Understanding crop producers' perceptions around crop health decision making and the impact of that on key metrics such as pesticide usage

Project Final Report

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1. Summary

To understand crop producers' (growers/farmers) perceptions for decision making in crop health and the impact of that on key metrics such as pesticide usage, this project aimed to understand how attitudes and responses to pest risk are influenced by perceived pest threat, economics and information sources (e.g. agronomist type) to identify Integrated Pest Management (IPM) solutions and routes to encourage the adoption of best practice. Three case studies were selected due to their importance to the sector in Scotland: 1) Aphid borne virus control in seed potatoes, 2) Aphid control in strawberries, 3) Disease management in spring barley. Each case study used stakeholder workshops and grower surveys to gather information.

Key recommendations:

1) **Research and Development Funding**: research and development initiatives focused on developing innovative pest management solutions, resilient crop varieties and IPM strategies should be prioritised and tested by independent bodies. Supporting scientific research can help identify new solutions and technologies to address pest threats while minimising economic and environmental impacts.

2) **Enhanced Knowledge Transfer and Exchange (KTE)**: The exchange of accurate evidence and current information on pest threats, IPM and other risk management strategies could be improved. KTE can be implemented through various channels, including extension services/agronomists, farmer networks, online platforms, agricultural publications, workshops, seminars, digital resources and demonstration farms to showcase sustainable and economically viable approaches to pest management and risk reduction. Ensuring that producers have access to reliable information can help them make informed IPM decisions.

3) **Improved Access to Advice and Advisory Services**: Often the role of KTE is filled by a trusted agronomist and therefore more investment in engagement with agronomists on IPM matters should be encouraged and incentivised. In this study producers with greater access to advice (i.e. often provided by independent agronomists) were found to be more tolerant to risk and open to reducing pesticide inputs. Policymakers could focus on facilitating and promoting greater access to independent advisory services for all sectors. This could involve funding programs to support advisory/extension services, providing training opportunities, or establishing partnerships with agricultural experts and institutions.

4) **Tailored Support for Different Agricultural Sectors**: Varying perceptions and risk tolerance levels across different crop production sectors must be recognised and support programmes should be tailored accordingly. For example, initiatives aimed at promoting risk management strategies could be customised to address the specific needs and challenges faced by each sector e.g. seed potato, strawberry, arable and mixed farms.

5) **Incentives for Sustainable Practices**: Incentive programs or support payments to encourage the adoption of sustainable agricultural practices that reduce risks associated with pesticides and other pest control measures while maintaining or enhancing productivity should be developed or enhanced. This could involve providing financial support for implementing IPM strategies including biologicals, crop rotation, diversification of crops, and soil health improvement measures.

Crop specific summaries

Spring barley

Spring barley growers perceived lower economic impacts arising from pest (disease) threat than the other sectors studied but they still tended to overestimate risks associated with reducing fungicide spray programmes. Mixed farms tended to perceive lower economic losses and therefore be more tolerant to risk. Specialist arable farmers tended to be more risk averse and overestimate the value of fungicides. Information source was important and growers with access to independent advice tended to be more tolerant to risk and more open to reducing fungicide inputs. This is likely due to the nature of the interactions between them and their agronomist who is likely to spend more time on farm engaging in IPM related discussion.

Specific recommendations for spring barley

- Growers with access to independent advice were found to be more tolerant to risk and open to reducing fungicide inputs, therefore this type of advice should be supported and encouraged.
- Farming system (arable/mixed) also influenced attitudes and willingness to uptake IPM indicating more potential for IPM amongst mixed farmers.

Strawberries

Economic impacts are largely due to contamination and cosmetic issues but, although showing risk avoidance tendencies, producers are open to innovative and novel approaches to IPM. There were interesting differences in terms of the perceived effectiveness of IPM and the risks associated with IPM between producers and the stakeholder group comprised of researchers and agronomists, which could indicate that further KTE is needed along supply chain showing broader benefits of IPM then there could be greater uptake.

Specific recommendations for strawberries

- There is a need to understand the potential to reduce insecticide sprays as current opinion indicates omitting insecticides would be disastrous for their businesses.
- Requirement for independently acquired evidence on innovative and novel approaches to IPM including efficacy and economic data.
- Co-developed IPM programmes must be introduced so that producers, advisers, buyers etc. are aware of the potential for, and limits to, IPM in current systems and collaborative R&D and KTE initiatives may result.

Seed Potatoes

Producers show risk avoidance preferences around reducing insecticide application due to the significant threat posed by the vector, the rapid nature of virus transfer and the significant economic impacts that may arise from suboptimal control, therefore encouraging adoption of IPM is a greater challenge within this system. There are many possible IPM approaches, but a lack of evidence and confidence from producers represent key barriers. Producers have divided views over some measures (e.g. use of mineral oils) which have a fairly good evidence base.

Specific recommendations for seed potatoes

- Policy interventions e.g. relating to the use of mineral oils, are likely to have a large impact due to the restrictive nature of the current system.
- Locally acquired, independent data are needed on the efficacy of many IPM measures e.g. mesh covering. This includes demonstrations of practicalities for producers, ideally by producers themselves. This approach has a higher potential of encouraging uptake.
- Requires a focused KTE programme on seed potato IPM that involves industry, agronomists, researchers, ware and seed potato producers.

2. Project background

Increased uptake of Integrated Pest Management (IPM) measures on Scottish farms will be key in improving resilience against pests, weeds, and diseases, and maintaining or improving crop yields and farm profitability, whilst reducing environmental impact and reliance on pesticides. Previous research shows that better informed producers and agronomists can make better IPM decisions and score higher in IPM metrics. Research has also identified that decision making on farm is often shared between the farm agronomist and the producer. A PHC funded survey in 2021 (Creissen & Meador 2022) identified many factors which influence IPM uptake including farm type, location, using an agronomist, producer age and producer education. Although using an agronomist was identified as one of the drivers of higher IPM scores, the project revealed that agronomists and producers rely on different information sources and have different perceptions of the relative importance of the plant health risks they must manage. This could lead to interventions (including the use of pesticides) which do not accurately reflect the risk to crop yield or quality. A key barrier to uptake has been identified as the perception that taking up IPM measures increases rather than decreases the risk of crop health issues. Identifying the drivers and barriers to further adoption of IPM practices for different decision makers and for different decision makers experiencing different pest and pathogen threats can improve the ability to tailor IPM research and knowledge transfer and exchange activities to consider, if not overcome, those barriers and improve uptake of sustainable crop protection practices.

2.1. Factors affecting IPM uptake and pesticide use in practice

Pesticides (or Plant Protection Products, hereon referred to as PPP) are an essential component of intensive agricultural systems to maintain output levels and efficiency of production. However, despite their benefits e.g. higher yield, reduced labour cost (Dasgupta *et al.*, 2001) they generate significant health and environmental concerns (Nagesh *et al.*, 2022, Sharma *et al.*, 2019; Silva *et al.*, 2019). As agricultural production intensifies and increases to meet growing global food demand, the use of pesticides may also rise (Chaplain *et al.* 2011; Hu, 2020). Pesticide use patterns can vary widely by crop type, climatic conditions, agricultural practice, pest pressure and consumer needs (Popp *et al.*, 2013; Bebber *et al.*, 2014; Möhring *et al.*, 2020; Brückler *et al.*, 2017; Peerzada *et al.*, 2019; Hader *et al.*, 2022). Climate change introduces additional complexities. Altered temperature and precipitation patterns, along with changes in humidity and other climatic factors, can affect the prevalence and distribution of pests, potentially necessitating adjustments in pest management strategies (Delcour *et al.*, 2015; Vernier *et al.*, 2016).

Government regulations and policies play a crucial role in shaping the use of pesticides as regulatory frameworks often impact the approval, sale, and application of pesticides, with the aim of balancing agricultural productivity with environmental and human health concerns (Lefebvre *et al.*, 2015; Silva *et al.*, 2022). UK government policies and schemes, and industry initiatives, in favour of biodiversity and climate friendly practices can influence PPP use. For example, support for 'regenerative' systems in which soil disturbance is minimized, natural enemies are encouraged through habitat provision and cover crops are included in the rotation may have implication for pests and diseases and their management including PPP use. Such changes must be considered in the context of the 'Agricultural Trilemma' (climate change mitigation, biodiversity enhancement and food security) as trade-offs may, and often do, exist meaning that priorities must be determined.

Producers must manage the risks associated with pests and diseases and their perceptions and attitudes to risk will influence their behaviours. Therefore, it is important to better understand the thought processes that accompany crop protection decisions, and the risk modifiers that influence the decisions. Economic barriers and information related barriers are often cited as the main reasons limiting further adoption of IPM practice (Adamson *et al.* 2020). Producers often make decisions around PPP use based on economic considerations, weighing the cost of purchasing and applying pesticides with the potential benefits in terms of increased yields and reduced crop losses (Cooper and Dobson, 2007; Hedlund *et al.*, 2020). However, great difficulties can arise when attempting to identify whether holistic IPM strategies are cost-effective because: i) it is heavily dependent on the economic price context, ii) it requires a holistic analysis of economics (not only a mere comparison of say the cost of one herbicide compared to the cost of one mechanical weeding), iii) assessing real cost-efficiency of IPM strategies would require data including all details of a range of cropping systems over a gradient of IPM adoption, for different types of production situations and such data are not frequently available outside of networks of demonstration producers.

2.2. *Risk attitudes and crop producers' behaviour*

Producers' risk attitudes, such as risk aversion, play a significant role in shaping their behaviour and decisions in agriculture (Menapace *et al.*, 2013). In the context of agriculture, risk aversion refers to the tendency or inclination of the producer to avoid or minimize exposure to uncertain and potentially adverse outcomes in agricultural decision-making. A risk-averse producer is an individual who is expected to be more concerned about potential losses and uncertainties, seeking to manage and mitigate these risks in their farming practices (Hannus and Sauer, 2020). Risk aversion can manifest in various aspects of agricultural decision-making, including crop choices, input use, and adoption of new technologies (Sulewski *et al.*, 2020). A risk-averse producer is likely to prioritize strategies that minimize the variability of outcomes and ensure a more predictable and stable agricultural production (Crentsil *et al.*, 2020).

The implementation of IPM practices in agriculture may also be influenced by risk aversion (Mankad, 2016). Risk-averse producers are more likely to use conservative and risk-reducing agricultural practices. They may spend more on crop protection products, such as pesticides or fungicides, to ensure a more predictable and stable yield (Liu and Huang, 2013; Liu *et al.*, 2022). Their goal is often to minimize the potential for crop failure and financial losses. These producers are expected to require a larger financial incentive to make them reduce or minimise pesticide or fungicide use. In contrast, risk-taking or risk-tolerant producers, who are individuals with a higher tolerance for risk-taking, may be more willing to adopt cost-reducing measures, which may involve having a lower pesticide or fungicide use. They might take calculated risks in the hope of optimizing their returns, even if it means accepting a higher level of uncertainty. These producers are expected to require a smaller financial incentive to make them reduce or minimise pesticide or fungicide use.

Risk aversion may influence the implementation of other IPM practices (O'Reilly, 2020; Yu *et al.*, 2021). For example, risk-averse producers are expected to have a larger propensity to monitor and scout crops more regularly than risk-tolerant producers. In other words, risk-averse producers are expected to prefer a management strategy that favours the mitigation of a disease or pest outbreak than a management strategy that favours the control of the outbreak. By being proactive in pest management, risk-averse producers can minimize the uncertainty associated with pest outbreaks. Risk aversion may also influence the implementation of cultural practices, such as crop rotation (Menapace *et al.*, 2013). These practices disrupt the life cycles of pests and diseases, reducing the risk of widespread crop failure (Cooke *et al.*, 2013). By promoting stability in crop yields, risk-averse producers are expected to implement cultural practices that minimise yield variability.

2.3. *Study aims*

This study aims to identify IPM solutions and routes to encourage the adoption of best practice. This project aimed to understand how attitudes and responses to pest risk are influenced by perceived pest threat, economics and information sources. Three case studies were selected due to their importance to the sector in Scotland: 1) Aphid borne virus control in seed potatoes, 2) Aphid control in strawberries, 3) Disease management in spring barley.

Each case study used stakeholder workshops and grower surveys to gather information on:

a) Drivers for IPM uptake e.g. pesticide withdrawals/loss of efficacy, economic/environmental cost of current pest management strategy.
b) Enablers of IPM uptake e.g. evidence of effectiveness, knowledge/advice provision, subsidies/incentive schemes.
c) Barriers to IPM uptake e.g. lack of supporting evidence, lack of knowledge/advice provision, market constraints, legislation issues.
d) Routes to improved IPM adoption e.g. research, knowledge exchange, policy.

2.4. Crop-Pest case studies

2.4.1. Spring barley disease management in Scotland

Barley remains the most widely grown cereal crop in Scotland and contributes significantly to a multibillion-pound Scottish whisky industry. The spring barley area in Scotland is ca. 250,000 ha which equates to a Scotland gross margin of ca. £177m and has a farm gross margin of ca. £700/ha (Dimmock *et al.,* 2023). One of the major threats to the yield and quality of barley remains diseases caused by fungi which, if not properly managed, will often lead to yield losses of 10-15% (AHDB 2023) fungicide treated yields-untreated yields) and may exceed 50% in certain situations. In Scotland 95% of the crop area is treated with fungicide to control the most economically important diseases which are Rhynchosporium leaf scald (causal agent, *Rhynchosporium graminicola,* powdery mildew (causal agent *Blumeria graminis* f. sp. *hordei*) and Ramularia leaf spot (causal agent *Ramularia collo-cygni*) (Davis *et al.* 2020). Control of these challenges has traditionally relied on a combination of varietal resistance and the use of pesticides but increasingly other measures including rotation, biological alternatives to fungicides are being adopted to maximise efficiency and minimise the risks associated with pesticides. As an example, results from trials recently conducted by SRUC have indicated that a combination of elicitor (biological alternative to fungicide) products could, in best the scenarios, control disease and lead to a 50% reduction in fungicide use in barley crops, giving an economic and environmental boost to growers. However, results are highly variable with many factors e.g. variety, environment application timing, affecting efficacy. As a result, grower interest in biological alternatives is low. This project aims to identify the reasoning behind this apparent lack of motivation to change behaviour around PPP use.

2.4.2. Managing aphid borne viruses of seed potato in Scotland.

The UK potato industry has a farmgate value of ca. £928 M (Toth *et al.*, 2020) but if up and downstream impacts are considered the economic significance of the sector could be as high as £4.5 billion rather than the commonly-used estimate of £765 million (The Courier, 26th January 2023). Scottish seed potatoes have a worldwide reputation for high seed health with minimal impact from viruses spread by aphids who favour warmer climes. Scotland currently provides 77% of the UK seed potatoes with £55 million of UK seed potatoes being exported, chiefly to markets such as Egypt. The seed potato sector in Scotland has a farmgate output value of ca. £100 million (Dimmock *et al.,* 2023) and represents a significant proportion of the value of the potato sector which is estimated to be worth £250 million. (SOAS, 2023). It is a high value crop for farmers (farm gross margin ca. £2.2k/ha). There are just 186 registered seed potato growers in Scotland meaning they each contribute significantly to the economy. Furthermore, as potatoes are a vegetatively propagated crop the health of early field generations of seed potatoes in turn affects later generations which are grown for consumption. If a seed grower fails to control aphid vectored viruses, economic losses can be incurred in subsequent crops.

Aphid vector-borne diseases caused by viruses such as Potato Leafroll virus (PLRV) and Potato virus Y (PVY) are an increasingly important concern for Scottish potato production due to the combination of climate change, loss of PPP actives through regulation and insecticide resistance in vectors, peach potato aphid (*Myzus persicae*) and grain aphid (*Sitobion avenae*) (IRAG, 2021) and a lack of coordinated IPM strategies. These viruses can cause significant direct and indirect losses to the industry (see Dupuis *et al.* 2023 for EU case study) and the threat is rising. Over the last 5 years virus health in Scottish seed potato crops has declined significantly, from over 90% of the crop being free of virus symptoms in 2018 at inspection to less than 60% in 2023 (C. Lacomme, SASA, personal communication). Current data on the economic losses and the most impactful methods of control associated with vector-borne virus diseases in Scottish grown potatoes is lacking. Growers frequently make decisions based on instinct or, at best, research conducted elsewhere in the world which may or may not be appropriate for Scottish growing conditions.

Seed potato crops are inspected by SASA and classified as part of the SPCS (Seed Potato Classification Scheme) – tolerances are extremely strict and even a small ingress of virus into seed crops could have disastrous consequences. As virus related losses occur in the following daughter crop if the seed crop is downgraded due to virus levels, then the value may decrease by 35%. It may even fail to meet seed potato grade entirely. Failed seed crops are commonly not be suitable for use as ware crops as they will have been treated with pesticides not approved for use on ware crops, for example the insecticide acetamiprid where only one application is permitted in ware crops but two are permitted in a seed crop. Currently 97% of seed crops are treated with insecticides, the most commonly used being the broad spectrum pyrethroid, Lambda-cyhalothrin (applied to 85% of seed crops in 2020 according to SASA's Pesticide Use Survey (Davis *et al*., 2022)) which negatively impacts natural enemies as well as the pest.

The Scottish Aphid-Borne Virus Working Group (SABVWG) promotes six steps for effective virus management in seed potato crops: 1) Seed and Location e.g. use high grade of seed, locate crops away from sources of virus or high aphid pressure, 2) Virus removal e.g. rouge crops and destroy dumps, 3) Understand your varieties and virus interactions e.g. target high risk varieties with extra control measures, 4) Use decision support systems e.g. to track the movement of aphids, 5) Target your spray programmes e.g. spray effective insecticides when aphids are flying, 6) Manage crops until the haulm is dead e.g. early burn down reduces transmission risk. However, it may be difficult for growers to implement all 6 steps in practice as, for example, the grower may have to grow susceptible varieties for the market and may not have the capacity to separate these crops from other potato crops or aphid hotspots. Steps 3-6 also rely on the use of effective insecticides which may not be available in the future (Dimmock *et al.,* 2023).

The high value of the seed potato crop may influence attitudes to pest risk and insecticide usage. This project aims to identify what information is being used by advisers and growers and what the perceived effectiveness of currently available control measures is, and whether new control options are on the horizon.

2.4.3. Managing aphids in Strawberries grown in Scotland

Strawberries, although grown on a relatively small area (ca. 1200 ha) compared to the other case study crops, are very profitable (farm gross margin ca. £8.5k/ha) with a farmgate value of £119 million and generate ca. £10 million gross margin to Scotland annually (Dimmock *et al.* 2023). Pests such as aphids, spider mite, vine weevil and Western flower thrips can halve the crops value. The main aphid species infesting strawberry in Scotland are strawberry aphid

(*Chaetosiphon fragaefolli*) and potato aphid (M*acrosiphum euphorbiae)* which impact the crop through direct damage (contamination of foliage or final fruit product) rather than disease transmission. Several aphid-borne viruses infect strawberry (e.g. strawberry crinkle virus, strawberry mottle virus, strawberry vein banding virus and strawberry mild yellow edge virus) and are mainly controlled through the use of virus-free planting material and aphid vector control. Biological control measures are commonly employed in Scottish strawberry cropping systems with crops receiving an average of 18.9 pesticide applications which includes 9.9 biological applications. These cropping systems have the advantage of being enclosed (only 37 ha of the 1,226 ha of Strawberries grown in Scotland is non-protected (Wardlaw *et al.,* 2022)). In 2021, half the crop was semi-protected (grown under temporary tunnels), and the other half was permanently protected (grown in permanent tunnels or glasshouses) (Wardlaw *et al.,* 2022). This makes the release of natural enemies far more feasible than it is in an open field setting where they can disperse outside of the target area and environmental conditions prevent establishment and efficacy. However, biological solutions alone are rarely sufficient to protect crop yields and quality, and represent a significant investment to implement at scale, and so they must be integrated with insecticides, the availability of which is under regulatory threat, in IPM strategies. The withdrawal of chlorpyrifos in 2016 and thiacloprid in 2020 leaves soft fruit growers with fewer insecticide options for early season aphid control; further, when aphid colonies establish in the crown of strawberry plants, it can be difficult to target them with contact-acting insecticides.

To gather information on the IPM practices currently adopted, the perceived effectiveness of control measures, the barriers to further IPM uptake, and the influence of information sources on IPM adoption, two approaches were used; crop producers were interviewed, and stakeholders (which included crop producers) were consulted at workshops.

3. Stakeholder workshops to gather information on IPM priorities

Stakeholder workshops used group discussion and individual surveys to identify priorities related to each case study.

Priorities were determined by scoring IPM measures on a 1 - 5 scale for: a) Effectiveness b) Strength of evidence c) Inexpensive to implement d) Reliability/consistency of control e) Ease of implementation f) Speed of Impact g) Current use h) Potential use (Tables 1-3).

For all factors, high scores represent a positive effect for the producer or end user. For each relevant pest-strategy combination, a priority score was calculated using the following equation (letters refer to above list):

Priority score = $(a + d) + ((c + e + f + (h - g))/4)$

Effectiveness (a) and Reliability/Consistency of control (d) were deemed to be the most important factors, so were given a higher weighting in our calculation (which was modified from Blake *et al.,* 2021 and Young *et al.,* 2022). Factors related to feasibility and scope of implementation were deemed to be of lesser importance and were given a lower weighting. The difference between current and potential use (h - g) was included to give higher weighting to those factors that have the highest scope for increased adoption. Factors are classified into recommended actions (KTE, R&D or both) according to priority score. If Evidence or Effectiveness scores are >3.5 then Knowledge Transfer and Exchange (KTE) can be considered the primary action required. For scores lower than 3.5, it may be considered a Research and Development (R&D) priority or may require both KTE and R&D investment (Tables 1-3) (methodology based on Blake et al., 2021 and Young et al., 2022).

3.1. Workshop on 'Managing aphids and the viruses they transmit'

A joint stakeholder workshop on aphid control in strawberries and aphid borne virus control in seed potatoes took place on 14th June 2023 at James Hutton Institute, Dundee. The 20 stakeholders who attended comprised: Agronomist x 7, Researcher x 6, Agronomist/researcher x 2, Crop protection company representative x 2, Grower/Producer x 2 and a Scottish government representative.

Stakeholders were split into 3 groups (2 groups were potato focused and 1 strawberry focused) to discuss and evaluate IPM measures that are currently adopted or could be adopted in the near future (within the next couple of years). Each group comprised a range of professions and a facilitator.

3.2. Managing aphids in Scottish seed potatoes: Current Status

Aphid-borne potato viruses represent a significant threat to the seed, and ware potato sectors in Scotland. In 2022 and 2023 virus levels have been at their highest level for several decades. Effective aphid insecticides are increasingly scant due to pest resistance and regulations that have limited the number of actives available or restrict their use leaving the sector without consistently reliable chemical control measures. Despite the issues, insecticides are often regarded as an insurance policy. They are applied to the vast majority of seed crops prophylactically and always used in pre-basic programmes. A new, integrated approach to virus control will be needed to ensure a continued sustainable and profitable seed potato sector.

Many common potato varieties are susceptible to aphid borne viruses (e.g. PVY, PLRV). Varietal virus resistance is almost always a secondary concern when selecting a variety, as the market dictates the product quality requirements meaning growers often have very limited choices so plant genetic resistance cannot be relied upon for control. Although potentially having a high impact on virus levels, the relative role of local and landscape factors (field location, geography, other virus sources) on aphid populations/virus inoculum and IPM efficacy are currently unknown. The SABVWG consortium, who create and share advice and guidance documents with the industry, have highlighted the lack of knowledge on the effect of field proximity and agri-environmental measures on the prevalence of aphids and the potato virus they spread, and their six step guidance is available at this link: https://www.sasa.gov.uk/document-library/six-steps-leaflet

There is the perception that seed crop proximity to ware crops can increase virus risk and most of the workshop participants were of this view (score 4.33/5; Table 1) despite being regarded as moderately effective in managing virus (score 3/5; Table 1). Some level of collective responsibility amongst growers may help limit the horizontal spread of virus from ware to seed crops. Alternatively, regulations could be brought in to maximise the distance between ware and seed crops, but this may be challenging to implement in practice due to the widespread coverage of ware potato crops in Scotland. Control of groundkeepers (volunteer potatoes) and weeds (especially *Solanum* spp. and aphid hosts) in ware crops and in nearby fields may also reduce aphid pressure by reducing the availability of suitable host plants. In Scotland, seed potato production tends to occur on rented land, with management of fields returning to the owner following harvest of the potato crop. Control of groundkeepers is sometimes poor in these circumstances as the landlord may have little incentive to do so.

Natural enemies (predators, parasitoids) can potentially control aphid populations and reduce virus transmission, yet the perceived effectiveness is currently low (score 2.33/5; Table 1). Strategies to encourage natural regulation of aphids and their efficiency as vectors include push and pull, using cereal buffer strips or adjacent fields of barley which aphids prefer to feed on and thus clean their stylet of virus (PVY) before they enter a potato crop, and habitat provision for aphid natural enemies, via wildflower strips, conservation headlands or hedgerow management. Phenology (timing) is key, as the natural enemy population must be in place before the pest population builds up. There is currently very little evidence available (score 1.83/5; Table 1) and therefore it is rarely factored into IPM decisions. However, natural enemies may become more important as reliance on the use of insecticides declines (George *et al.* 2010). This evidence is needed as it could have management implications for practitioners (producers, agronomists), provide preliminary data for researchers, and assist policy makers in identifying agri-environment measures with an IPM value. Seed potato crops have a short growing season (typically May - July) meaning establishing natural enemy populations to appropriate levels at a time that coincides with crop vulnerability may be very challenging.

Table 1: IPM measures for managing aphids and their viruses in Scottish seed potatoes ranked according to their priority for investment.

IPM measure	Priority Score	Evidence	Potential for further uptake	Effectiveness	Primary Action
Managing groundkeepers/weeds	12.50	3.50	2.50	5.00	KTE
Early haulm destruction	11.63	4.00	2.00	4.25	KTE
Seed input	11.44	5.00	0.25	4.50	KTE
Variety virus resistance	11.00	4.33	2.00	3.67	KTE
Variety choice	10.95	4.10	2.00	3.90	KTE
Seed testing	10.42	4.33	1.33	4.00	KTE
Insecticides	10.31	4.50	0.75	3.75	KTE
DSS: Water traps (YWT) for monitoring aphids	10.13	4.00	0.75	3.75	KTE
Mineral oils	10.00	3.60	1.90	3.50	R&D
Roguing and destroying dumps	9.91	4.17	0.57	3.57	KTE
Field location	9.67	4.33	0.67	3.00	KTE
Classification scheme	9.58	4.67	1.33	3.67	KTE
Crop inspection	8.75	4.00	0.67	3.33	KTE
Straw mulching	8.38	3.00	2.00	3.40	R&D
Insecticide application timing	8.17	3.67	1.67	2.67	KTE
Cereal buffer/purge strips	8.00	2.33	1.75	3.00	R&D
Meshing/Netting	8.00	2.33	1.50	3.75	R&D
Encouraging natural enemies	6.71	1.83	2.17	2.33	R&D

Crop inspectors only see a relatively limited proportion of the crop and the effectiveness of the inspection in manging virus is dependent upon the inspector. Classification schemes can be effective if properly enforced. Some workshop participants indicated a lack of confidence surrounding seed input sampling and seed virus testing protocols despite the mean scores for 'Strength of evidence' and 'Effectiveness' both being over 4/5 (Table 1), although molecular testing of potato tubers is only used for specific varieties and situations within the classification scheme. Monitoring aphids via a network of yellow water traps (YWT) can be a useful aid to inform insecticide use but only if the guidelines are interpreted correctly. Coordination of sprays between growers can reduce windows for aphids to establish if linked to YWT decision support systems.

Natural alternatives to synthetic pesticides such as mineral oils have been tested overseas (Yang *et al.,* 2019) and are currently being tested in Scotland but uptake is currently limited by legal restrictions on use and availability of products. More evidence from field trials involving horticultural/mineral oils is currently needed to understand their role in an IPM programme and how to avoid the potential crop damage they can cause. Straw mulching (often using barley straw) may also decrease the effectiveness of aphid foraging behaviour, although practical barriers around evidence (3/5; Table 1), financial cost, and issues in acquiring and applying straw mulch may prevent high levels of uptake. Meshing or netting barriers may also be effective but can be expensive and impractical. Their efficacy is debated, but it should be noted that this technique has very little use in Scottish potato production, meaning growers have little awareness or experience with it.

3.3. Managing aphids in Scottish strawberries: Current Status

Insecticides are effective and routinely used in Scottish strawberry production systems (Table 2). Standard practice is to apply the active substance spirotetramat (e.g. Batavia), at least two weeks before flowering. Environmental conditions must be optimal to ensure high levels of efficacy. Spirotetramet controls hidden aphids and due to its systemic nature also protects new plant growth (after application) from sap-feeding pests.

Pesticide alternatives such as the broad-spectrum contact bio-insecticide Flipper (Bayer), which contains fatty acids derived from a natural by-product of virgin olive oil and a variety of mineral oils, can be effective but only if good coverage is achieved (effectiveness 3/5; Table 2). Use of these products is considered a firefighting measure as they 'knock back' aphids but, in the opinion of the workshop participants, offers no sustained control. The entomopathogenic fungus *Beauveria bassiana* (e.g. products Naturalis-L and Botanigard WP) will give some control of aphids but often requires several applications which may influence the use of some control options. The fungus needs high humidity to sporulate and grow on the insect body, therefore spray applications need to be timed carefully. Compatibility with biological control agents must always be considered, for example, minute pirate bug (*Orius* spp.) is commonly used for thrips but will also eat aphids and is vulnerable to biological control agents and fungicides. More research is needed to optimise the use of pesticide alternatives and biological control agents in soft fruit. The introduction of new chemistries can slow progress in use of alternatives.

Table 2: IPM measures for managing aphids in Scottish strawberries ranked according to their priority for investment.

IPM measure	Priority Score	Evidence	Potential for further uptake	Effective-ness	Primary Action
Insecticide before flowering	11.63	4.00	0.00	4.50	KTE
Parasitoids	11.25	4.00	0.50	4.50	KTE
Optimal nutrition, disinfect irrigation lines, lighting	11.00	4.00	0.00	5.00	KTE
Control weeds	11.00	5.00	1.00	4.00	KTE
Biological predators (lacewing larvae; hoverfly)	10.75	4.00	1.50	4.50	KTE
Clean tunnels and compost weeds etc.	10.75	5.00	0.00	5.00	KTE
Clean substrate	10.50	5.00	0.00	5.00	KTE
Growing on Tabletops	9.25	4.00	0.50	3.00	R&D
Pesticide Alternatives (e.g. biopesticides, mineral oils)	9.00	4.00	1.00	3.00	R&D

One third of the UK strawberry area is treated with biological control agents for a range of pest species, and the most widely used for aphid control is *Aphidius colemani*. The parasitoid is only really effective against the melon and cotton aphid, *Aphis gossypii*, and is not effective against one of the most common aphid species infesting UK strawberry crops, the potato aphid, *Macrosiphum euphorbiae,* which is parasitised by *Aphidius ervi* and *Praon volucre*. In strawberry crops, aphid parasitoids are often deployed as a mix of five or six species and can take three weeks to be effective, so timing is key. A naturally occurring parasitoid, *Aphidius eglanteriae* can occur in strawberry crops and can help in control (AHDB, 2022). KTE demonstrating evidence of the benefits and information on best use is needed to convince growers to adopt biologicals, and to convince retailers/consumers that mummies of larvae in fruit does not warrant rejection.

Biological predators (lacewing larvae; hoverfly larvae, ladybird larvae/adults) can control aphids but their efficacy depends on when and where they are used, and by whom. Effective control can take 3 weeks from deployment to be effective so, as with parasitoids, timing is key.

Phytosanitary measures such as sourcing clean certified substrate, cleaning tunnels, regular weeding etc. are considered highly effective preventative pest control measures (5/5; Table 2) as is maintaining an optimum temperature inside the polytunnel to maintain the efficacy of biological control agents e.g. hoverflies optimum temperature is 14-40°C.

Optimal nutrition, disinfecting irrigation lines, and controlling light levels can affect aphids (effectiveness 5/5; Table 2) but it can be hard to convince growers that measures with high input costs can lead to savings, so more knowledge transfer is needed to encourage more growers to be doing this. With most crops now grown in substrate there is good scope to reduce aphid problems associated with excess nitrogen levels through precision fertigation practices tailored to the needs of specific varieties and local water quality.

Controlling weeds using polypropylene mulch (e.g. Mypex) can remove possible reservoirs of aphids but may also affect the temperature and humidity levels in the crops which might adversely affected pest activity and lead to disease challenges (e.g. mildew & botrytis). Insect-proof netting can be used to exclude immigrant aphids from protected structures, either by screening glasshouse vents or by using nets over the ends or sides of tunnels (AHDB 2021) but again these must be implemented carefully to avoid adverse effects on crop environmental conditions.

3.4. Workshop on managing spring barley diseases in Scotland

On 7th September 2023 an online stakeholder workshop was held using Microsoft Teams. The format was the same as the in-person aphid focused workshop. The workshop was designed to encourage friendly discussions to understand the best approaches to managing disease in Scottish spring barley crops. The 11 attendees included 2 barley producers, 4 agronomists, 3 researchers, a chemical company representative and a representative from Scottish Government. The data are presented in Table 3.

Table 3: IPM measures for managing disease in Scottish spring barley crops ranked according to their priority for investment.

IPM measure	Priority Score	Evidence	Potential for further uptake	Effective-ness	Primary Action
Varietal resistance	12.50	4.30	2.00	4.90	KTE
Fungicide - 2 Foliar sprays	12.08	4.30	0.30	4.50	KTE
Certified seed source	11.90	4.70	0.80	4.50	KTE
Testing home saved seed	11.75	3.90	1.90	4.20	KTE
Fungicide - Seed dressing	11.73	4.40	0.50	4.20	KTE
Fungicide - 1 Foliar spray	11.20	4.50	0.60	4.00	KTE
Rotation	11.13	4.33	1.40	4.20	KTE
Burying crop residue (ploughing)	10.43	3.70	0.30	4.00	KTE
Optimised nutrition	10.33	3.70	1.20	3.60	KTE
Adjusted sowing date	9.65	3.60	1.00	3.50	KTE
Decision Support Tools/Systems	8.83	2.70	2.10	2.80	R&D
Varietal mixtures	8.80	3.20	1.60	3.30	R&D
Adjusted seed rate	8.65	3.00	1.20	3.00	R&D
Field location (proximity to other barley crops)	8.53	2.90	1.00	2.80	R&D
Cover cropping (e.g. grown overwinter before spring barley)	8.23	2.50	1.50	3.10	R&D
Biologicals/elicitors	7.28	2.40	1.70	2.50	R&D
Biostimulants	7.25	2.30	1.50	2.60	R&D
Intercropping (e.g. pea and barley mix)	7.13	2.60	1.60	2.60	R&D
Companion cropping (e.g. clover understory)	7.08	2.60	1.50	2.50	R&D

3.5. *Managing spring barley diseases in Scotland: Current Status*

Varietal resistance to disease is regarded as a very effective measure (4.9/5; Table 3) where available (e.g. *mlo* gene provides complete control of mildew) and is strongly supported by the evidence yet there is much room for further uptake as the end users often determine the list of marketable varieties especially if intended for malting (potential for further update 2/5; Table 3). Uptake of varietal mixtures, although effective in controlling disease, is also limited by the perceived problems associated with heterogeneity of the end-product (Creissen *et al.* 2016; Tratwal and Bocianowski 2017).

Producers and agronomists often overestimate the yield benefits of foliar fungicide application and therefore there is scope to use less. A two-spray foliar application programme is considered standard practice in Scotland but in low-risk situations, a single foliar fungicidal spray may be sufficient (Bingham *et al.* 2020). If grown for malting the risk of rejections due to small, light grains may make the risk of omitting a second spray greater, but, where grown for animal feed, a second spray may not be economical unless disease pressure is very high and there may be more scope to omit.

Certified seed sources are often considered critical for control of traditional seed borne diseases such as loose smut (causal agent *Ustilago nuda*) and seedling blight (casual agents *Microdochium nivale* and *Fusarium* spp.) (effectiveness 4.5/5; Table 3). When home saved seed is used it is important to test for diseases, however, in practice seed is often only tested for germination rate and thousand grain weight (seed size) and diseases only tested if considering a fungicidal seed treatment. Development of more efficient and effective methods of seed testing has potential to reduce threat from a wider range of economically damaging seed-borne foliar diseases, such as Ramularia leaf spot and Rhynchosporium leaf scald. However, in the case of Ramularia, fungicides applied to the seed coating will likely be ineffective due to resistance issues with all the main groups of fungicides which limits the potential value of additional seed testing and subsequent fungicide treating (Havis *et al.* 2014; Erreguerena *et al.* 2022). Certified seed ensures low levels of certain seed-borne diseases e.g. loose smut and seedling blight and is often bought by growers pretreated with a fungicidal seed dressing. They only control the seed borne element of the disease, leaving the crop open to infection later in the season. It can be difficult to buy untreated seed and the seed dressing provided may not be the most suitable for the pest and disease threats facing the crop, and therefore represent an unsound IPM decision (Lamichhane, 2020). Seed dressings may even negatively affect crop growth by removing beneficial endophytes (Ayesha *et al.,* 2021).

Rotations and ploughing received strong scores for effectiveness and evidence (Table 3), however they will have limited impact for most economically impacting foliar diseases which represent the biggest threat. Some mixed farms only grow grass and spring barley which restricts rotational options. Changing rotation and cultivation systems can be relatively simple to implement but their cost effectiveness depends heavily on crops grown which may be restricted by the growing environment i.e. fewer crops thrive in the north of Scotland due to less favourable temperatures, light levels and rain patterns. Often changes to the cultivation system and rotation are driven by factors other than disease such as grass weed pressure requiring a shift away from reduced tillage, as ploughing is a very effective grass weed control measures, and winter cereals which often experience the most grass weed issues and have fewer safe and effective herbicide options.

Ploughing is being discouraged under many agri-environmental/climate mitigation schemes due to the issues around loss of soil structure leading to nutrient losses through leaching and loss of soil organic carbon through GHG emissions during tilling. Optimised nutrition may also be encouraged under future government schemes aiming to reduce diffuse pollution and improve efficiency of the growing system. However, spring barley can be harder to establish in minimum tilled situations compared to ploughed. Some diseases, such as powdery mildew, can be encouraged by excessive application of nitrogen fertilisers (Veresoglou *et al.*, 2013) and plants can succumb to many different diseases if undersupplied with nutrients (Colquhoun 1940). Crop diversification in the form of cover cropping (non-cash crops, such as oilseed radish and vetch, that are primarily used to improve soils), intercropping (e.g. pea and barley mix) or companion cropping (e.g. clover understory) is being encouraged in England's Sustainable Farming Incentive (SFI). Despite their inclusion in SFI as IPM actions there is limited evidence supporting their potential to reduce the risks associated with pesticides and they can potentially cause pest, weed, disease issues via the 'green bridge' effect reducing 'break crop' effects. Workshop attendees reported that growing cover crops ahead of spring barley in Scotland can lead to poor crop establishment, due to competition for resources at the crop establishment stage. Co-cultivating multiple species in the same place and time can be very difficult in practice and can lead to quality issues if legumes are grown before or with spring barley leading to higher grain protein levels which may lead to rejection by the maltster.

Adjusted sowing dates may reduce pressure from some diseases, such as Rhynchosporium, but may lead to other disease issues seedling blight due to poorer establishment in cooler wetter conditions. In the north of Scotland this is rarely considered a viable option due to the limited windows for sowing (hence effectiveness is 3.5/5; Table 3).

Simple decision support tools/systems can provide useful information on the risks prevailing in each season e.g. adopt-a-crop, FAS Crop & Soils Bulletin, AHDB UK aphid monitoring network, but more complicated models and systems are unavailable and would require massive resource to keep updated.

Biologicals in the form of biological control agents/biopesticides/elicitors/biostimulants receive a lot of attention but are backed by limited evidence and so the extra costs may not be justified (effectiveness 2.5 and 2.6/5; Table 3). There is no evidence showing a value in biostimulants when the crop isn't nutrient deficient (Storer *et al.,* 2016). There are currently few commercially available and they require careful regulation.

4. Crop producer surveys to identify current practice, attitude to pest risk and barriers to IPM adoption

Crop producer (grower/farmer) surveys were conducted to understand which practices are being adopted over others and the reasons why. The surveys were conducted via phone interview or written questionnaire in August-October 2023. The primary aim was gathering economic information to calculate risk preference. Three surveys (questionnaires) were co-developed with agronomists and piloted on several crop producers prior to launch. In total 29 spring barley growers, 10 potato growers, and 6 strawberry growers were surveyed.

4.1. Cropping system influence on IPM adoption

Spring barley producers are predominantly arable farmers, growing combinable crops such as various cereals and oilseed rape. However, a third of those surveyed (N=10 of 29) also grow grass in the rotation indicating that they are mixed (livestock/arable) producers, some of whom only grow spring barley and grass (N=4 of 29). These mixed farmers typically have lower IPM scores compared to specialist arable farmers (Creissen and Meador 2022). Seed potato producers tend to utilise more diverse crops in their rotations than barley growers who tend to concentrate on growing other combinable crops and/or grass (Appendix 1; Appendix 2). Rotations are necessarily longer and more diverse for seed potato growers as pest/virus tolerance levels are very low and often nil. Certification rules also prevent tight rotations i.e., they have to wait 5 years before growing seed potatoes on the same land, so a 6 or 7 year rotation is not uncommon for seed potato producers in Scotland. Strawberry producers focus on growing other protected/semi protected crops such as blackberries, blueberries, raspberries (Appendix 1). Each group of producers shows a level of specialization but variability in crop choices exists within each group, indicating different preferences or adaptations based on environmental conditions, market demands, or other factors.

4.2. Perceived effectiveness of IPM measures

Ranking IPM measures according to their effectiveness in controlling aphids and aphid-related viruses is crucial for the development of IPM strategies and contribute to a better understanding of IPM adoption.

4.2.1. Barley

Spring barley producers have fewer disease control options available than potato or strawberry producers, but they have more evidence on the effectiveness of control measures available (from advisers/researchers/AHDB etc.) potentially allowing for more informed decision making. However, much of the available evidence is focused on the effectiveness of varietal resistance or fungicide use and not the interactions and synergies that may occur in a fully integrated control programme, which can impede the decision process. Spring barley producers scored each of the following measures for their effectiveness in controlling disease on a scale of 1-5 with 5 being highly effective; resistant varieties (score 4.4/5), rotation (4.3/5), fungicides (4.2/5), cultivation (3.8/5) (Table 4). Varietal resistance is regarded as a cornerstone of IPM, however, farmers must grow for the market and in Scotland variety choice is restricted by the malting process. 25/29 survey participants are growing for malting and as a result over 75% of the spring barley grown by was cv. Laureate. Spring barley is Scotland's biggest crop (234k ha) (after grass (4.4 million ha) (Wardlaw *et al.,* 2021; Davis *et al.,* 2022). The limited genetic diversity in the spring barley grown represents a high risk of disease epidemic as the pathogen is often able to overcome the genetic resistance present in just a few varieties. Much of the disease threat to the crop arises from aerial and seed dispersal of foliar fungal pathogens, such as Rhynchosporium and Ramularia, as opposed to dispersal via soil, plant trash or volunteers. The ability of soil cultivation and rotation to control disease therefore is significantly compromised. Despite this fact crop rotation was regarded as more effective than fungicides which indicates greater KTE is required on the value of different measures to control the most important diseases.

Table 4: Perceived effectiveness of measures to control diseases in spring barley

Measures	Mean	SD	Min	Median	Max
Varietal resistance	4.4	0.5	4	4	5
Rotation	4.3	0.6	3	4	5
Fungicides	4.2	0.6	3	4	5
Cultivations	3.8	0.8	2	4	5

Limited resources, such as time and budget, can be allocated more efficiently when producers have a clear ranking of the most effective measures and the potential interactions that may occur between them. This helps optimize resource use and ensures that interventions with the highest impact are prioritized and IPM plans can be tailored to their specific context i.e. different regions or crops with varying levels of aphid pressure. Moreover, knowing the effectiveness of IPM measures aids in evaluating the economic viability of adoption. Producers can assess the cost-effectiveness of different strategies, considering both the expenses associated with implementation and the potential economic benefits in terms of crop protection. They can also better manage risks associated with aphids and viruses by focusing on the most effective and easily adopted measures.

4.2.2. Strawberries

Strawberry producers consider floral strips to have low effectiveness (2/5; Table 5). Pesticide use and husbandry, including alternative pesticides, are regarded as the most effective methods to control aphids in strawberries although responses varied considerably between the respondents (Table 5). The growers disagreed with the stakeholders attending the workshop on the value of natural enemies (predators/parasitoids) (score 4.5/5 at workshop; Table 2, and 2.5/5 and 3.3/5 in the survey; Table 5), and also phytosanitary measures such as clean substrate (score 5 at workshop; Table 2, score 2/5 in survey; Table 5). Half of the growers interviewed expected to lose 100% of the value of their crop if they committed to not spraying insecticides for a 5-year period. This indicates that the growers are risk averse and generally more conventional in their IPM approach (relying more on insecticides) than the diverse stakeholder group who attending the workshop. However, this should be taken cautiously since the team was only able to interview six strawberry producers, which may bias the results in favour of the measures utilised by this small sample of producers.

Table 5: Perceived effectiveness of measures to control aphids in strawberries

Measures	Mean	SD	Min	Median	Max
Insecticides	4.5	0.9	3	5	5
Low risk insecticide application timing	4.5	0.9	3	5	5
Alternative pesticides	3.8	1.1	2	4	5
Weed control	3.3	1.5	1	3.5	5
Biological predators	3.3	1.1	2	3	5
Clean tunnels	3.0	1.6	1	3	5
Disinfect irrigation lines	2.5	1.7	1	2	5
Parasitoids	2.5	1.7	1	2	5
Purge/buffer strips	2.5	1.5	1	2.5	4
Meshes	2.3	1.3	1	2	4
Clean substrate	2.0	1.0	1	2	3
Floral Strips	2.0	1.2	1	1.5	4
Grow on Tabletops	1.5	0.9	1	1	3

4.2.3. Seed potatoes

In terms of perceived effectiveness seed potato growers highly rated control of groundkeepers, input field generation, use of translaminar insecticides, proximity to ware crops, and early haulm destruction (score >4/5; Table 6). Opinion was divided over the value of pyrethroid insecticides and mineral oils. Growers ranked labour intensive field-level modifications to the production systems as infective (mulching, floral and buffer strips, mesh covers) – these all have very minimal use in Scotland, with only a few individual growers experimenting with each measure at a small scale, so it is difficult to explain where this perception of low efficacy has arisen.

Table 6: Perceived effectiveness of measures to control aphid-borne viruses in seed potatoes.

Measures	Mean	SD	Min	Median	Max
Groundkeeper control	4.4	1.1	2	5	5
Input field generation	4.4	0.8	3	5	5
Proximity to other sources of aphids	4.4	0.7	3	5	5
Translaminar insecticides	4.2	0.8	3	4	5
Early haulm destruction	4.1	1.0	2	4	5
Pyrethroid insecticides	3.1	0.7	2	3	4
Rotation	2.6	1.6	1	2	5
Mineral Oils	2.4	1.3	1	2	5
Mulching	2.3	1.4	1	2	5
Purge/buffer strips	1.7	0.7	1	2	3
Floral Strips	1.6	0.7	1	1	3
Meshes	1.2	0.4	1	1	2

Seed potato crops are high value, and that value is contingent on their health status. Even if infection with a given virus causes no yield or quality penalty (as it does in some potato varieties) the fact that seed potato crops are classified at particular grades under governmental oversight means that the system is a very challenging one for IPM uptake. In fact, for pre-basic grades there is a nil tolerance for the presence of viral infection. Seed potato producers' rogue crops before inspections to remove plants that would cause a fault during inspections (including PVY and PLRV infected plants), as a result seed potato producers are generally well informed on disease prevalence in and around their crops.

These features of the seed potato crop (high value, vegetative propagation, rigorous crop inspection) are reflected in growers' priorities for management planning (Table 7). Seed source and quality scores highly (4.02/5; Table 7) for perceived importance for forward planning, as does the location a crop will be sited (3.67/5; Table 7) and virus pressure from the previous season (4.29/5; Table 7). Opinion was divided over the importance of insecticide resistance management and the value of technical information.

Mineral oils and straw mulching both have strong evidence bases for effectiveness in management of aphid vectored viruses – particularly if they are used together in addition to targeted insecticide applications within an IPM framework (Lacomme *et al.*, 2017). The fact that growers hold either ambivalent or negative opinions of this is disappointing. Research and knowledge exchange measures to make these approaches more practical and appealing should be a priority.

Table 7: Factors seed potatoes producers consider when developing plans for managing aphid borne viruses.

Measures	Mean score (1-5)
Knowledge about virus/aphid pressure in the previous year	4.29
Source and quality of seed (field generation, etc.)	4.02
Position of each individual crop in the planned rotation and in nearby fields	3.67
End-market requirements	3.58
Crop walking data from last season used to assess the performance of various control measures	3.31
Technical research on plant protection plant efficacy and efficacy of cultural control measures	3.09
Previous management of groundkeepers and weeds that host aphids/virus	2.90
Variety resistance	2.75
Cost-benefit analysis management options	2.38
Pesticide anti-resistance strategies	2.33

Perhaps surprisingly, few seed potato growers preformed a cost-benefit analysis when formulating their management plans. In conversation growers explained that due to the importance of keeping crops as free from viral infections as possible, high input costs were acceptable. Most growers were referring to insecticide (and perhaps to a lesser degree mineral oils) when responding to this question. A full insecticide programme consisting of perhaps 8 insecticide applications may be as little as 5% of the growing crop costs (Beattie, 2023), with the pyrethroid insecticides in particular being exceptionally inexpensive. Cost-benefit analysis will be more likely if expensive and logistically challenging IPM measures become more widely adopted.

Most of the seed potato producers we spoke with (60%) apply 6-8 insecticide treatments during the growing season. Typically, these will be applied every 7-14 days, commencing when the producer perceives the risk of aphid flights. One grower stated that they apply the "*legal maximum*" number of applications. Thus, there is less scope for a straightforward risk-loss calculation as was the case for the spring barley producers. Timing of, and intervals between, applications may be as important as number of treatments in influencing the efficacy of crop protection programmes.

Aside from a few exceptions, most growers placed a strong weight on the opinion of their agronomist or advisory specialist (4.37/5; Appendix 3). Although most seed potato producers in Scotland are very well informed, the complex and dynamic nature of the biotic pressure (in this instance aphid vectored viruses) that the crop is subjected to means that they have a heavily reliance on technical advice. Growers participating in this survey received support from either a company involved in manufacture/distribution of PPPs, SAC Consulting, or Scottish Agronomy.

Opinion was well dispersed for most of the other factors, with potato prices being the least important (1.62; Appendix 3) influence in decision making. Potato prices on the open market are volatile, and many growers sign contracts with specialist merchants which fixes prices for specific size backets and tonnages.

Seed potato producers appear to pay little heed to the cost of PPPs, the actions of other producers, or the predictions of decision support systems (DSS). In truth there are few decision support systems currently available and validated that are of direct utility for this particular pathosystem. It is however relatively common practice for growers to begin applications of translaminar insecticides once potato colonising aphids are found in yellow water traps.

Survey participants were not able to clearly identify factors that acted as barriers to IPM. Opinions were divided on the relative importance of almost all factors. If ranked via mean scores, lack of evidence (3.6/5; Appendix 3) and perceived increased risk (3.4/5; Appendix 3) were viewed as perhaps the most important factors, but this is not a clear finding.

In conversation, growers tended to cite PPPs as synonymous with control of aphid vectored viruses and gave relatively little consideration to other measures. A comment repeated by several producers was that "modern insecticides are not strong enough" or that there were "too many restrictions" on their use. A fairly representative direct quotation follows: "I feel that while there is plenty of advice to carry out IPM practices, there seems to be very little evidence to back it up and leaves the obvious issue that it is unlikely to make any difference whatsoever when you have no control over neighbouring crops belonging to other growers". This was a common concern – growers are aware that inoculum sources such as infected surrounding crops, infected volunteer potatoes, and allotments/gardens are viral reservoirs that threaten the health of their crops. There was resistance to considering management (including IPM) without consideration of these factors. Survey participants gave many unprompted comments regarding ware crops, the classification process, etc. For this crop production system in particular an integrated management strategy will need to encompass landscape considerations. It should also be noted that there are a large number of potential cultural and information-based management methods that can be used to limit the impact of aphid vectored viruses on seed potato crops, but that the evidence base varies on a case-by-case basis.

5. Influence of Risk Perception on Pesticide Use

Reducing pesticide (insecticide) use in strawberry and seed potato crops was largely considered not feasible due to the high perceived risks associated with indirect damage (vector for potato viruses) and direct damage (strawberry) to yield and quality. There is more potential to reduce pesticide (fungicide) use in spring barley as profitability is less likely to be heavily impacted by a reduction in use. This potential variability in pesticide use allows for investigations into risk aversion behaviour amongst spring barley producers.

5.1. Determining risk aversion amongst spring barley growers

Spring barley producers in Scotland traditionally apply fungicides twice during the growing season to protect the crop from foliar fungal pathogens such as Rhynchosporium leaf scald. A producer's decision to apply fungicides twice is likely driven by a risk-reduction approach to crop management. Requesting a barley producer to reduce their fungicide applications introduces a new risk scenario during the growing season. This barley producer now faces a higher likelihood of disease outbreaks. Depending on the degree of risk aversion of the producer, a request to reduce fungicide applications may be seen by the producer as a benefit. If the perceived risk of disease is lower than expected, reducing fungicide applications may be a reasonable decision if it also reduces the costs of production. However, if disease probability is high, the producer may face an increased risk of crop losses, which can be interpreted as more important than the reduction in the costs of production. In this new situation, the overall risk scenario for the barley producer involves a trade-off between cost reduction and the potential increase in the risk of disease outbreaks.

The spring barley producer needs to weigh the potential cost savings against the increased risk of crop losses due to reduced disease control. This decision-making process reflects the complex interplay between risk aversion, cost considerations, and the uncertainty associated with changes in fungicide application practices. We can employ this risk scenario to determine the level of risk aversion of a barley producer. By requesting the barley producer to provide us with the monetary quantity that they are willing to accept to play the risky lottery of making one fungicide application instead of the normal two applications, we can compute their risk aversion employing the concept of certainty equivalence (Mas-Colell *et al.,* 1995). The certainty equivalent is the monetary amount that an individual would consider equivalent to a risky situation. In this case, it would be the compensation that makes each producer indifferent between the risky scenario (reduced fungicide use) and a certain outcome (no disease outbreak), which is assumed to occur when the producer makes two fungicide applications during the growing season (at least, this is expected to be true in their mind).

If a producer is risk-averse, the financial quantity requested will be larger than the difference between the expected value of the risky scenario and the value of the sure scenario. This reflects their preference for a guaranteed amount over taking a chance with uncertain outcomes. On the other hand, if a producer is risk-tolerant, the financial quantity requested will be lower than the difference between expected value of the risky scenario and the value of the sure scenario, indicating a preference for the uncertain possibility of higher returns.

To determine the certainty equivalent for each producer, we need to compare the economic compensation a barley producer would require to be indifferent between the certain outcome (yield under two fungicide applications) and the lottery, given their perceived probability of the negative outcome. To clarify this condition, let us assume that every barley producer is confronted with the following comparison:

$$PQ_0 - C_0 - f \leq P[Q_o\alpha + Q_1(1-\alpha)] - C_o + s \quad (1)$$

Where P is the price of barley per tonne, Q_0 is the yield of barley per hectare expressed in tonnes when there was not a disease outbreak either because the producer made two fungicide applications or because the producer was confronted with the positive outcome of no outbreak in the lottery case, f is the cost of a fungicide application per hectare, C_0 is the total cost of production per hectare excluding the cost of fungicide application per hectare, Q_1 is the yield of barley per hectare when the producer was confronted with the negative outcome of a fungal outbreak, and α is the probability of a fungal outbreak. Producers are considered to be a risk averse if they prefer the certain outcome that produces a revenue smaller than or equal to the expected revenue produced by the lottery (Mas-Colell *et al.*, 1995; Proposition 6.C.1., (iii)). In equation (1), the revenue of the certain outcome is expressed on the left-hand side of the equation and the expected revenue of the lottery is expressed on the right-hand side. Alternatively, producers are risk averse if they require a monetary compensation s to accept the lottery that satisfies the following condition, which is obtained by re-arranging equation (1):

$$s \geq s^* = P(1-\alpha)[Q_0 - Q_1] - f \quad (2)$$

Where $s^*$is the monetary compensation that makes the barley producer indifferent between applying fungicide one time during the growing season and applying fungicide twice (i.e. the regular fungicide programme for barley). Notice that equation (2) depends on α and the difference between Q_0 and Q_1. Barley producers generally do not count with precise enough information to easily determine these two variables, and agronomists who advise barley producers may have a biased estimation of these two variables. To compute s^* based on the information that producers have, we defined $Q_1 = (1-\beta)Q_0$, where β is the percentage of yield lost that is expected to occur by the producer with one less fungicide application. β is also not known by producers or agronomists for every field in the country. Producers may have a subjective estimation of β, which they may use to estimate a value of s^*. We asked to interviewed producers to provide us with their estimation of α and β under two scenarios: a) only one fungicide application is allowed per growing season, and b) no fungicide application is allowed to grow barley. We also requested producers to provide us with an estimation of the minimum monetary compensation they would accept to make either one or zero fungicide applications under the constrains that the price of barley is at current market value (£180/t), the average barley yield is 7.5t/ha, and the cost of one fungicide application is £38/ha.

5.2. Perceived pest damage to the crop

5.2.1. Barley

The research team interviewed 29 barley producers. However, only 21 producers provided usable answers to compute their risk aversion based on the methodology developed in the previous section for all the scenarios proposed. Appendix 4 presents the values of α and β provided by the interviewed producers. Evidence in the literature suggests that the primary enhancement in yield for spring barley due to fungicide application is derived from treatments administered during the booting stage (T2 timing). In addition, the inclusion of an earlier application (T1 timing) leading to a further yield increase is infrequent, occurring only in cases where there is a high risk of fungal outbreaks spreading to the upper canopy. As a result, only one fungicide spray might be needed during the growing season. This literature also computes that the probability of a fungal outbreak is low, being highly dependent on seasonal rainfall levels and humidity levels in the soil (Bingham *et al.* 2020). Even though there is some evidence of the real values of α and β in Scotland, Appendix 4 shows that Scottish barley producers do not have the same estimation of either the probability of a fungal outbreak (α) or the percentage of yield lost (β) when they do not make two fungicide applications. The most frequently occurring (mode) answer for the expected yield lost was 5% when only one fungicide application is made and 30% when no fungicide application is made. In addition, the mode answer for the probability of a fungal outbreak was 60% when only one fungicide application is made and 80%-100% when no fungicide application is made. Nonetheless, there was not a general agreement among the interviewed producers about the exact value of the probability of a fungal outbreak and the percentage of yield lost when a full programme of fungicide is not applied to barley. For instance, some producers believed that they may lose up to 30% of their yield with a probability of 0.8 if they only make one fungicide application. In contrast, there was a minority of barley producers who believed that they may lose up to 10% of their yield with a probability of 20% or less if they do not make fungicide applications during the growing season. These contrasting perceptions make the computation of s^* producer-dependent since it depends on the estimation of α and β that each producer makes.

We also requested producers to provide us with the minimum monetary compensation they would accept to reduce their fungicide application to one or zero sprays. Appendix 5 presents the distribution of minimum monetary compensations asked for by barley producers to accept reducing their fungicide sprays to one and zero applications. The mode value requested was £180/ha under the first scenario and £200/ha under the second. However, there was no agreement around this value among the interviewed producers either. There were two producers who requested only the value of the fungicide application forgone and there were three producers who considered that any economic compensation was too low to forgo a fungicide application under the first scenario, with the latter number increasing to five producers when no fungicide could be utilised to grow barley. In addition, some producers requested large values, which may represent their misestimation of the probability of a fungal outbreak and/or the negative effect of a fungal outbreak on yield, which led them to request a monetary compensation that recovers at least half of the total cost of production per hectare or even more. Interestingly, there was a producer who requested no monetary compensation to forgo fungicide altogether. However, this producer is a very particular case since they only apply T1 to their barley crops, which is utilised as feed for animals, and considers that fungal outbreaks generate a very low reduction in yield.

We utilised the information contained in Appendix 4 and Appendix 5 to classify producers as risk averse or risk tolerant. A risk averse producer is an individual who requests more than the monetary compensation that makes both the certain outcome and the lottery equivalent (s^*). A risk tolerant producer is an individual who requests less. A risk-neutral producer is an individual who requests exactly the quantity s^*. Using the resulting classification, we computed the distribution of producers (Table 8).

There are 13 producers that can be considered as risk tolerant under the first scenario since they requested a quantity less than s^* (Table 8). This quantity drops to 4 producers under the second scenario. This result show that, when confronted with a riskier scenario, some producers tend become risk averse when they appear to be risk tolerant when confronted with a less risky scenario. This implies that the degree of risk aversion of producers may depend on how risky decision-makers perceive the situation. Yet, there are still four producers that are classified as risk tolerant. These individuals requested a very low monetary compensation to never apply fungicides and considered that zero sprays have a low negative impact on their crops. These producers also grow barley to feed their animals. As a result, the results in Appendix 5 show that producers who grow barley as feed are the ones with the largest probability to accept a lower monetary compensation to not apply fungicides to their barley crops.

Table 8: Classification of producers based on their risk aversion

Classification	No T1	Neither T1 nor T2
Risk Averse	8	17
Risk Tolerant	13	4

We employed the latter classification to organise some socioeconomic information collected from interviewed barley producers. Appendix 6 presents this information organised by risk aversion class and shows that older producers tend to appear more risk loving when they are the owners of the farm, and they are only asked to reduce one fungicide application. Once they are asked to forgo the entire fungicide programme, older producers tended to become more risk averse. Interestingly, producers with smaller land holdings tended to be more risk averse than producers with larger land holdings. Experience is also associated with risk aversion: the more experience the producer has, the more risk averse the producer appeared to be.

The crops grown in rotation with spring barley by producers that are classified as risk averse or risk tolerant (Appendix 7) showed that the most common crop utilised the surveyed producers in the rotation was spring barley. However, risk tolerant tended to employ a temporary grass lay, which confirms that most risk tolerant tend to be mixed farmers. In contrast, the most preferred rotations by risk averse barley producers were winter barley with spring cereal, and winter cereal with spring barley.

One hypothesis that arises from this research is whether spring barley producers are risk averse because their agronomists exaggerate the potential negative effects of a reduced fungicide programme. This is because the agronomist will share none of the benefits of any costs savings but will likely carry blame if the crop is subsequently infected. They may also have an incentive to sell fungicides to their clients if the advice given is part of a serviced sales package. With this latter hypothesis in mind, we asked barley producers to indicate where they get their advice from. If producers pay for advice separately to the fungicide costs, these producers may get different advice to those producers who receive advice from agronomists who also sell the fungicide. Table 9 shows that producers who pay for advice tend to be more risk tolerant than those producers who receive advice as part of the services provided by the company that sells them fungicides. It could be that farmers who are more willing to engage in deeper discussions with their agronomist are inclined to pay for more crop monitoring and IPM advice (i.e. from an independent agronomist) allowing them to fully understand the topic and make well-informed decisions around reducing pesticide input as they are aware of the risks and mitigating factors e.g. other agronomic practices, environmental conditions. Farmers using a merchant/distributor agronomist may have more transient conversations on IPM at the point of product sale. It is also worth considering that merchant/distributor agronomists have an economic incentive to exaggerate the negative consequences of reducing fungicides applications, and so their producer clients tend to be more risk averse. In any case this finding needs further investigation.

Table 9: Payment for agronomic advice and risk aversion in spring barley growers.

Advice Cost	T2 only (no T1)		Neither T1 nor T2	
	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
I pay for advice	3	4	5	2
Incorporated in the price of PPP	5	2	12	2

5.2.2. Seed potatoes

The research team interviewed 10 seed potato producers. Damage inflicted by aphid vectored potato virus is not straightforward to quantify or estimate. Whilst virus infection can cause a yield penalty and generate quality issues (such as cracked tubers or necrotic rings), infected plants frequently result in infected progeny tubers. If these are planted as seed potatoes, the yield and quality penalty can be suffered by the daughter crop, which may be grown by a customer of the seed potato producer. There is thus a strong reputational dimension for seed potato producers to keeping aphid vectored virus levels as low as possible. Seed potato crops are inspected during the growing season by SASA and assessed against strict tolerances. Failure to meet expected grade, or worse failure to be certified as seed may have a dramatic effect on crop value.

We asked seed potato producers to estimate their expected magnitude and frequency of economic injury should they reduce their insecticide spray programme or extend intervals. Many producers could not answer these questions and were unable to provide an estimate of their expected losses. For those that did answer, many expected to incur a loss more often than not. Of those that responded, all expected to incur losses over a 5-year period of over 20% with the highest value of 75% losses given by two growers. This highlights a knowledge gap; because of the complexity of the system, growers and advisers do not have a good understanding of the possible risks associated with reduction in insecticide applications in Scottish seed potatoes. This point was made to us by growers several times in the survey. Field experiments to determine yield penalties from PVY (Nolte *et al.*, 2004) and an assessment of industry scale losses due to PVY (Dupuis *et al.,* 2023) have been conducted in other jurisdictions. To our knowledge, no such assessment exits for PLRV.

5.2.3. Strawberries

In strawberries, pest damage can lead to reduced yields and compromised fruit quality. Retailers and consumers alike expect high-quality, undamaged, disease-free strawberries, and failure to meet these expectations due to pest and disease issues can lead to financial losses and damage to the grower's reputation. Therefore, implementing robust pest and disease management strategies is essential for maintaining the health and marketability of strawberry crops and preserving the long-term viability of strawberry farming operations.

We surveyed six strawberry producers to gauge their understanding of the potential economic impact of reducing insecticide applications in their cultivation practices. When asked about the expected magnitude of economic losses over a one-year period if they were to cease insecticide spraying, responses varied significantly. Four producers estimated potential losses of 70% and 75% and one producer estimated 50% indicating a substantial perceived impact on their strawberry yields and profitability. However, one producer expressed uncertainty and stated they "did not know how to respond," highlighting a knowledge gap and a lack of clarity regarding the potential consequences of altering their insecticide management practices.

Similarly, when questioned about the expected economic losses over a five-year period in the absence of insecticide applications, responses revealed notable apprehension among growers. Two producers expressed uncertainty and were unable to provide a response, underscoring the complexity and uncertainty surrounding the long-term implications of altering pest management strategies in strawberry production. However, among those who did respond, there was a consensus regarding the potential severity of economic losses. Two producers estimated losses of 100% over the five-year period, indicating a significant and potentially devastating impact on their strawberry yields and financial viability. Another producer reiterated the uncertainty by stating they "did not know how to respond," while two others estimated losses of 40-50%.

Overall, these responses highlight a pervasive knowledge gap regarding the potential risks and economic implications of reducing insecticide applications in their cultivation practices. The variability in responses underscores the need for enhanced KTE and R&D efforts to provide growers with a better understanding of the consequences associated with altering pest management strategies. Addressing this knowledge gap is essential for empowering farmers to make informed decisions that balance the economic, environmental, and social considerations inherent in sustainable strawberry production.

6. Research, Knowledge Exchange and Policy Priorities

Barriers to IPM uptake are numerous and varied though 'lack of evidence about IPM' and 'risks associated with IPM' adoption rank highly for all three sectors (Appendix 8; Appendix 9; Appendix 10). Greater investment in IPM research and the clear presentation of the research findings to the user (agronomist/producer) should help reduce the perception of risk through a greater understanding of the benefits and limitation of combinations of control measures in an IPM programme.

Across sectors (seed potato, barley, strawberry) there were varying levels of concern regarding specific barriers. In the seed potato sector, the most prominent barriers include the lack of evidence for IPM and the absence of financial incentives to reduce pesticide usage (scores 3.7/5 and 3.4/5, respectively; Appendix 8). This indicates that potato producers view the scarcity of scientific evidence supporting IPM practices and the lack of economic incentives as significant hurdles to embracing more sustainable pest management approaches. Similarly, the high mean score for risks associated with IPM (3.3/5; Appendix 8) suggests that crop producers perceive considerable uncertainties and potential negative consequences associated with transitioning to IPM strategies in seed potato cultivation.

In contrast, spring barley producers appear to prioritize different barriers, with risks associated with IPM topping the list (3.0/5; Appendix 9). This indicates that barley producers are particularly concerned about the uncertainties and potential drawbacks associated with implementing IPM practices in their farming operations. Additionally, the effort required to increase knowledge of IPM emerges as another notable barrier (2.9/5; Appendix 9), suggesting that barley producers perceive significant challenges in accessing and assimilating the necessary information and resources to effectively adopt IPM strategies. Furthermore, the relatively high mean score for being unaware of crop specific IPM advice (2.6/5; Appendix 9) highlights a perceived lack of tailored guidance and support for integrating IPM practices into barley production systems, further hindering adoption efforts.

In the strawberry sector, several common barriers emerge, including low confidence in IPM, lack of suitable IPM solutions, and equipment costs, all sharing the highest mean score of 2.8/5 (Appendix 10). These findings suggest that strawberry producers face similar challenges as potato and barley producers in terms of confidence in the efficacy of IPM, access to appropriate solutions, and the financial burden associated with acquiring necessary equipment for IPM implementation. Moreover, concerns related to labour costs and market constraints are also apparent, underscoring the multifaceted nature of barriers that strawberry producers encounter in embracing more sustainable pest management practices.

Research, Knowledge exchange and Policy priorities were identified by workshop participants through discussion and annotation of flipcharts. Barriers, enablers, and potential routes to further uptake of IPM were also discussed and the outcomes recorded on flipcharts (offline or online depending on workshop) (Table 10).

Table 10: Barriers to IPM adoption and the potential routes to overcome them.

Crop	Barrier to further IPM adoption	Action	Route
All	**Market specifications** Potato - Viral thresholds	KTE/R&D /Policy	Potato - Industry. Potential to review certification scheme thresholds to encourage IPM adoption. Breeders set minimum standards for virus resistance. Lowering standards would require changes to legislation and unlikely to be good marketing (home or abroad).
	Strawberry - Retailer rejections for contamination	KTE	Strawberry - Retailer/Consumer. Biological contamination is alternative to pesticide residues.
	Barley - purity and grain N content	KTE	Barley – Industry/processor. Maltster/Distiller quality parameters can prevent the uptake certain IPM measures related to crop diversity e.g. heterogeneity of the end product (i.e. mixed grains) or high grain protein content (i.e. through cover cropping or intercropping with legumes).
All	**Complex IPM systems** Require investment in knowledge	KTE	Practitioners - IPM strategies must be practically achievable and ideally easy to implement. Potential risks must be actual, not perceived (i.e. based on evidence).
All	**Pesticide alternatives role in IPM** Efficacy in IPM programmes unknown	R&D	Develop IPM programmes including pesticide alternatives e.g. biologicals, iRNA.
		R&D	Improve cost-effectiveness of alternatives to pesticides. Information on cost-effectiveness of alternatives is not always available.
		R&D/ Policy	Potato - Detailed economic impact of seed potato industry and threat of virus to leverage government funding for R&D.
		Policy	Improve speed of registration process for biologicals. Quicker approval of IPM compatible pesticides. Government approval for release of more native biocontrol agents. Financial incentives for reducing pesticide use.
		KTE	Industry: Insurance against risks of IPM failure.
All	**Variety choice** Marketable	KTE	Market acceptability of such varieties by processors retailers/consumers.
	Resistant varieties needed	R&D	Development of resistant varieties.
All	**Nutrient Inputs**	KTE	Strawberry + Potato - Train growers in crop nutrition.
		R&D	Strawberry - Impact of nitrate on aphids.

Crop	Barrier to further IPM adoption	Action	Route
	Limited grower knowledge of nutrient management	R&D	Barley – Impact of over/under supply of nutrients on diseases.
Strawberry + Potato	**Biodiversity** Limited data on role in pest management	R&D	Managing non-crop areas to improve biocontrol and reduce pest pressure. Need the evidence to support this.
Potato	**Landscape effects** Unknown	R&D	Landscape effects (field location, geography) on aphid populations/virus inoculum and IPM currently unknown.
Potato	**Push and Pull Strategies** Lack of evidence	R&D	Cereal buffer strips Vs adjacent fields of barley.
Strawberry	**Equipment** High costs	Policy R&D	Grants for equipment. Improve design and reduce costs.
Potato	**Seed source** Ware crops act as virus source for seed crops	Policy	Only use certified seed for ware production - protected areas.
Strawberry	**Growing media** Re-use protocols undefined	R&D	Substrate reuse – increased R & D in to options for sterilisation and reconditioning
Potato	**Mineral oils** Potential for use but current usage low	R&D Policy	Investigate varietal reactions and optimal application rates and how they can be implemented alongside other control measures. Grant approval of use through to crop burn down. Used for years in Europe - available as an adjuvant in UK, but not registered as PPP.
Strawberry	**Pesticides** Availability of critical pesticide active ingredients	Policy KTE	Authorise use. Improve distribution and availability.
Potato	**Weed control** Lack of volunteer potato control on rented land	Policy/ KTE R&D	Incentivise volunteer potato control in rented land. Improved weed control techniques.
Strawberry	**Growing systems**	R&D	Influence of tunnel types on IPM.

Crop	Barrier to further IPM adoption	Action	Route
	Protected cropping type effects on pests and IPM.		
Potato	**Advice and guidance** Current provision is insufficient	KTE Policy/ KTE KTE/ Policy	Improved knowledge exchange in both directions from research to growers/agronomists on new potential techniques and growers/agronomists to researchers. Incentivise growers to engage with financial rewards/compulsory training. Well-funded advisory services (best practice for crop protection, how to deploy IPM, interpreting testing and aphid monitoring data).
Potato	**Industry coordination** Currently lacking	KTE	KTE between industry stakeholders. Further involvement of major seed houses in IPM. Freely available information is vital. Industry is fragmented.
Strawberry	**Baseline of IPM already in practice** Not established	R&D	Quantify current levels of IPM practice.
Potato	**Demonstration platform** Practical IPM/ICM actions	KTE R&D KTE	Promote IPM messages. Practical, highly applicable research to support KTE. Industry funding for platforms.
Potato	**Monitoring** Data availability on aphid movement, virus prevalence and aphid trap information to inform DSS is limited	R&D/KTE /Policy R&D R&D R&D R&D KTE KTE KTE	Open free to all monitoring and trap information. More aphid resistance monitoring. Understand role of new tech in monitoring e.g. AI. Understand factors influencing aphid/ movements. Considering climate change. Genotypes and resistance test aphids from suction traps. Understand pyrethroid resistance – populations, species geography. Revise thresholds. Industry support for real-time monitoring to inform DSS. Simplify the complexity of DSS and improve information interpretation. Sharing agronomist information around monitoring – central real-time database.

Crop	Barrier to further IPM adoption	Action	Route
Strawberry	**Labour** High labour costs, availability, and quality	Policy Policy R&D	Same minimum wage across UK. Improved immigration policy. Increased efficiency making better use of the available labour. Minimise labour requirements e.g. automation to apply biocontrol agents.

Overall, the data highlight the diverse array of challenges and priorities that crop producers across different sectors face in adopting IPM practices. While certain barriers may be more pronounced in specific crops, addressing these challenges requires a comprehensive and tailored approach that considers the unique characteristics and needs of each farming context. Collaboration among crop producers, researchers, policymakers, and industry stakeholders is essential to develop targeted strategies and interventions aimed at overcoming these barriers and promoting the widespread adoption of IPM practices for sustainable crop production.

7. Discussion

This project aimed to understand how attitudes and responses to pest risk are influenced by perceived pest threat, economics and information sources, and identify IPM solutions and routes to encourage the adoption of best practice. Three case studies were selected due to their importance to the sector in Scotland: 1) Aphid borne virus control in seed potatoes, 2) Aphid control in strawberries, 3) Disease management in spring barley. Each case study used stakeholder workshops and crop producer surveys to gather information.

Attitudes to pest risk varied considerably by sector, producer and degree of threat posed. Aphid virus control in seed potatoes necessitates a low-risk approach as often there is no acceptable levels of damage, i.e. nil tolerance. Strawberry growers also have low thresholds for pest damage but are more able to implement biological control measures in protected production systems and combine multiple control measures into IPM strategies. The lack of aphid borne virus threat to strawberries means that there is time for the natural enemies to be effective in reducing the risk posed. Whereas, the main aphid vectored viruses affecting potatoes in Scotland, PVY and PLRV, PVY can be transmitted quickly (>1hr) after feeding initiates, which limits the potential for natural enemies to reduce risk. Despite receiving a lot of attention from government, NGOs, and the public, there is scant evidence that encouraging natural enemies is an effective and practical IPM measure which indicates the improving biodiversity is being prioritised over other aspects of IPM i.e. pest control, maintaining/improving crop yields.

The threat of aphid vectored virus to Scottish seed potato production has increased markedly in recent years, with 2023 in particular having exceptionally high levels of virus infected plant found in crops. Some progressive seed potato growers are adopting many different control measures, some of which are not well supported by the evidence base. As evidenced by the survey responses there are large differences in opinion relating to efficacy of different approaches. Research gaps exist on the efficacy of novel and existing control measures implemented in isolation and in combination with other control measures. Robust evidence is required to encourage producers to be confident about changing practice. There is much debate on the value of mineral oils to prevent aphids feeding but the evidence supporting this measure in the UK is scant, though research has been carried out in western Europe which shows their value. Anecdotally there certainly seems to be some merit in using mineral oils in Scotland if applied regularly (i.e. every 3-4 days, particularly early in the season) and a very small number of high-grade producers are combining this approach with a straw mulch applied early in the season.

Barriers to IPM uptake are numerous and varied though 'lack of evidence about IPM' and 'risks associated with IPM' adoption are the most common. Greater investment in IPM research and the clear presentation of the research findings (including the risks associated with the approach) to the user (agronomist/producer) may help reduce the perception of risk through a greater understanding of the benefits and limitation of combinations of control measures in an IPM programme.

Clear KTE priorities exist for crop producers and other stakeholders involved in the supply chain i.e. processers and retailers that could lead to increased adoption of IPM practices. Markets may limit the use of resistant varieties if they favour susceptible varieties with desirable quality traits. High damage/virus thresholds/end-product contamination (i.e. with aphid mummies) may limit the potential for IPM to be implemented as the risks associated are prohibitively high. Sharing of IPM best practice between producers is encouraged and regarded as a priority, however, competitiveness between producers and a reluctance to declare IPM failures for fear of shame results in a lack of openness which can result in the same mistakes being made by multiple producers. Despite the potential limitations, peer to peer interactions and demonstration platforms are regarded as effective KTE activities.

Policy has potentially a bigger role to play in the management of aphid vectored virus in seed potato as bad practice e.g. poor groundkeeper control, growing high grade seed in proximity (sometimes within the same field) to lower quality seed etc. can increase virus threat to other growers in the area. Enforced restrictions around growing potatoes close to high grade seed may alleviate some of these issues, but this is not straightforward to implement or enforce. Potato growers can multiply a single generation as “home saved seed” without entering the crop into the classification scheme (as it will not be marketed on), this was seen as a weak point by several workshop and survey participants. Tighter enforcement and perhaps compulsory post-harvest testing of home saved seed for virus levels may also help limit overall virus threat, but again this is a contentious proposal. A relaxation of the regulations around the use of mineral or paraffinic oils to prevent aphid feeding would be welcomed by the industry as current restrictions leave UK growers at a competitive disadvantage compared to the US and EU. The evidence base for the value of regular mineral oil applications as a protective measure against PVY transmission is strong (Al-Mrabeh *et al.,* 2010), but growers were divided on the utility of mineral oils – there were also several queries about best practice, possible interactions with PPP applied for late blight control and how oil treated plants (which can sometime display phytotoxicity symptoms) will fare within the seed potato classification scheme.

From a methodological perspective, there is plenty of room for the development of methods that capture farmers’ risk aversion. We presented a model for barley where risks scenarios were limited to two and only involved consideration of yield reductions due to disease outbreak. There is a need for more advanced methods to capture risk aversion in contexts where quality is also a variable to consider in the analysis. In the latter case, the financial compensation to reduce pesticide usage that is likely to be requested by crop producers is affected by considerations of quality. This is case of potatoes or strawberries, where producers are paid a premium based on the quality provided. In this case, producers’ risk aversion may be influenced by the perceived risks associated with quality reduction when an outbreak occurs. This dimension may heavily increase the quantity of money that producers are willing to accept to reduce one application of fungicides/pesticides. On the other hand, if IPM measures can be demonstrated to improve control, producers of high value crops are more likely to invest in their implementation.

8. Conclusion

The adoption of high levels of IPM is related to the perceived risks associated with a reduction in pesticide use. Seed potatoes and strawberries are only profitable if pests can be managed effectively to reduce viral infection (in the case of seed potato), and cosmetic damage (in the case of strawberries), both of which can lead to rejection. There is more room for a reduction in pesticide (fungicide) use amongst spring barley producers who are more able to consider taking risks associated with lower levels of control as the effect on profits are more quantitative (i.e. reduced yield) rather than qualitive (i.e. crop rejection).

Research and development initiatives focused on developing innovative pest management solutions, integrated pest management strategies, resilient crop varieties, and sustainable farming systems are a priority and must be tested by an independent body. New solutions and technologies are required to address pest threats while minimizing economic and environmental impacts. For example, there is a need for locally acquired, independent data on the efficacy of many IPM measures e.g. biological alternatives to pesticides, and physical methods such as mesh coverings. KTE should include demonstrations of practicalities for producers, ideally by producers.

The exchange of accurate, evidence-based and current information on pest threats, IPM and other risk management strategies could be improved. KTE can be implemented through various channels, including extension services/agronomists, farmer networks, online platforms, agricultural publications, workshops, seminars, online resources, and demonstration farms to showcase sustainable and economically viable approaches to pest management and risk reduction. Ensuring that producers have access to reliable information can help them make informed decisions and adopt more sustainable farming practices. Often the role of KTE is filled by their trusted agronomist and therefore more investment in engagement with agronomists on IPM matters should be encouraged and incentivised. In this study, barley producers with greater access to advice were found to be more tolerant to risk and open to reducing pesticide inputs. Policymakers could focus on facilitating and promoting greater access to advisory services for all sectors. This could involve funding programs to support advisory/extension services, providing training opportunities, or establishing partnerships with agricultural experts and institutions.

Varying perceptions and risk tolerance levels across different crop production sectors must be recognised and support programmes should be tailored accordingly. For example, initiatives aimed at promoting risk management strategies could be customised to address the specific needs and challenges faced by each sector e.g. seed potato, strawberry, arable and mixed farmers.

Incentive programs or support payments to encourage the adoption of sustainable agricultural practices that reduce risks associated with pesticides and other pest control measures while maintaining or enhancing productivity can be developed or enhanced. This could involve providing financial support for implementing IPM strategies, crop rotation, diversification of crops, and soil health improvement measures.

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10. Appendix

Appendix 1: Crops grown by Spring Barley, Seed Potato, and Strawberry Producers Interviewed (sample size = 29 barley producers, 9 potato producers, and 6 strawberry producers).

Spring barley		Seed Potatoes		Strawberries	
Crops	Producers	Crops	Producers	Crops	Producers
Barley Spring	26	Carrots	1	Blackberries	3
Barley Winter	8	Cereals	2	Blueberries	2
Beans Spring	3	Daffodils	1	Broccoli	1
Brussel Sprouts	2	Grass	1	Cherries	1
Carrot	1	Oilseed Rape	2	Raspberries	4
Hay	1	Seed Pots	6	Strawberries	6
Mustard	1	Spring Barley	4	Tree Saplings	1
Oats Spring	3	Ware Pots	4		
Oats Winter	3	Wheat	1		
Oilseed Rape Winter	10	Winter Barley	1		
Parsnip	1				
Pea Dry	1				
Potato Main Crop	6				
Potato Seed	1				
Rye Winter	1				
Wheat Winter	12				
Whole Crop	1				

Appendix 2: Crops in the Rotation with Spring Barley and Seed Potatoes (sample size = 29 barley producers and 9 potato producers).

Barley		Potatoes	
Crops in Rotation	Producers	Crops in Rotation	Producers
Barley Spring	1	Carrots	1
Barley Winter	2	Daffodil Bulbs	1
Brassica	4	Oilseeds	1
Brussel Sprouts	1	Spring Oilseed Rape	4
Carrot	1	Spring Barley	5
Fits round Potatoes	1	Spring Cereal	4
Legume	4	Temporary Grass Lay	5
No Rotation	1	Vining Peas	1
Oats	2	Winter Barley	4
Oilseed Rape Spring	6	Winter Cereal	3
Oilseed Rape Winter	2	Winter Oilseed Rape	1
Parsnip	1	Winter Wheat	4
Peas	1		
Potatoes	8		
Rye Winter	1		
Spring Cereal	20		
Temporary Grass Ley	10		
Wheat Winter	2		
Whole Crop	1		
Winter Cereal	19		

Appendix 3: Factors that influence seed potato producers' decision to adjust their aphid insecticide programme.

Measures	Average Score
BASIS qualified agronomist recommendation	4.37
Growth stage of the crop	3.93
Weather conditions and forecasts	3.71
Resistance management	3.52
Crop economic potential	3.37
Availability of plant protection products	3.30
Calendar date	3.11
Predictions of Decision Support Systems (where available)	2.93
Observed levels of pest/weed/disease presence in the field (including thresholds)	2.85
Insecticide costs	2.67
Actions of or advice from other crop producers in the area	2.42
Potato Prices	1.62

Appendix 4: Expected Losses and Outbreaks of making only one fungicide application and zero fungicide applications as perceived by spring barley producers.

T2 only (No T1)				Neither T1 nor T2			
Expected Losses (β) (%/ha)	Number of Producers	Expected outbreaks (α) (%)	Number of Producers	Expected Losses (β) (%/ha)	Number of Producers	Expected outbreaks (α) (%)	Number of Producers
2	1	0	1	10	1	0	1
3.5	1	20	0	15	2	5	1
5	6	40	5	20	2	40	2
10	5	60	12	25	3	60	3
12	2	80	3	30	9	80	10
15	2	100	5	35	1	100	10
20	5	DNRO	3	40	2	DNRO	2
30	2	Total	29	45	1	Total	29
DNRO	5			50	2		
Total	29			70	1		
				80	1		
				DNRO	4		
				Total	29		

Appendix 5: Minimum monetary compensation requested by spring barley producers to accept making less fungicide applications (price of barley £180/t, price of one fungicide application £38/ha).

Only T2 (No T1)		Neither T1 nor T2	
Required Compensation (£/ha)	Number of Producers	Required Compensation (£/ha)	Number of Producers
38	2	0	1
80	1	38	1
95	1	110	1
110	1	125	1
125	1	200	4
150	1	250	2
185	4	400	3
235	2	450	1
250	3	470	2
300	2	480	1
336	1	550	1
375	1	889	1
593	1	950	1
741	1	1037	1
DNRO	4	DNRO	3
No value	3	No value	5
Total	29	Total	29

Appendix 6: Some socioeconomic variables of Spring Barley producers vs Risk Aversion.

Variables	T2 only (No T1)	Neither T1 nor T2

Age	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
30-40	1	2	2	1
40-50	2	4	5	1
50-60	3	3	6	0
60-70	2	4	4	2
Ownership	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
Owner	8	9	14	3
Tenant	0	3	2	1
Manager	0	1	1	0
Land Owned(ha)	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
0-243	5	5	9	1
243-486	2	6	5	3
486-729	0	2	2	0
>970	0	0	0	0
Land Rented (ha)	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
0-243	7	13	16	4
>970	0	0	0	0
Experience	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
0-10	1	1	2	0
10-25	2	3	4	1
25-35	3	4	6	1
35-50	2	4	5	1
>50	0	0	0	0

Appendix 7: Crops in the rotation with Spring Barley vs Risk Aversion.

Crops	T2 only (No T1)		Neither T1 nor T2	
	Risk Averse	Risk Tolerant	Risk Averse	Risk Tolerant
Barley Spring	1	0	1	0
Barley Winter	1	1	2	0
Brassica	0	2	2	0
Brussel Sprouts	1	0	1	0
Fits Round Potatoes	0	1	1	0
Legume	1	2	3	0
Oats	0	2	0	2
Oilseed Rape Spring	3	2	4	1
Oilseed Rape Winter	1	0	1	0
Potato	1	3	4	0
Rye Winter	1	0	1	0
Spring Cereal	6	8	12	2
Temporary Grass Ley	1	5	4	2
Wheat Winter	1	1	2	0
Whole Crop	0	1	1	0
Winter Cereal	6	7	12	1

Appendix 8: Barriers to adoption of IPM practices by Seed Potato producers.

Barriers	Mean	SD	Min	Median	Max

Lack of evidence for IPM	3.7	1.5	1	4	5
Lack of financial incentives to reduce prays	3.4	1.7	1	4	5
Risks associated with IPM	3.3	1.4	1	3	5
Farm constraints	3.1	1.4	1	3	5
Low confidence in IPM	3.0	1.2	1	3	5
Lack of suitable IPM solutions	3.0	1.2	1	3	4
Equipment costs	2.9	1.4	1	3	5
Labour costs	2.9	1.2	1	3	5
Effort to increase knowledge of IPM	2.9	1.4	1	3	5
Market constraints	2.8	1.4	1	2	5
Unaware of crop specific IPM advice	2.1	1.0	1	2	4

Appendix 9: Barriers to adoption of IPM practices by Spring Barley producers.

Barriers	Mean	STD	Min	Median	Max
Risks associated with IPM	3.0	1.7	1	3.5	5
Effort to increase knowledge of IPM	2.9	1.6	1	3	5
Unaware of crop specific IPM advice	2.6	1.5	1	2	5
Low confidence in IPM	2.4	1.5	1	2	5
Equipment costs	2.3	1.6	1	1.5	5
Labour costs	2.1	1.5	1	1	5
Farm constraints	2.1	1.6	1	1	5
Lack of evidence for IPM	2.0	1.3	1	1	5
Lack of suitable IPM solutions	2.0	1.2	1	1	4
Market constraints	1.8	1.3	1	1	5

Appendix 10: Barriers to adoption of IPM practices by strawberry producers

Measures	Mean	SD	Min	Median	Max
Low confidence in IPM	2.8	1.3	1	3	5
Lack of suitable IPM solutions	2.8	1.5	1	4	4
Equipment costs	2.8	1.6	1	3	5
Risks associated with IPM	2.6	1.6	1	2	5
Labour costs	2.4	1.4	1	2	4
Lack of financial incentives to reduce sprays	2.4	1.4	1	2	4
Market constraints	2.2	1.6	1	1	5
Effort required to increase knowledge of IPM	2.0	1.1	1	2	4
Lack of evidence for IPM	1.6	1.2	1	1	4
Unaware of crop specific IPM advice	1.6	0.8	1	1	3
Farm constraints	1.6	1.2	1	1	4

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