can be sensitive to the discount rate used, there is often not the data required for desired site scale predictions, and the uncertainties can be large. The practitioners we interviewed are aware of these issues and as such aren't confident in the utility of cost-effectiveness predictions for their context. Indeed, attempts as part of this project to collect site-scale economic data received no responses from interviewees, indicating potentially that site level data collection is not straightforward. However, cost benefit calculations were seen as valuable to justify behaviour change to powerful stakeholders such as owners or clients, and to those working at greater scales. There is a need for longitudinal social and economic studies to evaluate what has changes over time when precautionary (and other) measures are employed, as well as looking back to see the accuracy and usefulness of previous predictions. Additionally, we should seek to understand the best ways powerful actors (government, industry) can act to reduce the risks of taking precautionary measures providing greater certainty and making up for market shortfall which doesn’t current account for the large public benefits of pest control.

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8 Appendices

Appendix 1 – Rapid assessment search terms
Appendix 2 – Economic survey for practitioners
Appendix 3 – Semi-structured interview schedule

8.1 *Appendix 1 – Rapid assessment search terms*

Table 8 - Search terms for rapid evidence assessment to describe existing precautionary measures

Topic	Search terms
Industry	agricultur* OR horticultur* OR forest* OR agroforest* OR "natural environment" OR nurser*
Pests and diseases	("pest impact" OR "pest invasion" OR "plant health" OR melampsora OR dothistroma OR "needle blight" OR dieback OR chalara OR "hymenoscyphus fraxineus" OR "ips typographus" OR phytophthora OR "emerald ash borer" OR aphid OR pinifolia OR xylella OR "bark beetle" OR "dutch elm disease" OR "oak processionary moth" OR "sudden oak death" OR "acute oak decline" OR "oak wilt" OR blight OR "longhorn beetle" OR agrilus OR borer OR canker OR massaria OR budworm OR "potato brown rot" OR "potato ring rot" OR dickeya OR elatobium OR "pine beauty" OR panolis OR "leaf miner" OR buprestidae)
Measures	iwm OR "integrated weed management" OR idm OR "integrated disease management" OR icm OR "integrated crop management" OR "reasoned action approach" OR "detection instrument" OR "laser viscometry" OR "acoustic detection" OR "trap* program*" OR "bait* trap" OR "visual* inspect* OR "phytosanitary tool" OR "pest monitor*" OR "bio-surveillance" OR "host removal" OR "surveillance program*" OR "restricted movement zone" OR "cost of eradication" OR "cost of response" OR "pathogen detection" OR "pest detection" OR "pest response" OR "eradication program*" OR "practical resource" OR "environment* control" OR biosecur* OR "pest risk analysis" OR "phytosanitary measure" OR "tactical decision" OR "pest risk map*" OR "pest risk assessment" OR "risk mitigation" OR "invasion process" OR "natural resource management" OR "ecological intervention" OR imp OR "integrated pest management" OR "precautionary measur*"
Year of publication	From 2000 onwards
Number of papers included in the assessment	30 (Scopus) + 1 identified through snowballing
Final screening criteria	Language: English Location: UK/Europe (non-UK)/North America/Australia/New-Zealand/temperate regions not included in any of the former. Relevance: precautionary measures, behaviours, biosecurity measures

Table 9 - Search terms for rapid evidence assessment to identify behavioural barriers

Topic	Search terms
Industry	"farmers" OR "horticulture" OR "forestry" OR "forester*" OR "agriculture" OR "conservation management"
Management	"stakeholder engagement" OR "risk perception*" OR "social considerations" OR "human dimensions" OR "adoption" OR "threat perception*" OR "self-efficacy" OR "innovation adoption" OR "pest management"
Behaviour	"attitudes" OR "norms" OR "cognitions" OR "behaviour*" OR "behavior*"
Subject area	"social science"
Year of publication	From 2012 onwards
Number of papers	28 (Scopus) + 6 identified through project team

included in the assessment	
Final screening criteria	Language: English Location: UK (10)/Europe (non-UK) (6)/North America (11)/Australia (6)/New Zealand (0) Relevance: behaviour change in target stakeholders, adoption of new practices, support for changes in practice Availability: not behind a paywall

Table 10 - Search terms for rapid evidence assessment to measure value of precautionary measures

Topic	Search terms
Industry	agricultur* OR horticultur* OR forest* OR agroforest* OR "natural environment" OR nurser* OR "natural resource management"
Pests and diseases	"pest invasion" OR "pest impact" OR "integrated pest management" OR IPM OR biosecur* OR "plant health" OR phytosanitary OR "precautionary measure" OR dothistroma OR "needle blight" OR dieback OR chalara OR "hymenoscyphus fraxineus" OR "ips typographus" OR phytophthora OR "emerald ash borer" OR aphid OR pinifolia OR xylella OR "bark beetle" OR "dutch elm disease" OR "processionary moth" OR "sudden oak death" OR "acute oak decline" OR "oak wilt" OR blight OR "longhorn beetle" OR agrilus OR borer OR canker OR massaria OR budworm OR "potato brown rot" OR "potato ring rot" OR dickeya OR elatobium OR "pine beauty" OR "panolis" OR "leaf miner" OR buprestidae
Economic impact	((*econom* OR finance* OR social) PRE/0 (barrier OR cost OR benefit OR value OR model* OR effect OR loss OR damage OR impact))
Economic measurement	"net present value" OR NPV OR "impact assessment" OR "estimated loss" OR "cost benefit" OR "benefit cost" OR "avoided loss" OR "evaluation index" OR "economic evaluation" OR "partial budgeting"
Year of publication	From 2000 onwards
Number of papers included in the assessment	25 (Scopus) + 1 identified through project team
Final screening criteria	Language: English Location: UK (2)/Europe (non-UK) (3)/North America (12)/Australia (4)/New Zealand (5)/temperate regions not included in any of the former (0) Relevance: Some reference to economic evaluation

8.2 *Appendix 2 – Economic survey for practitioners*

Economic costs and benefits of precautionary measures for plant health
Introduction

This research project is aiming to help us understand the risks faced from pests and diseases in your sector, your experiences of precautionary measures, barriers to adoption, and to better understand how people could change their behaviour towards the adoption of greater precautionary measures.
In this survey we will be talking about PRECAUTIONARY MEASURES for tackling pest and disease issues. By precautionary measures, we mean a wide range of actions which can be taken prior to detection of pests and diseases to reduce possibility or impact of introduction or of spread.

Instructions:
Please fill in the following survey as best as you can. Type your responses into the table or space provided.
There is no right or wrong answer, be honest and as detailed as you can. Each answer will be treated with confidentiality (see consent form). If you believe that you need further information prior to (or at any stage) filling in the form please do not hesitate to contact the researcher Marios Theocharopoulos(m.theocharopoulos@forestresearch.gov.uk) or
Chris Pollard (chris.pollard@forestresearch.gov.uk)

Costs of precautionary measure
Please consider the following questions to be relating to costs in addition to measures that were/are used to maintain general plant health (i.e. not directly related to biosecurity) within your business.
Please give one or more examples of precautionary measures you implemented regarding a specific pest/crop. List the different measures you have taken for that pest/crop, but total up implementation & outgoing costs. No need to cost every single measure you have taken.

Specific pest / crop	What precautionary measures to prevent the spread of pests and diseases do you currently implement in your business?	Implementation: • When • How long did it take? • What were the total costs (including staff time) in the implementation period?	Ongoing costs: • Cost (including staff time) annually after the implementation period?

Thinking about additional precautionary measures which could be applied to your business/organisation, what would be the COSTS and BENEFITS? Could you give best estimates the initial and annual costs of these (including staff time)? Include costs such as loss of production and premiums paid for certified plants/seeds. Try to estimate in monetary terms, or if not possible, describe as best you can.

Specific pest / crop	What additional precautionary measures	What would be the financial cost (including staff time) of this in the implementation period?	What would be the annual financial cost (including staff time) of this after the implementation period??	For the pests and diseases targeted by this/these measures what would be the cost of an outbreak to your business/organisation (including loss of yield from plants	What is the annual probability of an outbreak without this/these measures ?	What is the annual probability of an outbreak with this/these measures ?

				affected and the costs of controlling the outbreak)?		

Are you currently planning on implementing any precautionary measures within the next 5 years? If so, what are they?

Probability of introduction

What do you believe is the probability of a major outbreak of a pest or disease in your sector in any given year over the next 5 years?

	% probability of major pest(s) or disease(s) outbreak(s) in your sector in any given year over the next 5 years?
With range & diversity of biosecurity practices currently in place across the sector	
With no industry biosecurity practices	
With most strict/best biosecurity practices	

Horizon

How far into the future do you look when making investment decisions? Does this vary depending on the type of decision and, if so, how?

When making plans that will have future costs and benefits do you put more weight on those that will happen sooner rather than later? If so, how do you calculate this?

8.3 Appendix 3 – Semi-structured interview schedule

Background

Q1. Can you tell me briefly about the company/organization that you work for and your role within the company/organization? *Record which sector, and identity of the practitioners who the participant will be discussing*

Q2. What specific crops and P&D threats affecting your business/sector could be tackled by improved biosecurity measures, where do those measures need to be & who needs to implement them? *Prompt: estimation of likelihood and impact, in their own words, location (e.g., border, park entrance, glasshouse door), implementer (e.g., business, government, local authority, industry associations).*

Experiences of precautionary measures

In this section we will be talking about PRECAUTIONARY MEASURES for tackling pest and disease issues. By precautionary measures, we mean a wide range of actions which can be taken <u>prior</u> to detection of pests and diseases on the site you work/manage, to reduce possibility or impact of introduction or spread of one or more pests and diseases.

Q3. What are your experiences with adoption of precautionary on the site you work/manage? Prompt: ask for examples from other parts of the sector if not from own land

a. Do you have examples of poor outcomes (failure)?
    i. Record: background, when, duration, pest, stakeholder, region, land type, outcome, reasons/barriers (and how they were overcame), lessons learned.
b. Do you have examples of good outcomes (success)?
    i. Record: background, when, duration, pest, stakeholder, region, land type, outcome, reasons/barriers (and how they were overcame), lessons learned

Q4. Do you think that it is more important to try and encourage greater use of precautionary measures, rather than reactive measures, for tackling pests and diseases? Why?
Prompt – is the current situation too reliant on precautionary, about right, too reliant on reactive? Who needs to change practice i.e. producers, customers, government?

Q5. What large scale (landscape, state, country scale) precautionary biosecurity measures (if any) do you think would be useful to the site you work/manage / your sector? Why?

A conscious adoption of a more precautionary approach by a land manager broadly requires an individual to first become motivated about the benefits of precautionary measures, then to take actions to change management practices, followed by ongoing maintenance of new practices over time.

Q6. What do you think are the barriers to long-term adoption of precautionary measures in your sector in each of these three stages (motivation, set-up, maintenance)?
Prompt: which barriers are the hardest to overcome?

Economic barriers

An economic valuation can be made for any business investment, detailing costs for implementation and as an ongoing maintenance, and the predicted financial saving or profit associated.

Q7. Recalling any pest impact valuations you have seen in your industry/sector or made, are there any aspects of how those valuations are conducted that you are sceptical of? Why? *Prompt: Source of valuation*

Q8. Do you think there are any financial benefits to implementing precautionary measures other than reduced risk of pest outbreaks? *Prompt: for example, increases in reputation leading to increased business, potential for pesticide free status and access to premium markets*

Q9. It is possible that some businesses who do not invest in costly measures will benefit from those around them that do. Does this affect your willingness / willingness in the sector to implement precautionary measures? *Prompt: Any examples of this happening?*

Q10. To what degree do you think that additional precautionary measures should be the financial responsibility of the land manager, with additional costs paid for by them? Why?

Q11. To what degree do you think the following costs (e.g., financial) of a pest invasion should be covered by the land manager, and why?

a. controlling an outbreak after it happens
b. Covering the damage costs

Mechanisms to encourage adoption
One way of communicating the benefits of various precautionary measures is to use CASE STUDIES. By case studies, we mean descriptions of the experiences of people, businesses, or organisations in adopting (or failing to adopt) precautionary measures to tackle the risks presented by pests and diseases.

Q12. Do you have examples of using case studies that have been used to try and convince practitioners to take on greater (pest) precautionary measures in your sector? *Prompt: Background (e.g., some kind of a disaster), industry/sector, type / size of business, pest, stakeholder, region, type of land, outcome, reasons/barriers*

Q13. In your experience, what are the key aspects of a case study that you think lead to positive behaviour change (increased uptake of precautionary measures)?
Prompt: detailed economic data, detailed example of practical actions required and the feasibility for others to implement same, detail on identity of individual/organisation in the case study, positive impacts / successes, negative impacts of NOT adopting / cautionary tales, delivery mechanism (in person, video, written descriptions, decision-support tools), frequency of delivery, detail on timelines e.g. long term/how sustainable this has been

Q14. If the site that you work on/manage had a successful outcome after the use of precautionary measures, would you be willing to create/be involved in a case study? Why/why not? *Prompt. Help others vs. competitive advantage*

Risks
Q15. What kind of things do folk in your sector take into account when they judge risks of pest and disease? *Prompt: undertake structured risk assessments? What about subsequent actions: e.g. Act based on likelihood of it coming, act on severity of impact should it come, act based on resources to implement?*

Q16. When it comes to the information, tools and other guidance you use when thinking about any of these risks and challenges what are your "go to" sources/resources.

Q17. How confident do you feel in your understanding of the process and outcomes for precautionary measures regarding existing and future challenges, risks and threats?

Concluding Remarks
Q18. Is there anything you think is important that I should have asked about and you would like to add??

Thank you for participating.

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