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| **Project title:** | Review and guidance for integrated management of economically significant weeds, pests and diseases in a range of horticultural and other edible field crops. |
| **Project number:** | CP 211 |
| **Project leader:** | Caroline Young, ADAS |
| **Report:** | Final report, March 2022 |
| **Previous report:** | N/A |
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| **Date project commenced:** | 1st Nov 2021 |

## DISCLAIMER

# AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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# CONTENTS

# GROWER SUMMARY

## Headline

Integrated Pest Management (IPM) is widely used to reduce chemical inputs for pest, disease and weed control in many horticultural and arable crops. Strategies include cultural control techniques, monitoring and forecasting methods and the use of bioprotectants (invertebrate biocontrols, semiochemicals, microbials and natural substances). This review highlighted key non-chemical methods that growers are currently using but could be more widely adopted, such as decision support tools and cultural control methods including variety choice and crop hygiene. In addition, the review identified a wide range of crop and pest specific approaches that with further development, may also provide alternative and sustainable solutions. The review identified where more knowledge exchange is needed to facilitate adoption of effective practices and where further research is needed to further understand and develop new strategies.

## Background

This project was designed to consider IPM strategies on 'non-broadacre' crops in the UK. This follows on from AHDB Research Review 98, which considered the 'broadacre' crops of wheat, barley, oilseed rape and potatoes in the same way. The review was written by ADAS and SRUC, who took responsibility for specific crops as indicated below.

The following crops were included in the current review:

- Field vegetables - carrot, onion, leafy and root brassicas, endive and lettuce. (ADAS)
- Arable crops – rye, triticale, fodder crops, linseed, peas and beans (fresh and dry harvested). (SRUC)
- Top fruit - apple and pear. (ADAS)
- Soft fruit - strawberry, raspberry and grapevine. (ADAS)

## Summary

Integrated Pest Management is an effective approach to control pests, diseases, and weeds economically with reduced chemical plant protection product input. Within the horticulture sector, IPM is already widely adopted, and in some cases is the only viable option. In soft fruit crops, for example, there are no currently available chemical plant protection products for vine weevil control, therefore this pest can only be controlled through a carefully planned IPM programme using a combination of cultural and biological methods. This review has identified over 1500 IPM strategies for non-broadacre crops which either could be used more by growers or where there is little potential for increased use as growers are already adopting them, or strategies that justify further research and development.

The review examines the pest, disease and weed problems considered to be of greatest economic importance for each crop with the four groups, and existing and potential ways to reduce their impact other than by using conventional plant protection products. Measures were reviewed starting with those at crop planning, and then during pre-cropping, before turning to those enacted within the crop. On completion of the review, the perceived effectiveness of each measure, its speed of action, its ease of implementation and the cost of doing it were each rated and utilised in an equation that incorporated the likely greater potential use over the current use. The resulting tables created were then filtered to identify priorities for attention where there was potential for an increase in use of a given strategy. Those measures having a low strength of evidence were recommended for further research before greater knowledge exchange. Strong evidence of effectiveness was found for 368 of these IPM strategies (including many decision support systems, variety choice and good hygiene). Here further uptake may require more knowledge exchange with growers for them to be fully implemented. The tables provide pointers to the review and should be read in conjunction with the full text of the review.

For 343 strategies, more research to develop the methods and to fully understand how to implement them is required. Across the crops, the number of references (~1000) emphasises the volume of research that has already been carried out in this area, however there is a need for further research to improve our understanding and uptake of the various components of IPM. Research tends to focus on a particular measure; however, it is the implementation of a series of steps that will culminate in the ultimate protection of the crop; from planning where the crop is to grow, pre-cropping decisions ensuring the growing area and the seeds or plants to be grown are as free from pests and pathogens as possible, to finally implementing in-crop husbandry. Each crop situation is unique, but this review provides details of measures, both established and more recently developed, that can be integrated within individual crop management plans.

### Soft Fruit (strawberry, raspberry and grapevine)

Of the 450 control strategy combinations identified, the highest priority scores focused on pests and diseases rather than weeds.

 

Spotted winged drosophila (SWD) IPM control measures were prioritised for greater adoption across the three crop types. On raspberry and strawberry these measures included decision support, hygiene and mass monitoring, which although already practised, were considered to have scope for further uptake. Sterile male technique was also highlighted as a novel approach for SWD control but one that would to benefit from further research, validation and knowledge exchange to support uptake. Raspberry cane midge and blackberry leaf midge are key pests of raspberry that have no effective chemical control options. Breeding less susceptible varieties was identified as a potential method for the control of both these pests, however soft fruit growers often have little choice in selecting varieties to grow as these are stipulated by their marketing group. Similarly, breeding strawberry varieties less susceptible to thrips damage was identified as a potential control method, as although western flower thrips is well controlled by predatory mites in IPM, other thrips species are not and it has been observed that some varieties are more commonly damaged than others. Aphid control is an increasing problem in both strawberry and raspberry due to the shortage of available aphicides. Biological control with a range of aphid parasitoid species is used by some growers and there is scope for wider uptake with further KE, however growers consider this to be an expensive option.

Several approaches to powdery mildew and botrytis control in strawberry were highlighted, with potential for greater attention to the production of clean stock, maintaining crop hygiene and manipulating the environment to reduce infection. More research is needed on the use of microbial bioprotectants within IPM. Less widely employed strategies for powdery mildew control such as hot-water treatment of propagation material and UV-C, are supported by good evidence and could be more widely utilised.

### Arable crops (rye, triticale, fodder crops, linseed, peas and beans).

A total of 334 non-chemical strategies were considered to control the main pests of these crops. The leading strategies considered to have the greatest potential are discussed below.

*Rye and triticale*

Varietal choice for the control of yellow and brown rust of rye and triticale was top of the priority lists, although this clearly represents a simple and easy to implement solution, it is noted that selecting less susceptible varieties can narrow variety choice and may result in growers having to accept some other less favourable features. Weed and volunteer control in preceding crops may also prevent rusts from bridging between old and new crops. Hygiene and prevention was also prioritised for the control of annual grasses and ergot, also noted was the potential for non-chemical control of ergot and annual grassweeds through primary and secondary cultivations.

 

*Fodder crops*

Non-chemical control strategies for flea beetle and clubroot were considered of highest economic importance. The use of soil testing and stubble management could help to control both, undersowing for flea beetle may also have potential although less is known about this. Decision support, and hygiene and prevention for clubroot and rhizoctonia could be more widely used, to good effect.

*Peas and beans (fresh and dry harvested)*

Due to the economic importance of grassweed control within the rotation, non-chemical approaches such as cultivations (primary and secondary), fallow, undersowing companion crops as well as hygiene and prevention were all prioritised as effective approaches that could be more widely utilised. The use of bioprotectants for the control of Sclerotinia (in peas and beans) and pea moth although not currently used much were noted as effective, and both could be more widely implemented. In the case of pea moth control the strength of evidence is such that more work on bioprotectants may be required to validate this approach.

## Top Fruit (apple and pear)

Strategies for the control of invertebrate pests were highlighted in particular. The potential for increased use of bioprotectants (both microbial and macrobiological) was identified for the control of pear sucker, caterpillars, aphids, and fruit tree red spider mite on apples and pears,. There is good evidence that they are effective, and greater awareness could result in wider use.

The use of pruning, physical exclusion, and decision support systems for caterpillar control in apples and pears were also considered as an approach that could be more widely adopted, however more research may be required for validation.

Aphid control strategies prioritised (in addition to the use of bioprotectants as previously mentioned), included nutrient management and variety or rootstock choice. Evidence is strong that these work. Other strategies such as the use of undersowing or companion cropping or the physical exclusion of aphids from the plant were also highlighted and as approaches with potential, but a lack of validating research may be currently limiting uptake.

For the control of apple scab, pruning and canopy management, plus monitoring and forecasting to aid decisions on control measures are already commonly practised, and there is good evidence that they are effective and could be more widely adopted. Microbial bioprotectants and the end-of-season use of urea to aid infested leaf decomposition are less widely used but have been shown to be effective so have potential for greater use.

Hygiene and prevention strategies for the control of weeds in apple and pear orchards were also highlighted as approaches that are practised but could more widely used. Mechanical weed control is less common but is effective, and its use could be expanded.

### Field Vegetables

Strategies with the greatest further potential use focused on diseases and pests rather than weeds as weed control strategies were generally already being widely implemented and there was less scope for greater use.

Disease control here tended to focus on pre-cropping approaches, with rotations and selection of low-risk locations already often used but with some greater potential where soil-borne pathogens are a risk. For the control of cavity spot of carrot and sclerotinia there is good evidence that hygiene techniques, such as cleaning equipment to reduce the movement of infested soil, are effective and could be implemented more widely. The use of soil tests was identified as an approach with potential for greater uptake for onion white rot and fusarium and carrot cavity spot, following recent developments in molecular techniques, although the evidence of the value of such pre-planting soil tests is currently limited. In the root brassicas, as well as rotation, there was recognition of the need for spatial separation from other brassicas to reduce foliar diseases.

The use of precision irrigation to reduce soil water and canopy humidity was highlighted for lettuce, onion and carrot crops as a way to reduce disease spread and infection success. Similarly, well-timed irrigation of brassica crops, aided by pheromone traps and a prediction model can avoid the need for chemical pesticides by washing the young cutworms off the plants. Irrigation of lettuce crops can reduce damage by lettuce root aphid.

Decision support and monitoring were identified as approaches that could and should be used more for the control of pests and diseases of all field vegetables. Much is already known in this area and decision support tools are already in use. More knowledge exchange could lead to greater uptake, however the future availability of some of these decision support systems is currently uncertain.

Breeding commercial varieties of carrot and lettuce with resistance to carrot fly and aphids respectively was identified as a potential method for contributing towards control of these pests within IPM but research and development would be needed. Pre-sowing soil sampling to predict the risk of damage to carrot by free-living nematodes offers a valuable decision support tool, however threshold numbers of different nematode genera and species need to be reviewed and validated.

 

## Financial Benefits

Non-chemical control strategies within IPM programmes are a vital part of crop protection. They can bring significant financial benefits; extending the life of chemical plant protection products by reducing the development of resistance, reducing the number or applications or replacing them altogether. Where chemical solutions are no longer available or are not effective, non-chemical control strategies may offer the only viable long term form of control. This review identified non-chemical approaches available for management of the major pests, weeds and diseases of a wide range of field crops and poly tunnel-grown soft fruit. However, uptake of some measures could be greater, and it is recognised that this may sometimes relate to the implications of adoption. The main trade-offs when adopting IPM measures have therefore been identified in this review. However, the longer-term financial benefits from sustainable non-chemical management of pests, diseases and weeds can only be considered by each individual grower and/or via collaboration in on-farm research and development projects focussed on the development of integrated management programmes.

## Action Points

1. Check the prioritised strategies at the rear of this report and also read the relevant sections in the text in order to identify the non-chemical control strategies with good potential that are not already being used.
2. Consider the practicality and value of the approach and its suitability for use in each situation taking account of any potential trade-offs.
3. Seek further information or advice from a consultant or agronomist if needed.
4. Implement strategies which are likely to have a net positive effect on crop margins and which have other key benefits such as not disrupting biological control programmes already being used, increasing biodiversity and improving soil health.

 

# SCIENCE SECTION

## Abstract

Integrated pest management (IPM) methods are already an integral part of growing crops in the UK, but there is considerable scope for increased uptake. IPM includes combining non-chemical control methods (for example, through choice of resistant varieties and appropriate agronomy) to reduce the need for pesticides, and then targeting pesticide inputs according to need (including the use of decision support such as treatment thresholds or pest forecasts). This review identified the different IPM control methods growers have at their disposal for the major pests of a number of non-broadacre crops. 'Pests' here includes weeds, invertebrate pests and diseases.

A total of 61 IPM control strategies and 150 of the most significant crop pests affecting field vegetables (carrot, onion, leafy and root brassicas, endive and lettuce), non-broadacre arable crops (rye triticale, fodder crops, linseed, peas and beans), top fruit (apples and pears) and soft fruit (strawberry, raspberry and grape vine) were considered in this review. These were scored (on a 1 to 5 scale) for effectiveness of control, the economic importance of the pest, and aspects related to practicality of implementation. IPM methods where there is scope for increased adoption were identified.

Despite reviewing hundreds of sources of information there were still many IPM control methods for which there is inadequate evidence on efficacy or implementation. Scores were therefore assigned by ADAS and SRUC specialists in pathology, entomology, and weed science. The scores were used to identify priorities for research (where the current strength of evidence was poor) or knowledge exchange (where there is already sufficient evidence that implementing the control methods would be effective).

## Introduction

The production of soft fruit, arable crops, top fruit and field vegetables in the UK currently relies heavily on plant protection products (PPPs). These are widely used to prevent yield loss due to pests, diseases, and weeds and to prevent crop lodging. Many factors can influence the perceived or actual requirement for this chemical intervention.

This review extends the crop range of AHDB review of broadacre crops[D109] which details the non-chemical crop protection strategies for cereals (wheat and barley), oilseed and potato crops in the UK, by reviewing the non-chemical crop protection strategies that are, or could be used in growing soft fruit, several acre arable crops, top fruit and field vegetables in the UK. It summarises the evidence available on the viability of specific non-chemical strategies as alternatives to PPPs for controlling the main pests, diseases, and weeds of these crops. It establishes their performance and considers limitations to their use.

A wide range of non-chemical strategies exist and are practised by growers of different crops to varying degrees. These strategies can be employed (i) pre cropping as part of crop rotation planning across years (e.g. decreasing the frequency of a crop in the rotation to reduce pest build-up over growing seasons), (ii) at the start of the season before the crop is planted (e.g. adjusting sowing date to enable early season weed or disease control or selecting resistant varieties which can affect pest and disease control requirements and (iii) within the crop growing season (e.g. using biopesticides, nutrient management or mechanical weeders). The review considers non-chemical control methods at these three time points as this allows for suitable comparisons between strategies to be made. The review is based on published information on non-chemical control methods from peer-reviewed scientific papers, and information from appropriate, independent papers such as government reports. Additionally, the evidence for the performance of the different control methods has been evaluated by a panel of ADAS experts in the control of weeds, pests, and diseases.

The tables below indicate the specific crop adversity (pests, weeds, and diseases) and the relevant non-chemical control methods of value. Further tables in Section 8 go further and rate the performance of each non-chemical control method on effectiveness, strength of evidence, cost of implementation, ease of implementation and speed of applicability and economic viability, for each crop adversity. Where the published information on a particular control method was considered insufficient or unsuitable, expert judgement has been used to evaluate performance.

The review also identifies the non-chemical control strategies that could increase in usage either through a focus on the knowledge exchange of existing information (where there is already good evidence that they work) or following further primary research where strategies with potential require more evidence on how and where they can be effectively used, prior to their adoption.

## Objectives

The aim of the project is to provide better information on the effectiveness of non-chemical measures in major UK crops (not covered by the previous review) to reduce pests and ranking them so they can be prioritised for knowledge exchange and research to fill knowledge gaps.

The specific objectives were to:

1. Establish the baseline evidence for non-chemical interventions in non-broadacre crops against the most economically significant pests for each crop.

 

2. Rank each control measure based on its effectiveness, strength of evidence, cost, economic importance, ease of implementation, and speed of impact following adoption. Both current and potential use of each measure will also be scored to determine where increased uptake could occur.

3. Summarise recommendations for each crop in terms of the most effective measures and identify where both KE and research should be prioritised to support uptake.

## General introduction: IPM across non-broadacre crops

The latter half of the twentieth century saw increasing availability of plant protection products able to control a wide range of pests, diseases and weeds, with routine chemical treatments being used by many to maintain high quality fruit and vegetable crops. This century, new active ingredients and pesticide product formulations have continued to be released; however, many others have been withdrawn from sale for various reasons. Horticultural products tend to be first approved for broad-acre crops and so often do not have on-label approval but are applied at growers' own risk under the system of specific Extensions of Authorisation for Minor Use (EAMUs) supported by funding through a UK grower levy or by the manufacturer of that product. Some crops now have a very restricted number of available products, usually with a limited number of applications per crop to reduce the chance of resistance to the active ingredient being developed by the pest, pathogen or weed being controlled. Recent reviews have highlighted the potential consequences to crop production of further product loss[D153 D154 D155]. Coincidental with these changes has been an increased intensification of production that has resulted in greater risk of disease build-up and transfer between crops. With no break in cultivation of many vegetable crops in the UK, and the introduction of oilseed rape, this has provided a `green bridge', enabling many diseases to be active at any stage of the year. There is an increasing realisation that using integrated crop management, in which crop husbandry is used to reduce the presence and build-up of pest, pathogen and weed populations, with plant protection products used as the second option, is not just “a good thing” to do but is essential to be able to continue to produce crops. The Sustainable Use Directive 2009/128/EC (SUD)[D145] requiring European Member states to promote low pesticide-input management, giving wherever possible priority to non-chemical methods has now been transposed into UK law and all users of professional pesticides are required to abide by it[D146]. The UK’s National Action Plan of 2013 sets out a framework for action to achieve the sustainable use of pesticides. One of the three things that users of professional pesticides must be able to demonstrate is that Integrated Pest Management (IPM) is being followed [D147].

 

The majority of growers in the UK are required by their clients to work to Red Tractor Standards [D148 D149] and / or standards specific to the marketing group or supermarket that they are contracted to, with regular audits of all aspects of production, including the use of IPM. The National Farmers Union has developed the Integrated Pest Management Plan (IPMP) for the Voluntary Initiative with an online plan that farmers of combinable, forage and/or field scale vegetable crops should complete [D150.] For growers in Scotland, the Plant Health Centre has produced online forms in order to baseline practices and track the impact of changes; the Scottish IPM Assessment Plan [D151], with separate plans depending on whether farmers mainly growing either arable, field-scale vegetables, forage and potato crops, or grass crops. These online forms pose a series of multiple-choice questions to provide the form-filler with a measure of the adoption of IPM by their business.

As part of the Voluntary Initiative, a booklet has been produced on IPM, developed by LEAF with assistance from ADAS, Agricology, AHDB, Crop Protection Association, Game & Wildlife Conservation Trust, NFU, The James Hutton Institute and the Voluntary Initiative [D152]. The booklet is based on the eight principles of IPM and gives “Eight Simple Steps” which enable practical techniques that achieve sustainable crop production with reduced pesticide inputs. These are:

1. Prevention and Suppression
2. Monitoring
3. Decisions based on Monitoring and Thresholds
4. Non-Chemical Methods
5. Pesticide Selection
6. Reduced Pesticide Use
7. Anti-Resistance Strategies
8. Evaluation

Farmers and growers are encouraged to assess their current practices as poor, medium or good based on pest, disease or weed management options given under each of those eight categories.

A review for Defra [D201] covered sources of information on IPM worldwide. It confirmed that a decrease in chemical pesticide followed the introduction of described IPM methods across arable and horticulture and different crops, with most measures having been in association with pest or weed control. For horticulture, the use of microbial or botanical bioprotectants was noted as a measure commonly used on protected crops. An appendix table, spanning 70 pages, summarised a broad range of IPM measures and their effect on pesticide use.

 

More recently a review of IPM practices in UK arable rotations produced evidence for the management measures for specific weeds, pests and diseases [D109]

Crop protection options to reconcile land use for agriculture and the protection of the environment were set out following the 2007 ENDURE Foresight Study [D238]. Five protection systems / scenarios were outlined, and part of the contrast between them lies in the relative weight placed on three approaches that are part of IPM; a) control methods proper which need to be diversified and used in combination  b) surveillance and forecast methods allowing appropriate timing, spatial positioning and intensity of control to ensure a good match with needs and c) prevention methods which include the design of systems resilient to the action of pests and contributing to limiting their populations. Growers faced with further loss of routinely used chemical pesticides will need to be aware of, and consider, what balance of measures they should adopt to continue to protect their crops, and such measures are the focus of the current review.

Until recently, Assured Produce Crop Protocols were available for UK growers to download from the Red Tractor website. These gave crop management information including crop planning and in-crop pest and disease control guidance which was updated at regular intervals by agronomists with expertise in those crops and integrated pest and disease management. For Version 5 of the Red Tractor Assurance Standards (launched in November 2021) [D148 D149] the Crop Protocols were removed. This was because Red Tractor's research indicated that the increased professionalism in the sector meant the texts were part of passing the assessment rather than a best practice guide that actively informed cropping decisions (Simon Thorpe, Fresh Produce Manger Red Tractor Assurance, pers. comm.). The Protocols are recognised as a valuable reference source and it had been agreed that AHDB Horticulture would take on the texts, but as this body has been shut down this is no longer an option and no further decision has been made on their future (Simon Thorpe, pers. comm.). A new archive website has been set up to host the legacy report and knowledge exchange resources previously hosted on the main AHDB website.  However, it would be of benefit to consolidate the information scattered through these various resources into crop-specific guidance documents on integrated crop management, ideally cross-referenced to AHDB publications thus increasing grower, advisor and researcher awareness of their existence. AHDB Horticulture had recently commenced commissioning the updating and conversion of factsheets to webpage content to enable browsing on a smart phone with a view to ongoing incorporation of new information from research. UK growers moving away from high reliance on chemical plant protection products to greater use of integrated crop management will, with the cessation of levy funded non-broadacre research and knowledge exchange, continue to need sources of research, development and advisory information.

## Reference tables: Non-chemical control strategies, and their activity.

These tables show the main pests selected for review in this report, and the applicable strategies.

Table 1. Soft fruit: Strawberry. IPM strategies for the control of the major pests weeds and diseases.

| | | Diseases | | | | | Pests | | | | | Weeds | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Point of use** | **Non- chemical control strategy** | Powdery mildew | Botrytis | Phytophthora spp | Colletotrichum | Verticillium wilt | Spotted winged drosophila | Aphids | Thrips | vine weevil | strawberry blossom weevil | Perennial grasses | Perennial broad-leaved, various | Annual grasses various | Annual broad-leaved various | All weeds Pre-emergence |
| **Crop planning** | Fallow | | | | | | | | | | | | | | | |
| | Field history, rotation & break crops | | | ✓ | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| | Select low-risk locations | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | | | | | |
| | Spatial separation | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | | | | | | |
| **Pre-cropping** | Alternative seed treatments | | | | | | | | | | | | | | | |
| | Anaerobic soil disinfestation | | | ✓ | | ✓ | | | | | | | | | | |
| | Biofumigation | | | ✓ | | | | | | | | | | | | |
| | Biosecurity / industry regulation | | | ✓ | ✓ | | | | | | | | | | | |
| | Clean stock | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Control volunteers & weeds | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | |
| | Drainage | | | ✓ | | | | | | | | | | | | |
| | Early harvest | | | | | | | | | | | | | | | |
| | Flooding | | | | | | | | | | | | | | | |
| | Hygiene and prevention | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Lime | | | | | | | | | | | | | | | |
| | Meristemming | | | | | | | | | | | | | | | |
| | Phytosanitary legislation | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | | | | | |
| | Pre-plant soil tests | | | ✓ | | ✓ | | | | | | | | | | |
| | Primary cultivations (crop residue burial) | | ✓ | | | | | | | ✓ | | | | | | |
| | Secondary cultivations (drilling method) | | | | | | | | | | | | | | | |
| | Seed and young plant testing | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Seed rate (incl. variable seed rate) | | | | | | | | | | | | | | | |
| | Seedbed quality | | | | | | | | | | | | | | | |
| | Soil organic amendments | | | ✓ | | ✓ | | | | | | | | | | |
| | Sowing or planting date | ✓ | | ✓ | | ✓ | | | | | | | | | | |
| | Stubble management | | | | | | | | | | | | | | | |
| | Substrate | | | ✓ | | | | | | | | | | | | |
| | Trap crops | | | | | | | | | | | | | | | |
| | Use of cover crops | | | | | | | | | | | | | | | |
| | Variety choice/Breeding | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | | | | | |
| | Variety mixtures | ✓ | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| **In-Crop (includes propagation)** | Biennial cropping | | | | | | | | | | | | | | | |
| | Bioprotectants invertebrate biocontrols | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | |
| | Bioprotectants natural substances | ✓ | | | | | | ✓ | ✓ | | | | | | | |
| | Bioprotectants microbial | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | | | | | | |
| | Bioprotectants semiochemical | | | | | | ✓ | | ✓ | | | | | | | |
| | Biostimulants & elicitors & physically acting products | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | | | | |
| | CATT treatment | | | | | | | | ✓ | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | |
| | Defoliation (incl. pruning, mowing, grazing) | ✓ | ✓ | | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Environmental control (including overhead protection) | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Hand weeding/roguing | | ✓ | ✓ | ✓ | | | | | | | | | | | |
| | Hot water dipping | ✓ | ✓ | | ✓ | | | | | | | | | | | |
| | Hygiene | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| | In-field non-cropped areas | | | | | | | ✓ | ✓ | | | | | | | |
| | Intercropping | | | | | | | ✓ | | | | | | | | |
| | Mass monitoring (e.g. roller traps) or Suction | | | | | | ✓ | | ✓ | | | | | | | |
| | Mechanical weeding | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Nutrient management | ✓ | ✓ | | | | | ✓ | | | | | | | | |
| | Organic amendments | | | | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | | ✓ | ✓ | ✓ | | | | | | | |
| | Physical mulches | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| | Plant sauna | | | ✓ | ✓ | | | | | | | | | | | |
| | Precision irrigation | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Removal of alternative hosts | | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | | | | | |
| | Sterile male technique | | | | | | ✓ | | | | | | | | | |
| | Test & treat irrigation water | | | ✓ | | | | | | | | | | | | |
| | Thermal weed control | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | UV-C | ✓ | ✓ | | | | | | | | | | | | | |

 

Table 2. Soft fruit: Raspberry. IPM strategies for the control of the major pests weeds and diseases.

| | | Diseases | | | | | Pests | | | | | Weeds | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Point of use** | **Non- chemical control strategy** | Phytophthora spp | Botrytis (cane & fruit) | Cane blight | Powdery mildew | Yellow Rust | Spotted winged drosophila | Aphids | Raspberry cane midge | Blackberry leaf midge | raspberry leaf & bud mite | Perennial grasses | Perennial broad-leaved, various | Annual grasses various | Annual broad-leaved various | All weeds Pre-emergence |
| **Crop planning** | Fallow | | | | | | | | | | | | | | | |
| | Field history, rotation & break crops | ✓ | | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| | Select low-risk locations | ✓ | | ✓ | ✓ | | ✓ | | | | ✓ | | | | | |
| | Spatial separation | ✓ | ✓ | | ✓ | ✓ | | | | | | | | | | |
| **Pre-cropping** | Alternative seed treatments | | | | | | | | | | | | | | | |
| | Anaerobic soil disinfestation | | | | | | | | | | | | | | | |
| | Biofumigation | ✓ | | | | | | | | | | | | | | |
| | Biosecurity / industry regulation | ✓ | | | | | | | | | | | | | | |
| | Clean stock | ✓ | | | | | | | | | | | | | | |
| | Control volunteers & weeds | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | ✓ | | | | | |
| | Drainage | ✓ | | | | | | | | | | | | | | |
| | Early harvest | | | | | | | | | | | | | | | |
| | Flooding | | | | | | | | | | | | | | | |
| | Hygiene and prevention | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Lime | | | | | | | | | | | | | | | |
| | Meristemming | | | | | | | | | | | | | | | |
| | Phytosanitary legislation | ✓ | | | | | | ✓ | | | ✓ | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | | | | | |
| | Pre-plant soil tests | ✓ | | | | | | | | | | | | | | |
| | Primary cultivations (crop residue burial) | | | | | | | | | | | | | | | |
| | Secondary cultivations (drilling method) | | | | | | | | | | | | | | | |
| | Seed and young plant testing | ✓ | | ✓ | | | | | ✓ | ✓ | | | | | | |
| | Seed rate (incl. variable seed rate) | | | | | | | | | | | | | | | |
| | Seedbed quality | | | | | | | | | | | | | | | |
| | Soil organic amendments | | | | | | | | | | | | | | | |
| | Sowing or planting date | ✓ | | | | | | | | | | | | | | |
| | Stubble management | | | | | | | | | | | | | | | |
| | Substrate | ✓ | | | | | | | | | | | | | | |
| | Trap crops | | | | | | | | | | | | | | | |
| | Use of cover crops | | | | | | | | | | | | | | | |
| | Variety choice/Breeding | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | | | | |
| | Variety mixtures | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| **In-Crop (includes propagation)** | Biennial cropping | | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | | | | | |
| | Bioprotectants invertebrate biocontrols | | | | | | ✓ | ✓ | | | ✓ | | | | | |
| | Bioprotectants natural substances | ✓ | | | ✓ | | | ✓ | ✓ | ✓ | | | | | | |
| | Bioprotectants microbial | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | | | | | |
| | Bioprotectants semiochemical | | | | | | ✓ | | ✓ | ✓ | | | | | | |
| | Biostimulants & elicitors & physically acting products | ✓ | ✓ | | ✓ | | | ✓ | ✓ | ✓ | | | | | | |
| | CATT treatment | | | | | | | | | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | |
| | Defoliation (incl. pruning, mowing, grazing) | | ✓ | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Environmental control (including overhead protection) | | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Hand weeding/roguing | | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Hot water dipping | | | | | | | | | | | | | | | |
| | Hygiene | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| | In-field non-cropped areas | | | | | | | ✓ | | | | | | | | |
| | Intercropping | | | | | | | | | | | | | | | |
| | Mass monitoring (e.g. roller traps) or Suction | | | | | | ✓ | | | | | | | | | |
| | Mechanical weeding | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Nutrient management | ✓ | ✓ | | ✓ | | | ✓ | | | | | | | | |
| | Organic amendments | ✓ | | | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | | ✓ | ✓ | | | | | | | | |
| | Physical mulches | | | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| | Plant sauna | ✓ | | | | | | | | | | | | | | |
| | Precision irrigation | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | |
| | Removal of alternative hosts | | | ✓ | | | | ✓ | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | | | | | |
| | Sterile male technique | | | | | | ✓ | | | | | | | | | |
| | Test & treat irrigation water | ✓ | | | | | | | | | | | | | | |
| | Thermal weed control | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | UV-C | | ✓ | | ✓ | | | | | | | | | | | |

Table 3. Soft fruit: Grape Vine. IPM strategies for the control of the major pests weeds and diseases.

| | | Diseases | | | | Pests | | Weeds | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Point of use** | **Non- chemical control strategy** | Downy mildew | Powdery mildew | Botrytis | ESCA Stem & shoot dieback | Spotted winged drosophila | Moths | Perennial grasses | Perennial broad-leaved, various | Annual grasses various | Annual broad-leaved various | All weeds Pre-emergence |
| **Crop planning** | Fallow | | | | | | | | | | | |
| | Field history, rotation & break crops | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | |
| | Select low-risk locations | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | |
| | Spatial separation | ✓ | ✓ | ✓ | ✓ | | | | | | | |
| **Pre-cropping** | Alternative seed treatments | | | | | | | | | | | |
| | Anaerobic soil disinfestation | | | | | | | | | | | |
| | Biofumigation | | | | | | | | | | | |
| | Biosecurity / industry regulation | | | | | | | | | | | |
| | Clean stock | | | | | | | | | | | |
| | Control volunteers & weeds | ✓ | ✓ | ✓ | | | | | | | | |
| | Drainage | | | | ✓ | | | | | | | |
| | Early harvest | | | | | | | | | | | |
| | Flooding | | | | | | | | | | | |
| | Hygiene and prevention | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Lime | | | | | | | | | | | |
| | Meristemming | | | | | | | | | | | |
| | Phytosanitary legislation | | | | | | | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | |
| | Pre-plant soil tests | | | | ✓ | | | | | | | |
| | Primary cultivations (crop residue burial) | | | | | | | | | | | |
| | Secondary cultivations (drilling method) | | | | | | | | | | | |
| | Seed and young plant testing | | | | ✓ | | | | | | | |
| | Seed rate (incl. variable seed rate) | | | | | | | | | | | |
| | Seedbed quality | | | | | | | | | | | |
| | Soil organic amendments | | | | | | | | | | | |
| | Sowing or planting date | | | | | | | | | | | |
| | Stubble management | | | | | | | | | | | |
| | Substrate | | | | | | | | | | | |
| | Trap crops | | | | | | | | | | | |
| | Use of cover crops | | | | | | | | | | | |
| | Variety choice/Breeding | ✓ | ✓ | ✓ | ✓ | | | | | | | |
| | Variety mixtures | ✓ | | | | | | | | | | |
| | | | | | | | | | | | | |
| **In-Crop (includes propagation)** | Biennial cropping | | | | | | | | | | | |
| | Bioprotectants invertebrate biocontrols | | | | | | | | | | | |
| | Bioprotectants natural substances | ✓ | ✓ | ✓ | | | | | | | | |
| | Bioprotectants microbial | | ✓ | ✓ | ✓ | | ✓ | | | | | |
| | Bioprotectants semiochemical | | | | | | ✓ | | | | | |
| | Biostimulants & elicitors & physically acting products | ✓ | ✓ | ✓ | | | | | | | | |
| | CATT treatment | | | | | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | |
| | Defoliation (incl. pruning, mowing, grazing) | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | |
| | Environmental control (including overhead protection) | ✓ | ✓ | ✓ | | | | | | | | |
| | Hand weeding/roguing | ✓ | ✓ | ✓ | | | | | | | | |
| | Hot water dipping | | | | | | | | | | | |
| | Hygiene | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | |
| | In-field non-cropped areas | | | | | | | | | | | |
| | Intercropping | | | | | | | | | | | |
| | Mass monitoring (e.g. roller traps) or Suction | | | | | | | | | | | |
| | Mechanical weeding | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Nutrient management | | | ✓ | ✓ | | | | | | | |
| | Organic amendments | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | ✓ | | | | | | |
| | Physical mulches | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Plant sauna | | | | | | | | | | | |
| | Precision irrigation | | | | | | | | | | | |
| | Removal of alternative hosts | | | ✓ | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | |
| | Sterile male technique | | | | | ✓ | | | | | | |
| | Test & treat irrigation water | | | | | | | | | | | |
| | Thermal weed control | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | |
| | UV-C | | ✓ | ✓ | | | | | | | | |

Table 4. Arable crops: Rye, Triticale, Fodder and Linseed. IPM strategies for the control of the major pests weeds and diseases.

| | | Rye/Triticale | | | | | | Fodder Crops | | | | | | | | Linseed | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diseases | | | | Pests | Weeds | Diseases | | | Pests | | weeds | | | Diseases | | Weeds | | | Pests |
| Point of use | Non- chemical control strategy | yellow rust (Puccinia striiformis f. sp. tritici) | brown rust (Puccinia recondita f. sp. recondita) | Ergot (Claviceps purpurea) | powdery mildew (Blumeria graminis) | aphids (BYDV) | Annual grasses | mildew | clubroot | rhizoctonia | flea beetle | cabbage root fly | nettle | fat hen | thistle | Fusarium | alternaria | knotgrass | chickweed | fat hen | flax flea beetle |
| Crop planning | Fallow | | | | | | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| | Field history, rotation & break crops | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| | Select low-risk locations | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | | | | | | ✓ | | | |
| | Spatial separation | | | | | | | | | | | | | | | | | | | | |
| Pre-cropping | Alternative seed treatments | | | | | | | | | | | | | | | | | | | | |
| | Biofumigation | | | | | | | | | | | | | | | | | | | | |
| | Control volunteers & weeds | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | | | ✓ | ✓ | ✓ | |
| | Early harvest | | | | | | | | | | | | | | | | | | | | |
| | Drainage | | | | | | | | | | | | | | | | | | | | |
| | Flooding | | | | | | | | | | | | | | | | | | | | |
| | Hygiene and prevention | | | ✓ | | | ✓ | | ✓ | ✓ | | | | | | | | | | | |
| | Lime | | | | | | | | ✓ | | | | ✓ | | | | | | | | |
| | Pre-cropping nutrition | | | | ✓ | | | | | | | | | | | | | | | | |
| | Primary cultivations (crop residue burial) | | | ✓ | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | |
| | Secondary cultivations (drilling method) | | | | | | ✓ | | | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | |
| | Seed rate (incl. variable seed rate) | | | | ✓ | | ✓ | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ |
| | Seed and young plant testing | | | ✓ | | | | | | | | | | | | | | | | | |
| | Seedbed quality | | | | | | ✓ | | | | ✓ | ✓ | | | | | | | | | |
| | Sowing or planting date | ✓ | ✓ | | | ✓ | | ✓ | | | | | | | | | | ✓ | ✓ | ✓ | |
| | Stubble management | | | | | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| | Trap crops | | | | | | | | | | ✓ | | | | | | | | | | |
| | Undersowing & Companion cropping | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | |
| | Use of cover crops | | | | | | ✓ | | | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | |
| | Phytosanitary legislation | | | | | | | | | | | | | | | | | | | | |
| | Substrate | | | | | | | | | | | | | | | | | | | | |
| | Pre-plant soil tests | | | | | | | | ✓ | ✓ | | | | | | | | | | | |
| | soil organic amendments | | | | | | | | | | | | | | | ✓ | | | | | |
| | Variety choice | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | | | |
| | Variety mixtures | ✓ | ✓ | | ✓ | | | | | | | | | | | | | | | | |
| | Bioprotectants Macrobiological | | | | | | | | | | | | | | | | | | | | |
| n-Crop (includes propagation | Bioprotectants Botanical | | | | | | | | | | | | | | | | | | | | |
| | Bioprotectants Semiochemical | | | | | | | | | | | | | | | | | | | | |
| | Biostimulants & elicitors | | | | | | | | | | | | | | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | | | | ✓ | | | | | |
| | Defoliation (incl. mowing and grazing) | | | | | | ✓ | | | | | | | | | | | | | | |
| | Environmental control | | | | | | | | | | | | | | | | | | | | |
| | Hand weeding/roguing | | | | | | ✓ | | | ✓ | | | | | ✓ | | | | | | |
| | Hygiene | | | | | | | | | | | | | | | | | | | | |
| | Intercropping | | | | | | ✓ | | | | | | | | | | | | | | |
| | Mechanical weeding | ✓ | ✓ | ✓ | | | ✓ | | | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | |
| | Microbial bioprotectants | | | | | | ✓ | | | | | | | | | | | | | | |
| | Nutrient management | | | | | | | | | | | | ✓ | | | | | | | | |
| | Organic amendments | ✓ | ✓ | | ✓ | | | | | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | | | | | | | | | | | | | | | | |
| | Physical mulches | | | | | | | | | | | | | | | | | | | | |
| | Precision irrigation | | | | | | | | | | | | | | | | | | | | |
| | Removal of alternative hosts | | | | | | | | ✓ | ✓ | | | | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| | Test & treat irrigation water | | | | | | | | | | | | | | | | | | | | |
| | Thermal weed control | | | | | | ✓ | | | | | | | | | | | | | | |
| | Undersowing companion crops | | | | | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ |

 

Table 5. Arable crops: Bean and Peas (dry and fresh). IPM strategies for the control of the major pests weeds and diseases.

| | | Peas (dry and fresh) | | | | | | | Beans (dry and fresh) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diseases | | | Pests | | weeds | | Diseases | | | Pests | | | Weeds | |
| **Point of use** | **Non- chemical control strategy** | botrytis | downy mildew | leaf spot | pea moth | pea aphid | annual grasses | BLWs | Botrytis | Rust | Sclerotinia | Bruchid beetle | bean weevil | Black bean aphid | Annual grasses | Bradleaved Weeds |
| **Crop planning** | Fallow | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Field history, rotation & break crops | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ |
| | Select low-risk locations | | | ✓ | | ✓ | ✓ | ✓ | | | | | ✓ | | ✓ | ✓ |
| | Spatial separation | ✓ | ✓ | | | | | | ✓ | | | | | | | |
| **Pre-cropping** | Alternative seed treatments | | | | | | | | | | | | | | | |
| | Biofumigation | | | | | | | | | | | | | | | |
| | Control volunteers & weeds | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | | | | | |
| | Early harvest | | | | | | | | | | | ✓ | | | | |
| | Drainage | | | | | | | | | | | | | | | |
| | Flooding | | | | | | | | | | | | | | | |
| | Hygiene and prevention | | ✓ | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Lime | | | | | | | | | | | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | | | | | |
| | Primary cultivations (crop residue burial) | ✓ | ✓ | | ✓ | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Secondary cultivations (drilling method) | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Seed rate (incl. variable seed rate) | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Seed and young plant testing | | | ✓ | | | | | | | | | | | | |
| | Seedbed quality | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Sowing or planting date | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| | Stubble management | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ |
| | Trap crops | | | | | | | | | | | | | | | |
| | Undersowing & Companion cropping | | | | | | | | | | | | | | | |
| | Use of cover crops | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Phytosanitary legislation | | | | | | | | | | | | | | | |
| | Substrate | | | | | | | | | | | | | | | |
| | Pre-plant soil tests | | | | | | | | | | | | | | | |
| | soil organic amendments | | | | | | | | | | | | | | | |
| | Variety choice | | ✓ | ✓ | | | | | | | | | | | | |
| | Variety mixtures | | | | | | | | | | | | | | | |
| **n-Crop (includes propagation** | Bioprotectants Macrobiological | | | | ✓ | ✓ | | | | | | | ✓ | ✓ | | |
| | Bioprotectants Botanical | | | | | | | | | | | | | | | |
| | Bioprotectants Semiochemical | | | | | | | | | | | | | | | |
| | Biostimulants & elicitors | | | | | | | | | | | | | | | |
| | Decision support, incl. monitoring | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | | |
| | Defoliation (incl. mowing and grazing) | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Environmental control | | | | | | | | | | | | | | | |
| | Hand weeding/roguing | | | | | | ✓ | | | | | | | | ✓ | |
| | Hygiene | | ✓ | | | | | | | | | | | | | |
| | Intercropping | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Mechanical weeding | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Microbial bioprotectants | ✓ | | | ✓ | | | | | | ✓ | | | ✓ | | |
| | Nutrient management | ✓ | ✓ | | | | | | ✓ | ✓ | | | | | | |
| | Organic amendments | | | | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | | | | | | | | | | | |
| | Physical mulches | | | | | | | | | | | | | | | |
| | Precision irrigation | | | | | | | | | | | | | | | |
| | Removal of alternative hosts | | | | | | | | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | | | | | |
| | Test & treat irrigation water | | | | | | | | | | | | | | | |
| | Thermal weed control | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |
| | Undersowing companion crops | | | | | | ✓ | ✓ | | | | | | | ✓ | ✓ |

 

Table 6. Top fruit: Apples and Pears. IPM strategies for the control of the major pests, weeds and diseases.

| | | Apple | | | | | | | | | | | Pears | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diseases | | | | Pests | | | Weeds | | | | Diseases | | Pests | | Weeds | | | |
| **Point of use** | **Non- chemical control strategy** | **Apple scab** | **Canker** | **powdery mildew** | **replant disease** | **Aphids** | **fruit tree spider mite** | **lepidopterous caterpillars** | **Perennial grasses** | **Perennial broad-leaved various** | **Annual grasses various** | **Annual broad-leaved various** | **Scab** | **canker** | **Pear sucker** | **lepidopterous caterpillars** | **Perennial grasses** | **Perennial broad-leaved various** | **Annual grasses various** | **Annual broad-leaved various** |
| **Crop planning** | Field history, rotation & break crops | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | | | | |
| | Select low-risk locations | | ✓ | | ✓ | | | | | | | | | ✓ | | | | | | |
| | Spatial separation | | | | | | | ✓ | | | | | | | | ✓ | | | | |
| **Pre-crop** | Drainage | | | | ✓ | | | | | | | | | | | | | | | |
| | Hygiene and prevention | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Undersowing & Companion cropping | | | | | ✓ | ✓ | | | | | | | | | | | | | |
| | Use of cover crops | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | Variety choice | ✓ | ✓ | ✓ | | ✓ | | | | | | | ✓ | ✓ | ✓ | | | | | |
| **In-Crop (includes propagation)** | Bioprotectants Macrobiological | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | | | | |
| | Bioprotectants Botanical | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| | Bioprotectants Microbial | | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | | ✓ | | | | |
| | Bioprotectants Semiochemical | | ✓ | ✓ | | | | ✓ | | | | | | ✓ | | ✓ | | | | |
| | Biostimulants & elicitors | | ✓ | ✓ | | | | | | | | | ✓ | ✓ | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | | | | | ✓ | | | | | | | ✓ | ✓ | | | | |
| | Defoliation (incl. pruning, mowing, grazing) | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| | Hand weeding/roguing | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | Hygiene | | | | | | | | | | | | ✓ | | | | | | | |
| | Mechanical weeding | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | Nutrient management | ✓ | ✓ | | | ✓ | | | | | | | ✓ | | ✓ | | | | | |
| | Organic amendments | | | | ✓ | | | | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | ✓ | | ✓ | | | | | | | ✓ | ✓ | | | | |
| | Physical mulches | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | Thermal weed control | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | Pruning/canopy management | ✓ | ✓ | ✓ | | ✓ | | ✓ | | | | | ✓ | ✓ | | ✓ | | | | |
| | Forecasting | ✓ | | ✓ | | | | | | | | | ✓ | | | | | | | |
| | UV light | | | ✓ | | | | | | | | | | | | | | | | |

 

Table 7. Vegetable crops: Carrot and Onion. IPM strategies for the control of the major pests, weeds, and diseases.

| | | Carrot | | | | | | | | | | | Onion | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diseases | | | Pests | | | Weeds | | | | | Diseases | | | Pests | | | Weeds | | | | |
| **Point of use** | **Non- chemical control strategy (in alphabetical order)** | **Alternaria leaf blight ( *Alternaria dauci* )** | **Cavity spot (*Pythium violae* & *Pythium sulcatum*)** | **Powdery mildew ( *Erysiphe heraclei*)** | **carrot fly** | **aphids** | **Free living nematodes** | **Annual grasses** | **BLW - fibrous root** | **BLW - tap root** | **Perenial grasses** | **All weeds (Pre-emergence)** | **Downy mildew ( *Peronospora destructor*)** | **Fusarium basal rot (*Fusarium oxysporum* f.sp. *cepae*)** | **White rot ( *Stromatinia cepivora*)** | **Thrips** | **Bean seed fly** | **Stem nematode** | **Annual grasses** | **BLW - fibrous root** | **BLW - tap root** | **Perenial grasses** | **All weeds (Pre-emergence)** |
| | Fallow | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Field history, rotation & break crops | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Crop planning** | Select low-risk locations | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Growing in substrate not soil | | ✓ | | | | | | | | | | | | | | | | | | | | |
| | Spatial separation | | | | ✓ | | | | | | | | ✓ | | | | | | | | | | |
| | Alternative seed treatments | ✓ | | | | | | | | | | | | | | | | | | | | | |
| | Biofumigation | | | | | | | | | | | | | | | | | | | | | | |
| | Control volunteers & weeds | | | | | ✓ | | | | | | | | | | | | ✓ | | | | | |
| | Drainage | | | | | | | | | | | | | | | | | | | | | | |
| | Early harvest | | ✓ | | ✓ | | | | | | | | | | | | | | | | | | |
| | Flooding | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Hygiene and prevention | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Lime | | | | | | | | | | | | | | | | | | | | | | |
| | Phytosanitary legislation | | | | | | | | | | | | | | | | | | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | | | | | | | | | | | | |
| | Pre-plant soil tests | | ✓ | | | | ✓ | | | | | | | | | | | ✓ | | | | | |
| | Primary cultivations (crop residue burial) | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Pre-cropping** | Secondary cultivations (drilling method) | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Seed and young plant testing | ✓ | | | | | | | | | | | | ✓ | | | | | | | | | |
| | Seed rate (incl. variable seed rate) | | | | | | | | | | | | | | | | | | | | | | |
| | Seedbed quality | | | | | | | ✓ | ✓ | ✓ | | ✓ | | | | | | | ✓ | ✓ | ✓ | | ✓ |
| | soil organic amendments | | | | | | | | | | | | | | | | | | | | | | |
| | Sowing or planting date | | | | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | | ✓ | | ✓ | | | | | | ✓ |
| | Stubble management | | | | | | | | | | | | | | | | | | | | | | |
| | Substrate | | | | | | | | | | | | | | | | | | | | | | |
| | Trap crops | | | | | | | | | | | | | | | | | | | | | | |
| | Undersowing & Companion cropping | | | | | | | | | | | | | | | | | | | | | | |
| | Use of cover crops | | | | | | ✓ | | | | | ✓ | | | | | | | | | | | ✓ |
| | Variety choice | ✓ | ✓ | ✓ | ✓ | | | | | | | | ✓ | | | ✓ | | | | | | | |
| | Variety mixtures | | | | | | | | | | | | | | | | | | | | | | |
| | Bioprotectants invertebrate biocontrols | | | | | | | | | | | | | | | | | | | | | | |
| | Bioprotectants natural substances | | | | | | ✓ | | | | | ✓ | | | | | | ✓ | | | | | ✓ |
| | Bioprotectants Microbial | | | ✓ | | | ✓ | | | | | | | | | | | | | | | | |
| | Bioprotectants Semiochemical | | | | | | | | | | | | | | | | | | | | | | |
| | Biostimulants & elicitors & physically acting products | | | | | | | | | | | | ✓ | | | | | | | | | | |
| | Commodity substances/salts | | | ✓ | | | | | | | | | | | | | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | | ✓ | ✓ | | | | | | |
| | Defoliation (incl. mowing and grazing) | | | | | | | | | | | | | | | | | | | | | | |
| | Environmental control | | | | | | | | | | | | | | | | | | | | | | |
| | Hand weeding/roguing | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Hygiene | ✓ | ✓ | | ✓ | | | | | | | | | | | | | | | | | | |
| | In-field non-cropped areas | | | | ✓ | | | | | | | | | | | | | | | | | | |
| | Intercropping | | | | | | | | | | | | | | | ✓ | | | | | | | |
| **In-Crop (includes propagation)** | Mechanical weeding | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Nutrient management | | | ✓ | | | | | | | | | ✓ | | | | | | | | | | |
| | Organic amendments | | | | | | ✓ | | | | | | | | ✓ | | | | | | | | |
| | Physical exclusion of pests | | | | ✓ | | | | | | | | | | | | | | | | | | |
| | Physical mulches | | | | | | | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Precision irrigation | | | | | | | | | | | | | | | ✓ | | | | | | | |
| | Removal of alternative hosts | | | | | | | | | | | | | | | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | | | | | | | | | | | | |
| | Test & treat irrigation water | | | | | | | | | | | | | | | | | | | | | | |
| | Thermal weed control | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Undersowing/ companion crops | | | | ✓ | | | | | | | | | | | | | | | | | | |

 

Table 8. Vegetable crops: Leafy brassicas and root brassicas. IPM strategies for the control of the major pests, weeds, and diseases.

| | | Leafy brassicas | | | | | | | | | | | | | Root brassicas | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diseases | | | | | Pests | | | Weeds | | | | | Diseases | | | Pests | | | Weeds | | | | |
| **Point of use** | **Non- chemical control strategy (in alphabetical order)** | **Dark leaf spot (*Alternaria brassicae* & *Alternaria brassicicola*)** | **Downy mildew (*Hyaloperonospora brassicae*)** | **Light leaf spot (*Pyrenopeziza brassicae*)** | **Ringspot (*Mycosphaerella brassicicola*)** | **Xanthomonas (*Xanthomonas campestris pv.* campestris)** | **Cabbage root fly** | **Aphids** | **Caterpillars** | **Annual grasses** | **BLW - fibrous root** | **BLW - tap root** | **Perenial grasses** | **All weeds (Pre-emergence)** | **Club root (*Plasmodiophora brassicae*)** | **Phoma leaf spot or canker (*Phoma lingham*)** | **Scab (*Streptomyces spp.*)** | **Cabbage root fly** | **Aphids** | **Caterpillars** | **Annual grasses** | **BLW - fibrous root** | **BLW - tap root** | **Perenial grasses** | **All weeds (Pre-emergence)** |
| **Crop planning** | Fallow | ✓ | | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Field history, rotation & break crops | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Select low-risk locations | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Growing in substrate not soil | | | | | | | | | | | | | | ✓ | | | | | | | | | | |
| | Spatial separation | ✓ | | ✓ | ✓ | | | | | | | | | | | ✓ | | | | | | | | | |
| **Pre-cropping** | Alternative seed treatments | ✓ | | | | ✓ | | | | | | | | | | ✓ | | | | | | | | | |
| | Biofumigation | | | | | | | | | | | | | | | | | | | | | | | | |
| | Control volunteers & weeds | ✓ | | | | | ✓ | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | |
| | Drainage | | | | | | | | | | | | | | | | | | | | | | | | |
| | Early harvest | | | | | | | | | | | | | | | | | | | | | | | | |
| | Flooding | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Hygiene and prevention | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Lime | | | | | | | | | | | | | | ✓ | | | | | | | | | | |
| | Phytosanitary legislation | | | | | | | | | | | | | | | | | | | | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | | | | | | | | | | | | | | |
| | Pre-plant soil tests | | | | | | | | | | | | | | ✓ | | | | | | | | | | |
| | Primary cultivations (crop residue burial) | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Secondary cultivations (drilling method) | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Seed and young plant testing | ✓ | | | | ✓ | | | | | | | | | | ✓ | | | | | | | | | |
| | Seed rate (incl. variable seed rate) | | | | | | | | | | | | | | | | | | | | | | | | |
| | Seedbed quality | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | | | | | | | ✓ | ✓ | ✓ | | ✓ |
| | soil organic amendments | | | | | | | | | | | | | | | | | | | | | | | | |
| | Sowing or planting date | | ✓ | | | | ✓ | | | | | | | ✓ | ✓ | | | ✓ | | | | | | | ✓ |
| | Stubble management | | | | | | | | | | | | | | | | | | | | | | | | |
| | Substrate | | | | | | | | | | | | | | | | | | | | | | | | |
| | Trap crops | | | | | | | | | | | | | | | | | | | | | | | | |
| | Undersowing & Companion cropping | | | | | | ✓ | | | ✓ | ✓ | ✓ | | | | | | | | | ✓ | ✓ | ✓ | | |
| | Use of cover crops | | | | | | | | | | | | | ✓ | | | | | | | | | | | ✓ |
| | Variety choice | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| | Variety mixtures | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| **In-Crop (includes propagation)** | Bioprotectants invertebrate biocontrols | | | | | | ✓ | | | | | | | | | | | | | | | | | | |
| | Bioprotectants natural substances | | | | | | | | | | | | | ✓ | | | | | | | | | | | ✓ |
| | Bioprotectants Microbial | | | | | | ✓ | | | | | | | | | | | | | | | | | | |
| | Bioprotectants Semiochemical | | | | | | | | | | | | | | | | | | | | | | | | |
| | Biostimulants & elicitors & physically acting products | | | | | | | | | | | | | | | | | | | | | | | | |
| | Commodity substances/salts | | | | | | | | | | | | | | | | | | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | | | | ✓ | ✓ | | ✓ | | | | | | | |
| | Defoliation (incl. mowing and grazing) | | | | | | | | | | | | | | | | | | | | | | | | |
| | Environmental control | | ✓ | | | | | | | | | | | | | | | | | | | | | | |
| | Hand weeding/roguing | | | | | | | | | ✓ | ✓ | ✓ | ✓ | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Hygiene | | | | | | | | | | | | | | | | | | | | | | | | |
| | In-field non-cropped areas | | | | | | | | | | | | | | | | | | | | | | | | |
| | Intercropping | | | | | | | | | | | | | | | | | | | | | | | | |
| | Mechanical weeding | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Nutrient management | | ✓ | | | | | | | | | | | | ✓ | | | | | | | | | | |
| | Organic amendments | | | | | | | | | | | | | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | | ✓ | | | | | | | | | | | ✓ | | | | | | | |
| | Physical mulches | | | | | | | | | | | | | | | | | | | | | | | | |
| | Precision irrigation | | | | | | | | | | | | | | | | | | | | | | | | |
| | Removal of alternative hosts | | | | | | | | | | | | | | | | | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | | | | | | | | | | | | | | |
| | Test & treat irrigation water | | | | | | | | | | | | | | | | | | | | | | | | |
| | Thermal weed control | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Undersowing/ companion crops | | | | | | ✓ | | | | | | | | | | | | | | | | | | |

 

Table 9. vegetable crops: Endive and lettuce (outdoor). IPM strategies for the control of the major pests, weeds, and diseases.

| | | Endive & lettuce (outdoor) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diseases | | | | Pests | | | Weeds | | | | |
| Point of use | Non- chemical control strategy (in alphabetical order) | Downy mildew ( *Bremia lactucae*) | Grey mould (*Botrytis cinerea*) | Rhizoctonia bottom rot (*Rhizoctonia solani*) | Sclerotinia ( *Sclerotinia sclerotiorum*) | Aphids | Slugs | Caterpillars | Annual grasses | BLW - fibrous root | BLW - tap root | Perenial grasses | All weeds (Pre-emergence) |
| Crop planning | Fallow | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Field history, rotation & break crops | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Select low-risk locations | ✓ | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Growing in substrate not soil | | | | ✓ | | | | | | | | |
| | Spatial separation | ✓ | ✓ | ✓ | | | | | | | | | |
| Pre-cropping | Alternative seed treatments | | | | | | | | | | | | |
| | Biofumigation | | | | | | | | | | | | |
| | Control volunteers & weeds | | | | ✓ | | | | | | | | |
| | Drainage | | | | | | | | | | | | |
| | Early harvest | | | | | | | | | | | | |
| | Flooding | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Hygiene and prevention | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Lime | | | | | | | | | | | | |
| | Phytosanitary legislation | | | | | | | | | | | | |
| | Pre-cropping nutrition | | | | | | | | | | | | |
| | Pre-plant soil tests | | | | | | | | | | | | |
| | Primary cultivations (crop residue burial) | ✓ | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Secondary cultivations (drilling method) | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Seed and young plant testing | | | | | | | | | | | | |
| | Seed rate (incl. variable seed rate) | | | | | | | | | | | | |
| | Seedbed quality | | | | | | | | ✓ | ✓ | ✓ | | ✓ |
| | soil organic amendments | | | | | | | | | | | | |
| | Sowing or planting date | ✓ | ✓ | | ✓ | | | | | | | | ✓ |
| | Stubble management | | | | | | | | | | | | |
| | Substrate | | | | | | | | | | | | |
| | Trap crops | | | | | | | | | | | | |
| | Undersowing & Companion cropping | | | | | | | | | | | | |
| | Use of cover crops | | | | | | | | | | | | ✓ |
| | Variety choice | ✓ | | | | | | | | | | | |
| | Variety mixtures | | | | | | | | | | | | |
| In-Crop (includes propagation) | Bioprotectants invertebrate biocontrols | | | | | | | | | | | | |
| | Bioprotectants natural substances | | | | | | | | | | | | ✓ |
| | Bioprotectants Microbial | | ✓ | | ✓ | | | | | | | | |
| | Bioprotectants Semiochemical | | | | | | | | | | | | |
| | Biostimulants & elicitors & physically acting products | ✓ | | | | | | | | | | | |
| | Commodity substances/salts | | | | | | | | | | | | |
| | Decision support, incl. monitoring | ✓ | ✓ | | ✓ | | | | | | | | |
| | Defoliation (incl. mowing and grazing) | | | | | | | | | | | | |
| | Environmental control | ✓ | ✓ | | | | | | | | | | |
| | Hand weeding/roguing | | | | | | | | ✓ | ✓ | ✓ | ✓ | |
| | Hygiene | | | | | | | | | | | | |
| | In-field non-cropped areas | | | | | | | | | | | | |
| | Intercropping | | | | | | | | | | | | |
| | Mechanical weeding | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Nutrient management | | | | | | | | | | | | |
| | Organic amendments | | | | | | | | | | | | |
| | Physical exclusion of pests | | | | | | | | | | | | |
| | Physical mulches | | | | | | | | | | | | |
| | Precision irrigation | | | | | | | | | | | | |
| | Removal of alternative hosts | | | | | | | | | | | | |
| | Rolling soil post-planting | | | | | | | | | | | | |
| | Test & treat irrigation water | | | | | | | | | | | | |
| | Thermal weed control | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Undersowing/ companion crops | | | | | | | | | | | | |

 

## Soft fruit

This section reviews the non-chemical control strategies that may have a role in controlling the key diseases, pests and weeds in soft fruit, focusing on strawberries, raspberries and grapevines. Reference should also be made to the 2012 review carried out for Defra on the efficacy of non-chemical control methods in agriculture and horticulture [D109].

### Current status

According to the current National Statistics report for soft fruit strawberries, raspberries and grapevines accounted for 33%, 21% and 12% respectively of total area of soft fruit grown in the UK in 2020 [P120]. 95% of all the strawberry crops by area were covered by tunnels for at least part of their growing season, with 23% grown in the soil not in substrate. All grapevines were grown in the soil, with <1% in tunnels. 88% of the raspberry crop was grown under the protection of polythene clad tunnels for some, but in the majority of cases not all, of their growing season, with 69% in substrate not in the soil [P120]. Strawberries, grapevines and raspberries accounted for 56%, 21%, and 6% respectively, of the total pesticide and microbiological treated area in 2020 [P120]. Fungicides accounted for 52% of the total pesticide-treated area of soft fruit grown in the UK in 2020. Biological control agents (defined as "usually living parasites or predators" – biopesticides being grouped within fungicides or insecticides in recent Defra reports) were used on 19% of the pesticide-treated area of soft fruit, insecticides on 12% and acaricides on 1% [P120].

The most used insecticides in soft fruit in 2020 were pyrethroids, neonicotinoids and Spinosad, accounting for 27%, 24% and 20% respectively of insecticide use [P120]. *Neoseiulus cucumeris*, *Phytoseiulus persimilis* and *Orius* spp. were the most used biological control agents in 2020, accounting for 35%, 27% and 14% of use respectively[P120]. When citing reasons for insecticide use in grapevines, growers attributed 33% to spotted wing drosophila, 23% to light brown apple moth and 14% to other moth species [P120].

The most extensively used formulations of fungicides in the 2019/2020 strawberry cropping year were (in order of area treated) fenhexamid, fluopyram / trifloxystrobin, *Bacillus amyloliquefaciens* strain QST 713, myclobutanil and difenoconazole / fluxapyroxad. In raspberry, the most common were fenhexamid, boscalid / pyraclostrobin, cyprodinil / fludioxonil, dimethomorph (to the roots) and tebuconazole [P120]. In strawberries, powdery mildew control was given as the dominant reason for fungicide use (47%), botrytis (grey mould) 34%, and botrytis / powdery mildew as 18% of uses. Scheduled prophylactic sprays were used against both powdery mildew and botrytis fruit rot of strawberry [D486 D456].The overwhelming reason given for fungicide use in raspberries (72%), was for botrytis control, 15% for cane blight, 6% for phytophthora and 3% against rust [P120]. Botrytis is the major cause of post-harvest fruit rotting in raspberry, but canes are also infected which can result in shoot death [D472] and management has been through scheduled applications during flowering and post-harvest [D359]. Scheduled prophylactic sprays are used against both powdery mildew and botrytis fruit rot of strawberry [D486]. The most commonly used formulations of fungicides on grapevines in 2019/20 were mancozeb, copper oxychloride, ametoctradin / dimethomorph, proquinazid and benthiavalicarb / mancozeb. The most used formulations on grapevine differed from those on strawberry and raspberry (where fenhexamid has high area usage against botrytis) because in grapevines downy mildew is a major problem, accounting for 37% of fungicide usage in the 2019/20 crop year, with powdery mildew 24%, botrytis 17% and 6% for downy mildew / powdery mildew [P120].

## Soft fruit disease control

### Crop planning

*Field history, rotation and break crops and growing out of the soil*

Rotation of crops is fundamental to the control of pests and diseases, while also helping to maintain soil organic matter and soil structure and assist with crop nutrition, however foliar, stem and root diseases can carry over on crop residues between seasons [D102]. In soft fruit the same plants have traditionally been grown in the same position in the soil for at least a couple of years, often twice as long for cane fruit if the stools continue to be productive, and even longer for vines.

Both *Phytophthora* spp. and *Verticillium* spp. are soil-borne pathogens that invade roots and cause wilting that can lead to death of soft fruit. Both are able to survive many years in soil. Although some growers rent fields from arable or vegetable farmers to increase the years before re-planting fruit crops, there are often insufficient fields of a suitable soil type local to the fruit packing area to avoid re-using the same field. Another consideration is that most soft fruit crops are now covered by polythene tunnels during fruiting (with the frameworks left in place in winter) and local planning restrictions can limit where these can be erected. Phytophthora infection has become so common in raspberries in the UK, that sites that have grown raspberries before should be considered to have a high risk of containing the pathogen. Advice is to plant on virgin sites or to use soil-less substrates rather than to use previously cropped soils [D363]. There has been a significant move in the UK away from soil growing towards growing in substrate (peat or coir) in containers.

The *Phytophthora* species of major concern to cane fruit, *Phytophthora rubi,* is acknowledged as being highly pathogenic to raspberry [D363], although several other species have been found in rotted roots from UK plantations and may gain in importance [D368]. The species attacking strawberry are *Phytophthora cactorum,* causing crown rot, and *Phytophthora fragariae,* causing red root rot. Species such as *Phytophthora cinnamomi* and *Phytophthora cryptogea* are more generalist and are known to cause root and crown rots in the grapevines of many countries [D381]. *P. cactorum* and *Phytophthora syringae* are the most common causes of crown, collar and root rot of apple trees [D370]. Many more *Phytophthora* spp. have been listed worldwide from various hosts with the availability of molecular techniques rather than relying on morphological identification [D382 D383]. The main chance of infection of new crops from *Phytophthora* spp. arises if the same crop type is re-planted in the same area of the field. However, wet soil conditions increase the chance of *Phytophthora* spp. multiplication and so fields with poor soil conditions causing root rot to one host will also be conducive to the pathogen affecting another.

There is much ongoing work internationally on the management of verticillium wilt, with a regularly updated review and extensive database of research papers maintained by the Centre of Agriculture and Bioscience International (CABI) [D365]. *Verticillium dahliae* has a very wide host range including strawberry, raspberry, blackberry, blackcurrant, gooseberry, blueberry, cherry, plum, lettuce, sugar beet, oilseed rape, cabbage, pea, linseed, hops and potato. When choosing a field to plant it should not have had any of these hosts[D362]. It can also colonise dicotyledonous weeds such as *Capsella bursa-pastoris*, *Cirsium arvense*, *Geranium dissectum* and *Taraxacum officinale* [D365]. The pathogen can survive 14 years in soil as microsclerotia, which are stimulated to germinate in response to root exudates. As the wide host range of *V. dahliae* limits the chance of finding a pathogen-free soil for planting, the soil fumigants methyl bromide, chloropicrin, dazomet or metam sodium were used at bed-forming to gain an acceptable level of control [D362], but their use in no longer permitted in the UK. Although there are many reports of the value of crop rotation in controlling verticillium wilt, there is considerable disagreement as to its overall effectiveness. The inclusion of green manures (such as Sudan grass) in a rotation has shown some effectiveness in verticillium management, however, results in various locations and cropping systems have been highly variable [D365].

Many soft fruit crops are now grown in substrate on polythene covered raised soil beds, in pots or troughs or occasionally bags for raspberries. Grow-bags or troughs are more common for strawberries. These strawberries are often placed on table-tops so reducing the chance of infection from the soil and most importantly improving the presentation of fruit to pickers during harvest thus reducing the time and hence cost of picking. However, it is not unusual for diseases to be carried on the propagation material because most pathogens have a latent/symptomless period following infection of the tissue before the leaves, stems or roots show symptoms of the attack. Symptoms can also easily be missed within large batches of plants. Early stages of root infection of raspberries by phytophthora root will not be visible in the growing plants and so the pathogen can then contaminate clean land [D363]. Diseases such as crown rot may only initially be visible on destructive assessment, opening up the crown of the strawberry plant [D361].

*Selection of a low-risk location*

The selection of lower risk locations can be an effective part of an IPM disease control strategy. Consideration of location can be made based on numerous factors, including location in the country, field topography, altitude, aspect and soil type. Poor growing conditions such as difficult rooting or low nutrient availability can result in slower or sparser crop establishment and subsequent less-vigorous growth with such plants tending to be more susceptible to the disease damage.

Soil testing for the presence of *Verticillium dahliae*, the cause of wilt, should be carried out before selecting a field for planting. This is usually carried out at the same time (taking from the same soil sample) as testing for the presence of free-living nematodes that can damage roots. This has become even more important since the loss, due to regulations, of various methods of chemical soil sterilisation / fumigation which until relatively recently were not uncommonly used by fruit growers.

The Harris test has traditionally been used by growers to alert them to pre-cropping levels of verticillium in the soil that are likely to cause crop loss. For strawberry in the UK, guidance was available on which varieties could tolerate particular ranges of *V. dahliae* microsclerotia counts in the soil, allowing growers to avoid planting susceptible varieties [D362]. However, the Harris test only detects *V. dahliae*, not *Verticillium albo-atrum*, as the latter species does not produce microsclerotia and so cannot be sieved out of the soil. Both *Verticillium* species can cause wilt. It is now possible to use molecular diagnostics (PCR), for detection of both verticillium species, and also *P. rubi* and certain other pathogens, using the same soil sample. In 2015, Real-time, or Quantitative, PCR assays for testing soils for *V. dahliae* developed in AHDB Project SF 97 [D384], provided results within a few days, with detection of *V. dahliae* down to levels correlating with 0.5 microsclerotia / g soil. Subsequently, during AHDB Project SF 158 [D368] the *V. dahliae* PCR assay was assessed for sensitivity using DNA extracts from pure cultures of *V. dahliae* and detected down to 0.04 pg/ul of extract. However, although *V.*

 

*dahliae* was detected in almost half of the raspberry plants showing symptoms collected from plantations, very few detections were made from the soil beneath these plants.

Recent work in the AHDB Soil Biology Soil Health Projects 5 and 7 [D349] to refine the verticillium assay has struggled to be able to detect *V. dahliae* in soil from around raspberry roots by qPCR although pre-planting high levels of 41 viable microsclerotia per gramme of soil had been extracted and grown by conventional Harris testing of the soil before planting. Molecular quantification was however successful using recently artificially inoculated soil. It was concluded that further optimisation of DNA extraction and purification methods would be needed before qPCR can be used for reliable quantification of plant pathogens across a range of naturally infested soils. Both yield and quality of extracted DNA is known to vary with the chemical and physical properties of different soils [D377] as well as the extraction method used [D376]. In addition, the PCR reaction can be inhibited to different extents by common soil components such as humic acids and phenolics and changes in magnesium and calcium levels [D378].

Since the withdrawal of authorisation of use of soil sterilants, the ability to replace the Harris test with a quicker molecular test for a wide range of soil-borne pathogens would allow growers to be aware of their presence and give time to use cultural control measures such as vegetable wastes [D380] or anaerobic soil disinfestation [D227] before planting the crop. However, knowledge needs to be gained on what concentrations of a particular pathogen (thresholds) can be tolerated by particular crops and varieties, especially as non-chemical control measures may be unlikely to reduce pathogen populations to the extent achieved by most chemical plant protection products approved for use against them. Procedures which determine whether the molecular material extracted for soil is actually viable are still being refined.

If strawberries or raspberries are to be soil grown then field soils should be chosen which are free-draining and devoid of low-lying areas, field drainage should be installed and ditches ensured to be free-flowing to further reduce the risk of waterlogging. This will reduce the risk of zoospores of strawberry crown rot (*P. cactorum*) or phytophthora root rot (*P. rubi*) swimming to invade the roots of their respective hosts. Growers should beware of planting in a field to which drainage water may run after heavy rainfall or excessive irrigation as any infection that becomes established in the drained field can be spread to the “clean” site [D361] [D363]. Field sites with heavy clay soil should be avoided for raspberries, but sub-soiling during periods when the soils are dry will provide new channels in the soil profile to further improve drainage [D363].

 

Grapevines, unlike some soft fruit crops, are only grown directly in the soil and as they are kept growing for many years longer than soft fruit it is important that the chosen planting location does not have areas present in which other crops have failed to thrive, perhaps determining this by gaining access to digital maps or satellite images of the field over several years. Good internal soil drainage is needed for a vineyard site, with effective drains that remove excess water. A minimum rooting depth of 0.75m is required for grapevines [D464 D466].

Grapevines need a site open to good airflow and not positioned at the lower part of a slope which could collect either cold air, be a frost pocket or hold dampness. Poor airflow resulting in humid conditions can favour the development of botrytis, downy and powdery mildews and the planting of inter-row cover crops to stabilise moisture, as well as to reduce soil run-off, could be planned [D463 D464 D466 D467 D468].

Plans should be made to plant grapevines, if possible, with rows running North-South as this allows more-equal amounts of sunlight exposure for vine foliage and will lead to even growth and better resistance to diseases such as botrytis and downy and powdery mildews [D463 D464 D466].

As for soft fruit and other field-grown crops, grapevines benefit from pre-planting soil tests to gain information on pH, major and minor nutrients, organic matter and cation exchange capacity as this gives scope to create better crop growth, health and disease resistance. Generally, a ratio of 1:1 row spacing to canopy height ensures that between-row shading is minimised and allows good air movement to help disease suppression [D464 D469]. Observations suggest that cane fruit plants which are grown in soils with a neutral pH value appear to be less susceptible to phytophthora infection [D363].

*Spatial separation*

The proximity of a new crop to one that is already infected can significantly increase the risk of infection where the pathogen is wind dispersed. Rust and powdery mildew spores are abundantly produced in dry conditions and can be blown long distances in the wind. Sitting new crops out of the prevailing wind direction from old crops may be possible if e.g., proximity to the packing area limits site options.

Most UK strawberry production has moved away from double cropping and is an annual system. There is also a trend for the use of cold-stored module grown plants that fruit in the year of planting and may not be kept for a second year. The practice of single cropping gives a more-predictably timed and potentially more-substantial first year harvest, and also removes the risk of overwintering plants and debris serving as a sources of inoculum for the second year crop.

 

Biennial cropping in raspberries significantly reduces the spread from old to new cane of pests and diseases. Most commonly instead in summer fruiting crops the new cane produced after winter (primocane) is grown up between the canes produced the previous year that will be fruiting (floricanes). Many pests and diseases have become increasingly difficult to contain with a diminishing number of crop protection products remaining available and some having a long harvest interval that limits their period of use. The benefit of separating the two phases of growth in raspberry is in breaking the life-cycles of cane blight (*Paraconiothyrium fuckelii*, previously known as *Leptosphaeria coniothyrium*), raspberry cane midge (*Resseliella theobaldi*) and associated midge blight, and also of yellow rust (*Phragmidium rubi-idaei*) [D369].

UK raspberry growers have seen higher levels of infection of cane blight in recent years [D368]. Cane blight is being seen in double cropping primocane as well as summer fruiting raspberries. Cane blight is a relatively weak pathogen, so often requires damage to the cane in order to enter the plant. Damage can follow poor control of raspberry cane midge (which has been exacerbated by the loss of chlorpyrifos), frost, strimming or poor application of desiccant to control unwanted primocane. The current restrictions upon use and imminent loss of Folicur (tebuconazole), the sole product for control of cane blight has become Signum (pyraclostrobin + boscalid), but at a lower permitted dose rate than that which gave efficacy in the most recent UK trials in 2006 [D368 D432].

In biennial cropping the canes are allowed to fruit every other year and the primocane in the “off-year” is less likely to be damaged by operations, so it is less likely for the pathogen to gain entry, and there are no old canes which are the pathogen source [D368]. Information was gathered for the AHDB [D368] on the relative costs and benefits of raspberry production systems including traditional, annual and biennial cropping of a summer fruiting variety and traditional annual cropping of a primocane (long-cane) raspberry (long-canes fruiting around 90 days after planting). The differences between the systems in each of the three years was calculated comparing the yield per hectare for each, the cane management costs for each and the gross margin for each. In conclusion, the yields and gross margins following the first year of biennial cropping were envisaged to be poorer than in the second and third year of traditional systems, in the absence of losses to pests and diseases. However, as the availability of pesticide products declines further, raspberry growers may find they have no alternative but to turn to annual cropping of long-canes or biennial cropping of summer fruiting varieties to achieve satisfactory pest and disease control [D368].

## Pre-cropping

 

*Hygiene and prevention*

Hygiene to obviate or reduce pathogen inoculum carry-over is the cornerstone of good plant protection practice, especially for pathogens with either limited dispersal or a single disease cycle in a growing season. Hygiene measures are important in both propagation facilities and in the locations in which fruiting crops are due to be planted in either glasshouse, polytunnel or the field. Most pathogens (bacteria, fungi, oomycetes and viruses) can be spread from diseased leaves, stems or roots left in the area from previous crops by wind, water splash, insects or contact. Pathogens often have both short (hours or a few days) and longer (years) surviving types of propagules and treatments need to encompass control of both.

Maintaining good farm hygiene is the first defence against the introduction of soil-borne diseases such as *Verticillium* spp., *Fusarium* spp., *Pythium* spp. and *Phytophthora* spp. into clean land. This is particularly important for soil grown fruit but is still very important for substrate grown plants as soil can be splashed up around containers or grow-bags near the ground. Machinery used in infested fields should be power-washed before use in uninfected fields. Soil should at least be knocked off from boots and tools, but ideally disinfectant boot dip and hand sanitisation stations should be located at the entrances of all fields and visitors from other farms should be given disposable boot covers before walking fields. Work should be planned so that movement is from ‘clean’ to ‘dirty’. The cleanest sites e.g., propagation sites should be visited first, followed by substrate grown plants and then soil planted plants. Ideally different teams of people should work in different areas and not move between them to avoid cross contamination. Equipment should be cleaned at the end of the day. If the first signs of disease are evident near the field entrance, then local transfer may have occurred.

Even with pathogens with a broad host range, such as *Botrytis cinerea* grey mould, that can be expected to be carried into proposed crop areas, removal of inoculum on debris before planting can delay epidemic development and prove beneficial. In fields, cultivations and weed control are important to minimise diseases spreading from plant debris to new plantings. Where containers are to be used, covering soil with woven ground-cover or other form of plastic sheeting can stop weed growth and soil splash. Hygiene measures revolve around removal of weeds, sweeping up of debris, disinfection of surfaces and purchase of new, or sterilisation of used, containers and matting [D527 D540 D541]. Extra care is required in propagation areas and should include disinfection of tools and cleaning of hands, to prevent the spread of diseases that may then need to be controlled further down the line – the phrase “start clean stay clean” is often stated.

In propagation areas disinfection of the glasshouse structure, production floors and benches, equipment and tools between crops contributes to control. It is especially important after a severe outbreak of an uncommon disease or an invasive pathogen. Disinfestation or disposal of horticultural fleeces in glasshouse or early-season forced crops in tunnel after use is needed due to risk of pathogen transfer from one crop to the next (e.g., botrytis or powdery mildew).

Routine disinfection of benches or floors has been questioned from time to time, on the hypothesis that beneficial micro-organisms might be present and able to counteract resident pathogen populations, however good control is less certain than from correctly managed disinfection procedures. It is important to ensure that as much debris is removed as possible before disinfecting so that the biocide can get good contact for the required period, and that the correct concentrations are used and replenished. In terms of non-chemical crop protection, if chemical biocides applied to structures or surfaces are considered unacceptable, more attention will need to be given to physical methods and their efficacy (e.g., heat, hot water, UV light). A biocide applied once before crop production can potentially save multiple applications of pesticides during crop production, and equally save cost [D132].

The treatment of water collected from glasshouse roofs or open reservoirs, and any recirculating water is very important if it is to be used in growing plants. Plant pathogens such as *Phytophthora* and *Pythium* species readily contaminate water, arriving in dust, rain or coming into reservoirs from run-off of infected plants. Whole propagation areas can quickly become infested if contaminated water is used. Methods of water treatment include chlorination, hydrogen peroxide, chlorine dioxide, UV light, and biological filtration (such as by slow sand filters or reed beds) [D133]. Where possible, alternatives to overhead sprinkler irrigation, such as to multicell trays of propagation material, should be sought as this can splash spores and create a period of leaf wetness conducive to infection. Sampling and testing of water for plant pathogens should be carried out to ensure the water treatment is working [D528 D217 D538 D539]. The guide for growers produced for the AHDB on water harvesting and recycling in soft fruit gives thorough details of the various methods of decontaminating water, including water collected from plant run-off [D538]. Plant pathogens such as *Phytophthora* and *Pythium* species readily contaminate water, arriving in dust, rain or coming into reservoirs from run-off of infected plants. Known *Phytophthora* spp. in the UK include *P. cinnamomi* of grapevines and raspberries, *P. idaei* and *P. rubi* of raspberries and *P. cactorum* and *P. fragariae* of strawberries [D217]. The level of risk of particular water sources carrying and spreading oomycete stem and root rots to strawberries and other crops have been identified [D217]. Whole propagation areas can quickly become infested if contaminated water is used. Methods of water treatment include chlorination, hydrogen peroxide, chlorine dioxide, UV light, and biological filtration (such as by slow sand filters or reed beds) [D133 D217 D538]. Where possible, alternatives to overhead sprinkler irrigation should be set up as this can splash spores and create a period of leaf wetness conducive to infection.

 

When propagation material is received, if at all possible it should be kept quarantined for up to a fortnight and checked regularly for disease development. Diseases can have a latent / symptomless period in their hosts after infection and their presence can also be masked by sprays applied by some propagators. In the UK, certified soft fruit propagation material is not permitted to be treated with fungicides as this suppresses symptom expression. Information on the various diagnostic techniques, either using laboratory services or at the crop site, is provided within the soft fruit in-crop sub-section below.

*Phytosanitary legislation & clean stock*

It is important to have clean propagation material. Producers of propagation material must comply with requirements that seek to ensure that pathogens and pests are not passed on in material bulked up for growers to plant. Starting with healthy plants and being vigilant in ongoing inspection by staff to stop any disease spread has become even more important where bioprotectants are in use, as there is no curative activity. Further information on procedures used in the production of clean propagation material production, including meristem tip culture and heat treatment, is given within the "in-crop" section on hygiene.

A major concern of the global fruit industry is a group of systemic pathogens for which there are no effective remedies once the plants are infected. These pathogens include viruses, viroids, phytoplasmas and systemic bacteria [D518]. Training of staff and monitoring of the procedures carried out is needed to ensure that standards are maintained so that growers purchasing Certified material are not in receipt of plants with untreatable diseases.

Global movement of strawberry, Rubus, grapevine and other fruit propagation material occurs, and each country has their own systems for testing to try to ensure that only clean plants pass through the stages of multiplication from the initial breeding stock. Diagnostic assessments are used to determine the health status of material entering propagation, including biological indicators and/or laboratory assays based on serology or nucleic acid analysis including next generation sequencing. The latter has been used to identify viruses that would previously have required testing with indicator plants [D518].

Compliance with legislation is important for biosecurity in order to keep invasive alien pests, diseases and weeds from Britain and Ireland. The UK Plant Health Risk Register database (updated monthly) and the UK Plant Health Information Portal database have been set up to keep everyone informed of risks to plant health [D253]. A plant passport system was introduced by the EU whereby material moving between members had to be inspected at source and declared to be free of pests and diseases. Since leaving the EU new regulations have come into force in the UK, with increased inspections by officers of the Animal and Plant Health Agency (APHA) of incoming plants and harvested crop material. Professional operators in

 

Great Britain no longer issue EU plant passports, instead UK plant passports are issued, and are required to move plants within Great Britain, to the Isle of Man or to the Channel Islands. Imports from the EU to Northern Ireland can continue to use an EU plant passport. Propagators must register with APHA and are then authorised to issue plant passports. Imports from the EU to Great Britain need a phytosanitary certificate.

In the UK, the Fruit Propagation Certification Scheme (FPCS) [D306] encourages the production and use of healthy planting stock. It is a requirement for propagators to join the scheme in order to supply certified plants to commercial growers. There are schemes for strawberry (Fragaria) [D303], raspberry and blackberry (Rubus) [D304], blueberries (Vaccinium) [D305], currants (black, red, white), gooseberries and top fruit (Cydonia, Malus, Prunus, Pyrus - complete trees, mother trees and rootstocks). The guide for each crop type is downloadable from the gov.uk website. The Scheme includes commercial growers of micro-propagated material of any of these crops. The FPCS listing does not include vine fruit (*Vitis* spp.), nor are grapes included in the list of species of fruit and nut plants and propagating material including rootstocks within the Marketing of Fruit Plant Material Regulations 2017 [D306]. The schemes define the growing conditions required (e.g., aphid free growing area, isolation distances for field grown material), set standards for pest and disease tolerances and sampling schedules and record keeping requirements. Record keeping is particularly important in the event of a pest or disease outbreak to allow track and trace. There is a grading system for plants representing different levels of hygiene; pre-basic, basic, and certified. Plants that do not meet these requirements but meet simpler standards are designated CAC which is the minimum category for sale of fruit plant material. CAC must be practically free from certain pests and diseases.

For pathogens that are present abroad but not widely established in the UK, such as that causing strawberry blackspot, *Colletotrichum acutatum,* which was first found in in the UK in 1983 on strawberry plants imported from California, it is particularly important that propagation material is officially inspected for Certification, and that those issuing plant passports for other material are aware of what to look for. The fungus can, however, remain unobserved in strawberry plants until fruiting when sunken circular brown spots develop as the fruit ripens [D501].

Grapevine death due to trunk disease, sometimes called Esca disease, is attributed to a group of systematically diverse fungi that are considered to be latent pathogens [D471]. Bench-grafted grapevines from mainland Europe (in particular high-grafted plants) are believed to have been the source of esca in new UK vineyards as, although hedgerows can hold alternate hosts, the absence of nearby established vines (unlike on the Continent) makes local spread to have been unlikely. Care should thus be taken when deciding on a supplier of planting material.

 

Hygiene during grafting is required, however hot-water treated bench grafts (to kill pathogens) can be supplied by some European nurseries. There is also a source of own-rooted plants being produced in the UK thus eliminating the problem of pathogen entry via graft wounds [D521]. There is currently no UK Certification standard for grapevines, but there is a European and Mediterranean Region (EPPO) standard of production that requires pathogen testing of grapevine varieties and rootstocks [D537]. This certification scheme is mainly concerned with viruses (which can be transmitted by nematodes mealy bugs and/or grafting) although the production conditions should also seek to minimize infection from other major pathogens. Testing for pathogens includes the use of grafting onto indicator plants, ELISA (antibody) testing and molecular testing using multiplex RT-PCR.  The scheme provides detailed guidance on the production of pathogen-tested material of grafted grapevine varieties and rootstocks. Plant material produced will be derived from nuclear-stock plants tested to ensure they are free from a listing of 19 viruses and two phytoplasmas (not all of which are worldwide in occurrence) [D537].

*Cultivations*

Where crops are to be grown in the ground then cultivations should aim to provide a soil structure that will allow for deep rooting by crops, providing adequate aeration and drainage so that the plant roots can exploit available nutrients in the full soil profile[D102]. *Phytophthora* spp. cause root rot of cane fruit as spores are spread in water and so rapid drainage of excess water from the plant root zone is of paramount importance [D369 D363]. Before preparation of the area to be planted, a pit should be dug to examine the soil profile and identify any pans or compacted layers. Sub-soiling when conditions are dry is essential to break any such layers, which are likely to impede drainage [D361].

*Control of weeds and alternative hosts*

Dicotyledonous weeds that can host verticillium [D365] and botrytis growing as a saprophyte on necrotic tissue can be completely destroyed during the cultivations necessary for the preparation of ridges or rows for soft fruit and grapevines. However, at least with strawberry, very little spread arises plant to plant with *V. dahliae* (some spread can occur through root contact), but crop hosts coming into contact with weed or previous crop host debris can become infected [D362]. It is thus important to have considered this in selecting the field (see above section). In between the rows the pathways may be sown with grass or other plants to supress host weeds such as fat hen and shepherd's purse and this can reduce the movement of water that can spread *V. dahliae* [D362], but in tunnelled soft fruit crops there will be no rain reaching the pathways when covered during the growing season so they will be dry.

Where cane fruits are to be grown in fields surrounded by hedgerows these often contain brambles (blackberries) that host the same diseases, and as the foliage can be retained for much (and increasingly, with mild winters, all) of the winter they host the overwintering stages of diseases such as yellow rust, botrytis, and cane blight [D310]. As it is not always feasible to avoid such fields, then strimming down the shoots in winter could be considered as part of site hygiene measures.

*Organic amendments*

Soil management before planting should ideally include the return of organic matter, derived from crop residues, straw incorporation, green manures, livestock manures or compost, as this provides a key role in maintaining the biological activity of the soil, providing soil micro-organisms and earthworms with energy to make nutrients available to crop plants maintaining a stable soil structure and for carbon sequestration [D102 D247 D550]. Organic matter can assist in the moisture-holding capacity of the soil as well as providing some nutrients [D245 D246]. Crop pathogens can, however, be introduced with green compost, sewage sludge, manures and anaerobic digestate so they must be adequately pasteurised [D132], and specific standards exist [D374 D375].

Anaerobic soil disinfestation (ASD) involves sealing organic matter, such as green manure, in the topsoil using a plastic film after irrigating, before planting a crop. In the six weeks of covering anaerobic conditions develop rapidly in which toxic fermentation products are formed which are responsible for elimination of fungal and bacterial pathogens as well as parasitic nematodes, insects and weeds. The cost of the work is quite high. The research work has been concentrated in the Netherlands. In strawberries the *V. dahliae* contamination in the soil decreased by between 75% to 100%. In a field with five microsclerotia /g of soil 100% of plants were killed, but between 5 % to 32% in ASD treated fields [D227]. The mechanism behind ASD has been hard to define, as research is needed to clarify the source of the chemicals released in the soil. More recently, Herbie products of defined mixtures of carbon hydrates and proteins to feed the anaerobic microbes have been sold by Thatchtec in the Netherlands and marketed for "soil resetting" [D228]. Work within AHDB Project SF 157 tested a Herbie product at a rate of 11 g / L of soil in 10 L pots. The soil used was collected from a field naturally infested with *V. dahliae.* The pots were watered, resulting in a 14% moisture content, and sealed with at gas tight (TIF) film for eight weeks at a mean 16°C. At termination, whereas the 16 untreated pots (whether or not sealed) had a mean 3.54 microsclerotia / g soil, those with the Herbie 82 had a mean 0.28 microsclerotia / g (with four out of the 16 pots having zero). Strawberries have a low wilt threshold of 0.5 to 1.0 microsclerotia / g of soil [D559], so this level of control might be insufficient except with more tolerant varieties, however, raspberries are much less susceptible to wilting at low infestation levels. It is possible this pre-planting treatment could "reset" soil to change a fungal population that might otherwise make grapevines at risk of esca stem and root die-back, however Herbie product and TIF costs may make this uneconomic across whole fields.

*Varietal selection*

For soft fruit there are often restrictions put on growers' selection of varieties related to both the grower's marketing group and supermarket requirements. Some cultivars of raspberry and strawberry available in the UK have been produced by breeding programmes part-funded by grower levy. These cultivars are covered by Plant Breeders' Rights and are available to all. Such cultivars, have been bred to provide reliable pest and disease resistance so as to reduce pesticide usage and improve reliability of cropping, can be unacceptable to growers who because of the markets they are supplying with fruit (for fresh fruit sales) are reliant on the supply and use of 'club' or 'exclusive' cultivars i.e. from breeding programmes that are providing plant material exclusively for producer organisations and other private enterprises. These latter cultivars are developed and marketed with specific multiple customers in mind to have a specific fruit size, shape, flavour, colour, shelf life and cropping season. These traits are usually prioritised over reliability of cropping, yield, pest and disease resistance, ease of crop management & harvesting.

With the ready availability of chemical fungicides and the use of routine spray programmes based on crop growth stage there has been less need for varieties with lower susceptibility to diseases. However, with bioprotectants likely to play an increasing part in disease management then varieties which slow the development of disease may give such products a greater chance of colonising tissue in advance of the pathogen.

Powdery mildew, caused by *Podosphaera aphanis,* is an important disease of strawberries and currently its control in the UK is very dependent on conventional fungicides [D457]. Plants grown under tunnels tend to have more powdery mildew infection than outdoor crops because in the latter there is an inhibitory effect of rain on conidia germination [D458]. Temperatures around 20°C and high relative humidity favour the development of strawberry powdery mildew [D445], such conditions are often satisfied under protected production systems in the UK from late June to October. Hence powdery mildew problems are mainly seen in late cropping June-bearers (planted in May and cropping in August and September) or in the later production of the ever-bearer crops[D453]. Strawberry cultivars vary in susceptibility [D442 D443 D444], but most of the cultivars preferred by the market are susceptible, especially June-bearers such as cv. Elsanta, or cv. Malling Centenary and the ever-bearer types on which a high incidence of mildew develops on leaves, flowers and fruits [D453].

Relatively recent work to identify resistance to verticillium in strawberry has used QTL mapping to identify multiple loci controlling resistance to verticillium in the field. Genetic markers (short DNA sequences) in genetic linkage with resistance genes have been identified and screened on the wider germplasm to validate their transferability [D551].

Unlike raspberry spur blight (*Didymella applanata*) and cane botrytis, which weaken or kill individual fruit nodes, cane blight (*Paraconiothyrium fuckelii*) kills floricanes, resulting in year on year decimation of infected plantations. Once *P. fuckelii* penetrates the cane epidermis, it invades the cortex and then enters the vascular tissue [D428]. Growers try to counteract the impact of spur and cane blight with fungicide treatments or by the use of resistant or tolerant raspberry genotypes with improved phenolic compositions [D430]. Phenolic compounds are secondary metabolites, encompassing several classes of structurally diverse products, that can be used for pigmentation and protection against adverse factors [D430]. The content of secondary metabolites varied considerably between the raspberry cultivars Himbo Top, Polka and Autumn Bliss, but although the level of phenolic compounds in canes was causally linked to the differences in disease susceptibility, additional factors such as trichomes, waxes and cuticle thickness were also likely to be involved in plant resistance to fungal infection [D430]. The more is understood about plant pest and disease resistance mechanisms the more factors can be considered in breeding programmes and pesticide use reduced.

Researchers in Scotland are using marker-assisted breeding to facilitate the introduction of fungal disease resistance into elite germplasm and breeding lines. Gene H, which determines cane pubescence is closely associated with resistance to cane botrytis and spur blight, but not rust, cane spot or cane blight [D431]. No new work in breeding resistance to *P. fuckelii* had taken place since 2008, at last review in 2019 [D368]. Work on improving raspberry cane midge control is also required because the increase in damage by this pest, (their feeding damaging the primocane periderms so enabling the fungus to penetrate internal cane tissue [D433]) is contributing to the increase in infection by cane blight [D368].

Raspberry varieties can vary widely in susceptibility to infection by phytophthora, but until recently all varieties of commercial value in the UK were liable to succumb to the disease. Research has been undertaken in the UK to identify genes in resistant raspberry varieties so that they can be used in possible future raspberry breeding programmes to screen new seedling selections for their presence or absence [D363]. In 2020 the variety Glen Mor was introduced to the industry from the UK Raspberry Breeding Consortium and the Scottish Government. It has the genetic marker Rub118b which confers resistance to raspberry root rot. This followed over a decade spent developing the first genetic linkage map for raspberry and subsequently identifying molecular markers to link important traits to genetic regions. Trials with Glenn Mor in infested soil for six years have shown no root rotting [D553]. This variety could replace the popular Glen Ample variety and is likely to be taken up overseas, but a number of UK growers have contracts that restrict which varieties they are able grow (Janet Allen, fruit consultant, pers. comm.).

Currently, winemaking grape varieties are genetically closely related and have low resistance to botrytis, powdery and downy mildew and viruses. Current genetic work should improve future disease resistance, particularly with mildew diseases. Planting vineyards with a mixture of grape varieties will not, at present, improve any aspect of disease resistance. Choice of grape variety is more likely to be dictated by the choice of grape for the planned market [D463 D464 D467] and makes acceptance of any newer, more resistant, varieties a challenge. In North America they have long grown the European grapevine (*Vitis vinifera*), with its associated powdery mildew susceptibility, although native American cultivars grown are only slightly susceptible [D569]. Recent work inoculation screening of 13 *Vitis* species collected from the USA and northern Mexico identified new sources of powdery mildew resistance that are suggested could be incorporated into powdery mildew resistance breeding programmes throughout the world [D462].

Plant defence responses have a genetic basis and the DRASTIC (Database Resource for the Analysis of Signal Transduction in Cells) gene expression database was set up in 2001 by the Scottish Crop Research Institute and the University of Abertay. The DRASTIC web site [D220] is a database of plant expressed sequence tags and genes up- or down-regulated in response to various pathogens (biotic stress), chemical treatments, and abiotic stress such as drought, salt and cold. There is a road map facility to enable the creation of look-up tables to find genes that are co-regulated by treatments.

## In-crop

*Decision support*

Decision support is based on using a knowledge of environmental factors, crop growth and disease development stages to determine the risk of a particular pathogen spreading from an inoculum source and infecting; either by forecasting / predicting or by recognising that recent conditions have been suitable. This information can be utilised well in advance of a high risk period to avoid crop exposure at the worst time by altering planting date, or flowering and fruiting period such as by the use of covers. Within the crop, decision support can reduce the number of fungicide applications by spraying only when conditions for disease spread have, or are forecast, to be attained. Ensuring inoculum, such as the sporulation of botrytis on discarded fruit, is minimised is also important and much more attention is now paid to this in soft fruit because such fruit also can harbour spotted wing drosophila. If a low level of disease increase is predicted then it is also possible to select to use products such as bioprotectants, or potentially elicitors, to keep the pathogen at a low level. Chemical fungicides can be reserved for if environmental conditions and inoculum increase is likely to be putting the crop at greater risk of higher disease incidence.

To be able to manage the pathogens that infect raspberries and strawberries, monitoring is required as part of IPM. The AHDB (under its former name of the HDC) crop walkers' guides for cane fruit [D385] and strawberries [D386] aid the identification of diseases and pests and a wide range of soft fruit factsheets and research reports which are available via the AHDB Horticulture and Potatoes archive website that can assist in disease identification and management. Each AHDB publication is usually targeted at a specific problem range and a more-consolidated information source could benefit the soft fruit industry, perhaps resembling the Raspberry and Blackberry Production Guide produced in Canada [D426] and the Production and IPM Guide for Organic Grapes produced in the USA [D427.] (An AHDB Best Practice Guide is available for apples [D391]). Pictures and guidance on pest and disease IPM for USA strawberry and grape growers are available to download[D500 D499]. The AHDB have not been a provider of information on vineyard management and most information on grape diseases that has been published originates from the traditional wine producing nations.

Diagnostics is an important element of IPM, it is integral to the certification processes of soft fruit and grapes and is of particular benefit where infection is initially latent / symptomless. In-house laboratories can be used but commercial plant clinics, such as Fera, also offer a service. The Fera website specifically mentions diagnosis of *P. cactorum, P. fragariae, C. acutatum, V. dahliae* and *X. fragariae* in strawberry plants [D564]. The detection and identification of pathogenic fungi has traditionally been performed using classical mycological methods involving isolation from host material, by plating plant parts, soil or soil extracts onto selective media, followed by morphological, biochemical, chemical and immunological analyses. However, these methods are often time-consuming, laborious, and require extensive knowledge of classical taxonomy. Since the early 1990's several molecular methods for more accurate characterization and differentiation of phytopathogenic fungi have been developed and are being implemented widely [D561].

The symptoms of common foliar diseases such as powdery mildews, downy mildews and rusts would normally be recognised by plant producers and growers without recourse to a plant clinic (and cannot be cultured as they are obligate pathogens), but the causes of plant collapse or root rotting can be harder to determine visually. Lateral flow devices (LFDs) utilising genus-specific monoclonal antibodies are available commercially to test for *Phytophthora* spp. [D563 D565] (not the individual species) and so any potentially infested, red-brown, roots on a plant could speedily be tested by propagators or before planting by growers. It is, however, not feasible, and would be costly, to check every plant and additionally infested roots might be missed in sampling particularly if infection has not progressed to rotting. The recent widescale use of LFDs in public health has introduced this form of pathogen detection to a wider audience and so may increase the confidence of growers in using those designed for plant health. In AHDB Project SF 158 [D368] a survey conducted in 2019 determined the *Phytophthora* species present in dying raspberry canes at both propagator and commercial grower sites in England utilising an experimental lateral flow device (LFD) for the diagnosis of pathogenic *Phytophthora* species (from Clades 1, 7 and 8), so excluding non-pathogenic species. Samples of root and stem tissue were simultaneously taken for extraction and amplification of the DNA of *Phytophthora* spp by nested PCR to enable sequences to be matched against a database of *Phytophthora* species. This determined the actual pathogenic species detected by the LFD and showed that positive readings were caused by the presence of the Clade 7 species *P. rubi* and *P. idaei* as well as Clade 2 species *P. citrophthora, P. bishii, P. citricola* and *P. plurivora* in a few plants. Methods for *Phytophthora* species detection, including immunoassay lateral flow tests and molecular DNA-based assays based on polymerase chain reactions (PCR) were reviewed in AHDB Project CP 126 [D217] and a detailed review including descriptions of molecular and immunological diagnostic techniques has been published [D561].

Methods including iso-enzyme comparisons, restriction fragment length polymorphism (RFLP) analyses of mitochondrial DNA, AT-rich analyses, random amplified polymorphic DNA (RAPD), genus and species-specific polymerase chain reactions (PCR) and enzyme-linked immunosorbent assay (ELISA). These methods are faster than isolations and can be used by personnel with little experience in plant pathology. Additionally, non-cultivable microorganisms (such as powdery and downy mildews) can also be detected and quantified, samples can be tested directly, and isolates do not require culturing because minute quantities of fungal DNA can be detected from environmental samples, even before symptoms occur. Diagnosis time can be reduced from a period of weeks, typically experienced with culture plating, to only a few days, thus allowing the appropriate control methods to be implemented much sooner and more effectively. Molecular methods in which non-viable or dead propagules are also detected can potentially overestimate the possibilities of risk in some cases, but the stated advantages outweigh those of conventional diagnostic methods in most situations and other methods can then provide viability confirmation if required [D561]. Using PCR-based methods for in-field diagnostics has been a challenge because of the thermocyclic equipment needed. With the advent of isothermal amplification methods, which provide amplification of nucleic acids at a certain temperature, in-field use has become possible. Molecular diagnostics in out-of-lab conditions are of particular importance for protecting against viral, bacterial, and fungal phytopathogens in order to quickly prevent and control the spread of disease [D562].

 

An understanding of the life cycle / epidemiology of diseases is important in decision making. Knowledge of the overwintering stages, dispersal modes, environmental conditions optimum for pathogen infection all aids cultural control measures including whether and when fungicide application may be needed and their integration in disease management programmes. This knowledge can be utilised in models that assist with disease forecasting and/or spray timings.

Fungicide applications are made against cane blight of raspberry of *Paraconiothyrium fuckelii* (Saccardo) (until recently previously classified as *Leptosphaeria coniothyrium* (Fuckel)) based on information on epidemiology gained when all UK crops were grown outdoors. Work for the AHDB in 2006 on a tunnelled crop indicated that infection may be able to take place far later than when fungicides are normally applied during and immediately post-harvest [D432]. Infection period is affected by levels of cane maturity, and with most crops now fruiting under protection and primocane selection being delayed, the primocane rind is far less mature going into winter than previously. A 2019 review for the AHDB concluded that there is a need to understand the disease life cycle in soil and soilless substrate grown crops under protection. In particular the time of year and conditions for spore dispersal and any changes to this brought about by growing the crop in tunnels for part of the year so that product application can be better timed [D368] . In open-field crops, air dispersed ascospores are released in April and May from overwintering pseudothecia on dead floricane stubs, but most infection arises from pycnidiospores splash-released from pycnidia that can be seen from February onwards on growing floricanes [D368]. Some understanding of the infection process of cane blight might be gained from existing work on the *Leptosphaeria* species *L. maculans,* which causes stem canker of oilseed rape [D436]. Knowledge of spore release timing, tissue infection susceptibility and the speed of mycelium movement in the host is important for decisions on fungicide spray timing for both of these species.

The lack of strawberry cultivars with durable resistance to powdery mildew means that in the UK managing this disease still relies on routine sprays of fungicides. However, changes to pesticide regulations in the UK mean that the number of products available for use in commercial strawberry production and the number of times that they can be used are decreasing rapidly [D453]. Overreliance on fungicides for strawberry mildew management may lead to selection for, and subsequent accelerated spread of, fungicide resistant or insensitive strains [D447].

Work over five years in AHDB Project SF 157 has recently been completed in the UK to determine the efficacy of several bioprotectant products used alone or in combination against strawberry powdery mildew, and then to evaluate several mildew management programmes in which these products were integrated with fungicides [D453 D456 D473]. Powdery mildew management decision-making was based on many factors, including disease risk (based on the past and forecast weather conditions), growth stage, current disease incidence, type of fungicide (curative, protectant, anti-sporulant) and control measures already applied.

In East Malling Research (EMR) AHDB SF 157 trials on strawberry a temperature and humidity data logger at crop height recorded every 15 minutes was downloaded once or twice weekly for estimating risks of spore survival and infection. Daily temperature and humidity forecasts for the week ahead were also obtained from the BBC internet service. Thus, management decisions were based on historical and future daily disease risks. Disease observations to use in decision making were made one or two times a week for visible mildew and in subsequent trials for sporing botrytis [D453 D456 D473]. A summary document bullet-pointing how growers can make the observations and decision steps themselves on powdery mildew control was produced for the AHDB at the end of the project in 2020 [D473].

The EMR model was tested out in 2020 on a commercial farm in which the predicted risk of infection calculated from the simplified “look-up” table using BBC weather forecasts agreed closely with the computer-based EMR model using data loggers in the ventilated (unsealed) tunnel [D481]. It was found to work effectively. One lesson learnt was that previous work had been based on cv. Amesti whereas the disease started more rapidly in the cv. Murano used in the trial so it was concluded “not to be too optimistic when making judgements on the risk of infection and to start spray programmes as soon as temperatures and humidity start to increase”. NIAB EMR WETCentre is now promoting their powdery mildew and botrytis models alongside their Precision Irrigation Package software system[D482].

An AHDB factsheet [D474] on the control of strawberry mildew under protection, gives assistance on powdery mildew recognition and lifecycle. It was produced at the conclusion of three AHDB funded projects (SF 62, SF 62a and SF 113 [D479]) that included work by PhD students at the University of Hertfordshire. The University developed a real-time decision support system [D479] to support growers in spraying only when conditions (temperature >15.5°C and <30°C, relative humidity >60%) are favourable for the development of strawberry powdery mildew. A PowerPoint presentation is available outlining the steps [D480]. This system was validated on eight commercial sites in England and Scotland and showed that the use of the prediction system gave commercially satisfactory disease control with fewer fungicide sprays and financial savings (£100-£400/ha). The prediction system was licensed and released in May 2020 for purchase from Agri-tech Services and has been in use in the UK [D479].

*Botrytis cinerea* can readily infect the receptacle of flowers and result in latent infection of soft fruit that can become symptomatic with fruit ripening [D485] mainly under open-field conditions, as well more commonly now causing postharvest rot. Infection of ripe fruit by mycelia can also occur in the presence of free water, with penetration assisted via necrotic tissue [D484].

 

Severe fruit loss can occur in open-field strawberry crops when fruit ripening coincides with heavy and/or frequent rainfall. Although botrytis risks under protection are much reduced, control of grey mould on strawberry and raspberry grown under protection is still often based on the strategy developed for open-field crops, i.e., scheduled applications of fungicides during the flowering and early fruiting period [D486]. One main objective of fungicide-based management of botrytis under protection is to reduce the extent of latent infection of fruit in order to reduce postharvest fruit rotting and so extend shelf life.

Work in AHDB project SF 157 on strawberry was targeted in the initial years at powdery mildew, with treatments for *B. cinerea* applied routinely to all treatments [D453]. However, in 2019, a decision-based management system for both powdery mildew and botrytis was run, with one programme excluding specific fungicide treatment for botrytis, in comparison with an untreated control and a routine fungicide programme [D456]. A detailed table of factors including disease risk, growth stage, temperature, humidity and visible disease for making strawberry powdery mildew and botrytis management decision, including product choice, under protected conditions has been given [D456]. This was based on knowledge gained from previous work in tunnelled strawberries using weather data which had allowed the production of a mildew [D456] and botrytis [D459] decision-based management programme. High, low or medium risks of infections were then defined based on temperature and humidity thresholds. Humidity equal or above 82% increases the risk for both diseases, with powdery mildew risk at a forecast daily average temperature or above 14°C and botrytis at or above 16°C. The results showed that botrytis-specific fungicides could be omitted and together with the simple decision-based system for determining treatments for strawberry powdery mildew this resulted in a 93% reduction in fungicide use and a cost saving of £924/ha with no penalties in yield, fruit quality or disease control and the additional benefit of reduced residues on fruit [D456]. Cool chain management delayed the development of both botrytis and soft rots [D456].

In raspberries, growers make decisions to apply fungicides both during flowering (to protect against botrytis infection of fruit able to take place via the pollen tubes over the few days in which petals open and remain held on each flower) and after harvest (e.g., from August in a summer fruiting crop) to further control cane botrytis. In AHDB Project SF 74, spores arising from botrytis sclerotia on overwintered canes (after wetting pre tunnel covering) were shown to be the principal source of flower infection in tunnelled crops, not in the sampled tunnels from either growing weeds or cane debris [D360 D368 D472]. Thus, it is not only the damage to axillary buds on the canes by botrytis lesions which can prevent fruiting laterals growing, but cane botrytis is a key phase in the cycle leading to fruit rotting.

In the UK, until AHDB Project SF 74 [D472], much of the knowledge of botrytis in raspberries was gathered from open-field crops, not those protected by tunnel polythene during flowering and fruiting [D486]. One project objective was to develop mathematical models that related the incidence of flower infection to inoculum concentration and weather conditions. The 2008 Annual SF 74 Report on tunnelled crops at two sites reported use of a Burkard cyclone spore sampler to enable daily collection in May and June of airborne botrytis spores (whose DNA was then quantified by PCR testing) and concurrent use of digital temperature and humidity loggers within the crop canopy. Fully opened flowers (susceptible to infection within the previous 48 hours) were collected every two or three days and cultured to determine the incidence of botrytis. On many days no spores were trapped. A model developed for open-field strawberry using daytime vapour pressure deficit and night-time temperature was used to predict the incidence of flower infection, but it over-estimated infection incidence. A more complicated botrytis model [D459] was also developed and at one site (only) this regression model using flower infection and weather variables showed that only daytime, not in tunnels night-time, temperature was needed to predict the incidence of flower infection, but it was not possible to develop the model further for verification in commercial crops [D486 D472 D461]. The results suggested that factors other than temperature and humidity may need to be considered [D486]. The model was based on logger data downloaded manually in the field at intervals and thus could indicate when conditions had been favourable for botrytis infection (of use for fruit quality intelligence not to guide spraying) whereas nowadays MET data can be received “real-time” via “The Cloud”. However, there was a high level of latent botrytis infection even in the sprayed fruit and so a predictive model for flower infection may not be of significant use [D486]. Comparison of stored fruit from unsprayed and sprayed flowering raspberry crops indicated, from their similar quality, that growers should consider not spraying, but instead use postharvest cool chain management, as it was shown to be as effective as preharvest fungicide control in reducing rot development and extending fruit shelf life. Rapid cooling within one hour of picking was critically important to delay the onset of fruit rotting [D461 D472 D486]. Fungicide application may be limited in its efficacy in strawberries and raspberries because new flowers continue to be produced that are susceptible to botrytis and spray interval lengths mean that only a proportion of flowers are open and can be treated at each application and additionally the spray also then needs to successfully land on them.

In the USA, two grape powdery mildew (*Uncinula necator*) models are recorded as having been developed in California [D498]. The model published by Snyder *et al*. in 1983 [D498] measured or forecasted daily high and low temperatures, and rain of greater than 0.10 inches (2.5 mm) using regional weather stations. This model was developed for wine and raisin grapes. It is based on the assumption that host tissue growth and weathering of sulphur used as a fungicide are the two main reasons why the sulphur must be reapplied in vineyards. Daily mildew indexes (DMI) were calculated from daily minimum and maximum temperatures and accumulated to determine the powdery mildew index (PMI). DMI should begin accumulating twelve days after either initial leaf appearance or 6-inch (150 mm) shoot growth, whichever comes first, and this is when the first sulphur application should be timed. DMI calculations continue throughout the season until the berries contain 12-15% sugar. After the first application, subsequent dustings should occur when the difference between the current PMI and the PMI on the last dusting date equals or exceeds 1.0. When precipitation exceeds 0.10 inch, the vineyard should also be re-dusted. Sulphur fungicides are authorised for use on table and wine grapes and strawberry in the UK [D195].

The model published for grapevines in 1994 by Thomas *et al.* contains two stages based on powdery mildew pathogen biology, an ascospore and a conidial stage [D498]. It uses sensors in the fruit zone of the canopy and records hourly average temperature, daily maximum temperature; hourly leaf wetness duration (ascospore model only). The amount of time that temperature is above 95°F (35°C) is calculated. To determine ascospore infection risk levels, the model calculates the daily average temperature and measures the hours of leaf wetness. The model modifies the Mills table developed for apple scab ascospore infection by predicting infection based on two to three of the hours of required wetness. The start of the conidial stage of the model is triggered early in the growing season by three consecutive days with six consecutive hours of temperatures between 70°F and 85° F (21° and 29°C); for each of these three days, the model assigns 20 points to the disease risk index. Subsequently temperature records are used to determine if conditions are suitable for infection and can allow spray intervals to be stretched.

In the USA, a Powdery Mildew Index is available to help grape growers anticipate outbreaks of powdery mildew and time their treatments according. Usage of the Index was surveyed by Davis UC in California (reported in 2017) [D492] and they determined that all growers used weather guidance when planning their powdery mildew fungicide applications, but those using the Index were more responsive to current disease pressure.

In Canada, powdery mildew causes significant grape yield loss [D493]. The rate of disease development varies annually due to complex interactions between the pathogen, its host and environmental conditions. Seeking to explore these interactions, a model-guided fungicide spray strategy was validated for guiding spray decision up to six days with a 10 day forecast of potential spray efficacy under rain wash-off conditions. This strategy improved fungicide spray decisions; decreased the number of sprays and identified the optimal time to spray to increase spray effectiveness.

A smartphone decision support application called “Grape Compass” for South African grape growers has recently been set up that makes forecasts of powdery mildew, downy mildew and botrytis, thereby enabling precisely timed and targeted spraying [D495]. It said to be easy to use, not require a weather station, and have minimal data inputs. It followed scientific research that aimed to maximize the quantity of high-quality grapes at the lowest business and environmental cost, thereby supporting farms' long-term sustainability.

In Italy, a decision support model for downy mildew, powdery mildew and botrytis (and grapevine moth) is available called "GrapeDSS" [D497]. For downy mildew, simulations are provided from primary infections following rainfall and secondary infections based on meteorological and crop measurements. A level of risk is given and the type of treatment carried out is based on this.

In the USA, Kentucky University have a website on which Kentucky grape growers select their county, and that day's date to determine the current risk for powdery mildew, downy mildew and botrytis bunch rot [D506]. Other dates may be entered if assessment of past risk is warranted. The website notes that grape powdery mildew can become a severe problem during dry weather. The risk of powdery mildew is highest in spring during leaf emergence and bloom, and again in autumn after berry colouring, especially during cool rainy conditions. Risk for downy mildew is highest during periods of heavy rain. Leaves are susceptible throughout the season, while fruit become resistant to infection 3 to 4 weeks after bloom. Risk for botrytis bunch rot is highest in spring during leaf emergence and bloom, and again in fall after berry colouring, especially during cool rainy conditions. All three prediction models are based on leaf wetness duration and average temperature during wetness events. Prediction models for apple scab (*Venturia inaequalis*) based on the previous 7 days of accumulated leaf wetness, and fireblight (*Erwinia amylovora*) of apple and pear incorporating the previous 4 days of weather data and a 7-day forecast for estimating leaf wetness and temperature are also available. Growers are presented with recent daily maximum temperature and precipitation and maximum relative humidity records for their county and given a traffic-light indication (low to extreme) of infection risk looking ahead six days. The service is free to access and it means that growers of more than one crop can access information in one place to plan their management of diseases across their enterprise.

In France, grape downy mildew (*Plasmopara viticola*) is stated to be a major disease of grapevine that has an impact both on the yields of vines and the quality of the harvested fruits [D496]. In 2013, on average 10 fungicide applications were made throughout the season. Models and machine learning algorithms have been used to predict the probability of high incidence and severity of the disease using a dataset of nine years of grape downy mildew observations [D496]. The date of disease onset and/or average monthly temperatures and precipitation were used as input variables. The date of onset of the disease had a greater influence on the accuracy of forecasts than weather inputs and, among weather inputs, precipitation had a greater influence than temperature. Results showed that risk of downy mildew at bunch closure decreases with reduced rainfall and increased temperatures in April-May. It was also shown that the use of fungicide treatment decision rules that take into account local characteristics would reduce the number of treatments against downy mildew in the Bordeaux vineyards compared to current practices by at least 50%.

In Italy, a mechanistic model was developed to predict secondary infections of grape downy mildew and their severity as influenced by environmental conditions [D494]. The model incorporated the processes of sporangia production and survival on downy mildew lesions, dispersal and deposition, and infection. The model was evaluated against observed data for its accuracy to predict periods with no sporangia or with peaks of sporangia, so that growers could identify periods with no/low risk or high risk. The model rarely failed to predict no sporulation and only failed to predict one of 40 sporulation peaks correctly. As the model was able to identify periods in which the downy mildew risk was nil or very low it was said this could help growers avoid fungicide sprays when not needed and lengthen the interval between two sprays, meaning growers could move from calendar-based to risk-based fungicide schedules for the control of *P. viticola* in vineyards.

*Environmental control - growing under covers*

A review of strawberry and raspberry management of botrytis in the UK was carried out following the trend from mainly open-field to soft fruit cropping under tunnels [D486] and experiments were also carried out on the management of raspberry grey mould as part of AHDB Project SF 74 [D472] [D461]. Botrytis is the major cause of post-harvest fruit rotting in raspberry, but canes are infected and axillary buds which were infected the previous year produce less productive shoots and may die. This work determined that covering crops early in the season did not significantly affect the incidence of raspberry fruit with latent botrytis infection at harvest but reduced latent infection in strawberry [D486]. One effect of covering raspberries in May was that the sclerotia of botrytis that form on the canes overwinter did not sporulate over the period usually seen outdoors of mid-May to at least mid-August. The sclerotia need to be wetted to initiate sporulation when temperatures rise in spring and the tunnels shield the canes from rain. For a similar reason although weeds and crop debris can be a source of botrytis spores in outdoor crops, these were not a main source of flower infection in the covered crop as their surfaces remained dry and thus unfavourable to spore infection [D472]. Most cane infection resulted from direct infection of growing canes through wounds around the petioles rather than moving down the petiole from the leaf blade. It was thought possible that botrytis infection became latent in the raspberry stools and moved into the primocanes that grow out of them, but further sampling was required [D472].

 

In raspberry, cladding of tunnels into late summer-early autumn (later than the past to cover a later fruiting period) may be resulting in increased cane blight (*P. fuckelii*) infection. Growth may remain "softer" under cover. There is also now widespread delay in selecting primocanes to become fruiting canes by removal of the first, and sometimes second, flush of primocanes, and the resulting very juvenile primocanes are then particularly susceptible to cane blight infection. The period of susceptibility to infection probably extends much later into the autumn/winter than in past open-field summer fruiting crops, and potentially into the new year. Fungicide spray timings immediately post-harvest based on open-field crops are likely to need to be reconsidered and additional attention given to removal of diseased floricanes from which spores will splash when covers are removed after harvest [D432 D367].

In raspberry, the uredospores of yellow rust require a water film to be present to allow germination (with temperature between 10.5°C and 25°C) and so polythene covered tunnels shielding from rainfall reduce the chance of successful penetration into the leaf stomata [D369 D360].

*Environmental control - temperature and humidity*

Early stage propagation material is principally grown in glasshouses or tunnels to be able to monitor watering and provide warmer conditions for rooting. The close spacing of such material is conducive to disease multiplication and spread and so greater use of in-crop real-time display loggers would heighten awareness of excess humidity or heat accumulation.

It is standard practice with raspberries and strawberries grown under polytunnels to raise and lower the sides of tunnels to manage humidity and temperature levels. This is both for fruit quality but also for disease management. Reducing humidity makes the conditions less conducive for botrytis and powdery mildew to develop. In sunny conditions care must be taken to consider the height of the sides with the exposure of the fruit to the sun which may cause damage. A balance needs to be found. Raising and lowering the sides of tunnels is also labour intensive.

In relation to reducing strawberry powdery mildew development, it is recommended that a tunnel management plan should be produced each night (or early next morning) by reference to a temperature and humidity forecast to trigger venting in order to keep tunnel temperatures within the range 18-25°C in the day and aim to reduce humidity to less than 75% [D474]. Further information on temperature and humidity monitoring, using in-crop electronic data loggers and weather forecasts that include humidity (e.g., BBC), to determine when conditions might favour powdery mildew and botrytis, is given in the decision support section of this report.

 

Botrytis can be more prevalent on the rows of covered soft fruit crops next to the tunnel frame legs as humidity can be greater there because of rain saturation of the ground and splashing. Guttering can be purchased to direct water from the tunnel roof away from the tunnel sides.

Tunnels kept in the same position for some time are likely to develop compacted, poorly draining areas between the rows. Strawing of strawberry crop ridges assist in keeping fruit trusses from sitting in moist conditions and so reduce the chance of rot, but if allowed to become compressed and damp may have the opposite effect. Where, particularly as in cane fruit, there are grass pathways these should not be allowed to become lush or weedy as this can also raise humidity and soil air movement around the cane bases, however care must be taken not to damage canes when mowing [D428].

Cane blight of raspberry is a major issue in the wet, humid conditions of south-east USA and there the growers are recommended to prune when at least four days of dry weather is expected to reduce infection of primocanes. Weed free strips under the canopy are recommended to aid drying and air movement [D434].

When strawberries and raspberries are picked it is important that their field heat is removed as quickly as possible to increase shelf-life. For raspberries, rapid post-harvest cooling by forced-air to 2°C and subsequent storage at 4-5°C generally led to a reduced level of fungal rotting of fruit 9 days after harvest (an average period before consumption) and doing this was shown to remove the requirement for fungicide application during flowering and fruiting [D486 D472].

In strawberries, air circulation can be improved by crown thinning. The reduction in humidity and warmth will make the environment less favourable for pathogens such as *Colletotrichum acutatum* [D501]. Reduction of humidity in the canopy to reduce the success of spore infection can also be achieved in raspberry and grapevines by de-leafing and pruning and more detail on these techniques is given within the section on pruning.

In grapevines, powdery mildew can be reduced by avoiding planting grapevines in low or shady areas. Keeping plants well-spaced and the canopy thinned out will help to promote good air circulation and reduce humidity [D569]. Orient rows to maximize sunlight exposure and reduce humidity within the vineyard. On highly susceptible varieties, thinning or removing leaves around clusters soon after fruit set will help to control this disease by exposing them to sunlight and, furthermore, will improve spray coverage of the fruit [D427]. Consistent control of botrytis requires the conscientious use of cultural management practices. Any practice that improves air circulation and thereby reduces humidity within the canopy is of significant benefit. Such practices include site selection to avoid fog pockets and heavily wooded areas; management of canopy densities through pruning, shoot positioning, and selectively removing leaves in the cluster zone immediately after fruit have set. On tight-clustered varieties the clusters should be thinned to promote open cluster architecture [D427].

*Environmental and nutrient control – irrigation / fertigation.*

Irrigation in soft fruit is usually carried out by drippers into pots, troughs and grow-bags containing substrate such as coir whereas leaky-hose or similar is favoured for rows of crops, often on ridges, in the soil and often then covered by plastic sheeting mulch. Misting is done during strawberry establishment, but in mature tunnelled crops the absence of spore splash and wet or humid leaves discourages foliar disease establishment. Such irrigation may be on a timer and staff will inspect to confirm crop needs; however, over-watering can encourage phytophthora and under-watering in verticillium infested soil can make permanent wilt more likely. Moisture sensors are available and can be monitored wirelessly, however soil variability across a field makes deciding where to place the sensors difficult. For vegetables the use of electromagnetic induction and creation of irrigation management zones has been studied and may prove useful for fruit [D509].

Fertiliser application during cropping is usually done using a liquid feed given by a dosing device into the irrigation water. Excessive feeding and irrigation in strawberries should be avoided as this can lead to dense canopies that give rise to high humidity and favour pathogens such as powdery mildew and botrytis [D474 D566]. The NIAB EMR WET Centre has a Precision Irrigation Package to help growers with irrigation monitoring and scheduling [D482].

In an efficacy experiment on tunnelled strawberries sprinklers were used to reduce transpiration rates and cool plants to improve establishment [D478]. It was noted that this stopped the expression of powdery mildew symptoms. In the experiment it was seen that as soon as the sprinklers were switched off, leaf cupping, mildew mycelium and purple blotching was seen. Misting of transplants is commonly practiced in the UK, however they must be switched off prior to flowering or else conditions become ideal for botrytis infection.

Raspberry root rot caused by *Phytophthora* spp., which a recent UK sampling survey of symptomatic plants showed to be mainly *P. rubi* using molecular diagnostics [D368] is the most devastating disease currently faced by cane fruit growers and in particular raspberry producers. The pathogen can cause the wilting and death of young shoots, and fruiting canes wilt and the disease spreads rapidly through the root system of the crop leading to complete deaths of large areas of a soil-grown plantation [D363]. Container grown crops also become infected and the pathogen is able to spread between containers via the water draining out of pots. Infection can come from resting spores in the plantation soil, however planting material may carry in the disease if soil-grown. Modules grown in substrate from root-cuttings can also be infested if taken from infested symptomless mother plants, with further spread in drainage water of the multicell propagation trays. Spread can be reduced by standing plant containers on batons or crenulated plastic matting [D363] or using pots with raised sections of base rim to act as feet and ensuring there are plenty of drainage holes. If standing pots on soil ridges then a covering of woven ground cover material allows better drainage than a polythene mulch sheet. It is possible to collect run-off from crops for re-use after treatment against pathogens such as *Phytophthora* spp. and this both saves water and reduces the risk of puddling around the crop and spore splash [D539].

For grapes in the UK the weather conditions mean that drip watering systems are better than overhead watering to avoid enhancing air humidity and encouraging disease spread[D468]. Drip irrigation of pots and troughs is standard and drip / leaky hose is used under plastic mulch covering the soil, however localised wet spots can arise and irrigation that is based on a time schedule rather than demand monitored by moisture loggers can also lead to roots sitting wet so increasing the chance of root infection. Wet growing media or soil encourages the development of root rots, and humidity around stems and foliage is required for spore germination and tissue infection. Checks for leaks or excess water output should ideally be made at a time the water is set to run and rectified as necessary.

In vines with esca their transpiration is reduced about a fortnight before the first esca-foliar leaf discolouration. Measurements have shown that leaf nitrogen availability to be lower in affected leaves and further research is needed. Nitrogen availability affects yields and defines grape quality via phenolic activity during maturation [D568].

The key considerations when managing vine nutrition organically include filling the trellis without promoting excess vine vigour, managing soil pH to optimize the potassium and magnesium balance and understanding carbon to nitrogen ratios in compost [D427]. Avoiding excessive nitrogen fertilization will reduce the chance of botrytis developing [D427].

*Hygiene and clean propagation material production*

Hygiene measures [D527 D540 D541 D528 D217 D538 D539], as described above within pre-cropping, including weed control, debris removal, water treatment and testing, disinfection of surfaces and/or replacement of matting and containers, all help to reduce the need for disease control in both propagation material and in plants for fruiting. Regular removal of weeds (that can host botrytis and pests) and plant debris and ensuring a clean water supply should continue.

Healthy plants that do not have any latent viral, fungal, or bacterial pathogens are easier to propagate and produce higher yields and better-quality fruit. Starting with clean stock is vital to a healthy and successful propagation program. Strawberry and raspberry viruses can often be asymptomatic and latent and only show symptoms when there is a coinfection with another virus. Meristem tip culture, often referred to as meristemming, is the process of excising a very small number of cells from the growing apical tip which is then grown on tissue culture growing media in order to generate callus and then rooted plantlets. This is often preceded by 4 - 6 weeks of heat, chemo, and cryotherapy to reduce viral loads and to maximise the chances of mersitemmed daughter plants not carrying infection. In many breeding programs meristemming is a standard part of the propagation process to ensure that the elite mother stock that is used for clonal propagation is the highest level of cleanliness. Meristemming is also used to clean up important plants and breeding selections that are known to have viral infection. The meristemming process is time consuming and success rates can be low, so typically high numbers of plants are produced via meristemming and then screened using diagnostic methods such as RT-PCR and ELISA laboratory testing in order to ensure that the virus is no longer present in the plants [D523].

In the production of EPPO Certified grapevine material, heat treatment can be carried out against pathogens, either with pots of rooted vines in a hot-air cabinet at 38 ±1°C, or by immersing dormant canes in water at 50°C for 45 minutes immediately before grafting [D537]. Cuttings and rootlings have been treated against the spread of grapevine wood necroses [D567].

Heat treatment of fungal and bacterial pathogens and nematodes [D293 D294 D295 D296 D297 D298 D299] is almost universal in its effectiveness, but if carried out on live plants these can also be damaged. A technology called a plant sauna has been developed by a Norwegian company [D556] in a research collaboration since 2015 with the University of Florida. The first commercial units were sold in 2020 and use precision thermal therapy to reduce or eliminate pests and pathogens from infected plants. The plant sauna uses water vapour within a controlled temperature environment (commonly a cabinet) to treat plants before planting. A vacuum is applied to the unit in order to draw the heated saturated air evenly through the plants contained in either open boxes or crates. This has the additional benefit that plants do not need to be unpacked for treatment, which saves time and the risk of contamination through additional handling.

The principle of the plant sauna is a two-step process. This first is a conditioning treatment consisting of 1 hour at 37˚C with a 1 hour cool down period at ambient temperature. This first step induces heat shock proteins in the plant that offer protection against higher temperatures required to kill the pathogen. The second step is an eradicative treatment of 4 hours at 44°C. The whole process takes 5-8 hours [D291 D292 D300 D301 D542 D558].

It is known that heat treatment effectively kills and reduces bacterial pathogen populations [D295], and plants have historically been treated with a hot water dip, but bacterial pathogens can spread in the water between plants in a treatment batch. The plant sauna has been shown to be very effective in controlling angular leaf spot in strawberry, caused by *Xanthomonas* *fragariae,* and also effective at minimizing heat damage to plants [D300]. *X. fragariae* is an A2 pathogen in Europe and is consequently controlled in plant propagation and for international plant movement.

In an experiment at the University of Florida, strawberry planting material was inoculated with *Phytophthora cactorum* before exposure to the aerated steam in a plant sauna. Death from Phytophthora crown rot after transplanting into beds was much lower (2.5%) than for untreated plants (80%). Thermotherapy of transplants may thus be a way to manage *Phytophthora* spp. in plant stock [D542 D301]. Strawberry tips used to produce plugs were shown to survive the steam treatment at 37°C for 1 hour followed by 44°C for 4 hours [D301].

In work with botrytis-infested strawberry foliage, heat treatment using the two-stage steam treatment resulted in a 3% incidence of sporulating *B. cinerea* compared with 75% for untreated plants. In research on eradicative plant-sauna treatment of five strawberry cultivars with botrytis (pre-treatment at 37°C for 1 h, followed by 1 h of cool-down at ambient temperature and eradicative treatment at 44°C for 2 h or 4 h) differences in incidence were found. Control was nearly complete after 44°C for 2 h for two varieties, and there was zero incidence after 4 hours, whereas the other three cultivars achieved reduction only after 4 hours and then by 72 to 77% only [D558]. In a separate study treatment at 44°C for 4 h killed 90 to 100% of botrytis sclerotia. The technique was declared as a safe and effective technique for reducing pathogen population, with no or insignificant negative impacts on transplants [D558].

Aerated steam reduced *Colletotrichum acutatum* (anthracnose), with petiole colonisation of 5% compared with over 70% in the untreated [D301]. Plant sauna treatment of strawberry transplants at 44°C for 4 hours, with or without a preheat step of 37°C for 2 hours significantly reduced the colonisation of petioles by *C. acutatum* [D292].

Use of plant sauna treatment of transplants could restore a measure of disease control to strawberry nurseries in Carolina and Florida where isolates of botrytis collected were resistant to thiophanate methyl, boscalid, pyrimetanil, pyraclostrobin and fenhexamid (ranging from 40% to 95% of isolates), with resistances also found by colletotrichum to thiophanate-methyl and azoxystrobin, and *P. cactorum* to mefenoxam [D557]. In Florida, management of anthracnose in strawberry nurseries and fruit production fields is challenging, *C. acutatum* is commonly spread (latently) by contaminated transplants from strawberry nurseries [D557].

Plant sauna treatment of strawberry transplant plugs is also effective against powdery mildew. *Podosphaera aphanis* was killed after 2 or 4 h at 40 - 44°C following pre-treatment at 37°C to increase heat tolerance of the plants. No viable conidia were found following treatments and new leaves formed after treatment were disease free. The highest temperature may reduce growth in plug plants, but no negative plant or yield effects were found from treating cold-stored bare root plants [D291]. Any additional benefit of steaming by killing spotted spider mites on strawberry transplants was studied but there was poor control of eggs after 46°C for 4 hours, although 60% of adult females were killed [D290]. This differs from Controlled Atmosphere Temperature Treatment (CATT) used against tarsonemid mites and nematodes as this is done at a lower temperature of 35°C for 48 hours plus an atmosphere of 50% $CO_2$ [D302].

*Hygiene in the fruiting crop and crop walking*

Good hygiene within all fruiting crops is paramount to preventing the spread of diseases. Some strawberry and raspberry varieties are more susceptible to fruit rots than others, but most suffer to some degree. The fruit rotting pathogens, botrytis, rhizopus and mucor can be present on ripening fruits and the mycelium is loaded with spores that can easily be spread through a crop during harvesting. These spores can be transferred to ripe picked fruit and then manifest as post-harvest rots. Pickers should clean hands and tools between working in different sections and ideally carry hand sanitiser with them at all times. During harvest, pickers should avoid touching mouldy fruit while picking. If labour availability allows, a team should follow the pickers and pass through recently picked areas to remove all mouldy or damaged fruit from plants and any that have been dropped on the floor. Similarly, if there has been de-leafing or de-runnering of plants then plant debris should be removed immediately rather than being left on the ground harbouring spores of botrytis and powdery mildew that will be dispersed by people and machinery moving through the tunnel, field or glasshouse. Weed control is important across all crops as these can be a source of botrytis and virus transmitting pests and will take up nutrients and water that would otherwise be used to keep the crop plants healthy.

In strawberries, the removal of old trash or leaf debris from second and third year crops in the spring will help to reduce the level of inoculum that overwinters in the crop (particularly in the form of powdery mildew chasmothecia), however labour resource issues have limited its practice [D474]. Infested debris removal out of the crop is also important to prevent any spread of strawberry black spot [D501]. The common practice within strawberries and raspberries of covering of soil ridges with polythene mulches and planting through or placing grow-bags or pots on top reduces both potentially *Phytophthora* spp. infested soil splashing into strawberry crowns and fruit sitting wet and succumbing to botrytis. Similar benefit is gained from the use of fresh straw around crops grown near ground-level. Weed suppression by plastic mulches assists maintenance of a less humid environment around the fruit thus reducing the ability of powdery mildew spores to germinate.

Pruning of woody soft fruit crops is carried out to remove diseased raspberry canes and grapevine stems, for the selection of fruiting stems, and for the reduction of the canopy to lower humidity and so make conditions less favourable to the development of many foliar and stem diseases. Information on how these measures can reduce disease levels is given in the section on pruning.

In vineyards, the removal and incineration of discarded grapes, leaves and branches is advised to reduce potential disease transmission from botrytis, downy and powdery mildews and shoot diebacks to the surviving canopy, however failing that it is indicated that incorporating the discarded vegetation under a layer of mulch material would help disease suppression [D463 D464 D466 D468]. Pruning debris in raspberries should ideally be removed and burnt as pathogens can spread from this straight away or overwinter to release spores to infect healthy tissue [D360]. If pruning waste removal is not feasible then it should be pulverised in the alleys so that the fungal fruiting bodies have reduced sustenance to grow due to enhanced decomposition of their host. Pyro-disinfection using a tractor mounted flame weeder with a shredder was shown to be an effective way of killing a bacterial pathogen in kiwifruit prunings. Pyro-weeding and pyro-de-suckering has also been demonstrated in grapevines where also this heat at over 100°C directed to the ground and the lower part of the vine trunk reduced over-wintering fungal inoculum [D519].

Work in AHDB Project CP 124 [D491] found that a technique for weed control involving the application of hot foam via a lance (Foamstream) produced wet heat at over 80°C that killed *Pythium* and *Phytophthora* spp. in small raspberry roots after a couple of seconds application. Cultures of these oomycete pathogens on woven ground cover were also killed. Fusarium mycelium on agar was also tested, but resting spores produced re-growth after a delay. It is probable that pathogens on debris would also be killed as most do not survive temperatures of 50-56°C [D491]. Hot foam could be suitable for regular cleaning of flooring and benching in propagation areas, particularly as it was able to swiftly kill the oomycetes within roots whereas a soaking time is often needed to allow permeation of disinfectants, and some can be deactivated by organic matter.

Electric weed control has been investigated in bush and cane fruit [W169]. Use in the alleyways and up under blackcurrant bushes could also be suitable for cane fruit and grapevines to maintain a clean growing environment.

The benefit of an absence of pathogens in the substrate that is given by using grow-bags may be lost when growers turn used bags over and re-plant strawberries in them. There needs to be certainty that the last crop was healthy by checking the roots of discarded plants. Plants struggling to establish in infested bags may be more susceptible to die following root infection than the previous crop.

 

In substrate grown strawberries, where several plants are grown in the same coir bag, it is particularly important to rogue out diseased and dying plants infected by *Phytophthora* spp.. These water-loving oomycetes can sporulate and spread through a bag quickly and infect neighbouring plants. Regular removal of infected plants can prevent this spread. During cropping, both in the field and in bags, plants should be regularly inspected and any that remain wilted should be uprooted and taken away for destruction, otherwise resting spores will be produced as the plant decays and zoospores will then be released into the substrate to infect other strawberry plants [D361]. If the infection has spread through an entire bag then it should all be removed, as there is a chance of spread to adjacent bags via irrigation water running through tabletop troughs.

Crop walking is regularly carried out in soft fruit to monitor crop development and pests and diseases. It is often impossible to inspect entire crops and inspections are likely to include locations where the environment or growing conditions have given problems in the past. Using the same person to assess each time maintains consistency so that changing levels can be assessed, as often fine judgement is needed if a spray is to be delayed [D364]. Monitoring strategies will include knowledge of particular disease susceptibilities of varieties. In raspberries, inspections of canes should be made after leaves have fallen in autumn and again prior to bud break as cane diseases can take a while to show symptoms. Inspections of canes should continue during the growing season alongside those for leaf and fruit diseases [D368]. For grapevines, (where the same plants are present over many years) it is recommended that owners map their vineyard layout and record where there are any disease or pest symptoms during regular scouting patrols. This will guide decisions to be made on the appropriate action to manage the problem [D464].

*Pruning & other tissue removal procedures*

Across all crops the removal of diseased tissue, or the whole plant if badly affected and unlikely to recover, will reduce inoculum that could spread to healthy plants either through the air or water splash (e.g., powdery and downy mildews, rusts and other leaf / stem / branch pathogens) or via water movement around the roots (e.g., *Phytophthora* spp.).

With regular annual out-of-season pruning of grapevines, growers should aim for a balance between volume of shoots and good canopy airflow to reduce the opportunity for colonisation by botrytis, downy and powdery mildews [D463 D466]. In grapevines, the aim should be to provide a good balance between yield potential, continuing capacity for air movement within the vine foliage and reducing foliage disease transmission. Leaf removal reduces botrytis by reducing foliar moisture and allows more sunlight access to assist with powdery mildew control and fruit ripening [D463 D464 D466]. A vertical shoot positioning system, or similar, can create a narrow canopy leading to good air movement, fruit exposure and access for protective or curative treatment [D463 D466].

In Germany, grey mould (caused by *Botrytis cinerea*) along with downy mildew (caused by *Plasmopara viticola*) powdery mildew (caused by *Erysiphe necator*) on grapevines require high fungicide application frequencies at optimal application dates. However, in six of the years within the period 2000 to 2014, bunch rot due to *B. cinerea* was unable to be controlled. The situation was attributed to climate change. Measures such as pruning for canopy design, defoliation achieving a loose cluster architecture and moderate fertilization were already in use. A further measure, of early harvest is now used to save the crop, but such fruit lack the key components responsible for high quality wines [D536].

Grapevine trunk diseases and stem diebacks in the UK comprise a broad range of pathogens including *Eutypha lata* and *Cylindrocarpon*, *Botryosphaeria* and *Phomopsis* species [D471 D521]. Phylloxera has been found in isolated cases in the UK, usually traced back to grafted material from mainland Europe where the pathogen is more widespread [D521]. Esca disease (also called black dead arm and black measles) is associated with a form causing foliar symptoms and weakening of the vine or alternatively death within a few days of planting. The formation of grapevine wood necroses by the fungal species involved in esca results in the deterioration of the vascular network transport capacity [D568]. A vineyard sampling survey in Switzerland concluded that the cause of esca remains elusive because the high range of fungi isolated were identical to those found in healthy tissue. They were non-invasive and were likely to be saprophytes that had entered via pruning, frost or grafting [D471]. However, the pathogens known to cause diebacks spread spores in wet weather and gain entry via wounds, thus although pruning should be avoided in wet weather it is important to prune out diseased tissue to remove fruiting bodies that will release spores to infect healthy tissue [D521]. Disinfecting of secateurs should be done as frequently as possible to reduce the chance of spores being spread to the wound. For larger cuts, products giving physical wound protection combined with a chemical fungicide are available in countries other than the UK. Although previous use in the UK of the product Nativo (trifloxystrobin) is now restricted to vegetables, *Trichoderma atroviride* strain SC1 is registered as a plant protection product (Vintec) for use on outdoor grapes (only in the UK), with two applications permitted [D196]. The manufacturers state that this biofungicide can be used to control esca woody diseases. Growers, including organic growers, can spray Vintec soon after pruning to protect the open wounds from pathogens [D475]. The product is said to contain a strain of the fungus that has evolved and adapted to living and protecting woody species from attack from pathogens [D475]. The ability of *Trichoderma* spp. to colonize pruning wounds and reduce infection by pruning wound pathogens has been demonstrated. Soaking rootstock cuttings prior to cold storage or grating in Trichoderma formulations has also reduced incidence [D567].

Post-harvest crown thinning of strawberries that are to be retained to fruit again will both remove diseased leaves, including the overwintering spores (cleistothecia) of powdery mildew, and reduce the humidity around the leaves that is conducive to spore infection.

In raspberry crops grown through the winter, the retention of excessive numbers of spring flush primocanes should be avoided as this creates ideal conditions for infection and spread of most foliar and cane diseases. Crops should be inspected to ensure primocanes are managed to prevent wind rock or abrasion as physical injury creates sites for infections [D360]. Pruning plants not covered by tunnels should be avoided when plants are wet or just before rain [D435]. In Canada, recommendations for the reduction of cane infections include pinching off rather than cutting tender primocanes in summer when they reach the desired height, as opposed to cutting [D434.]

The complete removal of the first flush of raspberry primocanes either by desiccant herbicide, by hand or by strimming, is a method widely used to reduce excessive cane vigour in some cultivars. The removal of primocane destroys yellow rust in the initial stages of its lifecycle before any symptoms appear and with no other source of inoculum the disease is effectively controlled. The yellow rust pathogen, *Phragmidium rubi-idaei*, overwinters as teliospores on floricanes, in particular in natural splits near the base, and the basidiospores released from the teliospores require young tissue together with correct environmental conditions to be released and infect [D369 D360].

Buds can be killed and fruiting laterals can collapse following cane blight infection of raspberry [D368] and so infested cane removal should be planned so that primocanes emerging for next year are not infected [D432 D367]. As well as minimising cane blight ascospores release in April and May from overwintered pseudothecia on dead floricane stubs by pruning them down as far as possible, growing floricanes should be inspected from February onwards for the production of dark spore bodies (pycnidia) close to old wounds (usually between the cane nodes) as these are the major source of spores (mainly spread by splash). If sufficient floricanes canes can be retained, then diseased ones should be removed.

Invasion by *P. fuckelii* through the epidermis into the cortex and thence into the vascular tissue to cause cane blight occurs slowly, but is enhanced by the weakening of a cane, such as during defoliation, or by mechanical, chemical or pest injury to the epidermis [D429]. As well as aiding *P. fuckelii* entry, wounding can also reduce the cane's ability to counter pathogen invasion using phenolic compounds. Phenolic compounds are secondary metabolites produced by canes that help, among other roles, to protect against various adverse factors

 

[D430]. In canes wounded and infected by *P. fuckelii*, the chemical pathway used in sealing up these wounds competed with the pathway involved in producing antifungal defence compounds [D430].

Prompt removal of spent floricanes after harvest will remove inoculum that could infect the new floricanes [D360]. The separation of the two phases of raspberry growth (floricanes and primocanes) by biennial cropping can help to reduce disease infection as diseases such as cane botrytis, cane blight and spur blight start to sporulate on floricanes in the year after infection and the pathogen then spreads to primocanes should they be growing alongside [D360]. The pros and cons of biennial cropping were reviewed as part of integrated pest and disease management AHDB Project SF 158 [D368] and within the current report soft fruit section under crop planning.

Dense primocanes increase humidity around the canes, favouring their infection by botrytis. AHDB Project SF 74 [D472 D461] showed that thinning the number of canes reduced the incidence of leaf and cane infection in a dense crop (20 canes/m) but did not significantly reduce the incidence of fruit botrytis. De-leafing to reduce canopy humidity was not recommended as it allowed botrytis entry via the wounds. Although cane infection by botrytis can arise when the pathogen moves through the leaf into the veins and down the petiole [D360] (with leaves on old canes more susceptible to botrytis than those on younger [D359]) direct cane infection is the more likely source of cane lesions in tunnelled raspberries [D472 D461 D359]. Botrytis control on canes is important, not only is the growth of lateral buds on the infected cane affected, but the spores produced from the damaged section can infect flowers and lead to fruit rot [D360].

When herbicide removal of primocanes is used it also controls weeds within the rows that will otherwise retain humidity around cane bases and favour fungal infection. In the UK, as alternative to non-selective herbicide, hot foam has been developed and patented by Weedingtech with a system called Foamstream using renewable plant oils and sugars including oilseed rape, potato, wheat and maize, to form a biodegradable hot blanket that covers and destroys weeds. Trials on the weed control efficacy of Foamstream carried out in strawberries and organic field vegetables [W170] showed a wide spectrum of weed control, including of perennial weeds, but some multiple applications were required. Strawberry plants were damaged when hot foam was applied over the top of the plant but not when it was applied around the crown. This could be a “cleaner” method than the application of herbicide as botrytis can at times be seen sporulating after treatment of primocanes, and in the raspberry LINK project SF 74 the herbicide paraquat was used in laboratory procedures to get latent botrytis to sporulate from raspberry leaves [D472].

 

*Amendments*

A study in New Zealand found that using a mulch of crushed mussel shells enhanced sunlight reception by grapevines, however black polythene strips in the row (as used in raspberry in the UK) are probably simpler [D463]. Various mulch mediums are available and some may help to accelerate the decomposition of botrytis mycelium and sclerotia [D465].

Development of powdery mildew in strawberry is affected by nitrogen input and water stress, but the reduction in powdery mildew development under low nitrogen input or deficit irrigation was found to be rather limited [D446]. Applying a straw mulch between rows and on any plastic mulch will limit the dispersal of spores such as of Colletotrichum [D501].

*Bioprotectants (microbial & chemical)*

Bioprotectants used against plant diseases (until recently termed biofungicides) are registered plant protection products based on either microbes or natural substances (sourced or synthesised) that have a direct effect on the pathogens [D526]. Research testing the efficacy of various fungal, yeast and bacterial isolates is the first stage in product development, but even if there is success *in vitro* against a target pathogen, and potential is still found from pot screening, very few are reported to finally be tested in field trials [D214 & D543]. Various fungal and bacterial species have been found effective against botrytis and powdery mildew in strawberry and grape, with a much smaller list showing efficacy against grape downy mildew [D214 & D543]. As common for scientific publications, reports showing poor control are perhaps less likely to be published. Few promising isolates make the step to formulation as a product and the large funds needed to produce dossiers on safety (environmental and human) and efficacy to enable registration are a further hurdle. However, as there are typically no harmful residues this part of registration is not required and the products have the benefit of a zero harvest interval.

Biocontrol organisms should be applied preventatively so they can colonise the target leaf and / or root surface and reduce the ability of pathogens to find the space and nutrients they need to colonise. Enzymatic activity may also be used directly against the pathogen, and there are also indications that systemic acquired resistance can be induced within the host, priming the plant's defence mechanisms ready for any pathogen attack [D222 D223].

UK Growers and advisors should search the Chemical Regulation Division (CRD) Health and Safety Executive (HSE) website to determine which crops bioprotectants are currently authorised for and against which pathogens they have activity [D195] and any off-label authorisations (EAMUs) [D196]. The LIASON pesticide database [D202], updated daily by Fera, can be accessed by subscribers. A number of microbial bioprotectant products have been restricted by HSE to on-label use under permanent protection, such as is provided by glasshouses, and so this restricts their use in the majority of soft fruit plantations and vineyards.

Chemical fungicide drenches such as dimethomorph (Paraat) have been used routinely after transplanting soft fruit. Dimethomorph was shown to be effective at reducing root rotting in raspberry modules whether applied before or after inoculation with *P. rubi* [D368]. However, neither Serenade ASO (originally registered as *Bacillus subtilis* strain QST 713 now renamed as *Bacillus amyloliquefaciens*) nor Prestop (*Gliocladium catenulatum* strain J1446) applied in the same way reduced rotting [D368], but these bioprotectants would in any case not be expected to have curative activity. However, the trials used artificial inoculation of the root ball with *P. rubi* which potentially results in a large release of zoospores, whereas these may naturally colonise the root zone more steadily so giving a competitive advantage to the bioprotectant organism drench. Prestop is recommended to be reapplied every three to four weeks up to three times a crop on-label for strawberries and under an EAMU for outdoor cane fruit, table and wine grapes, with application number on edible crops under protection not restricted. Serenade ASO currently has an EAMU for a single drenching to outdoor raspberry against *Phytophthora*, whereas the EAMU for use on protected and outdoor raspberry and grapevines and outdoor strawberry is for spray application against botrytis, with reapplication every seven days up to six times per crop [D195 D196]. Trianum-G (*Trichoderma harzianum* strain T22) is permitted under an EAMU for use against pythium, fusarium and rhizoctonia for cane fruit and strawberry in propagation under permanent full enclosure for incorporation in organic or synthetic rooting media in trays and modules. It is permitted to be also used when transplanting these crops into bags, with applications possible at any time of year [D196].

In June-bearer strawberry crops (which have a short harvesting period), control of mildew by fungicides is relatively straight forward. However, management of mildew in ever-bearer strawberry crops is much more challenging. The long growing period from March to November and with continuous flowering, fruiting and harvest from May to November means that a range of crop protection products is usually required, with around 15 or more spray rounds needed to cover the whole period [D453]. Fruiting takes places within the spraying period and although harvest intervals are complied with there is a concern that residues may be detected on picked fruit[D453.] Bioprotectants are often exempt from maximum residue levels [D477]. Products available in the UK such as Serenade ASO, Prestop, Sonata (*Bacillus pumilis* strain QRD 2808) and AQ10 (*Ampelomyces quisqualis* strain AQ10) are in early 2022 either fully authorised or under EAMUs for use on UK strawberry under protection [D195 D196]. These offer an alternative method of control to chemical fungicides. Of the fungal bioprotectants; AQ10 can be used against powdery mildew on table grapes under protection in propagation and on protected strawberry but not raspberry and it cannot be used outdoors. Prestop can also be used outdoors on strawberry, cane fruit and grapes against botrytis as well as in all protected edibles. Of the bacterial bioprotectants; Sonata can be used on protected strawberry and raspberry, but not on outdoor crops. Serenade ASO can also be used on outdoor strawberry, raspberry and grapes as well as protected crops. Amylo X WG is a newer product to the UK market, containing *B. amyloliquefaciens* strain D747 for use on strawberry, raspberry and grape under cover or outdoors under an EAMU in early 2022. As with chemical fungicides, full authorisations and EAMUs for biological products can change as information on them is updated by the Health and Safety Executive.

The commercial biopesticides, Serenade ASO and Prestop are routinely used to manage *B. cinerea* in UK strawberries [D453]. Urea application to raspberry canes appears to suppress the sporulation of botrytis sclerotia present within the epidermis [D472].

In efficacy tests, of the bioprotectants AQ10, Serenade ASO and Trichodex (*T. harzianum* T39) sprayed onto detached strawberry leaves prior to mildew inoculation, only the Serenade ASO significantly reduced conidia germination and development of the mildew germ tube development compared with the mildew on untreated leaves and was as effective as chemical fungicides. AQ10 performed badly regardless of whether or not it was applied together with ultrafine oil[D451].

Experiments were carried out to integrate conventional fungicides with biopesticides and biostimulants for mildew control within the five-year AHDB Project SF 157 [D473]. In 2015 and 2016, the biopesticides Sonata and AQ10 achieved at least as good as or better mildew control where they were applied alone rather than alternated with or tank mixed with conventional fungicides[D453]. In 2017, with plots of the ever-bearer cultivar cv. Amesti in coir bags on ridges under tunnels, three mildew management programmes that used Sonata and fungicides were compared with untreated and fungicide only. In the Sonata based programmes, the need for treatment and the choice of products were partially determined by predicted mildew risks. A biostimulant, either fortnightly for Sirius (a silicon-based product identified as building resilience in strawberry to mildew [D460]) or monthly for Cultigrow (containing natural flavonoids and identified as reducing mildew in the 2015 and 2016 trials) was also used in two of the Sonata programmes. Mildew on the fruit rose rapidly from 2% in late July to >90 % in late August in untreated plots. In treated plots, the percentage of fruit with mildew did not rise above 3% with the three managed programmes based on Sonata. There were no significant differences in total yield and marketable yield between the managed programmes and the routine fungicide programme, but all were significantly greater than the untreated control. Most of the unmarketable fruit in the untreated control was due to infection with powdery mildew. The results suggested that strawberry powdery mildew can be effectively managed by the integrated use of biopesticides, biostimulants and conventional fungicides [D453].

Further research at East Malling Research as part of SF 157 [D473], conducted in 2018 and 2019 [D456], extended their earlier work on decision-based management programme for powdery mildew with Sonata and Cultigrow, to include management of botrytis and other fruit rots in protected strawberries. Treatments set up as replicate blocks of treatments within polytunnels of the everbearer variety Amesti over the two years included, untreated, routine weekly fungicide treatment and programmes including Sonata managed according to risk for both botrytis and powdery mildew, and for each disease separately.  Disease risks were estimated with a simple lookup table based on past and forecast weather. The integrated management for both diseases resulted in a nearly 45% reduction in conventional fungicide use and a cost saving of £699/ha compared to a routine programme with no penalties in yield, fruit quality or disease control [D456]. There were no significant effects of treatments on botrytis rot incidence compared to the untreated control, suggesting that the fungicides applied for controlling botrytis gave no benefit [D456].

A privately funded field-based study at NIAB EMR showed that addition of Silwet (silicon-based adjuvant) greatly improved spray cover of Serenade ASO (*B. subtilis*) with improvements in control of strawberry powdery mildew compared to the untreated and to Serenade ASO applied without Silwet, where spray cover was poor [D453]

Preventative chemical fungicide use against botrytis bunch rot of grapes has resulted in fungicide resistance and a consequent review on alternatives reported research utilising applications of biological control agents such as *Trichoderma*, *Bacillus*, *Ulocladium* and *Streptomyces* species [D465]. In Great Britain and Northern Ireland *Trichoderma atroviride* strain SC1 is registered as a plant protection product (Vintec) but only for use on outdoor grapes, with two applications permitted [D196]. The manufacturers state that this biofungicide can be used to control Esca woody diseases and say it contains a strain of fungus which has evolved and adapted to living and protecting woody species from attack from pathogenic diseases. They indicate that growers, including organic growers, can spray Vintec soon after pruning to protect the open wounds from pathogens [D475]. *Trichoderma harzianum, Trichoderma longibrachiatum* and *Trichoderma atroviride* have all been found effective in experimental use on grapevine pruning or grafting wounds to prevent fungal infection [D567].

In theory there could be advantages in the combined use of biocontrol agents to manage plant diseases. However, a review of various research papers, including some on strawberry grey mould examined this using theoretical modelling and concluded that only in 2% of the total 465 published treatments was there evidence for synergistic effects among biocontrol agents. In the majority of cases antagonistic interactions among the agents were indicated [D520].

A factsheet was produced by the AHDB "Getting the best from biopesticides" [D207], following efficacy trials on vegetables under the SCEPTRE Project [D198]. Advice is given on application practices and environmental factors that can affect efficacy. The subsequent AHDB AMBER Project [D199] is producing further advice to growers, particularly on the water volumes used during foliar application and the environmental conditions that should be taken into consideration. The beneficial organisms in bioprotectants usually require humidity (over 60% RH) while they colonise the plant surface. Conditions of high humidity are also those that favour many pathogens and so are likely to be a factor in deciding on the preventative bioprotectant application. Warmer temperatures (20 – 25°C) are usually optimum for the growth of beneficial organisms such as *Bacillus amyloliquefaciens* in Serenade ASO, *Gliocladium catenulatum* in Prestop and *Ampelomyces quisqualis* in AQ10 [D207], but as this is also true for most plant pathogenic bacteria and fungi this is seasonally when application is most likely to take place. The number of viable colonies of the beneficial organism on the plant can decline from the concentration applied, particularly if environmental conditions are unfavourable, but the number of colonies needed to manage the pathogen and hence re-application intervals is a grey area. Molecular quantification of viable colonies washed from leaves has been developed and PMAxx™ -qPCRis as an alternative to colony counting on agar plates [D206]. Viable DNA of *B. subtilis* QST 713 and *G. catenulatum* J1446 was retrieved from bioprotectant sprayed lettuce and strawberry plants grown under various temperature and humidity regimes, and population survival and reproduction at optimal and sub-optimal temperatures shown to be favoured by increasing relative humidity [D205]. More work is needed to provide guidance to growers so that bioprotectants are applied in suitable environmental conditions and at the best concentrations for beneficial microbes to be able to colonise plant tissue and compete with pathogenic fungi and bacteria.

A review of alternative chemicals against botrytis in vineyards found oils from holy basil (*Odmum sanctum*) and peach (*Prunus persica*) could be of benefit [D465]..

*Biostimulants and elicitors*

Biostimulants, which are usually naturally occurring products such as plant extracts or nutrients that have no direct effect on the fungus, can act by boosting the disease resistance in the host plant and may also have benefits in yield and fruit quality. The term elicitor relates to particular biostimulants that stimulate / elicit a defence response in the plants to which they are applied. An AHDB review reported on biostimulant use on arable crops including the types of product and their contents and the evidence base for positive biostimulant effects [D110 D215]. A further AHDB review was produced in 2019 for the AHDB Project CP 184 on elicitors with potential activity against downy mildews and aerial spread *Phytophthora* spp. [D216]. A range of types of elicitor were reviewed and the tables below extracted from this report provides a knowledge summary of the resistance mechanisms that have been shown to be elicited in experiments with particular host plants.

Table 10. Elicitor types and examples of each with example product names, resistance types and the nature of resistance from tests against bacteria, fungi, oomycetes or viruses.

Resistance Key: ABA abscisic acid; SA, salicylic acid; SAR, Systemic acquired resistance; ISR, Induced systemic resistance; HR hyper-sensitive response.

| **Elicitor type** | **Name & commonly used abbreviation** | **Example products or source** | **Nature of resistance & pathogen/host noted** |
|---|---|---|---|
| **Chemical** | acibenzolar-S-methyl (ASM) = benzothiadiazole (BTH) | Bion, Actigard | Broad-spectrum of hosts & pathogens, SA-activated SAR |
| | β-amino butyric acid (BABA) | - | Broad-spectrum SAR (also some fungitoxicity) |
| | Probenazole and its metabolite Saccharin | Oryzemate | SAR. Mainly used on rice against a fungus & bacterium |
| | Potassium phosphite N.B. recently registered as a pesticide in EU | HortiPhyte, Farm-Fos, TKO Phosphite | Stimulation via SA & JA/ET pathways against oomycetes. Direct inhibition of *Phytophthora* spp. growth |
| | Silicon compounds (silicates, stabilised silicic acid & silica nanoparticles) | Sion | Repeated silicate application reduces powdery mildews. Silicic acid reduces bacterial & fungal infections |

| **Microbial Elicitor** | **Name & commonly used abbreviation** | **Example products or source** | **Nature of resistance & pathogen/host noted** |
|---|---|---|---|
| Bacterial | Curdlan (glycopentaose) | *Agrobacterium* sp. | *P. infestans* on potato |
| | 2,4-diacetylphloroglucinol | *Pseudomonas fluorescent* (PGPR) | ISR against *Peronospora parasitica* on Arabidopsis |
| | HrpN (harpin) | *Erwinia amylovora* | HR, SAR against *Peronospora parasitica* on Arabidopsis |
| Fungal | Chitin & chitosan | ex fungal cell walls, crustacean shells, algae | Against fungi, eliciting plant cell changes including DNA alteration, phytoalexins, lignification & callose deposition |
| | Poly- & oligoglucans | β-1,4-glucans ex plant cellulose | |

| **Plant Extract Elicitor** | **Name & commonly used abbreviation** | **Example products or source** | **Nature of resistance & pathogen/host noted** |
|---|---|---|---|
| Algal | Laminarins, β-1,3-glucans storage polysaccharides | Brown algae e.g., *Laminaria digitata* | Elicitor of defence responses & inducer of resistance against *Plasmopara viticola* in grapevine, fungi & virus |

 

| | | | |
|---|---|---|---|
| | Ulvans, heteropolysaccharides | Green algae of *Ulva* genus | Broad range of defence mechanisms, with jasmonic acid signalling & phytoalexins |
| | Carrageenans, linear polysaccharides | Red algae | Induce resistance against a broad range of pathogens |
| | Fucans | Brown algae *Ascophyllum nodosum, Fucus* & *Ecklonia* spp. | Local & systemic resistance to tobacco mosaic virus |
| Higher plants | Herbal extracts, a mixture of diverse compounds | Various | Direct antimicrobial effects. Likely influence plant metabolism synergistically directly or by priming. |
| | Giant knotweed extract | Milsana *Fallopia (Reynoutria) sachalinensis* | Anti-microbial. Defence induced peroxidase activity, phytoalexin concentration against fungi. |
| | (Neem) a pesticide | *Azadirachta indica* | Anti-microbial and resistance-inducing against fungi & bacteria |
| | Essential oil, containing methyl salicylate | *Gaultheria procumbens* | Salicylic acid defence response |
| Composts | Efficacy likely from the microbial populations | | Resistance similar to both SAR and ABA-abiotic stress responses |
| Biochar | Coproduct of pyrolised biomass | Carbon Gold | Systemic resistance including against *Phytophthora cinnamomi* & *Phytophthora cactorum* in oak and maple seedlings |

The use of a silicon nutrient in fertigation of strawberries has been shown to have increased their resilience against strawberry powdery mildew through enhancing the passive defence pathway of the treated plants. Epidemic development can be delayed by 12 to over 20 days depending on season and cultivar. This was attributed to the regular deposition of silicon in the leaves, leaf petioles and roots of strawberry plants which enhances the natural features of the plant's passive defence pathway (wax, cuticle, epidermis, palisade layer, xylem of leaf veins and stomata) [D474 D479].

The use of alfalfa hydrolysate, vitamins, chitosan, and silicon was able to promote strawberry development under condition of limited nutrients [D449].

Sirius (a silicon-based product) applied as fertigation to strawberries was identified as building resilience, delaying the development of strawberry powdery mildew [D460]. Work on powdery mildew control programmes in strawberry that included regular application of biostimulants; fortnightly for Sirius or monthly for Cultigrow (containing natural flavonoids and identified as reducing mildew in 2015 and 2016 trials) was detailed in the above section on the use of the bioprotectant Sonata (*B. pumilis*) [D453]. This trial, on a tunnel crop of the everbearer strawberry cultivar Amesti demonstrated that application of Cultigrow can contribute to powdery mildew control when used in programmes with conventional fungicides or biopesticides [D453].

In an efficacy trial on alternatives to chemical fungicides in a tunnelled 60 day strawberry crop for the control of powdery mildew [D478], a biostimulant plant protection product not approved in the UK based on an extract from the giant knotweed (*Reynoutria sachalinensis*) [D352 D483] was included in combinations with the commodity substance potassium bicarbonate or sulphur, or with both sulphur and Serenade ASO (*B. subtilis / amyloliquefaciens*). The latter three materials (approved for use on strawberry) were also used in various combinations, again weekly. All combinations significantly reduced the severity of mildew to a trace level that was consistent with commercial best practice, when at peak the untreated young leaves had under 2 cm diameter of mildew. The best combinations were potassium bicarbonate plus either Serenade ASO or sulphur, and also Serenade ASO plus sulphur. As Serenade ASO contains a bacteria, not a fungus, its efficacy remains good in combination with these two chemicals.

The elicitor derived from giant knotweed was tested in AHDB SCEPTRE trials and is now registered as a fungicide in the USA as Regalia for use on grapes and berry crops [D352], with activity against botrytis and powdery mildews. Its mode of action was said, in 2020, to remain elusive [D353]. Similarly, potassium phosphite is an elicitor still available in biostimulant products in the UK, although UK products Frutogard, for use on table and wine grapes, and Soriale, for use on apple and pear, have potassium phosphonates as their active ingredient and are registered plant protection products [D195], with direct inhibition of *Phytophthora* spp. growth recorded [D216].

Elicitors are best used preventatively and do not give 100% control [D211 D212] but can help in reducing the requirement for synthetic chemical pesticide usage. As with varietal resistance, there can be fitness costs to plants associated with the defence response perhaps resulting in reduced yield, and the secondary metabolites produced have potential to negatively affect the quality or taste of crops. The recent AHDB review [D219] produced a considerable list of uncertainties around elicitors, with further research needed on when, where and on what crops and pathogens each particular product could be used to give disease reductions.

Beneficial microbes such as arbuscular mycorrhizal fungi (AMF) may also be considered as having elicitor activity and through their colonisation of roots can improve strawberry tolerance to drought [D450]. Plant growth promoting rhizobacteria (PGPR) promote plant growth either directly by aiding resource acquisition and controlling the levels of plant hormones or indirectly by reducing the inhibitory effects of phytopathogens. Co-inoculation of both AMF and PGPR can combine the benefits of each for increased crop productivity [D234].

 

Mycorrhizal products are available to growers and can contain a mix of arbuscular mycorrhizal fungi (AMF) such as *Claroideoglomus claroideum*, *Funneliformis mosseae* (syn. *Glomus mosseae*), *Funneliformis geosporum*, *Rhizophagus irregularis (previously with Rhizophagus intraradices as Glomus intraradices)*, *Glomus microaggregatum* and *Diversispora* sp.. (pers. comm. Natallia Gulbis, PlantWorks UK Ltd.). AMF products may also contain biostimulants; e.g., a UK produced product contains molasses and plant derived amino acids that are said to support mycorrhizal development and further enhance benefits[D235], and consequently any contribution by the AMF could be harder to affirm. The same UK manufacturer [D235] sells PGPR products aimed at particular horticultural and arable crop groupings having found that different plant types can benefit from different formulations.

A 2015 review [D231] gave an overview of the advances in the production of quality AMF inocula and in the biostimulant properties of AMF on plant health, nutrition and quality of horticultural crops (fruit trees, vegetables, flower crops and ornamentals). It has been shown that AMF symbioses are able to modify host plant metabolism, stimulating the production of phytochemicals in the roots and shoots of mycorrhizal plants, with such changes potentially ascribed to a transient activation of host defence reactions and the accumulation of antioxidant compounds. The authors conclude that further research, particularly under field conditions, is needed to integrate the use of AMF into horticultural crop production.

A 2012 review of PGPRs [D236] showed these highly diverse rhizobacteria to act as biocontrol agents via local antagonism to soil-borne pathogens and / or by induction of systemic resistance (ISR) against pathogens throughout the entire plant. Rhizobacteria belonging to the genera Pseudomonas and Bacillus are well known for their antagonistic effects and their ability to trigger ISR. Several substances produced by antagonistic rhizobacteria have been related to pathogen control and indirect promotion of growth in many plants, such as siderophores and antibiotics. ISR in plants resembles pathogen-induced systemic acquired resistance (SAR) under conditions where the inducing bacteria and the challenging pathogen remain spatially separated. Both types of induced resistance render uninfected plant parts more resistant to pathogens in several plant species. Rhizobacteria induce resistance either through the salicylic acid-dependent SAR pathway or require jasmonic acid and ethylene perception from the plant for ISR. There is potential for both resistance-inducing and antagonistic rhizobacteria to be formulated in new inoculants to benefit from combinations of different mechanisms of action, leading to a more efficient use for biocontrol strategies to improve cropping systems.

*UV-C*

Powdery mildew, *Podosphaera aphanis*, is an obligate biotroph and is one of the greatest concerns of UK strawberry growers affecting both the leaves, trusses and fruit. There are several chemical products with some efficacy against mildew available, but many growers still struggle to control mildew infections in a bad year. The issue is particularly pronounced in tabletop strawberries grown in substrate under tunnels because relatively warm and humid conditions under tunnels can create an ideal environment for mildew to flourish. Mildew is a perennial problem and usually it is a case of anticipating when mildew will enter tunnels and how severely, rather than if it will come. Some growing seasons are more conducive to mildew and often growers in a region will all simultaneously experience a 'bad year' for mildew. There are conventional and biological fungicides available for mildew control, but growers often find themselves using the maximum number of sprays and still suffer issues. The application of UV-C as a non-chemical control for in-field powdery mildew has been a topic of research for several years and is now becoming a commercial reality in both field-grown and table-top grown strawberries [D448 D454]. Several companies are developing automated robotic delivered solutions including Saga Robotics, Octinion and Cleanlight.

Mildew requires temperatures above 18°C for sporulation and six hours between 15.5°C and less than 30°C for spore germination with relative humidity above 60% [D480]. This is the basis of mildew prediction models [D453 D456 D473 D474 D479 D482]. Breaking the replication cycle by treating at more frequent intervals than this is critical. UV-C treatments work by damaging the conidia which results from sporulation thereby knocking back the resident population. It has been shown that treatments followed by a period of darkness i.e., at night, are most effective[D288]. At night the fungus' repair systems that are usually protecting the fungus during the day are not active [D524].

In commercial strawberry table-top crop settings, a dose of up to 200 J/m$^2$ is being used 2-3 times per week at night in Saga Robotics trials to control mildew. Light arrays are mounted on automated battery powered Thorvald robots. The desired dose of UV-C is given by controlling the length of exposure of leaves to UV by controlling the speed of the robot. The light arrays are mounted with reflectors to maximise coverage of light and to help penetration of the canopy. Fruit that is presented well outside of the canopy and an open canopy both allow better coverage and penetration of the light. The Thorvald robots, which are commercially available to hire at a fee per hectare, currently need to be chaperoned by a person due to health and safety implications of UV-C light to bystanders. Saga Robotics trials at two sites in Kent showed that a full season using only UV-C successfully controlled powdery mildew [D525]. Researchers in the University of Florida have found that once or twice weekly application ranging from 65 – 170 J/m$^2$ provided suppression of foliar and fruit disease that was consistently equal to or better than that provided by a commercial calendar-based fungicide spray program [D289]. The University apparatus was tractor drawn and contained two 180 cm long hemicylindrical arrays of twenty 55 W low-pressure discharge UV-C lamps (operated at 30 W; peak wavelength 254 nm) covering two adjacent strawberry beds. Both tractor-drawn and fully autonomous robotic devices have also been used by Cornell AgriTech, with three seasons of weekly applications in strawberries providing season-long control of powdery mildew that was more effective than fungicides [D504]. Preliminary vineyard trials in Chardonnay grapes at Cornell AgriTech have also shown effective suppression of powdery mildew, as well as activity against downy mildew and mites. Night-time application is necessary to prevent the reversal of the UV effect due to the blue light and UVA component of natural sunlight [D504].

The key to success with both UV-C treatments and conventional control is to start applications before any visible symptoms of mildew are observed. UV-C can be used alone, but a program can also be a combination of conventional and UV treatment. For example, a clean-up spray at the very beginning of the season could be used to remove any possible infections that may have come from the nursery. Alternatively, UV-C can be used as the standard treatment but with occasional fungicide sprays to bring patches with high disease pressure under control, thereby substantially reducing the number of chemicals applied in a season.

UV-C treatment also has potential against botrytis in strawberries. Exposure of cultures of *B. cinerea* at 30 cm for 60 seconds at 206 μW/m² reduce spore viability, with a drastic increase in kill resulting from incubation for four hours in the dark immediately after exposure. Darkness may have prevented light activation of the DNA repair mechanism in microorganisms [D529]. Most pre and post-harvest strawberry fruit decays originate from flower infection. Infection after five days was reduced in strawberry petals sprayed with botrytis and then UV-treated for 60 seconds followed by a 4 hour dark period. There was no negative effect on strawberry pollen viability or germination from this period of irradiation, nor either fruit deformation or weight [D529]. *B. cinerea* occurs across a range of fruit and vegetables and these could benefit from this treatment. There are indications that strawberry powdery mildew (*Podosphaera aphanis*) and anthracnose caused by *Colletotrichum acutatum* could also be controlled [D529].

The use of UV-C was also shown to increase post-harvest life of strawberry fruit, reducing fungal infection particularly in combination with heat treatment of 45°C for three hours, with delayed germination of *B. cinerea* conidia shown *in vitro* [D532]. Similarly, inactivation of conidia of *Botrytis cinerea* and *Monilinia fructigena* was achieved using UV-C and heat treatment [D530 D531].

When the possible mechanisms of UV-C control of grey mould on strawberry fruit were investigated [D533], results suggested that UV-C treatment directly activated disease resistance. UV-C treatment significantly reduced lesion diameter and enhanced activities of chitinase, β-1, 3-glucanase, phenylalanine ammonia-lyase, peroxidase and polyphenoloxidase in strawberry fruit. Total phenolic content of the fruit was increased. The activities of antioxidant enzymes including superoxide dismutase, catalase and ascorbate peroxidase were higher in UV-C treated strawberry fruit than those in control. The expression of three defence related genes was greatly induced.

Reports have not been found for the use of UV-C against either mildew or botrytis in raspberry plantations. However, the vertical structure of the canopy should not be an issue, as in the USA UV-C treatments have been applied to a block of vertical shoot positioned Pinot Noir grapes [D534]. UV-C application once a week, one hour after sundown at a speed of two or three miles per hour, (a theoretical dose of 120 and 80 J/m$^2$, respectively) significantly reduced powdery mildew on leaves, but not on fruit. Post-harvest botrytis rotting was not reduced, but the results were affected by the poor condition of fruit bunches due to mildew [D534]. However, in other research, on table grapes, post-harvest irradiation with UV-C reduced lesion growth of *B. cinerea* after spores were applied post-treatment to intact or wounded fruit. There was an increase in the population of yeasts and bacteria within the microbial epiphytic population on UV-C treated grapes [D535].

Protype equipment trials with UV-C in Germany in a cv. Riesling vineyard have been carried out with leaves and cluster zones irradiated repeatedly at a distance of 10 cm from the canopy at a dose of ≤160 mWs/cm$^2$ alone or in combination with chemical control [D536]. Irradiation with UV-C, in addition to fungicide treatments at a reduced number of applications, was able to significantly decrease infection with grey mould to a degree of efficiency of 82% compared to standard chemical treatment that achieved 51% efficiency.

Low pressure discharge UVC lamps giving UV at precise dosing of a waveband of 254 nm give a germicidal effect. Powdery mildew can be suppressed with as little as six minutes of nighttime exposure twice per week [D504]. They could be used on fruit plants in propagation houses. LED lighting is now in use in various types of glasshouse crops and research is ongoing on how spectral composition affects crop physiology and may also affect the biology of pathogens, pests and their natural enemies, both directly and indirectly through an impact on induced plant resistance. For example, in work on aubergine, powdery mildew infection was reduced, but botrytis increased following treatments with additional far-red light [D544].

*Cold storage*

In AHDB Project SF 157 [D473] [D456] post-harvest testing of strawberries under ambient conditions showed that fruit rots caused by in particular mucor and rhizopus but also botrytis, were little affected by pre-harvest chemical or biological fungicide programmes. However, the onset of fruit rotting was able to be delayed within the commercially acceptable time frame by applying a cool chain post-harvest management regime (which included rapid removal of field heat followed by simulated on-farm storage at 3°C) [D456]. These results agree with previously obtained results in AHDB Project SF 74 on raspberry grown under protection where post-harvest cool chain management with rapid cooling to 2°C then storage for up to three days at 3°C (rather than the more generally used cold-storage of 4-5 °C) was effective in delaying fruit rotting but fungicide application failed to reduce rotting potential [D461].

## Soft fruit pest control

### Crop planning

*Field history, rotation and break crops*

Knowledge of any previous history of a pest infestation in a field, glasshouse or polytunnel can help to predict potential pest problems, particularly when considering pests that overwinter in the soil, substrate, glasshouse or polytunnel structure or on overwintering crop plants or weeds.

Although knowledge of pest infestation in the previous year's crop can help to plan pest management strategies, there is limited scope for rotation of strawberry and raspberry crops with non-host crops in order to break the life cycle of pests, as fewer crops are now grown in soil. Where soft fruit growers grow in the soil and the land is also used for arable or livestock production, it may be possible to rotate strawberry or raspberry crops with non-fruit crops. However, as most of the area of commercial strawberry and raspberry production is currently grown under either semi-permanent or permanent structures, providing them with protection against the weather for at least part of each growing season rotation is not usually a viable option. In 2020, only 23% of the UK strawberry crop was soil-grown, the rest being grown in substrate, in bags, pots or troughs. In addition, at least 75% of strawberry crops are now grown on table-tops, some of this production is outside, but most table-top crops are located within semi-permanent structures e.g., 'Spanish' tunnels with a minority of crops grown in glasshouses. In 2020, 95% of the strawberry area grown was under tunnels. Similarly, most of the raspberry crops grown to produce fruit for sale to the multiples are grown in substrate in containers in polythene clad tunnels; in 2020, 69% of the raspberry area was grown in pots and 88% of the crop grown under tunnels. There is still however some production in the open field of raspberries in substrate in pots & in the soil [P137].

In strawberry, western flower thrips (WFT), *Frankliniella occidentalis* is a major pest and overwinters as adults in soil, substrate, senescent overwintering strawberry flowers and weeds such as chickweed, groundsel and dandelion. Thus, WFT tends to be a greater problem in fields with a history of the pest and where strawberry plants, beds or growbags are kept from one year to the next, as high numbers of thrips can infest the crop early in the season and make biological control less successful [P138]. Avoiding keeping strawberry plants or used grow bags or substrate in troughs for more than one year will reduce problems with WFT control. Many strawberry crops are kept for one year only, these being plantings of ex cold stored, tray, plug or bare rooted runners of June bearing cultivars e.g., Elsanta which are used to produce a single harvest of fruit about 60 days after planting, in addition some everbearer cultivars e.g., Murano perform best in their planting year. In 2020 72% crops were one year old or less. Annual cropping of strawberry has reduced the incidence of WFT; however, some crops of everbearer & June bearing cultivars are kept for up to two years and this will increase the risk of carry-over of infestations. In addition, to reduce production costs some growers keep substrate filled bags or troughs for a second year, replanting them with a second batch of strawberry plants. This practice should be avoided to reduce the risk of overwintering WFT. In recent years, other thrips species have caused damage to strawberry fruit including rose thrips, *Thrips fuscipennis*; rubus thrips, *Thrips major;* onion thrips, *Thrips tabaci* and flower thrips, *Frankliniella occidentalis*. It is currently considered that adults of these species fly into strawberry crops from their overwintering sites or from other host plants. Much less is known about the overwintering habits of these species; rose and rubus thrips are recorded as spending the winter in tree bark crevices but onion thrips and flower thrips can overwinter in plant material. Keeping strawberry crops for only one year might reduce overwintering of some of these species but as they have caused problems on single season crops, this strategy does not seem to be as effective as with WFT. Further knowledge on the overwintering behaviour and source of these thrips species would be useful in order to confirm if field history can affect their incidence on strawberry crops [P139.]

Vine weevil, *Otiorhynchus sulcatus* can be a serious pest of soft fruit crops including strawberry, raspberry, currants and blueberry. The pest overwinters as larvae in the soil or substrate but some adult weevils can also overwinter in leaf litter and other sheltered areas. Strawberry blossom weevil, *Anthonomus rubi* also overwinters as adults in dead leaves and other plant debris. Therefore, annual cropping of strawberry crops and avoiding planting strawberry plants into used bags or substrate might reduce the risk of weevil infestations in the following crop. However, as strawberry blossom weevil often overwinters at the base of hedges surrounding soft fruit plantations, any strawberry crop is potentially vulnerable to attack [P140].

For the minority of raspberry crops grown in the soil, annual cropping is not an option for reducing vine weevil populations, although the plantation life is now five to six years rather than 10 years or more, due to problems with soil-borne disease. Therefore, if there is a history of vine weevil, avoiding successive plantings of raspberries in the same field or adjacent to other infested crops could potentially reduce the risk of infestation. However, 'long cane' summer & primocane fruiting raspberries that are grown in substrate in containers are usually retained for only one or two years, give vine weevil populations less time to build up to a damaging level [P141].

Raspberry cane midge, *Resseliella theobaldi* and blackberry leaf midge, *Dasineura plicatrix* are both important pests of raspberry. Both species overwinter as larvae in cocoons in the substrate or soil at the base of infested plants, pupate in the spring and emerge as adults. As the adults are weak fliers, they tend to infest the same or new crops at the emergence site the following year. Therefore, the identification of a problem with these midges will help to indicate the risk of infestation of crops the following year, where plantings of raspberries have been carried through the winter to crop or new plantings have been made in the same location. Similarly, raspberry leaf and bud mite, *Phyllocoptes gracilis* overwinters beneath the bud scales or in crevices in floricane bark, therefore if a raspberry crop has been infested with this pest, keeping it for two or more years may increase the risk of damage by this pest and infection with the virus it vectors [P129].

Similarly, the large and small raspberry aphid overwinter as eggs at the base of the canes, therefore any raspberry crops kept for more than one year will be at more risk of infestation and infection by the viruses that these aphid species vector [P143].

*Select low risk locations / spatial separation*

Incidence of pests that do not travel long distances to find a host might be reduced if it is possible to site new crops well away from other strawberry and raspberry crops. Most adult vine weevils move only short distances (around 40 cm per day) within a healthy strawberry crop. However, if the plants are senescing or are removed, adults can move over 50 m to find a new host crop. Planting new strawberry and raspberry crops at least 100 m from a previous infested crop can thus reduce the risk of any vine weevil adults transferring to the new crop. In practice however a high proportion of raspberry and strawberry plantings are in substrate, in troughs, bags or pots and on sites which are repeatedly used for these crops, due to their routine protection for at least part of each growing season by polythene clad tunnels. With the increasingly complicated irrigation, environmental monitoring and other crop management systems utilised for these crops, the sites of individual crop production have in many cases now become permanent [P141].

Western flower thrips (WFT) overwinters on crop plants and debris, also weeds, substrate and soil and this pest flies only short distances, although adults can be carried by the wind or on the clothing of staff from field to field. Therefore, if it is practical to site new strawberry crops on land not previously cropped with strawberry or other host plants this will reduce the risk of infestation with WFT. The invasive pest spotted wing drosophila (SWD), *Drosophila suzukii* is now a very serious pest of UK raspberry and strawberry. This pest overwinters as adults in woodland and hedgerows, therefore siting new crops well away from adjacent woodland may help along with precision monitoring of this pest in its over wintering sites to reduce the risk of infestation. However, most soft fruit crops are surrounded by hedgerows containing mixed native tree and shrub species some of which such as bramble, hawthorn and elder, provide egg laying sites in the fruit for SWD in the late summer, autumn and winter so these should also be closely monitored using suitable traps. Windbreaks comprised of single or several non-fruit bearing tree species e.g., alder, birch, willow and poplar are also planted to protect soft fruit crops and tunnels from wind damage. These do not offer sites egg laying sites for SWD unless they contain brambles or other weed species that are attractive to this pest [P144].

## Pre-cropping

*Control volunteers and weeds*

Weeds can often be the source of pests such as potato aphid, thrips and two spotted spider mite, in the spring as they can act as overwintering hosts and early season host plants before a strawberry crop is planted. Therefore, good weed control pre-cropping and throughout the growing season will reduce the potential sources of infestation with some pests. For example, western flower thrips can overwinter in chickweed, groundsel and dandelion [P138].

Weed hosts for vine weevil include dandelion, dock, knotweeds, mallow, orache, plantain and rosebay willow herb.[P141] The main aphid species infesting strawberry is the potato aphid, *Macrosiphum euphorbiae* can overwinter as eggs on rose, or more commonly as motile stages on weeds such as fat hen, rosebay willowherb and shepherd's purse or overwintered host plants. Weed control pre-cropping and avoiding keeping strawberry plants for more than one year will help to reduce early aphid infestations [P169].

*Hygiene*

In strawberry production, avoiding re-using grow bags or substrate will reduce the risk of this being a source of overwintered western flower thrips and vine weevils. Dead leaves and plant debris can be an overwintering site for strawberry blossom weevil, *Anthonomus rubi*. At the end of the season, plants, debris, grow bags and substrate should be disposed of by chopping up the plants and substrate and spreading this followed by incorporating it into the soil in the winter or early spring on a site well away from areas of soft fruit production, or disposed of at a green waste facility to avoid pests such as aphids, thrips, vine and strawberry blossom weevils transferring to the following year's crop.

 

Following good hygiene practices is essential for managing spotted-wing drosophila as the flies are attracted to volatiles from fermented fruit. Therefore, it is important to prevent the build-up of any damaged, fallen or over-ripened fruit. Removing or pruning back wild fruiting hosts can also help to reduce reinfestation of spotted-wing drosophila [P131].

In grapevines, pruning during the dormant season and pulverising the prunings can help to reduce numbers of overwintering light brown apple moth (LBAM) and grapevine moth, whereas the European grapevine moth is an immigrant to the south-east of the UK, adults fly into the crop typically in July and August but do not reproduce in the UK [P125, P122]. Removing mummified clusters of fruit, when pruning grapevines and removing overwintering sites under the vines can reduce populations of tortrix moths [P125].

*Phytosanitary legislation*

It is important to plant healthy young plants that are free from pests and diseases. The Fruit Propagation Certification Scheme (FPCS) encourages the production and use of healthy planting stock by UK soft fruit growers. Propagators must join the FCPS in order to sell certified plants to commercial growers [P145]. The Animal and Plant Health Agency (APHA) Plant Health and Seeds Inspectors (PHSI) inspect plants entered for certification under this scheme and according to their grade, at least once a year to check that they meet FPCS standards.

The APHA Certification scheme for strawberry and raspberry propagation requires at its highest foundation and elite grades plants to be grown in an aphid-proof structure. Plants are inspected by APHA and must be free from certain pests and diseases including strawberry aphid and tarsonemid mite on strawberry and meet very low tolerance levels of other pests and diseases including raspberry cane midge and some free living nematode species. These tolerance levels may be met by physical, biological, or chemical control methods as appropriate [P146 P147].

For further details on phytosanitary regulation for strawberry and raspberry, see sections 3.2.1 and 3.2.2. in the disease control section of this report.

*Crop residue burial*

For the minority of strawberry crops grown in soil, for crops that have been infested with vine weevil, replanting with strawberry the following year should be avoided. Cultivation will reduce any root system remaining in the soil that could provide a food source for vine weevil larvae and expose any larvae to predators including birds.

*Variety choice/breeding*

Although there has been considerable research into breeding soft fruit plants for disease resistance, relatively little has been done especially in regard to strawberries on breeding for resistance to pests or tolerance for fruit damage. Certain strawberry varieties such as Malling Centenary and Murano seem to be more susceptible than other varieties to thrips damage to fruit, including thrips species other than WFT such as rose thrips, *Thrips fuscipennis* that are currently damaging UK strawberry crops. It has been suggested that this may be partly due to the large, upward-facing flowers of these cultivars that could be particularly attractive to thrips and suitable for their feeding and reproduction [P139].

In UK research, mature flowers at the top of cv. Camarillo plants had twice as many adult WFT as flowers located at the side of plants. [P148] The cultivar Murano also has highly visible flowers held on flower trusses above the foliar canopy of plants and this, together with its earlier flowering time, was suggested to be the reason for higher numbers of flower thrips, *Frankliniella intonsa* and onion thrips, *Thrips tabaci* populations on this cultivar than on cv. Furore in Denmark [P149].

There could be many plant traits that confer host suitability to thrips. Although many strawberry cultivars, particularly everbearers now tend to be of relatively short term commercial importance before they are replaced with new ones, it would be very useful to identify the traits that could allow plant breeders to select for some host plant resistance or tolerance to thrips.

Similarly, raspberry cultivars vary considerably in their susceptibility to pests. Glen Ample and Tulameen are particularly susceptible to the large raspberry aphid, *Amphorophora idaei*. Currently there are at least five recognised biotypes of this aphid present in UK raspberry plantations. Plant breeders have been able to identify and utilise gene resistance to the feeding and thereby substantially reduce or prevent the transmission of several viruses vectored by this aphid species in raspberry. However, in recent years UK populations of large raspberry aphid have developed resistance-breaking biotypes. This has led to aphid-transmitted viruses such as black raspberry necrosis virus re-appearing in plantations containing the newest and some of the best cultivars available to the industry [P150 P151 P152].

Raspberry varieties that have few or no leaf hairs such as Glen Ample are more susceptible to raspberry leaf and bud mite. Varietal susceptibility to this pest was investigated in AHDB project SF 81. Eight raspberry varieties and a hybrid were assessed. Malling Landmark and Tayberry were the most susceptible and Autumn Bliss was the least susceptible. It was hypothesised that leaf or bud morphology may be important in controlling susceptibility [P153].

Raspberry varieties that have easily splitting canes such as Glen Moy and Glen Clova are more susceptible to raspberry cane midge egg laying than others such as Glen Prosen or Tulameen. In recent years the methods used for the management of unwanted primocane and late spring frost damage to primocane have induced cane splitting in cultivars which generally do not exhibit this trait e.g., Maravilla, rendering them also susceptible to damage by raspberry cane midge.

## In-crop

*Bioprotectants – invertebrate biocontrol agents*

Biological control agents are widely used for pest control on both strawberry and raspberry within Integrated Pest Management (IPM) programmes. This is due to pesticide resistance in some key pests, withdrawal of pesticides, increasing government and retail pressures to reduce reliance on chemical pesticides, and the need to protect bees used for pollination. In 2020, approximately one third of the UK strawberry area was treated with biological control agents and the most widely used for pest control were *Neoseiulus cucumeris* and *Orius* sp. for thrips control, *Phytoseiulus persimilis* for two-spotted spider mite control, *Aphidius colemani* for aphid control and entomopathogenic nematodes for vine weevil control. In the same year, approximately 25% of the UK raspberry area was treated with biological control agents and the most widely used for pest control were *Phytoseiulus persimilis* for the control of two-spotted spider mite, entomopathogenic nematodes for vine weevil and thrips control and *Neoseiulus cucumeris* for thrips control under Spanish tunnels [P137].

Western flower thrips (WFT) is resistant to spinosad and many other chemical pesticides. The predatory mite *Neoseiulus cucumeris* can give good control of WFT on both protected and outdoor strawberry if used preventively in sufficient numbers, despite it only feeding on first instar larvae. Growers often supplement biological control of WFT with the predatory bug *Orius laevigatus* which feeds on both thrips adults and larvae, and some growers also use the ground-dwelling predatory mite *Stratiolaelaps scimitus* for control of larvae and pupae once larvae have dropped to the ground to pupate [P138].

However, *N. cucumeris* used for WFT control on strawberry has not given control of other thrips species now damaging the fruit, such as the rose thrips, *Thrips fuscipennis*. The increased incidence of these other species could be due to the reduced use of broad-spectrum pesticides for control of other pests which used to give incidental control. The failure of *N. cucumeris* to give control of these species is considered to be due to the damage being caused by large numbers of adult thrips flying into the crop, as no rose thrips larvae and very few larvae of the other species except for WFT have been found in strawberry flowers in AHDB-funded research. Unlike *N. cucumeris*, *Orius laevigatus* feeds on both thrips larvae and adults. However, this predator takes several weeks to establish and needs warm temperatures to breed, therefore damage by these other thrips species can occur before sufficient *O. laevigatus* are present in the crop [P139]. The naturally occurring anthocorid bugs

 

*Anthocoris nemorum* often occur on both strawberry and raspberry crops and will give some control of thrips, aphids and other soft-bodied prey (ADAS, unpublished).

*Aphidius colemani* is the most common biological control agent used for aphid control on protected strawberry. Of the aphid species commonly infesting strawberry, this parasitoid is only effective against the melon and cotton aphid, *Aphis gossypii*. The most common aphid infesting UK strawberry crops is the potato aphid, *Macrosiphum euphorbiae* which is parasitised by *Aphidius ervi* and *Praon volucre.* These two parasitoids also parasitise the large raspberry aphid. Although the latter species often occurs naturally in strawberry and raspberry crops, it is only commercially available in species mixes. The best strategy for using aphid parasitoids in strawberry is to use a commercial mix of five or six species, which will control all aphids infesting the crop except for the strawberry aphid. However, a naturally occurring parasitoid, *Aphidius eglanteriae* can occur in strawberry crops and can help in control [P170].

The parasitoid mixes are more expensive than single parasitoid species and so they are not as widely used. But aphids are now one of the most important pests of strawberry and with the withdrawal of several key aphicides, growers are more interested in adopting biological control methods. Naturally occurring hyperparasitoids can occur in all crops where aphid parasitoids are active. These attack the parasitised aphids, so are a threat to biological control. Therefore, the release of aphid predators such as the predatory midge, *Aphidoletes aphidimyza*, hoverflies such as *Eupeodes* sp. and the lacewing, *Chrysoperla carnea* is often needed in addition to parasitoids and these should be effective against all aphid species. These predators, together with ladybird species, can also occur naturally in soft fruit crops, particularly where pesticide use is limited in IPM programmes.

There are a range of entomopathogenic nematode species available for vine weevil control and these are widely and effectively used on both protected and outdoor strawberry and raspberry. They are more effective in substrate-grown crops than those grown in soil, due to the more frequent and effective irrigation that provides a damp substrate suitable for nematode survival. Most strawberry and raspberry crops are irrigated with drip irrigation and this method is widely and cost effectively used for nematode application [P141].

Research in HDC project SF 81 showed that the predatory mite *Amblyseius andersoni* predated more raspberry leaf and bud mites than *Neoseiulus cucumeris* or *Typhlodromus pyri* in laboratory tests. *Amblyseius andersoni* greatly reduced the number of leaf and bud mites in a small-scale semi-field experiment under controlled conditions but was ineffective in a trial on a commercial raspberry crop, possibly due to the availability of alternative prey or food sources [P142].

 

Currently there are no commercially available biological control agents for spotted wing drosophila, but in recent research, five species of naturally occurring parasitoids have been confirmed emerging from spotted wing drosophila pupae from adults trapped in wild areas in the UK [P171].

Several biological control agents were evaluated for biological control of blackberry leaf midge in AHDB project SF 102. Both *Neoseiulus cucumeris* and *Amblyseius andersoni* predated blackberry leaf midge eggs and larvae in laboratory tests. *Neoseiulus cucumeris* reduced the percentage of infested leaf tips on blackberry in a research tunnel but were not tested on a commercial crop. As first blackberry midge adults can emerge as early as March when raspberry crops are not yet flowering, *N. cucumeris* is unlikely to establish well without pollen being available as food. A commercial pollen product, Nutrimite is available for helping predatory mites to establish but this does not seem to benefit *N. cucumeris* as much as other species [P154] .

The naturally occurring predatory bugs *Anthocoris nemorum* and *Orius laevigatus* were observed feeding on blackberry leaf midge larvae in a commercial blackberry crop. Laboratory studies with *O. laevigatus* showed that they were good predators of the larvae. However, they did not establish on a blackberry crop when released in March and April despite flowering plants being provided as a source of pollen. Releases in June led to good establishment by early August, but this was too late to provide any control of first generation midge larvae which is critical to control of this pest [P155].

In laboratory pot tests in AHDB project SF 158, the entomopathogenic nematode *Steinernema kraussei* reduced numbers of blackberry leaf midge adults emerging from compost infested with larvae, simulating them dropping to the ground to pupate. However, when used in a field trial on a soil-grown blackberry crop, drenches of the nematodes did not reduce leaf damage by the pest, possibly due to sub-optimal timing or to lack of sufficient moisture in the soil.

*Bioprotectants – microbial biocontrol agents*

The entomopathogenic fungus *Metarhizium brunneum* (*anisopliae*) is approved for use in growing media or soil against vine weevil larvae on strawberry but the commercial product Met52 Granular Bioinsecticide is no longer available and the UK availability of the new product Lalguard M52 is currently unclear. When Met52 Granular Biopesticide was available it gave disappointing control of vine weevil on some farms due to its inactivity at low temperatures. Therefore, it was recommended only to be used as part of an IPM programme together with nematodes [P141].

 

The entomopathogenic fungus *Beauveria bassiana* (the products Naturalis-L and Botanigard WP) is approved for use on strawberry grown under permanent protection (in glasshouses) for control of whitefly and it will also give some control of thrips and aphids. The fungus needs high humidity to sporulate and grow on the insect's body, therefore spray applications need to be timed carefully. Naturalis-L is approved for use on any edible crop and was tested on a commercial blackberry crop for control of blackberry leaf midge but was ineffective [P155].

*Beauveria bassiana* has also given promising results against spotted wing drosophila in laboratory experiments [P156]. Both *B. bassiana* and *M. anisopliae* have given promising control of raspberry leaf and bud mite in recent laboratory experiments in Switzerland [P157].

*Bioprotectants – natural substances*

The fatty acids product Flipper is approved for use on strawberry grown under permanent protection (in glasshouses) and has an EAMU for use on both outdoor and protected strawberry and raspberry (including in polytunnels) for the control of aphids, spider mites, thrips and strawberry blossom weevil. Flipper was tested against blackberry leaf midge in an AHDB funded trial but was ineffective [P158].

Flipper was also tested against aphids on strawberry in AHDB project SF 156 but this product, together with the maltodextrin product Majestik gave no control of either *Aphis gossypii* or *Macrosiphum euphorbiae*. However, the products were not applied as frequently as growers are likely to apply them and as both products need good contact activity to kill the target pest, frequent applications are often necessary [P159].

*Physically acting products*

Physically acting products for pest control are exempt from the approval process but as such should not be recommended as a plant protection product. An example product is Protac SF containing silicon polymers that is applied as a spray and forms a net over pests such as aphids, thrips, spider mites and whiteflies. Treatment immobilises the pest which subsequently dies. The product requires good contact and has potential harmful effects on beneficials, although it will be safe once spray residues are dry [P160].

*Bioprotectants – semiochemicals for monitoring and 'mass monitoring'*

Semiochemicals are substances given off by animals, plants or other organisms and used for communication within or between species. Examples of these are sex pheromones and naturally derived lures or repellents. If they are recommended to be used for pest control rather than monitoring, they must be approved for use as a plant protection product. However, the term 'mass monitoring' or 'precision monitoring' is sometimes used when semiochemicals are used to manipulate pests to aid control. For example, in Horticulture LINK project HL01107, the western flower thrips aggregation pheromone used in conjunction with blue roller traps as a 'mass monitoring' technique reduced numbers of WFT and fruit damage in strawberry [P161].

This method is being used by growers as part of an IPM programme in strawberry where WFT pressure is high. Current research in AHDB project SF 174 is evaluating whether different semiochemicals can be used in a push-pull strategy for controlling other species of thrips that damage strawberry such as the rose thrips, *Thrips fuscipennis*. Semiochemicals being tested include methyl salicylate (Magipal) as the push component, used as release sachets in the crop and two thrips lures used for 'pulling' thrips to blue roller traps; methyl isonicotinate (Lurem-TR) and Thripnok, used as sachets placed on roller traps positioned under the table-tops. Methyl salicylate is a signal molecule for systemic acquired resistance in plants; it is given off by plants in response to pest feeding. Magipal is marketed as a natural enemy attractant [P114] but it has also been shown to have some repellent activity against pests. Lurem-TR is known to attract several thrips species [P139].

A similar push-pull strategy using Magipal and the sex pheromones of either raspberry cane midge or blackberry leaf midge is also being researched in AHDB project SF 174.

*Decision support and monitoring*

Monitoring of pests, damage and biological control agents is key to successful IPM. Growers and agronomists can monitor by regularly checking plants and also by using traps such as sticky traps or pheromone traps. Insect sex pheromones are widely used as monitoring tools in both strawberry and raspberry. Examples include the raspberry cane midge and blackberry leaf midge sex pheromones which are used in delta traps to aid detection of the first generation male midges, to aid in timing of application of control measures when a threshold number is reached [P129].

Pheromone traps for strawberry blossom weevil use the sex aggregation pheromone that attracts both males and females and are used in vaned funnel traps [P140].

Bait traps are widely used in all soft fruit crops for monitoring spotted wing drosophila adults. These are containers baited with mixtures that include, for example, cider vinegar, grape must and sugar that attract both male and female flies and are available from several suppliers. They can be used at a low density for monitoring and at a higher density for 'precision monitoring' around the edges of fields [P162].

Mathematical models use data on pest development rates at different temperatures and other environmental parameters to predict important life events in pests to aid timing of control measures as a decision support system. One of the earliest prediction models developed for soft fruit pests was the prediction of the first raspberry cane midge adult emergence in outdoor field-grown raspberry crops based on cumulative soil temperatures. This model is no longer used due to the development of sex pheromone traps. More recently, a model to predict key spotted wing drosophila life stages such as first egg laying is currently being developed [P163].

*CATT treatment*

CATT (Controlled Atmosphere Temperature Treatment) was developed and scaled up for commercial use at Wageningen University in the Netherlands. Plants are held in an air-tight containers and held in conditions of increased temperature and controlled humidity, oxygen and carbon dioxide levels. CATT is applied over 48 hours at 35°C and 50% $CO_2$. The technique can be used to control pests such as tarsonemid mites and nematodes on propagating material such as strawberry and as a quarantine treatment for import and export. From 2009 it was scaled to a commercial level and widely applied by Dutch producers of planting stock [P229 P230]. Current research is evaluating its effect on additional pests such as western flower thrips and whiteflies. The technique may become more widely available in the future [P164].

*Hygiene*

Following good hygiene practices in strawberry and raspberry is essential for managing spotted-wing drosophila (SWD). Unlike native fruit flies, SWD adults are attracted to under-ripe fruit to lay eggs and any unpicked or fallen fruit may be infested with eggs or larvae that can then develop into adults if left in the crop. Therefore, it is important to collect any unpicked or fallen fruit at every pick followed by its appropriate disposal such as at an anaerobic digestion facility or by placing it into sealed plastic pallet bins. Once the bins are sealed, rapid depletion of oxygen occurs leads to anaerobic fermentation of the fruit, which results in the death of the larvae within 48 hours. The fermented fruit waste can then be disposed of by rotavating it into the soil [P165 P166].

Similarly, any plant material that is removed during the growing season, such as cut back raspberry canes, diseased plant material or plant debris should ideally be disposed of away from the farm. In practice, disposal at a green waste facility is usually impractical so spent floricane & unwanted primocane are generally cut and dropped into the tractor alleys of crops where they are macerated using a mower or pulveriser fitted to the rear of a tractor. Where feasible some growers will after harvest remove canes from the alleys post pruning to be disposed of by burning away from the area of crop production. Where long cane raspberry plants are grown in substrate in pots and used to produce a single or at most two crops, after the final harvest, the irrigation ceases and once wilted the plants are removed with their roots from the pots and pulverised in the crop alleys. This practice can give good results where the pulverisation is carried out correctly and involves the incorporation of the plant debris into well-established grassed down alleys.

 

*In-field non-cropped areas*

There is current interest in sowing wildflower strips around many crops including strawberry and raspberry to provide shelter and alternative food sources such as pollen and nectar for pollinators and natural enemies such as hoverflies. The wildflower seed mixes should be carefully selected as flowering plants can also be a source of pests such as capsids and thrips. Current research in AHDB project SF 174 is evaluating the beneficials and pests on wildflower margins around research tunnels growing strawberry and on commercial soft fruit farms. Hedgerows are also a source of anthocorid bugs which can contribute to control of various pests such as aphids and thrips. Further information on providing plants for beneficials is given in the top fruit section 1.1.3 of this report.

*Intercropping/companion crops*

Intercropping garlic with strawberry in tunnels reduced numbers of strawberry aphid, *Chaetosiphon fragaefolii* in an AHDB-funded experiment in project SF 156. Garlic cloves were planted into the grow bags and every two weeks, garlic leaves were broken off and placed onto the strawberry crop. This led to significantly fewer aphids on the strawberry plants than in untreated plots, possibly due to garlic volatiles repelling the aphids. However, only one experiment was completed, and it was not confirmed whether the garlic treatment reduced aphid damage. Some growers have tried this approach for aphid control but with very mixed results [P167].

*Nutrient management*

Some pests such as aphids increase in numbers on host plants receiving high nitrogen inputs. Avoiding using too much nitrogen fertiliser will help to avoid this problem. However, the production of strawberries in substrate requires the use of fertigation which can lead more often to an excessive of nitrogen application than when crops were grown in soil. Often growers fail to take account of the specific requirements for nitrogen of individual cultivars and also to take account of the nitrogen that is in the water they are using for irrigation [P167].

*Physical exclusion of pests*

Insect-proof netting can be used to exclude pests from protected structures, either by screening glasshouse vents or by using nets over the ends or sides of tunnels. In soft fruit production, this method is primarily used for exclusion of spotted wing drosophila and immigrant thrips species but will also exclude immigrant aphids [P172].

Mesh size should be selected according to the size of the pest. Although netting used to exclude SWD will reduce some thrips immigration, ideally thrips-proof netting needs to be much finer than that used for spotted wing drosophila and can lead to poor ventilation and disease problems. Therefore, lowering thrips-proof netting must be timed carefully, e.g., when immigrant thrips species begin to fly into crops. However, netting can also exclude natural beneficials which is a concern to growers.

*Physical mulches*

In AHDB project SF 102, use of groundcover matting on the surface of compost in a laboratory experiment gave a good reduction in numbers of blackberry leaf midge adults emerging from pupae after larvae had been placed onto the matting to simulate them dropping to the ground to pupate [P155]. In a subsequent AHDB review, anecdotal evidence indicated that use of ground-cover matting gave good cultural control of both blackberry leaf midge and raspberry cane midge in a commercial raspberry crop, by blocking first generation adult emergence from the soil and preventing any larvae successfully pupating once dropped to the ground to pupate. However, the matting would be needed over the entire floor of the polythene clad tunnel and this would be costly to install and maintain [P168].

## Soft fruit weed control

### Current status

Many weed species can be found in soft fruit crops. Wind dispersed species can be a particular problem in containerised fruit production, whilst most weeds can be problematic in soil grown crops.

Strawberries may be grown in the soil or in containers. In the 2020 survey [W131] 23% of the crop was grown directly in the soil with the remainder (67%) being grown in bags, pots or troughs. Approximately 75% of the crop was grown on a table-top system, bags were placed on the mulch or a ground mulch was used beneath the table-tops.

Strawberries grown in the soil are planted either in plastic covered raised bed rows or matted rows, where daughter plants are trained to grow in rows around the mother plant. The latter system has greater potential for weed control issues, with more inaccessible areas for weeds to become established. The survey [W131] also said forty-two percent of the crop was either planted through a ground mulch (polythene or woven fabric) or bags placed on the mulch. Ninety five percent of all crops, by area grown, was covered by tunnels.

Many strawberries are cropped for a single year only, as in the 2020 survey [W131] 72% of strawberries encountered were one year old or less with a further 23% between 1 & 2 years old.

Only 30% of strawberry crops received an herbicide, with treated crops only receiving 2 herbicides on average [W131]. The most commonly used herbicides were glyphosate, carfentrazone-ethyl, isoxaben, propyzamide and napropamide.

 

Soft fruit crops grown in the soil without plastic mulches generally have residual herbicides at the start of the season to reduce the numbers of germinating weed seedlings. Glyphosate and carfentrazone-ethyl are used for total control of weeds overall in the dormant season treatment to selectively clean up existing weeds in plastic mulched beds or can be applied through a shielded sprayer between the rows early in the season. Isoxaben is a selective herbicide applied during the dormant season, propyzamide is for outdoor crops only applied between 1st October and 31st December and napropamide is applied after topping foliage after 1 November and before end February.

For raspberries, the 2020 survey [W131] indicated that the majority (69%) are grow in pots with most of the remaining area grown in soil, and a small area (<1%) being grown in bags. Fifty-six percent of crops were one year old or less, 39% between two and five years old, and a further 3% being between six and ten years old. Overall, 88% of the crop was grown under tunnels, the majority of which were Spanish tunnels.

Only 57% of raspberry crops received a herbicide [W131] and the majority of these crops received two herbicides. The top five herbicides applied were carfentrazone-ethyl, glyphosate, propyzamide, pendimethalin and isoxaben. General weed control accounted for 76% of herbicide applications and 3% for grass weeds, 21% of herbicide usage was for spawn control. Spawn control involves using herbicides to remove new shoots that appear at the base of the mature plants in soil grown crops.

For vines, the 2020 survey showed that nearly all were grown in the soil and there was minimal (<1%) use of tunnels [W131]. Twenty seven percent of the crop was five years old or less, 36% was between six and ten years and 27% was over ten years old.

Only 55% of vines received a herbicide and the majority of these crops received two herbicide applications [W131]. The top five herbicides were glyphosate, carfentrazone-ethyl, propyzamide, fluazifop-p-butyl and pendimethalin. Herbicides were used to remove weeds from around the base of vines and prevent further emergence occurring.

## Crop planning

*Rotations*

Some soft fruit growers rent land from arable or livestock farmers, which can aid in weed control through rotation for annual crops grown in open fields. Where semi-permanent or permanent structures are used the rotation is often difficult to achieve.

## Pre-cropping

*Hygiene*

Weed control in adjacent areas is important for reducing the amount of air-borne seeds reaching containerised soft fruit. Timing of weed control is important to ensure that weeds are dealt with before setting seed and preferably before flowering. Non-cropping areas adjacent to the containers should be kept clean and clutter free, as weeds can germinate in a relatively small amount of debris left in the cropping area even on the weed membrane [W132].

Plants propagated in substrate, such as strawberry tray plants or long cane raspberry modules should be inspected at planting, and any weed seedlings removed.

Re-used substrate or containers can be a source of weeds in future plants. Wherever possible re-using substrate should not be practiced and substrate should not be left exposed in open bags before use, as seeds can collect there. Where containers are re-used they should be thoroughly cleaned to avoid contamination.

## In-crop

*Hygiene/mowing*

Mowing is often employed around the headland in a crop to stop weeds flowering and is used in both soil and containerised production, with timing of mowing critical to stop seed spread [W132].

Where vegetative alleyways are maintained in vines, the understory up to the base of the crop can be mown to control vegetation.

In tabletop strawberry production the area underneath the gantry may be left as vegetation, which will be mown or strimmed regularly to reduce humidity and the risk of disease, particularly if the crop is tunnelled. Mowing machinery is available where the mower head position can be altered to accommodate the tabletop legs.

*Mechanical weeding*

Hand weeding is generally employed by smaller farms and those growing containerised fruit, where the numbers of pots and area to cover is relatively small, unless a large work force is available. Specific weeds may be targeted, as the labour cost for this method of weed control is high.

Mechanical weeding is not possible within the pots of containerised fruit, but could be employed in soil cropping situations, for example in strawberries. Bespoke machinery is likely to be required for fruit crops. Where mechanical weeders are used the overall depth should be shallow enough not to cause damage to the roots. This will be more effective where the weed spectrum does not include species with rhizomes, as this method may spread these.

 

Shallow cultivation in the crop rows, no deeper than 2-3 cm, may be carried out where the use of plastic mulch is undesirable, which is more applicable to vines as there is a risk of damaging shallow rooted soft fruits.

*Mulches*

In general, containerised soft fruit pots are placed onto weed suppression membrane on the ground, such as woven polypropylene. This is often used in conjunction with residual herbicides in order to control weeds in container-grown soft fruit.

Raspberries grown in the soil are usually planted into ridges through black plastic sheet or woven polypropylene and this suppresses most weed growth and with irrigation from drip hose along the planting ridge under the sheeting soil drying around the roots is reduced.

Straw mulching is often used in between the rows of strawberry crops grown in the soil as it provides good weed suppression, however it can result in lower efficacy of residual herbicides if these are applied following mulching. There is also the risk that straw could bring in weed seed contamination. The straw may be combined with plastic mulches for an efficient covering of the soil for weed suppression.

*Thermal*

There is potential for hot foam application, but this requires a water source and when using a hand lance there is a limit to the hose length to the area to be treated and power from a generator is needed to pressurise and heat the foam. In the UK, hot foam has been developed and patented by Weedingtech with a system called Foamstream using renewable plant oils and sugars including oilseed rape, potato, wheat and maize, which is considered as a biodegradable hot blanket that covers and destroys weeds. Trials on the weed control efficacy of the hot foam technology from Foamstream were carried out in hardy ornamental nursery stock, strawberries and organic field vegetables [W170]. The results showed the wide spectrum of weed control, including of perennial weeds, that this method can provide, however multiple applications were required. Strawberry plants were damaged when hot foam was applied over the top of the plant but not when it was applied around the crown. It was identified that some improvements in the technique were required for crop applications which included treatment speed, application timing and design of tractor mounted equipment that could apply the foam between more than two rows in open field situations. Hot foam treatments have been trialled in other studies, such as for hardy nursery stock (HNS) in AHDB project CP 086 [W133] and have the potential for use in soil grown soft fruit. Multiple applications were necessary in this study in order to get good weed control.

Electric weed control was also investigated in bush and cane fruit within the AHDB SCEPTRE Project [W169] and evaluated for Defra together with the costs for raspberry, strawberry and blackcurrants [W168]. Use in the alleyways and up under blackcurrant bushes could also be suitable for grapevines.

 

# Arable Crops

## Current status

This section reviews the non-chemical control strategies that may have a role in controlling the key diseases, pests and weeds in arable crops, including rye, triticale, pea and beans (dry and fresh), fodder crops and linseed.

Approximately 35,000 hectares of linseed were grown in the United Kingdom in 2020[W174], of which 92% was spring sown. On average the crop received 3 herbicides, 1 fungicide and 1 insecticide predominantly applied between March and August. Glyphosate was used to control weeds prior to drilling, with spring germinating broad-leaved and grass weeds being the main target of post-emergence treatment. The crop was often desiccated to speed up harvesting. The main diseases reported were botrytis, leaf spot and septoria. Flea beetle was the main target for insecticide use during establishment.

In 2020, 31,000 hectares of rye were grown receiving 3 herbicides, 2 fungicides, 2 growth regulators and 1 insecticide[W174]. Rye is sown in the autumn and it is attractive for use in IPM situations as it is very competitive, has low disease levels, can be grown with low inputs and provides an early harvest for a following crop of oilseed rape. Its drought-tolerance makes it suitable for light soils.

Triticale is a cross between rye and wheat and has many of the positive attributes of rye making it again attractive for use in an IPM situation. In 2020 it was sown on 14,000 hectares in the UK. It has good disease resistance including resistance against take-all so it can be used as a 3$^{rd}$ or 4$^{th}$ cereal crop. Both tritcale and rye are tall making the use of growth regulators essential to reduce the risk of lodging.

The fodder crops grown in the UK and considered here, are fodder beet and mangolds (21,000ha), turnips and swedes (9,000ha) and kale, cabbage and rape (8,000 ha) (figures for 2017)[W173]. All fodder crops were treated with herbicides to control weeds during the establishment phase when they are susceptible to competition. In maize disease levels are starting to increase and some crops were treated for eyespot. Fodder beet and mangolds were treated for a number of insect pests. The brassica fodder crops were treated with an insecticide for flea beetle and sometimes a fungicide was applied for mildew or phoma. Generally applications were low.

Peas and beans as legumes form a valuable part of the rotation fixing nitrogen and providing the opportunity to use an alternate range of herbicides for weed control. Peas for dry harvest were sown on 51,000 ha in 2020 receiving 3 herbicide, 2 insecticide and 1 fungicide[W174]. Field beans were sown on 182,000 ha in 2020 with 70% of the area being spring sown. They received 3 herbicide, 2 insecticide and 2 fungicides.

Peas and beans for fresh harvest included vining peas (86% of the total), runner beans, broad beans, French beans and peas for picking were sown on 41,000ha in 2019, receiving on average 2 herbicides, 2 insecticides and 1 fungicide [D510].

## Arable crops, disease control

### Crop planning

*Field history, rotation and break crops*

Crop rotations are crucial for peas and beans to reduce levels of disease pressure. A five-year rotation is recommended as the minimum time to reduce levels of infection from diseases such as *Botrytis* [D163] and mildews [D164]. Control of sclerotinia disease requires a minimum of one non-host crop in a five-year rotation but more is beneficial [D165] and for bean rust at least a four-year rotation is recommended [D166]. Prescence of volunteer and weed plants can also be a source of inoculum for these diseases.

In cereals, such as rye and triticale, if the same crop species is grown in the same field for successive seasons, foliar and stem disease carry over from trash and volunteers can present an issue. Soil-borne diseases are encouraged by repeat cropping [D189, D191]. Foliar diseases such as yellow and brown rust, powdery mildew, Septoria leaf spot, *Rhynchosporium* and net blotch can also be introduced early into the following crop where there this a lack of cropping rotation [D191]. This can be through resting spores infecting new growth in the autumn, or via volunteers from the previous crop acting as a 'green bridge' for disease [D189].

It has long been recognized that a number of cultural practices influence the severity of clubroot and the longevity of resting spores in the soil. [P114] Early studies [D572 D573], led to recommendations for the removal of diseased plants, improved drainage, deep ploughing, ridging (or bedforming), and crop rotation. Many of these are still widely practiced today. Crop rotation with non-host species is commonly practiced to avoid clubroot, but very few long-term studies on the effect of crop rotation on the survival of resting spores of *P. brassicae* have been conducted. Wallenhammar[D577] demonstrated a half-life for *P. brassicae* spore inoculum of 3.6 years. Therefore, at high soil inoculum concentrations, extremely long rotations are needed to reduce soil inoculum to levels below a disease-causing threshold. This work also indicated that 17.3 years were required to reduce the level of infestation in soil from 100% infection to below that which could be detected using a plant bioassay. In another study conducted over a 5-year period, continuous fallow, or cultivation with a clubroot-resistant Japanese radish caused the greatest decrease in resting-spore viability. Reduction of *P. brassicae* spores using crop rotation depends upon the removal of cruciferous weeds [D573], including shepherd's purse and wild radishes and mustards, which are also hosts of *P. brassicae.*

Linseed suits most soil types and is not related to any other break crops which means that it can easily slot into most rotations. Linseed suffers from relatively few diseases, and for those with oilseed rape in the rotation it will provide a valuable break from clubroot (*Plasmodiophora brassicae*) and stem canker (*Leptosphaeria maculans*). Unlike oilseed rape, linseed does not suffer from Turnip Yellow Mosaic Virus (TYMV) either. Fusarium wilt in linseed, *Fusarium oxysporum* f. sp. *Lini*, is limited to a host range of linseed and flax, and it should not be confused with *Fusarium solani*, which is a complex species that is one cause of 'damping off' in a wide range of different host plants including peas, beans, potatoes and weeds such as fat hen, shepherd's purse, chickweed, thistle, field pansy, lucerne, as well as volunteer oilseed rape, cereals and linseed. Fusarium wilt *Fusarium oxysporum* is a soil fungus, but it can also be seed borne. Fusarium wilt can infect linseed at any growth stage and invades through the roots and develops in the water-conducting tissues which impairs water transport, resulting in characteristic wilting and plant death. The best control method is an integrated control consisting of rotation (minimum interval of three, preferably five years), tolerant varieties and crop nutrition. Acidic and sandy soils are more conducive to disease infection so identifying and correcting soil pH is relevant. [D287]

Relating to fodder crops, information about the uptake of IPM measures by Scottish growers was collected alongside the 2017 grass and fodder crop pesticide usage survey. [P113] In total, IPM data was collected from 119 farmers, collectively growing 18,711 ha of crops (17,408 ha grass, 1,302 ha fodder). The crops surveyed included direct sown grass, undersown grass, grass one to four years old, grass over five years old, rough grazing, arable silage, fodder beet, fodder rape, kale and cabbage, maize, stubble turnips, turnips and swedes and other fodder crops.

65 per cent of growers used crop rotation to reduce the risk of pest damage. Rotation breaks the link between pest and host, reducing pest population build-up. It can also improve soil fertility and structure, and consequently crop vigour.

Table 10. Summary of responses to IPM risk management questions

| Risk management activity | Percentage positive response |
|---|---|
| Crop rotation | 65 |
| Soil testing | 84 |

 

| | |
|---|---|
| Cultivation of seed bed | 82 |
| Cultivations at sowing | 48 |
| Varietal or seed choice | 51 |
| Catch and cover cropping | 9 |
| Protection or enhancement of beneficial organism populations | 57 |
| Any risk management activity | 97 |

The majority of growers (84 per cent) tested their soil in order to tailor inputs to improve crop performance (Table 11). By testing for nutritional and pest status, farmers' can make informed decisions about the inputs required and optimal crop choice for their land. Most testing encountered was for soil nutrients (76 per cent) and soil pH and/or lime requirements (soil buffering capacity) (19 per cent). Lower proportions of growers tested for soil pests such as nematodes, leatherjackets and wheat bulb fly (3, 3 and 1 per cent respectively) or soil-borne disease (clubroot, one per cent). Soil mapping and testing for earthworm activity were also each reported by 1 per cent of growers.

*Select low risk locations*

Epidemics of yellow rust, which represents a significant threat to triticale, tend to be more severe in coastal regions due to the favourable conditions created of cooler summers and frequent sea mists. This is particularly the case in the eastern regions [D189]. Brown rust, a particular problem for rye, thrives in higher summer temperatures, so is a greater threat in the south [D189]. There is also anecdotal evidence that powdery mildew, which affects both rye and triticale, tends to favour sheltered, low-lying fields where humidity tends to be higher during the late autumn and spring. As it is not practical to completely avoid growing cereals in high risk locations in the UK integrated strategies, including adjustments to sowing dates and selection of disease resistant varieties, may be required.

*Spatial separation*

Increasing the distance between susceptible crops can significantly decrease the risk of infection by wind-borne cereal pathogens, such as powdery mildew, yellow and brown rust. Crop diversification strategies to limit the spread of wheat yellow rust, by identifying appropriate neighbouring varieties containing different resistance genes, was promoted in the 1990s and early 2000s [D181]; however, the ability to control the pathogen with fungicides has limited the value of varietal diversification.

Winter and spring varieties of beans growing at the same time should be spatially separated and should be grown away from sites where beans were grown in the previous year to reduce infection by *Botrytis* [D163]. To avoid infection with mildew in peas, and *Botrytis* in peas and beans, dense plantings should be avoided to create an open canopy less favourable to disease [D163, D164]. Sites where peas are to be planted should be suitably distanced from fields with high levels of leaf spot inoculum [D167].

*Drainage and Lime*

Clubroot caused by *Plasmodiophora brassicae* affects the Brassicaceae family of plants, including many important vegetable and broadacre crops as well as fodder crops. In the last 20 years increasing intensity of vegetable production and the rapid growth in popularity of oilseed rape as a broadacre or arable break crop have increased the severity of clubroot and the area of land affected in both the vegetable and broadacre industries.

Biofumigant crops such as high-glucosinolate-containing cultivars of *B. rapa* and *B. napus* have been shown to reduce soil inoculum of *P. brassicae* [D570, D571], however, as these crops are hosts for *P. brassicae*, their use in rotation with vegetable brassicas carries significant associated risk.

Managing clubroot by raising soil alkalinity is one of the oldest and most widely practiced methods of control[D572]. Incidence and severity of disease is generally reduced at soil pH 7.2 [D573, D572], but a number of control failures have been reported at or above pH 7.2 [D574, D575].

The contradictory results may be explained in terms of the number of variables that exist when lime is applied in the field. Particle distribution, for example, depends upon soil preparation, moisture and texture, particle size and quantity of lime, and the incubation interval between application and planting.

### Pre-cropping

*Cultivations*

Beans sown in winter are more likely to succumb to *Botrytis* infection which can be present at low levels over winter and then rapidly develop during wet periods in spring[D163]. Soil cultivations can be effective in controlling ergot, as if the sclerotia are buried they cannot infect the standing crop.

*Seed rate*

The work has not been done (or at least published) for rye and triticale but there is some evidence showing an effect of humidity associated with high crop density on powdery mildew crop development (see sections on grapes and strawberries). Crop density is related to seed rate and increasing seed rate too high can contribute to an excessive canopy size, which creates a microclimate favourable to disease.

 

*Sowing date*

Delayed sowing of peas can reduce *Botrytis* infection due to wet conditions in early spring. Delayed sowing of peas can also reduce the risk of leaf spot infection [D167]. Later sowing (mid-October) has been shown to reduce the severity of cereal diseases such as Septoria leaf spot [D192], take-all [D187], eyespot [D186]. Spring epidemics of yellow rust in winter wheat have been found to increase in severity with later sowings so this is also likely to be true for triticale (a hybrid between rye and wheat) [D185]. This may be due to younger plants being more susceptible to severe rust infection [D184]. Yellow rust infection and development is also known to be influenced by temperature [D177]. Powdery mildew epidemics are also often more severe in late sown cereals crops [D183]. Overwintering brown rust tends to be higher in earlier sown wheat and barley, increasing risk of severe epidemics if spring and summer weather conditions are favourable.

*Seed testing and Variety choice*

In peas, seeds should be tested against leaf spot pathogens to ensure disease-free material is planted. In addition, there are varieties of peas with some resistance to leaf spot pathogens [D167]. Resistance ratings to downy mildew are published for peas allowing growers to select varieties with resistance [D164]. To further prevent downy mildew disease good hygiene practices and biosecurity must be followed. Any irrigation should avoid creating prolonged periods of leaf wetness which can encourage infection [D164]. Sourcing clean seed that is free from weeds and diseases, such as ergot, can prevent the introduction and spread of annual weeds and many seed borne diseases. It is not possible to completely exclude some diseases, such as *Rhynchosporium*, as they are not screened through standard seed testing.

Different strategies are needed to control different diseases in linseed or fibre flax crops. Resistance breeding is the most important for the control of serious pathogens like *Fusarium oxysporum* f.sp. *lini,* which cannot be effectively controlled by other means, and *Melampsora lini* is also effective against several other pathogens [D286]

There are good sources of information on disease resistance to many of the major cereal pathogens in the Recommended Lists and Descriptive Lists published by AHDB and by other levy-funded projects [D193]. This information is updated annually, which is vital for tracking the emergence of new races of pathogens (and hence the breakdown of resistance in some varieties). Resistance to individual diseases is rated on a 1-9 scale. Although Recommended Lists are not available for rye and triticale varieties, Descriptive Lists that provide information on the varieties without a recommendation are available. Disease resistant scores are available for rye brown rust and triticale yellow rust. Powdery mildew can also be controlled through host resistance in rye [D172] and triticale [D173] but this information is not contained within the Descriptive Lists. This could be due to a lack of UK data on the performance of such genes in the varieties in the field, or a lack of effective disease resistance genes in the UK germplasm [D169].

*Variety mixtures*

Meta-analysis on cereal varietal mixture studies on yellow rust have shown that disease severity can be reduced in mixtures by up to 28% in wheat [D169]. Mixture effects were greater where disease pressure was higher. In barley, mixtures have also proven effective in controlling powdery mildew [D170] and brown rust [D171] so an effect of mixtures on the control of biotrophs, such as mildew and rust, in other cereal crops, i.e. rye and triticale, would be expected.

*Stubble management*

Regarding linseed, fusarium can survive in soil for 5-10 years, surviving as saprophytes (lives on dead/decaying organic matter) in plant debris in soil indefinitely and producing dormant and tough resting spores. Delayed drilling and ploughing down infected crop residues has a lower impact on disease levels, than environmental conducive conditions of the season on disease levels. *F. Solani* is an opportunistic disease and will infect stressed crops. To reduce stress sufficient soil moisture at sowing is important and if conditions are dry consider delaying drilling. Good seedbeds will give good seed to soil contact and aid plant establishment and improve plant resilience to weather and disease stresses. [D287]

*Soil/substrate tre*atments and amendments

Many pathogens affecting peas and beans, such as rusts and leaf spots, can overwinter in crop debris. Some pathogens including *Sclerotinia* and *Botrytis* produce sclerotia, specialised structures to aid long term survival [D168]. Removal of crop debris and volunteer plants can reduce the inoculum of all pea and bean diseases discussed, which in turn reduces potential infection of crops in the following years [D164, D166, D168].

## In-crop

*Decision support*

DSS are available on the CropMonitor Pro platform, for wheat septoria, yellow rust, brown rust, powdery mildew and fusarium. As these are the main diseases for triticale (a wheat/rye hybrid) they may be useful in guiding crop protection decisions for that crop.

The integrated management of ergot, a cereal grain disease, includes removal of grassweed hosts e.g., black-grass and ryegrass, either in the crop or in the field margins, which has been proven effective in reducing the level of infection [D108].

 

DDS are effective management tools for the prevention and control of clubroot, and rhizoctonia in fodder crops and sclerotinia in pulses and should be encouraged, developed and promoted.

*Amendments*

An adequate supply of soil phosphate is important for broad beans and peas to prevent early senescence which might provide an inoculum source of *Botrytis* for further infection [D168]. In addition, nutrient deficiencies should be avoided to ensure healthy plants are grown to avoid diseases such as rusts, *Botrytis* or mildews developing [D166].

*Microbial bioprotectants*

Some commercially available microbial biocontrol agents are available to control diseases of beans. Prestop® (*Gliocladium catenulatum* strain JI446) is available as a biological control agent against *Botrytis* in broad beans (AHDB 18/15) and Contans® WG (*Coniothyrium minitans* strain CON/M/91-08.), is available to control *Sclerotinia sclerotiorum* and *Sclerotinia minor* in bean crops.

Control of powdery mildew (*Blumeria graminis* spp.) in triticale and other cereals by the biofungicide Serenade (R) ASO (*Bacillus amyloliquefaciens* (former *subtilis*) strain QST 713) has been found to be moderate in the range of 20-65% [D174]. The benefits of the biofungicide were greater at the early stage of disease development i.e., when applied at the same time or soon after pathogen inoculation. Serenade (R) ASO is therefore not suitable as a stand-alone control measure and further research is needed to understand the role of biofungicides in an integrated disease management approach in cereals.

*Nutrient Management*

In cereals, nitrogen overfertilization can lead to thick, dense crop canopies. The increased humidity within the crop can drive development biotrophs, such as rusts [D180,D175] and powdery mildew as well as splash borne necrotrophs such as Septoria [D179]. Additionally, when excessive N is applied, rusts have been shown to reduce export of N to grains during filling, reducing grain protein content [D178].

## Arable crops, pest control

### Crop planning

*Field history and Rotation*

Invertebrate pests of arable crops cause damage either by direct feeding or by the transmission of viruses. In cereals, the most economically important pests are aphid vectors of barley yellow dwarf virus (BYDV). To limit the impact of bean weevils and pea aphids, sites where infestations have previously occurred should be avoided [P101].

The Flax flea beetle (*Aphthona euphorbiae*) is active in the spring and therefore only of potential consequence to spring-sown linseed crops. The winter linseed crop is not a target for Cabbage Stem Flea Beetle (*Psylliodes chrysocephala*) that causes so many of the problems associated with establishing oilseed rape and therefore growers may choose to opt for an autumn sown crop, particularly if local history predicates Flax flea beetle as a pest.

*Select low risk situations*

BYDV risk is higher in fields close to the sea and in fields in which the surrounding land use is dominated by arable land [P111]. The south-west is also considered a higher risk as the climate allows for a longer period of aphid migration than elsewhere in the country. As it is not practical to completely avoid growing cereals in high risk locations in the UK integrated strategies (including adjustments to sowing dates and selection of disease resistant/tolerant varieties) may be required.

## Pre-cropping

*Cover crops*

Cover crops can improve crop yield, environmental quality and improve soil physical, chemical and biological properties. In addition to enhancing organic matter, they can increase nutrient release, suppress weeds, and control pests. The species selected, their termination stage and termination method all have a bearing on these benefits[D576].

However, recent research has shown that the main impact which the use of cover crops have on grass weed control in a cereals and oilseeds rotation are a result of the underlying cultural control methods used, in conjunction with the establishment and use of cover crops (e.g. the use of spring cropping) and not the cover crop itself[147]. Cover crop studies have found that delayed sowing in combination with a stale seedbed considerably reduced weed pressure in all plots regardless of cover crop[314]

*Primary cultivations*

Ploughing is effective in removing volunteers and many weeds that may be sources of viruses, such as BYDV which infects cereals including rye and triticale. Green bridge transmission of BYDV can occur when aphids transfer from ploughed-down grass or weedy stubbles to new cereal crops. This can occur without the aphids having to appear above ground. Common grass weeds, such as rye grasses, can act as virus reservoirs for BYDV [D108] and therefore should be controlled through cultivations to bury the seed, mechanical/physical weeding with machinery or by hand, or through herbicides.

 

*Secondary cultivations*

Fodder crops surveyed [P116] demonstrated the majority of growers (82 per cent) also reported that they managed their seed bed agronomy to improve crop performance and reduce pest risk (Figure 1). 61 per cent increased soil organic matter, 8 per cent of growers used non-inversion tillage (primarily min till, with one report of strip tillage) and 10 per cent used direct drilling. Non-inversion techniques can preserve soil moisture and organic matter and reduce compaction and erosion. There is also evidence that it is beneficial for populations of earth worms and predatory ground beetles. 19 per cent employed rotational ploughing between periods of non-inversion cultivation; rotational ploughing can reduce weed burden and is also used to incorporate organic matter.

In addition, 6 per cent of growers reported other seed bed cultivations to improve crop performance, these included using mechanical methods such as disc harrowing, ploughing and rolling to attempt to reduce slug populations, rolling to combat leatherjacket larvae and application of lime to improve soil quality and crop health.

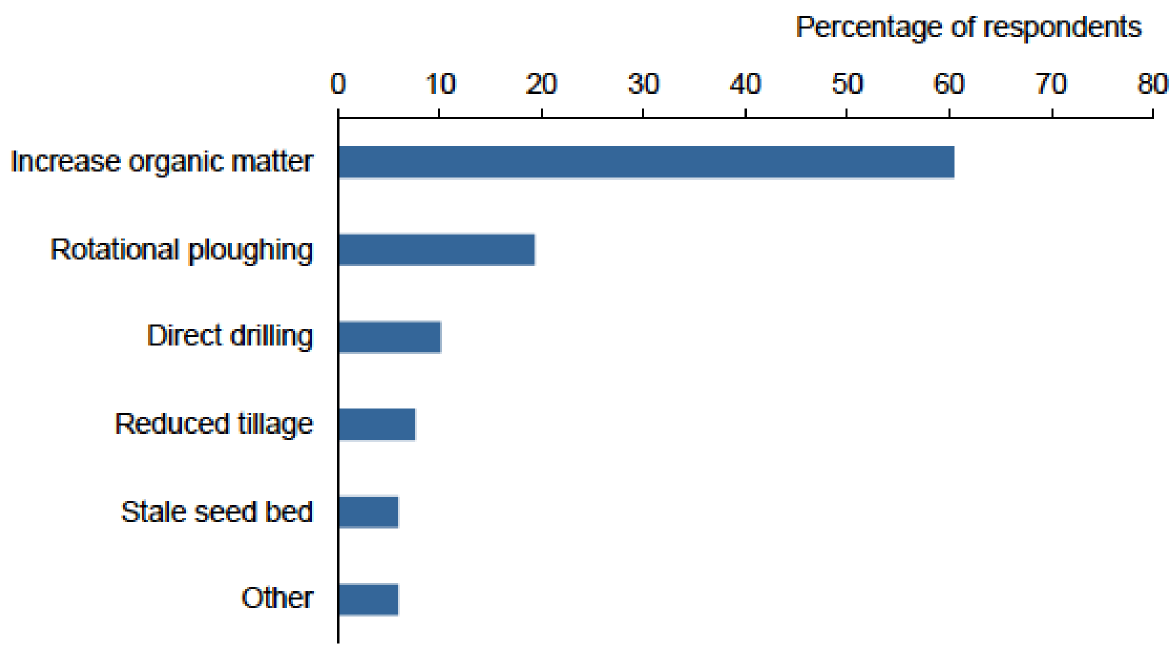


Figure 1: IPM: Seed bed cultivations

Note: 'other' includes using mechanical methods for slug (harrowing and rolling) and leatherjacket (rolling) control and liming soil

 

*Early harvest*

The impact of bruchid beetles can be reduced by harvesting beans before they reach maturity. If beans reach maturity, the bruchid beetle can complete its lifecycle and overwinter creating the potential for infestation in the following year [P102]. In peas, the pea moth can build large populations where plants reach full maturity. Unharvested green peas should be ploughed before the moth larvae can leave dried pods [P103].

*Sowing or planting date*

Spring sown beans are more susceptible to bean weevil damage than winter beans where growth is more advanced [P105]. Black bean aphids are also more likely to cause damage to spring beans since flowering and aphid migration are more likely to overlap [P104]. Pea moth flight periods are less likely to overlap with early or late sown peas and therefore are less likely to be affected [P103].

Later sowing (mid-October) has been shown to reduce the severity of BYDV in winter cereals though late sown spring cereals tend to be more prone to BYDV than early sown[P110] because the crop will be exposed to the aphid vectors for longer than if it is sown later and closer to the end of aphid migration.

*Seed rate*

Linseed is more susceptible to flax flea beetle damage at lower planting densities [P112]. The three-season trial between 2011 and 2013 concluded that there were several cases of significantly higher numbers of flea beetle feeding symptoms on plants grown at the lowest density as compared to the medium and highest densities. Over the last 20 years or so the standard seed rate for linseed has been circa 650 seeds/$m^2$ with the aim of establishing 400 plants/$m^2$. Growers have the option of increasing their seed rates to 800 seeds/$m^2$, with the aim of having thicker crops. Whilst this is no guarantee of a higher yield, it does improve the reliability of achieving the right plant population and give the crop the best possible chance to yield.

*Seed and variety choice*

Just over half (51 per cent) of growers [P116] reported that they considered risk management when selecting seeds and/or varieties (Figure 2). 24 per cent used certified seed and one per cent tested home saved seed. These actions ensure that seed meets the required quality standards and is pathogen free. 18 per cent of farmers selected pest resistant varieties, to reduce damage and the need for pesticide input, and 3 per cent implemented varietal diversification to increase overall crop resilience to pests and environmental stresses. 22 per cent of growers used pesticide seed treatments to protect seedlings at crop emergence.

 

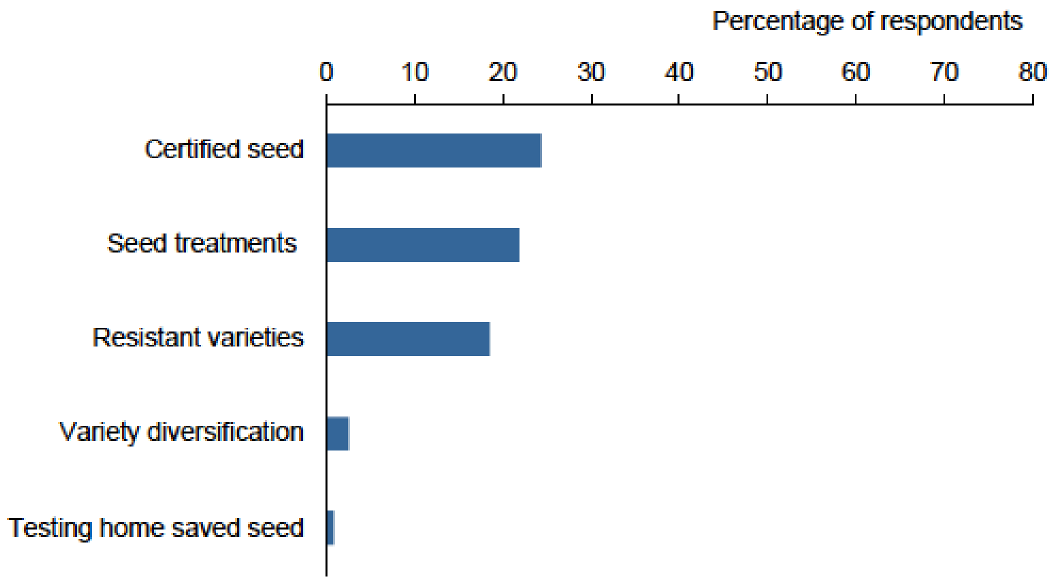


Figure 2: Variety and seed choice

## In-crop

*Bioprotectants Macrobiological*

Natural enemies should be encouraged to reduce severity of pest infestations. Spiders, ground beetles, predatory flies and parasitoids are natural predators of bean weevils [P101]. Parasitoids, ladybirds, hoverflies and lacewings are natural enemies of pea aphids [P104, P107]. The pea moth is attacked by four species of parasitic wasp [P103]. In addition, there are insect-pathogenic fungi which can infect black bean aphids and pea aphids and the pea moth [P103, P104, P107].

*Decision support including monitoring*

AHDB developed and launched a BYDV management tool in 2018 that incorporated a day degree model to encourage effective spray timing against cereal aphids in the autumn [P110]. However, the tool does not take into account important factors such as the presence of aphids or the proportion that are carrying the virus (% viruliferous). A further DSS for BYDV is available subscription to CropMonitor Pro. Other models have been developed for BYDV management and several have been identified as having good potential for use in the UK [P110].

A monitoring system made up of cone traps and a pheromone lure has been developed for bean weevils. Traps allow growers to identify whether crops should be treated for bean weevils and when they are most active so treatments can be targeted [P105]. Research to develop field traps for monitoring of bruchid beetles is ongoing. Past work has found that semiochemicals can attract the insect which could aid monitoring in the future [P102]. Beans should be inspected for black bean aphids regularly and if 10% of plants are infested treatment should start [P104]. Peas should be inspected for pea aphids and action should be taken when levels reach 15 – 20% [P104]. Monitoring for pea moth can be achieved with a pheromone trap which should be checked every two days from mid-May [P106].

Accurate models to predict adult flea beetle migration (1–2 weeks in advance) could allow fodder crop growers to better plan sowing dates to avoid peak migration. Work is ongoing on the influence of weather factors on population dynamics and additional field observation data regarding the interaction of pest pressure, crop growth stage and growing conditions. Similar work is already employed in the IPM strategy for sugar beet for example where emergency authorization is subject to the predicted level of virus yellows infection based on the migration date of the aphid vectors.

*Undersowing*

48 per cent of fodder crop growers surveyed [P113] amended cultivation methods at sowing with the aim of increasing crop success (Figure 3). 34 per cent under sowed with a secondary crop. Under sowing can increase soil fertility (when under sown with a nitrogen fixing crop), suppress weeds and provide a host for wildlife. 13 per cent varied the timing of sowing to reduce the risk from a range of pests; flea beetles, leatherjackets, pigeons, geese and weeds were all cited as reasons for changes in sowing date.

Some growers (10%) also increased sowing density to mitigate for damage from insect pests (flea beetle and leatherjackets), decrease competition from weeds or in order to improve crop establishment generally. One grower (1 per cent of sample) reported that they increased sowing depth to decrease seed loss to pigeons.

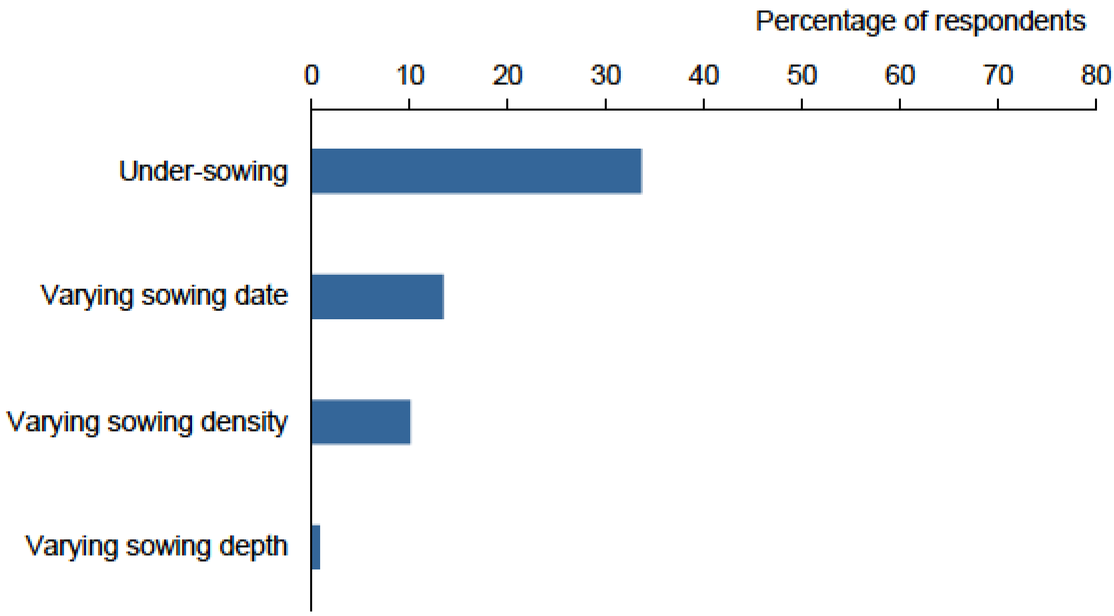


Figure 3: Cultivations at sowing

Only 9 per cent of those surveyed [P116] sowed cover crops as part of their crop production cycle. The cover crops were reported to improve soil quality, by ploughing in as a green manure, and/or to control weeds (7 and 5 per cent of the sample respectively).

*In- field non-cropped areas*

Fodder crops surveyed [P116] showed 57 per cent of growers stated that they adopted techniques to protect or enhance populations of beneficial organisms. 31 per cent left uncultivated areas, including fallow and grass margins, and five per cent planted wild flower strips. 13 per cent took part in an agri-environment scheme; the main scheme reported was the Scottish Government agri-environment climate scheme ( AECS) and actions primarily involved cultivation of wild bird seed mixes. A number of additional actions to support beneficial organism populations were also reported, some of which contributed to the Ecological Focus Area (EFA) element of the direct payment scheme. These additional measures included; planting and maintaining hedges (6 per cent) and woodland (3 per cent), planting wild bird seed crops (3 per cent) and maintaining species rich unimproved grassland (5 per cent). Other minor categories included beetle banks, conservation grazing, protecting ground nesting birds and maintenance of ponds (5 per cent in total).

## Arable crops, weed control

### Crop planning

 

*Fallow*

Fallow can be a useful tool to manage perennial and volunteer crops. Grass weeds readily emerge when soil is disturbed at the start of a fallow break and should be treated before seeds set [W102]. Since grass weed seeds cannot survive more than two to three years in the seed bank reduced tillage following a fallow break can be beneficial [W102].

*Field history and rotation*

Crop rotation can prevent weed species becoming dominant [W103]. A good rotation should include a balance of crops with different crop cycles and alternate between crops with high and low competitiveness [W103, W104]. Peas and beans are considered to have medium to low competitiveness with weeds [W104]. In sites with high weed infestation, crops with low competitiveness should be avoided [W103].

*Low risk situations*

Linseed is a poor competitor with weed plants, so it is important to determine the influence of weed populations on the subsequent performance of linseed.

Four weeds were studied at different plant populations to determine the relative importance of different weeds, and the reduction in linseed yield that weed populations could cause if left uncontrolled. [W130]

The four weed species considered were:

- Knotgrass (*Polygonum aviculare*)
- Chickweed (*Stellaria media*)
- Fat-hen (*Chenopodium album*)
- Cultivated oats (*Avena sativa*)

The main conclusions were:

- grass weeds are likely to be more damaging to linseed than broad-leaved weeds knotgrass is potentially more competitive than fat-hen, and common chickweed is the least damaging of the three studied weeds
- bearing in mind the cost of treatment, it would be uneconomic to treat infestations lower than 14 oat, 5 knotgrass, 6 fat-hen and 40 chickweed plants/m$^2$ in vigorous linseed crops.

## Pre-cropping

*Fallow*

Use of set-aside and fallow areas can help in the long-term management of grass weeds [W102].

 

*Primary cultivations*

Conventional tillage systems such as ploughing effectively mixes the seedbank through the ploughed soil but can bury seeds reducing seedling emergence for those seeds with poor longevity [W103]. In reduced tillage systems the weed seeds remain near the soil surface and as such could be prone to desiccation but equally seeds under such conditions could germinate. Any weed germination pre-planting must be controlled [W103, W104].

Common grass weeds, such as rye grasses, can act as virus reservoirs for BYDV [D108] and therefore should be controlled through cultivations to bury the seed, herbicides or mechanical weeding.

*Secondary cultivations*

The term ‘secondary’ cultivation is a broad-reaching term generally used to describe field operations with disc, tined or rotary cultivators intending to reduce average soil clod size ahead of drilling. Reducing clod size increases soil surface area and therefore encourages more weed seeds to germinate. Successive weed germination flushes can be obtained by repeating secondary cultivations at, for example, 7–10-day intervals. There is however an increase in fuel, labour and machinery use associated with this cultural control practice.

In contrast, it has been demonstrated that direct drilling, (in this case, of winter wheat), increases black-grass (*Alopecurus myosuroides*) populations by 16% when compared to non-inversion tillage. Direct drilling can decrease the weed seedbank density but increase weed diversity particularly for perennial and biennial species that have chance to thrive due to the lack of cultivation.

*Stubble management*

Volunteers and other weeds can act as a source of infection for following crops and those grown nearby. Cereal volunteers often carry a range of diseases but are most significant as a ‘green bridge’ for biotrophic pathogens such as powdery mildew, yellow rust and brown rust[D189]. Common grass weeds, such as rye grasses, can act as virus reservoirs for BYDV as well as diseases such as ergot and Ramularia [D108]. Ideally, these volunteers should be destroyed prior to the emergence of new crops. Ploughing is effective in removing volunteers and many weeds that may be sources of air-borne pathogens, such as rusts and powdery mildew. In practice, this is not always easily achieved as volunteers often emerge over several weeks and so the impact of removing volunteers is likely to be small. Thus, the integrated management of ergot includes removal of grassweed hosts e.g. black-grass and ryegrass, either in the crop or in the field margins, which has been proven effective in reducing the level of infection [D108].

 

Six per cent of fodder crop growers surveyed [P113] employed a stale seedbed technique for weed management. Stale seed beds allow weeds to germinate before sowing the next crop, these can be treated with an herbicide, or cultivated out, depleting the seed bank and resulting in lower weed pressure, and potentially herbicide use, in the subsequent crop.

*Seedbed quality and seed rate*

A good quality seedbed can improve crop establishment, allowing the canopy to close faster and enhance the effectiveness of mechanical weed control [W103]. Seeds which have not emerged under dry conditions could germinate and coincide with emerging crops. Therefore, allowing weeds to flush before drilling can reduce weed competition [W104]. Delayed drilling does not reduce annual meadow grasses [W104].

*Sowing date*

Delaying sowing date allows more time for cultural control of weeds through the creation of 'false' seedbeds however delaying the establishment of autumn sown crops reduces crop vigour and to compensate seed rates have to be increased with an accompanying increase in cost. Delaying spring established crop sowing dates may also provide opportunity for the cultivation of germinating weeds however the loss of moisture associated with repeated soil movements is a risk to subsequent crop germination.

*Cover crops*

Recent research has shown that the main impact which the use of cover crops have on grass weed control in a cereals and oilseeds rotation are a result of the underlying cultural control methods used, in conjunction with the establishment and use of cover crops (e.g. the use of spring cropping) and not the cover crop itself. Cover crop studies have found that delayed sowing in combination with a stale seedbed considerably reduced weed pressure in all plots regardless of cover crop type.

*Variety choice*

Some varieties will be more competitive against weeds due to differences in their growth habit, growth rate, plant/leaf architecture, hybrid breeding and allelopathic effects. There is little evidence however to support inclusion of varietal choice for the crops discussed in this review as an important component of IPM regarding effect on weed control.

### In-crop

 

*Defoliation and undersowing companion crops*

Defoliation, including mowing and grazing can decrease weed growth and their ability to compete with the crop. This practice can also prevent seed being returned to the seed bank which could present an issue in subsequent crops.

*Mechanical weeding and hand weeding/rouging*

Mechanical weeding is an important aspect of weed control; it is effective and does not leave chemical residues on crops. Many different tools are available to target both inter-row and intra-row weeding [W103]. 87 per cent of farmers surveyed [P113] reported that they used non-chemical control in partnership or instead of chemical control with regard to fodder crops. The most common non-chemical method employed was mowing/topping grass to control a range of grass weeds (76 per cent). Thistles were the most common weed cited but mowing was also used to control rushes, ragwort, nettles and docks. Just over a third of farmers (36 per cent) used hand rogueing/manual weeding as part of their weed control measures. Hand weeding was primarily employed to control ragwort and wild oats. Some growers also used mechanical weed control (10 per cent). The mechanical control encountered was mostly for inter-row weed control in fodder swede and turnip crops, but was also employed to control rushes, thistles and bracken in grassland. A further 10 per cent of growers used intensive grazing to control weeds, with a single grower using grazing for disease control (removal of disease inoculum). There was lower uptake of mechanical control of insects (rolling for leatherjacket larvae, 2 per cent of sample) and pest trapping and use of biocontrol/biopesticides (both 1 per cent).

In summary hand-rouging is a particularly useful practice for removing small amounts of problem weeds such as wild oats, blackgrass, sterile brome which may be difficult to control in crop due to a lack of herbicide options (e.g. to control brome in barley crops) or issues related to herbicide resistance (black grass, wild oats). The practice is only cost effective when weed populations are small due to the high cost of labour.

*Thermal weed control*

Flaming is the most common form of thermal weed control. The effectiveness is dependent on the weed growth stage and morphology but can be effectively used to control broad-leaved weeds, particularly before the crop emerges [W103].

*Undersowing companion crops and intercropping*

Under sowing companion crops and Intercropping can increase competition with weeds leading to their suppression, although there is little empirical evidence to support this theory in the UK. Studies have suggested that in cereals, weed densities can be equal to or up to

 

55% lower with companion cropping. Timing of establishment is also important. For example, if clover is planted late, it might not provide competition against weeds [D109].

## Apples and pears

### Current status

Apple and pear varieties accounted for 91% of the total area of orchard crops grown in the UK in 2020 [P120]. Insecticides accounted for 14% of the total pesticide-treated area of orchard crops and acaricides, biocontrol agents, physical control agents, growth stimulants and repellents combined only accounted for 1% of the total pesticide-treated area [P120]. Chlorantraniliprole, flonicamid and thiacloprid were the most extensively used insecticides in orchards in 2020, accounting for 20%, 15% and 13%, respectively, of insecticide use, predominantly used for the control of lepidoptera and aphid pests [P120]. In contrast, use of the repellent kaolin accounted for less than 1% of the treated crop area in 2020, its use having not been recorded since 2016 [P120]. This section reviews the non-chemical control strategies that may have a role in controlling the key diseases, pests and weeds in apples and pears.

Current status of apple and pear disease control: The main diseases in UK apples are caused by fungal pathogens, and control relies heavily on the main routine prophylactic fungicide applications. For example, in 2020, the average Cox orchard received 16 fungicide spray rounds, and for other desert apple varieties, mainly Gala and Braeburn, the average was 19 spray applications [D412]. Cox apples have been important historically but the area has substantially declined and is being replaced with other dessert varieties such as Gala and Braeburn. Dessert pears, the majority of which are variety Conference, are also a high-fungicide-input crop: in 2020 they received on average 13 fungicide applications [D412]. The main diseases of apple trees in the UK include scab (*Venturia inaequalis*), canker (*Neonectria ditissima),* powdery mildew (*Podosphaera leucotricha*) and apple replant disease [D413], which is caused by a complex of soil borne organisms including soil borne fungi such as pythium, oomycetes and nematodes [D414]. The main diseases of pears in the UK are similar to those of apples: scab (*Venturia pyrina*), powdery mildew (*Podosphaera leucotricha)*, and canker (*Neonectria ditissima).* The largest proportion of fungicide sprays are targeted specifically for scab control in both apples and pears, e.g., in 2020, 57% of fungicides on Cox were to control scab, likewise 49% on other dessert apples and 70% on pears [D412]. The intensive use of fungicides gives impetus for finding ways to reduce chemical inputs. In general, for non-chemical approaches, a sustainable reduction in disease incidence is possible when IPM approaches are used, but the effects can be more variable than with chemical control and the results achieved longer-term. In 2019 an emergency authorisation of a plant protection product permitted the use of a copper based fungicide (copper oxychloride) in UK organic apple and pear orchards for apple scab control, from just before bud burst until BBCH 69 (end of flowering). This authorisation expired on 1 August 2019 and copper sprays can no longer be used in these crops. In contrast, sulphur use is permitted but restricted to a single proprietary product (Microthiol Special) which has an extension of authorisation for a minor use of a plant protection product (EAMU) for apple powdery mildew and scab control during the growing season [D394]. Good control of apple scab with non-chemical means is difficult, but control of powdery mildew and storage diseases may be possible using cultural methods [D392, D397]. Monitoring apple and pear diseases is a vital part of disease management and there are practical guides available: AHDB crop walkers' guides for apples [D395] and for pears [D396] which aid the identification of diseases and other problems. There is more guidance for growing trees and more research on non-chemical disease control for apple crops than there is for pears.

## Apples and pears, disease control

### Crop planning

*Field history, rotation* & break crops

Selecting as low a risk location as possible for orchards is effective at reducing some diseases, in particular, apple replant disease (ARD). ARD occurs when new trees are planted in the same soil as previous trees of the same pome or stone fruit crop, i.e., apples following apples [D420 D551] and they may develop various symptoms including stunted growth, shorter internodes, reduced biomass and reduced yields [D393]. ARD is caused by the presence of a complex of soil pathogens [D437, D421] including *Phytophthora* spp, *Pythium* spp, *Fusarium* spp, etc [D422 D414]. ARD may be exacerbated by a lack of beneficial soil microorganisms, including *Bacillus* spp, *Pseudomonas* and *Chaetomium* spp [D401.] Planting new trees inter-row will help avoid ARD [D438] provided weeds are controlled effectively [D437]. Crop rotations of five years or more are likely to be effective at reducing ARD, and it is clear across all crops that the more years between planting the same crop in the same soil, the better. In general, there have been relatively few field experiments which specifically demonstrate the effects of extended rotation intervals [D416], due mainly to limitations of funding for long-term field work, but it is clear that longer rotations are an effective component of IPM with regard to managing crop diseases [D406].

Grass with white clover swards are commonly established in fields, and strips then killed where trees are to be planted, so acting as a break crop, although sowing 2 m wide strips after tree planting is also done. Complete grass cover is intensely competitive and dramatically reduces the availability of water to the tree and the uptake of nitrogen [D547]. The substitution of a pollinator mix (grasses, clover, lucerne and phacelia) or green manure [D550] (grasses, clover and lucerne) between the rows has been trialled and given improve soil structure so improving water infiltration but the lush growth can be more competitive than a mown pathway [D549].

*Drainage*

Good soil drainage is generally beneficial to tree health but with respect to disease management, it is of particular benefit for reducing the inoculum levels of soil borne diseases, including oomycete pathogens which are a likely component of ARD. Well drained soil is effective at reducing populations of oomycete spores, as it helps reduce phases of saturation which encourage oomycete proliferation and the infection of roots, and it will also encourage dispersal of oomycete spores through soil [D404].

## Pre-cropping

*Apple and pear rootstocks*

Careful rootstock selection for resistant varieties will help reduce the risk and incidence of canker (caused by *Neonectria ditissima*, formerly *Nectria galligena*) [D389, D390]. However, in general the effects of climate, soil factors, and management factors such as mowing and tree spacing will have a greater effect on canker numbers than the rootstock selection [D389]. Some rootstocks can also provide some tolerance to replant disease.

Variety choice

Most of the main culinary and dessert apple varieties in the UK are susceptible to infection by *Venturia inaequalis*, the cause of scab [D389]. Gala is very susceptible, Cox, Bramley, Jonagold, moderately susceptible; Discovery and Grenadier have a high degree of resistance (polygenic resistance). There are many varieties now available resistant to apple scab, based on Vf resistance, e.g., Saturn, Ecolette, Ahra, Topaz but few of these are commercially acceptable alternatives in the UK to the currently grown susceptible varieties.

There has been one major resistance gene introduced into commercial apple varieties, Rvi6 [D439] but breakdown of this resistance has been reported across Europe since the 1990s. A single resistance gene is unlikely to provide long term solution and there has been work on pyramiding multiple scab resistance genes in a single variety [D410].

There have been reports of decreased scab in mixed-variety orchards [D403] but the effects have not been large enough to warrant the use of multiple varieties in one orchard, although there may be more scope for using mixed varieties for apples destined for cider production.

 

Variety selection combined with IPM strategies can help reduce the levels of powdery mildew infection (caused by *Podosphaera leucotricha*, which also infects pear) [D389] but no varieties confer complete resistance. Discovery and Grenadier have a very low susceptibility to mildew, whereas varieties including Cox, Golden Delicious and Gala are very susceptible [D392].

The varieties grown are, however, in general dictated by growers' marketing groups and the public's familiarity with the taste and texture of particular varieties.

## In-crop

The AHDB online Apple Best Practice Guide provides growers with and action calendar for integrated pest and disease management tasks and details individual pest and diseases and crop husbandry measures to help to ensure a healthy crop [D391 D392 D393 D394 D548]. Much apple information also applies to pears and there is an AHDB Crop Walkers' Guide for each of the fruits [D395 D396].

*Microbial bioprotectants*

Beneficial microbes have been the subject of research towards the development of products for the reduction of apple diseases, in particular of apple scab. Various fungal species found normally inhabiting living leaf surfaces or decomposing leaves have been found to reduce the development of scab on apple leaves. This reduces the amount of spring ascospore production, which is the primary source of infection. The fungi *Chaetomium globosum* [D402] and *Cladosporium cladosporiodes* [D408] applied to apple trees have potential for reducing scab on infected leaves, and *Athelia bombacina* applied to leaf litter has the potential to prevent development of pseudothecia within leaves, as well as promote leaf degradation [D425]. Some bacteria and yeast strains have potential use in controlling scab, by suppressing the development of *Venturia inaequalis* (scab fungus) on leaves [D399]. Serenade ASO, which is a commercial product in the UK containing *Bacillus amyloliquefaciens* formerly named *B. subtilis* bacteria, was found to have limited effects [D423].

Some control of apple canker has been achieved using microbial bioprotectants, such as *Bacillus subtilis*, and *Alternaria* spp. [D390]. Use of *Trichoderma harzianum* (Trianum G) as a soil amendment had beneficial effects on canker control in two out of three experiments in orchards, reducing the number of dead trees caused by canker in newly planted orchards [D390]. No bioprotectants have been developed commercially yet for apple or pear canker control. Plant growth promoting rhizobacteria also have some promise, but evidence is limited so far [D390]. Arbuscular mycorrhizal fungi used as tree inoculants may also help [D476].

 

*Botanical and other bioprotectants*

Research with application of plant extracts [D409], e.g., thyme oil, cinnamon and orange (*Citrus sinensis*) has been trialled, but so far, effectiveness has been limited and uptake by growers has been low, due to costs and variable results achieved. In addition, there can be difficulties obtaining authorisation to use these products as pesticides.

Other 'natural products' have been tried in other countries, such as calcium hydroxide or kaolin (china clay) and have some activity against scab by acting directly on the fungus, or increasing the plant's resistance to scab, but usually, the control achieved is variable, and repeated applications are needed [D503]. Lime sulphur has been reported as a successful post-infection foliar spray, giving partial control but successfully reducing the number of spray rounds needed with conventional fungicides for pear [D502] and apple, although phytotoxic effects have been reported in some cases [D388]. Lime sulphur is available commercially, targeted at organic apple and pear production ('Curatio', 389g/l calcium polysulphide, Biofa AG, Andermatt).

SB Plant Invigorator (a blend of surfactants and foliar nutrient feed) and the adjuvant Wetcit (a natural adjuvant based on alcohol ethoxylate) can give a physical barrier to apple powdery mildew infection [D392].

*Biostimulants*

The effect of biostimulants on reducing diseases in apples is limited mainly to beneficial effects on physiological disorders in stored apples, e.g., biostimulant products based on alfalfa protein hydrolysate, seaweed extracts and B-group vitamins improved the final red colouration of apple var Jonathan [D440]. Biostimulants can provide significant yield increases [D407] which could offset the effects of diseases in organic apples not fully controlled in the absence of chemical fungicides. Alternation of conventional fungicides with biostimulants and physical acting products can reduce reliance on fungicides whilst maintaining acceptable mildew control [D389]. Recent research in AHDB Project TF 223 [D389 D390] and summarised within the Apple Best Practice Guide [D392], showed that spray programmes of monthly applied Cultigrow (a biostimulant based on flavonoids), and either Trident (a silicon-based nutrient) or Mantrac Pro (manganese nutrient) fortnightly, with conventional fungicides applied in the weeks between, gave similar levels of control to a routine seven-day fungicide programme.

*Monitoring, forecasting and decision support*

Growers undertake a yearly cycle of crop management to ensure branch, foliage and fruit health. Records of infection levels the previous year (such as for scab), knowledge of varietal susceptibility and disease lifecycles in relation to crop growth stages are all used in IPM together with observations of weather conditions conducive to disease and monitoring disease levels. Various thresholds for management options exist for apple scab, apple canker and powdery mildew across the seasons [D548 D391 D392 D394].

Apple scab monitoring and forecasting systems such as ADEM [D398] or RIM pro [D387] can help target fungicide use to high-risk weather phases, particularly in early season, and are likely to result in reduced spray applications, given the high number that are applied on average. For example, use of RimPro saved 2 to 4 sprays in field trials 2002-2004 in Denmark, achieving the same efficacy on scab as a conventional fungicide strategy based on Mills Periods [D411]. It is important to monitor trees frequently to make best use of DSS, and this includes the whole season for scab:  incidence in the orchard pre-bloom and during apple development, and then post bloom on rosette leaves and shoots and into harvest to estimate the likely scab inoculum carryover for the next year (include an estimate of leaf litter [D394]). Automated estimates of scab spore load in the air may be possible [D415]. Forecasting systems can be very helpful for targeting fungicide timings only to high-risk infection dates, not routinely. This may or may not save fungicide spray rounds [D398]. Currently, there is no non-chemical method for responding at short notice to infection alerts produced by forecasting/decision support systems.

For powdery mildew there are forecasting systems available to predict secondary infection, such as Podem [D424, D398 D392].  Podem is based on weather conditions, variety susceptibility, and observations of current infection on leaves, and gives a 3 - 4 day ahead forecast of the amount of sporulating mildew that will develop. As with scab, the response to a high infection alert is currently chemical based, and development of alternative fast-acting treatments is needed.

For canker, frequent monitoring to identify trees with symptoms is important [D390]. Prompt removal of cankers by pruning or taking out a heavily infected tree completely will be effective for reducing infection and spread of the canker fungus.

*Hygiene – leaf destruction*

Encouraging conditions in which fallen leaves are removed rapidly by earthworms, or are rotted more quickly, is an effective way to achieve a substantial reduction in the level of apple scab and pear scab ascospore inoculum in the spring [D400], [D405]. The *Venturia* sp. fungus forms fruiting bodies (pseudothecia) within leaves, which release ascospores into the air the following spring. But if leaves are degraded or removed, the number of pseudothecia and hence ascospores are reduced.  Urea sprays to trees from the start of leaf drop will encourage faster leaf degradation by encouraging microflora that speed up leaf breakdown, and will make leaves more palatable to earthworms, thus encouraging removal by earthworms. A 5% foliar urea spray applied to apple trees before leaf fall in the north-eastern USA reduced the number of scab ascospores trapped by 97% [D546]. Urea can be applied post-harvest and before leaf fall, and in spring, in non-organic orchards, but urea sprays are not allowed in organic apple production [D397]. Keeping grass well mown will encourage earthworm activity, which helps with leaf litter removal and hence helps reduce scab inoculum [D391]. Macerating excessive leaf litter with mowers is effective at encouraging faster breakdown [D394]. Some treatments, e.g., fish oil, help somewhat to promote leaf decay but results may be inconsistent [D397].

*Hygiene – pruning / canopy management*

This can play an important role in reducing infection by fungal pathogens, which often spread and infect more rapidly in humid environments. Spore infection by powdery mildew and botrytis is favoured by humidity. Pruning to allow good circulation of air is helpful, as it encourages faster drying of leaves and fruit following rain fall or dew, which will help decrease infection in particular by the humidity-loving scab fungus. Cutting out overwintering wood with scab is effective at eradication but labour intensive [D391 D413]. Pruning and cutting is effective for removing cankers and reducing further infection by the canker fungus *Neonectria*, but care must be taken to use wound protectant treatments to reduce the risk of further infection by *Neonectria* [D389], and removal of cankered prunings and apples from the orchard is essential because infected material can continue to produce ascospores for at least 1 - 2 years [D391]. Pruning and discarding infected shoots showing symptoms of primary mildew in early spring will reduce inoculum load but is labour intensive [D413]. Prunings can be burned on site, or if this is not possible, macerated to ensure rapid decay and breakdown.

The current Knip-boom propagation technique, a Dutch technique used for commercial trees where the central leader is retained with a tier of wide-angled side shoots at 70–100 cm, involves the wounding of trees, and hence sites for pathogen entry. The use of alternative methods such as producing maiden trees (single stem young trees usually 1–2 m tall) is being used during the production of particularly canker susceptible varieties as there is less wounding of trees [D413].

*Nutrient management*

Nitrogen plays and very important role in determining apple tree growth and development, fruit yield and quality [D545]. Further work is required into the effects of nitrogen fertiliser application on the quality of dessert apples under UK growing conditions [D547]. The use of nitrogen in the form of urea in the prevention of new scab infections was described previously.

Growth cracks are sites for pathogen entry to form cankers and these can be exacerbated by high nitrogen and irrigation inputs and subsequent rapid host growth. Growers can reduce this risk by optimising the amount and timing of nitrogen rich fertilisers and irrigation [D413].

 

*Organic amendments*

Generally, strategies to maintain a healthy soil, i.e., soil with a good population of microbes and organisms, are likely to reduce the severity of ARD [D413]. Some soil amendments have been trialled as treatments for ARD, such as, brassica seed meal [D417], biochar [D419] and seaweed-based fertilisers [D418] but long- term effectiveness has not been proven.

Anaerobic soil disinfestation (ASD) is a variation on organic amendment addition, where granular or liquid plant extracts (such as produced by Thatchtec in the Netherlands) have been added to ARD affected soil and covered for three to four weeks while the abundance of beneficial bacteria increases. Plants subsequently grown in this soil had increased vigour [D413].

*UV light*

UV light has been shown to be effective at controlling powdery mildew [D504], one of the main diseases affecting apple. UV light is now used in the UK for control of powdery mildew in table-top crops of strawberries in tunnels, with the UV light units working mainly at night so there is no inadvertent exposure to UV light of people working in the crops that are being treated. The approach is being used successfully on grapevines in the field, using tractor driven equipment [D504]. There is potential to develop the approach for control of powdery mildew on apple trees [D505] but there does not appear to be any current work to develop the equipment needed.

## Apples and pears, pest control

### Crop planning

*Spatial separation*

When siting a new commercial apple or pear orchard it is beneficial for it to be situated far from unsprayed orchards or gardens as these can be a source of infestation of flighted pests such lepidoptera [P118]. Alternatively, there could be an advantage in having an unsprayed orchard nearby as source of predatory insects and mites for new orchard e.g., the predatory mite *Typhlodromus, pyri*, Anthocorids & earwigs (Janet Allen, personal communication February 24, 2022).

### Pre-cropping

*Hygiene and prevention*

Removing dropped fruit from the floor of orchards can prevent lepidopteran larvae moving from dropped fruit into the soil to complete their development [P114]. This reduces the local population in the orchard the following spring. Fruit removal is expensive and some mixed farmers graze sheep or pigs under the trees to consume the dropped fruit [P114]. However, managing livestock has its own associated costs and risks damaging the soil and trees. Very few growers can do this as livestock presence in modern intensive orchard could cause irreparable damage to the trees. Shropshire Sheep Society have promoted this breed of sheep for grazing in orchards including intensive ones, but few growers have tried it so far (Janet Allen, personal communication February 24, 2022).

*Variety choice*

Apple scion varieties such as Florina and Prima are less susceptible to the rosy apple aphid [P114]. Rosy apple aphid resistance is linked to the presence of hydroxycinnamic acids, which protect fruit skin from UV light and are common in cider apple varieties [P114]. Apple varieties which are susceptible to rosy apple aphid but who's buds burst later in the season, after egg hatch tend to have fewer rosy apple aphids as the neonates cannot feed [P114]. Resistance to pear sucker has been associated with the profile of polyphenolic secondary metabolites within pear leaves, as increases in these compounds are linked to plant defence mechanisms [P114]. Winter morph pear suckers are more influenced by tree phenology than variety with a preference for advanced stage of leaf emergence for egg laying over susceptible varieties [P114]. Pear varieties such as Bartlet are less susceptible to damage from codling moth as the larvae are unable to pierce the fruit flesh due to the presence of thick stone cells (scleroids) around the calyx [P118]. Apple rootstocks MM111 & MM 106 have good resistance to Woolly apple aphid *Erisoma lanigerum* whereas M9 & M26 are very susceptible to this pest (Janet Allen, personal communication February 24, 2022).

### In-crop

*Bioprotectants - macrobiological*

There are many generalist predator species which occur naturally within an orchard habitat when conventional pesticide sprays are withheld or reduced through use of an IPM programme. Shoots with predators on can be cut and moved to other trees. Anthocorid species help to control the pear sucker, fruit tree red spider mite, and aphids [P114]. Release of commercially available *Anthocoris nemoralis* and other generalist predators such as ladybirds and lacewings can help to control pear sucker in spring when natural populations are too low for effective control [P114, P121]. Earwigs are generalist predators of pests in apple and pear orchards such as aphids, and moth caterpillars [P114]. Earwigs can cause damage in soft fruit crops, but where fruit quality and skin finish are good they are not considered a pest in top fruit [P114]. Earwig nests can be used to encourage earwig populations, these can be made from rolled up cardboard in milk bottles with dried cat food as a food source or a commercial refuge is available from Russell IPM called 'Wignest' [P114]. In organic orchards releases of five to six earwigs per tree reduced aphid numbers to 50 per tree compared with 2000 - 3000 aphids per tree in the control plots [P114]. In UK apple and pear orchards many of the insecticides currently in use have been identified as damaging to earwigs [P133].

Introducing commercially available biocontrol agents can help to suppress pest numbers before natural biocontrol agents are present in sufficient numbers, although introductions are not common in unprotected orchards due to associated costs [P114]. Predatory mites such as the generalist *Amblyseius andersoni* can be released early in the season preventatively, as it is active at low temperatures, to control pest mites such as the fruit tree red spider mite and two-spotted spider mite [P114]. This predatory mite is now being used for two-spotted spider mite and fruit tree red spider mite control in cherry orchards, mainly but not exclusively those under protection of polythene clad tunnels, or specialised covering systems [P134]. This predator can also be used in apple or pear orchards and the population can be increased in young orchards by transferring ground litter from established orchards [P135].

Parasitic wasps are commonly released in protected systems and have potential for release in orchards. *Ascogaster quadridentate* is a native parasitoid of codling moth, summer fruit tortrix and tree fruit tortrix. These are not commonly used by growers as the caterpillars can cause economic damage even at low levels [P114].

Entomopathogenic nematode species *Steinernema carpocapsae* and *Steinernema feltiae* applied to the soil can be used to contribute to control codling moth and tortrix moth during the soil dwelling stage of their lifecycles [P114]. Foliar and trunk application of nematodes can also be effective against other stages of the life cycle but require high levels of humidity to prevent nematode death by desiccation [P114, P118].

*Bioprotectants – microbial*

Granuloviruses which specifically target the codling moth can be used to provide control without affecting other species. Madex Top (*Cydia pomonella* Granulovirus isolate V15) is currently approved for use on apples and pears in the UK [P115]. It is best to apply the virus just before egg hatch to ensure that the vulnerable neonates will ingest the virus when feeding on the fruit surface [P115]. The infected larvae will continue feeding for two to four days before death, leaving shallow feeding holes known as 'sting injury', which may lead to downgrading of the fruit and is not recommended close to harvest [P118]. Older larvae are killed more slowly and may cause more damage before death or even pupate with a sublethal infection of the virus [P115, P118]. Upon death of the host the virus is released and can infect multiple generations[P115, P118]. Susceptibility of individuals to the virus can vary within a population and there are several cases of resistance to CpGV-M in Europe prompting manufacturers to develop new strains to combat resistance [P136].

 

Entomopathogenic fungi (EPF) can be an effective form of pest control, but uptake is limited due to the time between infection and death of the host, during which the pest can continue to feed and reproduce [P114]. The EPF *Beauveria bassiana* has activity against aphids, caterpillars and some mite species (two-spotted spider mite, carmine mite and tomato russet mite) [P119]. The soil-borne pathogen can infect all stages of the life cycle of most pests if sufficient contact is achieved [P119]. The fungus infects through the cuticle of the host and multiples, causing death in three to five days [P119].

The bacterium *Bacillus thuringiensis* subspecies *kurstaki* can be used to control lepidopterous larvae in many crops including apples and pears. Caterpillars ingest the bacteria which produce a crystal protein in the stomach, which releases a fatal toxin as it breaks down, destroying the insect midgut by formation of pores in the midgut cells [P116, P136]. Caterpillar activity and feeding stops immediately, followed by death from septicaemia after four to five days [P116]. This biopesticide is most effective when applied to actively feeding, young larvae, however codling moth larvae only feed for a limited time before boring into the fruit and may not ingest a lethal dose [P116, P118].

*Bioprotectants – semiochemicals*

Sex pheromones are a type of semiochemical that can be used for monitoring and mating disruption. Mating disruption can be achieved with passive pheromone dispensers, regular aerial sprays or timed-release aerosols to coincide with the female's natural pheromone release to confuse males [P114]. RAK 3+4 is a pheromone system designed to control codling moth and summer fruit tortrix by mating disruption [P118]. The system is best used in orchards greater than 1 ha in size, with a low pest population where no more than 1% of fruit was damaged in the previous year if no other controls have been used, and spatially isolated from other tall trees [P118].

Methyl salicylate is a signal molecule for systemic acquired resistance in plants. This chemical can be artificially released from dispensary sachets to attract beneficial insects such as hoverflies, lacewings, ladybirds and *Orius* to predate orchard pests [P114].

*Decision support, including monitoring*

Pheromone monitoring traps can be used to alert growers to the presence of codling moth, fruit tree tortrix, and summer fruit tortrix moths. Pheromone traps should be put out before blossom to monitor numbers of male moths to time mating disruption strategies [P118]. Pheromone trap catches only account for numbers of males and do not always indicate when egg laying occurs [P118]. The RIMpro-Cydia forecasting model can be used with trap catches to predict when egg laying occurs and inform remedial decisions such as application of biopesticides, netting or application of pesticides [P118]. Agrovista UK Ltd Growers Choice

 

Interactive service also uses computer modelling and weather data to show graphs of codling moth flight activity, egg deposition and larval emergence [P117].

*Nutrient management*

Higher soil fertility and organic matter content have been linked to lower pest pressure and avoiding excessive nutrient levels can help to prevent excessive new tree growth, which can result in high numbers of aphids e.g., Woolly apple aphid *Erisoma lanigerum* and pear suckers [P114].

*Physical exclusion of pests*

Netting individual trees to exclude insects and prevent access from the soil reduced codling moth fruit damage by 91% compared with the control in one experiment [P114]. However, netting except to provide protection against damage for hail & birds is less common in apple and pear orchards compared with stone fruit orchards, as the netting can exclude beneficial insects from their prey, allowing populations of aphids to increase [P114]. Kaolin white clay films, which are commonly used in olive production, can be used to control pear sucker in pear orchards by coating the fruit in a protective layer, which is later washed off [P114]. However, a negative effect on beneficial organisms when using this technique was observed and linked to an increase in rosy apple aphid and woolly aphid in trials [P114].

Exclusion bands can be used to prevent ants from gaining access to defend aphid colonies or supplementary sugar feeders can be used to distract ants from the aphids, enabling predators and parasitoids to access undefended aphids [P114]. Fabric or cardboard bands can be affixed to tree trunks to provide shelter for predators and to aid monitoring of some pests such as codling moth [P114].

*Undersown and companion crops*

Providing alternative vegetation in an orchard will provide many predators and parasitoids with shelter and alternative food sources, such as non-pest herbivorous invertebrates. Hedgerows consisting of goat and grey willow, hawthorn and nettle provide a habitat for anthocorids early in the season, enabling these predators to establish early, which can help provide control of pear sucker [P114]. Hoverfly larvae are voracious predators of aphids but adults feed on pollen and nectar, so providing access to flowering plants such as alyssum can help to boost the hoverfly population and improve aphid control [P114]. The common nettle can be used as a banker plant to establish the nettle aphid, which provides a food source to beneficial insects such as ladybirds, lacewings, hoverflies and parasitoids [P114]. Where ageratum, French marigold and summer savory were planted in organic orchards there was a reduction in numbers of tortrix moths and an increase in natural enemies [P114]. Many companion species can also be a host for some pest species and should be used and monitored with care.

*Pruning / canopy management*

Pruning changes environmental conditions in the tree canopy, such as humidity, temperature, ventilation, and light penetration. Training the architecture of fruit trees as they grow can reduce pest pressure, for example centrifugal pruning enabled predators to access pests more easily and reduce the numbers of aphids [P114]. Removal of curled leaves in young orchard can reduce colonies of rosy apple aphid as the founding aphids are found in these leaves during blossom [P114]. Some aphid species such as the rosy apple aphid can be attended by ant colonies of the common black ant; the ants defend aphids from predators and parasitoids in exchange for honeydew secreted by the aphids in a mutualistic relationship [P114]. In older orchards removing excess growth from the central tree zone prevents aphid colonies from establishing where they are easily accessible to ants [P114]. Instead, aphids will establish on new peripheral growth where they are more easily accessible to flying predators and parasitoids [P114]. Birds predate several pests in apple and pear orchards and can have a beneficial impact on numbers of codling moth and tortrix caterpillars during the nesting season [P114]. Pruning helps to open the canopy and allow birds access to the pests, however netting or bird scarers may be required to prevent any damage from birds when the fruit is near to ripening [P114]. Thinning the orchard canopy facilitates monitoring during crop walking and can also improve the spray coverage of biopesticides [P114].

## Apples and pears, weed control

There are just under 12,000 ha of apples, split into desert (e.g., Cox) and culinary (e.g., Bramley), 8,000 ha of cider apples and perry pears and 2,000 ha of pears were grown in the UK in 2020 [W134]. Between 74 and 85% of apples and pears were treated with herbicides and 40% of cider apples and perry pears. Apples received 2 herbicide applications predominantly applied between January and July. Pears received 3 herbicides predominantly in spring and summer with some during the autumn. The major weeds controlled were grasses, thistles and cleavers. Up to 30% of cider apples and perry pears did not receive a herbicide, these were generally older orchards grassed to the tree base and grazed by sheep.

Newly established orchards are sensitive to compaction so a 1-1.5m bare strip around the trees is kept weed free.

### Pre-cropping

*Hygiene*

Weed control in adjacent areas is important for reducing the amount of air-borne seeds reaching the crop. Timing of weed control is important to ensure that weeds are dealt with before setting seed and preferably before flowering [W132].

Where vegetative alleyways are maintained in vines, the understory up to the base of the crop can be mown to control vegetation.

In tabletop strawberry production the area underneath the gantry may be left as vegetation, which will be mown or strimmed regularly to reduce humidity and the risk of disease, particularly if the crop is tunnelled. Mowing machinery is available where the mower head position can be altered to accommodate the tabletop legs.

*Cover crops*

The use of cover cropping can be beneficial to supress weeds, as well as creating an improved soil structure and an increase in organic matter. Using red fescue (*Festuca rubra*) and black medic (*Medicago lupulina*) cover crops prior to planting blackcurrant cuttings was found to supress noxious weeds in AHDB project CP 086 [W133] with no effect on blackcurrant establishment, however the effects on yields over multiple seasons were not fully assessed. This approach could be employed prior to planting of new tree fruit orchards provided that the cover crop is completely killed off before planting.

## In-crop

*Bioprotectants botanical*

Bioherbicides, particularly essential oils and organic acids, often give poor to moderate weed control and require repeated applications at high rates, as they are not systemic and leave the plant meristem intact[W142]. However, due to initial scorching symptoms and ‘knock-down’ there is potential for bioherbicides to be used as part of an integrated weed management programme [W143].

*Mowing*

Mowing machinery can be used to maintain control of weeds in orchards, particularly in organic apple production. As with tilling machinery these mowers have ‘feeler’ bars that allow the machinery to move in and out between the trees.

Mown alleyways are maintained within orchards, as this reduces herbicide applications, stabilises the soil and maintains soil structure. There has been more of a move towards having species rich alleyways in recent years that are mown less frequently in order to encourage natural predators in orchards [W140].

 

The clippings from mowing alleyways and intra row may be spread into the row behind the tractor to act as a green mulch.

*Mechanical weeding*

Organic tree fruit production often used mechanical methods of weed removal during the season. Different front mounted machinery options are available including mechanical hoes, where a blade runs under the soil surface uprooting vegetation, and shallow depth tilling using a gang of rolling spider wheels. These may have 'feeler' bars that moves the blades away from the trees allowing the machinery to move in and out between the plants. These should be used with caution in newly established orchards as the bars can cause damage to young trees.

Orchard floor management systems trialled in an organic orchard included acetic acid application plus tilling, traditional mechanical tilling and a 'sandwich' system that combined a modified tillage system with a living mulch [W139]. The mechanical tilling was performed on a 1.5 m strip three times during the season. The 'sandwich' system had a living mulch established that was mown three times during the season with the clippings mulched on top, and a 40 cm strip tilled on either side. The three systems that included mechanical tilling performed better in terms of yield than a living mulch on its own.

*Mulches*

Mulches are often used in orchards within the herbicide strip. These may consist of green compost, bark, clippings from alleyway mowing or woven plastic. Numerous studies have demonstrated the effectiveness of organic mulches in orchard situations, either alone or in conjunction with herbicide applications [W135, W136, W137]. These studies have evaluated the effects of mulches on the yield and quality of the fruit and found no difference when compared to herbicide application alone. Particle mulches need to be kept topped-up for a continuous effect and monitored so weeds do not establish.

Living mulches, where a low competitive seed mix is sown in the strip at the time of orchard establishment, were trialled in the AHDB Weed Fellowship CP 086 [W133]. Whilst some mixes performed well in terms of weed control all treatments resulted in a yield penalty at harvest compared to the standard herbicide application, indicating how sensitive tree fruit can be to competition. Similar effects were seen in recent studies [W138, W139], where different living mulches caused smaller apples and lower yields when compared to herbicide application.

*Thermal weeding*

Thermal weeding techniques, such as flame weeding, steaming and hot foam treatment have been evaluated in apple orchards in several studies.

 

Steaming and flame weeding were evaluated in an organic orchard, comparing it to mulching [W141]. Steam application provided some initial weed control; however this was reasonably short lived, with further applications necessary seven days after the initial application. Flame weeding provided good initial control of seedlings of annual weeds but did not perform well on perennial or weeds with six or more true leaves. A driving speed of 2 km/hr provided the best weed control in the trial. Flame application should not be applied in conjunction with a mulch due to fire risks involved.

Hot foam treatments have been trialled in other studies, such as for HNS in AHDB project CP 086 [W133] and have the potential for use in tree fruit crops. Multiple applications were necessary in this study in order to get good weed control. Trialling would need to be performed on each crop as each one will differ in their sensitivity to the treatment.

If suitable technologies are developed for use in orchards work will need to be done on making them cost effective for large scale applications.

## Field vegetables

### Current status

This section reviews the non-chemical control strategies that may have a role in controlling the key diseases, pests and weeds in some of the main field vegetable crops, including carrots, onions, leafy brassicas, root brassicas, endive and lettuce. Reference should also be made to the 2012 review carried out for Defra on the efficacy of non-chemical control methods in agriculture and horticulture [D109] and the recent AHDB review on IPM in arable rotations [D109].

As with most horticultural produce, the high quality standards expected that result in products with foliar spotting, root deformity or blemishes becoming unmarketable for human consumption mean that routine preventative fungicide use is practised, particularly against pathogens infecting foliage.

The Pesticide Usage Survey for outdoor vegetables for the 2018/19 [D510] season states that of the total UK area of outdoor vegetables grown; brassicas accounted for 21%, carrots, parsnips and celery 13%, onions and leeks 10%, lettuce, endive and radicchio 4% while root crucifers and other root vegetables covered 3%. Pea and bean crops accounted for 34% of the area and are covered in a separate section of the current report. Celery and leeks have been omitted from specific review in the current report. The main foliar applied fungicides were azoxystrobin, mancozeb, prothioconazole, difenoconazole, pyraclostrobin and boscalid.

The diseases the growers' named as their reason for fungicide treating their outdoor vegetable diseases in the UK in 2018/19 [D510], in order of descending commonest mention were; for leafy brassicas - downy mildew, ringspot, powdery mildew and ringspot; onions and leeks – downy mildew, white rot and botrytis; carrots, parsnips and celery – sclerotinia, crown rot, cavity spot, late blight, septoria; lettuce, endive and radicchio – unspecified mildew, downy mildew, botrytis, sclerotinia, white tip and ringspot. For root brassicas, growers recorded usage only as “for general disease control”, and so within the current report the control of the root diseases club root, phoma and common scab was reviewed, with foliar pathogens covered within leafy brassicas. The diseases covered by this current review can be seen on the summary tables and include pathogens that are more likely to cause losses in propagation, such as xanthomonas in brassicas and rhizoctonia in lettuce, and where there is little tolerance blemish by a disease such as from light leaf spot on Brussels sprouts.

Information on management of vegetable pests, disease and weeds can also be related to fodder rape, kale and cabbage, stubble turnips, turnips and swedes reviewed within the arable section of this report, although these crops will not be subject to treatment against “cosmetic” damage.

## Field vegetables, disease control

### Crop planning

*Field history, rotation and break crops*

For root and vegetable crops, the rotation is fundamental to the control of pests and diseases, while also helping to maintain soil organic matter and soil structure and assist with crop nutrition. Where the same crop is grown in successive seasons, foliar, stem and root disease carry over from trash and volunteers can be significant. Volunteers from the previous crop can also act as a ‘green bridge’ for disease [D102]. Well-designed crop rotations are central to organic production systems [D101]. The Organic Farm Management Handbook [D102] provides advised rotation intervals (Table 12).

Table 11. Intervals that should be used between crops when planning rotations.

| Crop | Interval (yrs) | Crop | Interval (yrs) |
|---|---|---|---|
| Red clover | 5 - 6 * | Fodder & sugar beets | 4 - 5 |
| Lucerne | 5 | Swedes & turnips | 3 - 4 |
| Oilseed rape | 3 - 4 | Brassicas | 4 |
| Oats | 3 - 4 | Onions & other Alliums | 4 - 6 |
| Peas and beans | 4 - 5 | Potatoes | 5 - 6 |

***** Maximum 3 years of continuous clover use, after that period a break of 5 years applies.

Plants of the same family tend to be prone to the same pests and diseases so should not be grown on the same site in successive years [D112]. Rotations should also be developed to balance the nutritional and structural demands on the soil, with crops with different rooting structures acknowledged to improve soil structure and health [D111]. Those relevant to the crops covered by this report section are tabulated below (Table 13).

Table 12**.** Members of vegetable families that should not be grown in successive years.

| Family | Example crops |
|---|---|
| *Apiaceae* | Carrot, celeriac, celery, fennel, parsley, parsnip |
| *Amaryllidaceae* | Garlic, leek, onion, shallot |
| *Brassicaceae* | Brussels sprouts, broccoli, kale, cabbage, swede, kohlrabi, cauliflower, calabrese, radish, turnip, mustard, oriental brassicas |

Oilseed rape is also a brassica (crucifer) and so vegetable brassicas should not be grown after it. It is also important to maintain the defined intervals if planning cover crops, green manures etc. to ensure they do not contain a species of a same crop family, such as oil radish (*Raphanus sativus*) or white or brown mustards (*Brassica juncae* or *Sinapis alba*).

There are disease interactions between different crops in the rotation. For example, sclerotinia rot risks will be higher where combinations of oilseed rape, peas, potatoes, green beans, lettuce and carrots are grown in the same rotation [D116]. Violet root rot would be favoured by combinations of carrots, potatoes and sugar beet, particularly if there were also perennial weeds hosts present as well [D132]. It is possible that *Pythium violae* is more common in UK carrot crops than *Pythium sulcatum* [D278] because the former has a wider host range that includes most of the commonly grown crops except onions [D269]. Mycelial growth of *P. violae* and *P. sulcatum* is sensitive to temperature changes and so mycelium overwintering without a host is unlikely, whereas oospores of both pathogens are known to survive for several years in the soil and are thought to be the primary inoculum source for plant infection [D270 D269].

Many diseases of vegetables and lettuce can be transmitted via crop residues and debris [D101 D256] including *Alternaria* spp. (leaf spots) of brassicas and carrots, and *Helicobasidium purpureum* (violet root rot) of carrots, *Pyrenopeziza brassicae* (light leaf spot) of brassicas, *Mycosphaerella brassicicola* (ringspot), *Alternaria brassicicola*, *Alternaria brassicae* and *Xanthomonas campestris* pv. *campestris* (blackspot) of Brussels sprouts. *Botrytis* spp. (grey mould) causes tissue rotting of many crops, particularly following any wounding. When plant debris degrades, resting spores such as the sclerotia of *Sclerotinia* (rot), *Stromatinia* (allium white rot) and *Verticillium* (wilt) species and the chlamydospores of *Fusarium* spp. (wilt and root rots) and the oospores of *Phytophthora* and *Pythium* spp. (root rots) are released into the soil and persist for years.

 

A history of sclerotinia infection in fields on the farm is a key factor increasing the risk of infection in current fields [D130]. *S. sclerotiorum* sclerotia can survive in soil for five years or more depending on soil conditions, so rotations of five years or longer must be used for effective control [D113 D239]. In organic production, land known to carry allium white rot should not be used for at least 20 years [D102]. Avoiding fields with a past history of infection and using rotations of four years or more to reduce pathogen propagule viability is effective for reducing the incidence of many diseases, especially those soil borne. A wide range of brassica plants can be affected by the soil borne disease clubroot, caused by *Plasmodiophora brassicae*. It tends to occur in patches within fields, particularly in damp areas, and can survive for up to 15 years in soil [D116] with a half-life estimated at 3.7 years [D117]. Avoiding affected fields completely is effective, but impractical, as the disease is now widespread in the UK; 52% of 96 commercial sites tested positive for clubroot in a 2008-2010 survey [D115]. In lettuce, a rotation of two to three years is advised to reduce the risk of downy mildew, (*Bremia lactucae)*, infection [D126]. Leaving a fallow, uncropped, year is not an economically viable practice in rotations. One year fallow is more than needed for many pathogens as the mycelium and dispersal spores can be killed or sufficiently eliminated by cultural means not long after crop destruction, and for others, with durable resting spores, one year is too short a gap if returning to the same crop type.

*Select Low Risk Locations*

The selection of lower risk locations can be an effective part of an IPM disease control strategy. Consideration of location can be made based on numerous factors, including location in the country, field topography, altitude, aspect and soil type. Poor growing conditions such as difficult rooting or low nutrient availability can result in slower or sparser crop establishment and subsequent less-vigorous growth with such plants tending to be more susceptible to the disease damage.

If there are sclerotia of *Sclerotinia* spp. in the soil, damp soil conditions will encourage germination of sclerotia in spring [D121] and subsequent production of airborne spores which infect the crops. For clubroot, drier, well-drained soils will be lower risk [D122].

Propagation of plants out of the soil, in plugs or blocks e.g., for brassicas, lettuce and leeks is done to provide transplants for the field, rather than as a disease reduction measure and the closely spaced, usually water-splashed plants, can be at greater risk of foliar and root pathogens when growing in module trays if hygiene is poor. In soft fruit crops, there has been a move out of the soil into peat, coir or other substrate held in grow-bags, troughs or pots, for husbandry reasons that include seeking to avoid soil-borne diseases such as verticillium and phytophthora. There may be potential to utilise growing out of the soil for some high value field vegetable crops; in the Netherlands lettuce and leek were piloted. Good irrigation management and healthy planting stock are critical to retain root health [D132]. Vertical farming of baby leaf is already taking place in the UK.

*Spatial Separation*

The proximity of a susceptible crop to one that is already infected can significantly increase the risk of infection where the pathogen is wind dispersed. Rust and powdery mildew spores are abundantly produced in dry conditions to be blown long distances in the wind. Local splash dispersal occurs for bacteria and the spores of downy mildews and pycnidial fungi such as phoma leaf spot and stem canker [D129, D125] caused by *L. maculans*, whose propagule production and release are also greatest under wet conditions. However, spore dispersal by wind-driven rain or carriage in mists is also possible over some distance, as known from the movement of potato blight (*Phytophthora infestans*) and *Phytophthora ramorum* infection of shrubs from larch. It is recommended that new lettuce crops should not be planted downwind of earlier crops because of wind-borne spores of *Bremia lactucae* [D126].

*L. maculans* produces wind-blown ascospores on old tissue (as well as splash-dispersed pycnidiospores from leaves) and so separating a vegetable brassica crop 2 km from fields containing infected stubble from the previous year's oilseed rape crop, or debris from another vegetable brassica, is beneficial [D118] [D127]. Australian research has shown that the distance and the direction of wind from oilseed rape stubble to the nearest oilseed rape field is a major determinant of *L. maculans* severity [D123]. Spatial separation of new brassica crops as far away as possible from infected crop debris in previous fields is advised for *Pyrenopeziza brassicae* light leaf spot [D128].

Spatial separation to reduce the incidence of *S. sclerotiorum* is partially effective, as the airborne spores can travel across fields but in general, most sclerotinia spores are deposited relatively close to the source of production, within 50 m or so [D124], although some exceptions have been found. Lettuce crops can be lost to both *S. sclerotiorum* and *Sclerotinia minor*, but the latter is only soil-borne, it does not produce aerial spores [D104]. Even if no other infected host crops are nearby, many wild plants are hosts of sclerotinia, e.g., buttercups and shepherds purse, and so can be sources of sclerotinia inoculum [D120].

Ensuring that fields designated for vegetable brassicas are not adjacent to fields with known clubroot patches may be effective at reducing incidence if there is the potential for soil-splashed tractors or uncleaned cultivation equipment to move between them. Clubroot tends to be confined to localised patches and ways of avoiding enlarging the patches through soil and debris movement on vehicles should be considered.

There are few reports of intercropping providing a benefit in disease control. This is unlikely to be a general disease control option [D132].

 

## Pre-cropping

*Cultivations*

Tillage deteriorates soil structure and promotes organic matter mineralisation, leading to significant health degradation of field soil [D319]. No-till or min-till, with crops drilled amongst the stubble and debris of preceding crops, has benefits of improving soil organic matter content, water holding capacity and aiding root penetration by retaining root and earthworm runs and the binding of fungal hyphae [D319]. A disadvantage of this compared with ploughing is that pathogens carried on debris are then close to the plants of the next crop. However, where crops such as carrot and onion are grown in ridges or beds, the primary cultivation is more likely to be ploughing so that a fine tilth can later be produced.

Deep ploughing will bury sclerotia of sclerotinia to depths where germination and spore production are limited [D113]. However, as sclerotia are able to survive for several years whilst buried, future deep ploughing may return viable sclerotia to the soil surface where they can germinate and cause infection of the next susceptible host crop.

To reduce the risk of *B. lactucae* spreading to cause new downy mildew infections it is recommended to collect lettuce plant remains after harvest and to burn or bury them to a least one metre depth [D126].

*Liming*

Application of lime to raise soil pH and calcium levels is a method used for the control of clubroot, as the disease favours acidic soil with low calcium levels. Clubroot caused by *P. brassicae* affects all vegetable brassica species [D522] with the distortion caused being problematic in turnip and swede. Application of lime is thought to be more effective where it is mixed into the soil by ploughing and cultivation, as opposed to surface casting before sowing. In oilseed rape, and thus likely other brassicas, the creation of a fine seedbed using a rototiller or multiple passes with a disc or power harrow, with the application of lime would be expected to improve consistency and effectiveness of increasing pH [D134]. Calcium has been used successfully against club root in vegetable brassicas [D267]. The manufacturers, AlzChem, of the product Perlka (calcium cyanamide) give instructions for use before and after planting brassicas in relation to fertilising club root infested areas and indicate suppression of resting spore germination and reduction of root hair penetration by zoospores due to the effects of the calcium [D268]. A recent review [D266] has evaluated the effects of calcium on the life-cycle stages of *P. brassicae* and the development of clubroot disease and concluded that it has properties deserving wider assessment. Liming does not provide complete or consistent protection in short rotations, as shown for oilseed rape, and is particularly ineffective where levels of clubroot infection are very high [D141 D175].

 

The calcium carbonate precipitate product LimeX (derived from sugar beet and used in the UK for the correction of soil pH, and containing the nutrients calcium, phosphate, magnesium and sulphur) at 15t/ha incorporated into soil seven days before drilling carrots was effective against *Pythium* spp. causing cavity spot at one field site, decreasing cavity spot incidence by 19% [D263]. Pot and field tests have shown some useful activity from calcium treatments [D265]. The effects of calcium are complex, extending beyond changes in soil pH to modification of soil microflora and direct effects on the host plant [D263]. Decreased incidence of cavity spot has been reported in tests where soil exchangeable calcium exceeded 8 milliequivalents per 100 g soil [D264]. The type of calcium added to the soil to reduce cavity spot is important, compounds like lime (calcium carbonate) and calcium hydroxide will achieve the desired effects but gypsum (calcium sulphate) will not [D269].

Due to its economic important, cavity spot has been the subject of a series of AHDB projects seeking to find alternatives to metalaxyl and improve our understanding of the pathogen epidemiology and diagnostics [D262 D278]. A factsheet produced by the HDC (now the AHDB) in 2003 summarised research and is a good source of information for growers on cultural control measures, including the use of calcium [D269].

*Control of weeds and volunteers*

In all crops, volunteers and particular weeds can act as a source of infection for following crops grown nearby. Volunteers often carry a range of diseases but are most significant as a 'green bridge' for biotrophic / obligatory pathogens such as powdery mildews (e.g., *Erysiphe heraclei* on carrot and *Erysiphe cruciferarum* on brassicas) and downy mildews (e.g., *Peronospora destructor* on onions, *Hyaloperonospora brassicae* on brassicas and *B. lactucae* on lettuce). Ideally these volunteers should be destroyed prior to the emergence or planting of new crops. Weed or volunteer control can be achieved chemically or by cultivations. Ploughing is effective in removing volunteers and many weeds that may be sources of air-borne pathogens and insect-carried viruses. In practice, weed control is not always easily achieved as these disease sources often emerge over several weeks, rather than in a flush that can be cleaned up with a single pass.

The wide crop host range of *S. sclerotiorum* includes carrots, lettuce and brassicas, but it can complete its lifecycle on more than 400 host species, including common weeds like sow-thistle (*Sonchus arvensis*), dandelion (*Taraxacum officinale*), and shepherd's purse (*Capsella bursa-pastoris*) [D113]. Other pathogens can also be present on weeds; early removal of oilseed rape volunteers has been shown to significantly reduce clubroot in succeeding crops compared to later removal [D135] and violet root rot (*Helicobasidium brebissonii* syn. *H. purpureum*) produces long-surviving sclerotia around infested rootlets and its survival is assisted by the presence of perennial weeds such as bindweed (Convolvulus) [D101]. Turnip mosaic virus occurs spasmodically on vegetable brassicas [D101] following transmission by cabbage aphid (*Brevicoryne brassicae*) and the peach potato aphid (*Myzus persicae*) from oilseed rape and other brassica species, such as wild radish (*Raphanus raphanistrum*) [D136] and so removal of volunteers should be carried out.

Weeds including black nightshade, prickly sow-thistle and knot-grass, as well as crops including wheat, beetroot, cauliflower and clover, can be alternative plant hosts for *P. violae*, and so can support mycelial growth and/or replenish oospores in the soil [D270]. Removal of volunteers and weeds with their roots by e.g., raking or destruction of tissue by pulverisation and/or heat treatment [D519] might need to be considered as otherwise the resting spores of *P. violae* in the roots will remain to infect the next crop. Thermal techniques include electrical, flaming, infrared, hot water/foam, steaming and dry heating, radiation, freezing and ultraviolet and lasers. Flame weeding is currently the only technology ready for use in field scale horticulture and is widely used in organic vegetable production as a stale seedbed technique [W146].

*Drainage*

Good drainage is effective for managing clubroot infection and the spread of clubroot. Soils which are compacted, poorly drained or even prone to flooding will encourage proliferation of clubroot zoospores, especially in a warm autumn (>15°C) [D137]. In addition, the zoospores are motile: they have flagellae and can move through wet soil, attracted by host root exudates [D139]. They can also be spread by water flow.

Oomycete pathogens, such as those causing pythium and phytophthora root rots, can infect roots using zoospores that are favoured by free-water in the soil. Zoospores have never been observed from *P. violae*, one of the oomycete causes of carrot cavity spot, although spread from mycelium in cavities on carrot debris or on a growing carrot tap root to nearby healthy carrot roots has been demonstrated experimentally [D138] and will be favoured by moist soils. One of the only environmental factors that has been correlated with cavity spot development is soil moisture, causing increased incidence [D271]. Increased cavity spot occurred in wet seasons and in poorly drained fields [D273]. In pot experiments, cavity spot incidence was positively correlated with flooding [D274]. A ‘tentative relationship’ was observed between cavity spot incidence and total water input during July and August in two years of monitoring carrot sites in the UK [D275]. In general, infections of carrot taproots are thought to form rapidly following periods of prolonged rainfall and can be exacerbated by poor aeration, compaction or impeded drainage [D269]. Addressing waterlogged / compacted areas as well as avoiding poorly drained fields and areas prone to flooding is to be recommended generally as crops struggling in such areas will be less able to tolerate pest and disease damage.

 

*Hygiene and prevention*

Maintaining good farm hygiene is the first defence against the introduction of soil-borne diseases such as *Sclerotinia* spp., *Sclerotium cepivorum*, club root, *Verticillium* spp., *Fusarium* spp., *Pythium* spp. and *Phytophthora* spp. into clean land. Machinery used in infested fields should be power-washed before use in uninfected fields, and soil should at least be knocked off from boots and tools. Clean fields should be visited first in the sequence of crops so that cleaning down equipment can be done at the end of the day. If the first signs of disease are evident near the field entrance, then this can be a sign that local transfer of the pathogen has occurred.

Limiting the movement of infected or potentially infected soils, and of organic material, is especially effective for managing and preventing spread of clubroot infection in brassicas. In practice this includes restricting access to infected fields and ensuring that machinery does not travel from infected to clean fields, and taking into consideration that animal manures, composts etc., are also possible sources of infected material [D131].

Hygiene to obviate or reduce pathogen inoculum carry-over is a cornerstone of good plant protection practice, especially for pathogens with either limited dispersal or a single disease cycle in a growing season. Even with ubiquitous pathogens with a broad host range, such as *Botrytis cinerea* (grey mould), that can be expected to arrive in crops, removal of inoculum on debris before planting can delay epidemic development and prove beneficial. In brassicas the ploughing of crop residues at the end of the crop is particularly important in areas of intensive cropping where surrounding fields also contain brassicas [D132].

In propagation areas for e.g., vegetable brassicas or lettuce, disinfection of the glasshouse structure, production floors and benches, equipment and tools between crops contributes to control. It is especially important after a severe outbreak of an uncommon disease or an invasive pathogen. Disinfestation, or disposal, of crop covers after use is needed, e.g., fleece protection in glasshouse crops and early-season outdoor field vegetables, due to risk of pathogen transfer from one crop to the next (e.g., septoria blight on celery) [D132].

A recent AHDB survey [D254] of UK protected edible growers examined all the measures they have in place, most of which should also be able to be used where vegetables and lettuce are propagated in multicell trays or peat blocks under protection. Virtually all-year round production in protected edibles has challenges for keeping crops healthy, and growing methods for crops such as tomato, leafy salads and herbs include hydroponic systems such as nutrient film technique (NFT), ebb and flood growing-media (such as rockwool and coir) as well as planting in soil and each have their own problems. A new technique for protected edibles is vertical cropping, where cultivation on benches in trays in a contained environment with strict within and between-crop hygiene protocols enables virtually continuous production.

When propagation material is received by growers, if at all possible it should be kept quarantined for up to a fortnight and checked regularly for disease development. Diseases can have a latent / symptomless period in their hosts after infection, in particular downy mildews such as *B. lactucae* on lettuce and *P. destructor* on brassicas, and the changed environment during transport can either facilitate infection or stimulate disease expression.

Routine disinfection of benches or floors has been questioned from time to time, on the hypothesis that beneficial micro-organisms might be present and able to counteract resident pathogen populations, however good control is less certain than from correctly managed disinfection procedures. It is important to ensure that as much debris is removed as possible before disinfecting so that the biocide can get good contact for the required period, and that the correct concentrations are used and replenished. In terms of non-chemical crop protection, if chemical biocides applied to structures or surfaces are considered unacceptable, more attention will need to be given to physical methods and their efficacy (e.g., heat, hot water, UV light). Use of flame guns may be appropriate (e.g., for lettuce crop residues with sclerotinia and basal rots). However, it should be remembered that a biocide applied once before crop production can potentially save multiple applications of pesticides during crop production, and equally save cost [D132].

The treatment of water collected from glasshouse roofs or open reservoirs, and any recirculating water is very important. Plant pathogens such as *Phytophthora* and *Pythium* species readily contaminate water, arriving in dust, rain or coming into reservoirs from run-off of infected plants. The level of risk of particular water sources carrying and spreading oomycete stem and root rots to field vegetables have been identified [D217]. Whole propagation areas can quickly become infested if contaminated water is used. Methods of water treatment include chlorination, hydrogen peroxide, chlorine dioxide, UV light, and biological filtration (such as by slow sand filters or reed beds) [D133 D217]. Where possible, alternatives to overhead sprinkler irrigation should be sought as this can splash spores and create a period of leaf wetness conducive to infection.

*Phytosanitary legislation*

It is important to have clean propagation material. This can be assisted by growers complying with legislation as well as being vigilant in inspecting plants. Starting with healthy plants has become even more important where bioprotectants are in use, as there is no curative activity.

Compliance with legislation is important for biosecurity in order to keep invasive alien pests, diseases and weeds from Britain and Ireland. The UK Plant Health Risk Register (updated monthly) database and the UK Plant Health Information Portal database have been set up to keep everyone informed of risks to plant health [D253]. A plant passport system was introduced by the EU whereby material moving between members had to be inspected at source and declared to be free of pests and diseases. Since leaving the EU new regulations have come into force in the UK, with increased inspections by officers of the Animal and Plant Health Agency (APHA) of incoming plants and harvested crop material. Professional operators in Great Britain no longer issue EU plant passports, instead UK plant passports are issued, and are required to move plants within Great Britain, to the Isle of Man or to the Channel Islands. Imports from the EU to Northern Ireland can continue to use an EU plant passport. Propagators must register with APHA and are then authorised to issue plant passports. Imports from the EU to Great Britain need a phytosanitary certificate. Supplier documents are also still needed for planting material (under the Marketing of Vegetable Plant Material Regulations 1995) including *Allium cepa* (onion), *Brassica oleracea* (vegetable brassicas), *Brassica rapa* (Chinese cabbage and turnip), *Chicorium endivia* (endives) and *Daucus carota* (carrot).

*Soil disinfestation without chemicals*

Soil steaming is a good replacement for synthetic chemical soil disinfestation (as fumigant products containing actives such as methyl bromide, chloropicrin and metam sodium are no longer authorised in the UK) but is much more expensive because of energy costs [D132]. Soil steaming gives good broad-spectrum activity, provided the soil is heated to the correct temperature (65°C for 10 minutes for most pathogens, higher if in woody stems) for the correct length of time and to sufficient depth to stop any viable pathogen contact with the next crop. There is a short-replanting interval. A range of methods are available including sheet-steaming, vacuum-steaming, a winch-operated steam plough and plate-steaming [D237]. The procedure can be labour intensive, but robotic plate steamers have been developed. Efficacy is very dependent on good soil preparation to break up large lumps to facilitate steam penetration and the appropriate moisture content. Treatment rate is slow, so generally steaming is not applicable to field crops, except perhaps small areas such as nursery propagation beds. Its use has been restricted to high value crops in glasshouses particularly where there are limited rotation options, and multiple-cropping field production of some leafy salad, or intensively grown vegetables.  There is potential for the use of beneficial microorganisms to re-colonise the treated soil so that they would be ready to compete should pathogen re-contamination happen.

A system, called Bioflash, using steam and activating compounds (CaO and KOH) developed by the Celli company (Forlì, Italy) was used within the ENDURE project [D209]. Specific tests were performed on the following combinations: *Sclerotinia minor* and *S. sclerotiorum* / lettuce and radish, *Pythium* spp., *Sclerotium rolfsii* and *Fusarium oxysporum* f.sp. *lycopersici* / tomato, *S. minor and F. oxysporum* f.sp. *basilici* / basil, *Rhizoctonia solani* /radish and rocket. Bioflash gave a mean 85 – 95% reduction in infections with respect to the untreated control.

Soil solarisation, in which soil is sheeted-over with plastic tarpaulins to retain the heat of the sun, is increasingly used in Southern Europe [D132] often in combination with another method (e.g., soil organic amendments). Solarisation can increase the soil temperatures to levels that are lethal to various weeds, pests and diseases [D241 D242]. It has particularly been used for weed control, but verticillium and fusarium wilts of several crops and *Plasmodiophora brassicae*, *Rhizoctonia solani*, *Stromatinia cepivora* and *Sclerotinia minor* have also been controlled [D240]. In the UK this would mean taking land out of production in the main summer cropping period for 4 - 8 weeks. The drawback for the UK is the unreliable occurrence of hot weather, but there may be greater scope, depending on future weather patterns, specifically for glasshouse crops growing out-of-season (e.g., late summer / autumn treatment).

*Biofumigation*

The chemical fumigant metham sodium gives rise to methyl isothiocyanate (methyl ITC). Methyl ITC has broad-spectrum biocidal activity against nematodes, fungi, insects and weeds and is produced naturally by the plants of several genera from the Brassicaceae, Capparaceae and Caricaceae families. In the process of biofumigation using isothiocyanate-generating brassicas as biologically active green manures between crops, isothiocyanates are released principally after the crushing of the brassica residues. The toxic potential of biofumigant crops is greatest during flowering [D209]. In an ENDURE (European Network for Durable Exploitation of Crop Protection strategies) study [D209] *Brassicae juncea*, was grown, crushed, and residues incorporated following a carrot crop inoculated with *Pythium sulcatum*. A second carrot crop was sown in the biofumigated soil and an area of untreated soil. 90% of carrots developed cavity spot with or without biofumigation, with only a slight reduction in severity in the carrots following biofumigation. Brown mustard, white mustard and radish sown in the autumn prior to drilling of the carrot crop, then incorporated in the spring had no effect on development of cavity spot. This may have been due to low biomass and low glucosinolate levels in the overwintered biofumigants caused by the short growing window and sub optimal environmental conditions associated with overwintering biofumigants before carrot drilling [D262]. Management of cavity spot has relied on the use of partially resistant or tolerant varieties and metalaxyl-M (e.g., SL567A) fungicide treatment early in the crop, however the efficacy of metalaxyl-M has been gradually eroded and this is considered, in a part at least, to have occurred as a result of enhanced degradation of the active molecule at some grower sites [D263].

 

In reviewing biofumigation [D132] it was noted that there can be problems in getting good biofumigant crop growth and that the poor and variable efficacy might be improved with ongoing breeding targets of brassica species with higher levels of isothiocyanate compounds. There has been considerable work, in particular overseas, in the use of brassica seed meals (e.g., Biofence), especially for control of verticillium wilt and other soilborne pathogens in potato [D132]. A separate ENDURE report [D210] highlighted a large number of gaps in knowledge on methods to control soil-borne disease through soil biofumigation and or soil steaming in field vegetable crops.

*Biological soil disinfestation (BSD)*

Also known as anaerobic soil disinfestation (ASD), this method was reviewed in 2010 [D227]. It is a potential alternative as a broad-spectrum treatment option (diseases, nematodes, weeds) where soil solarisation (practised where weather is hotter than Northern Europe) is not feasible. It involves covering soil with and air-impermeable film for 4 - 6 weeks and so is principally suited to glasshouse and field crops. Organic matter such as grass, or other green manure crop, is first incorporated into the moist soil. Efficacy is believed to arise from production of low molecular weight fungitoxic organic acids and other chemicals with reported efficacy against e.g., *Fusarium, Verticillium* and *Pyrenochaeta* species, but less so of *Pythium* and *Phytophthora* species. Granular products derived from food processing (called Herbie products) are marketed commercially in the Netherlands [D227] to provide the organic matter, so giving a more-consistent material for incorporation in the process that this company (Thatchtec) terms “soil resetting”.

*The microbiome*

A review of the rhizosphere microbiome and plant health [D230] has noted that the diversity of microbes associated with plant roots is enormous, and this complex plant-associated microbial community is crucial for plant health. Different plant species grown on the same soil host their own specific microbial communities. There is evidence that upon pathogen or insect attack, plants are able to recruit protective microorganisms, and enhance microbial activity to suppress pathogens in the rhizosphere. Recent PhD research (currently withheld from publication) by Matias Fernandez-Huarte within the AHDB/BBRO Soil Biology Soil Health (SBSH) Projects 4 and 6 has examined the long-term effects of pH, of inorganic fertiliser organic amendments, of tillage, of drainage and of companion crops or mulching on soil bacterial and fungal diversity by using DNA metabarcoding. The SBSH project [D318] has worked over the last five years within 14 sub-projects to increase understanding of soil biology and provide guidance to farmers and growers on soil assessment (including the soil health scorecard [D347]) and management. The final reports will provide new information and indications of where further knowledge is required on what can contribute to make various soils "healthy".

*Varietal choice*

For most crops, resistant varieties are an important part of non-chemical disease control. For cereals, oilseed rape and potatoes, there are good sources of information on disease resistance to many of the major pathogens in the annually updated Recommended Lists published by AHDB and by other levy-funded projects [D144]. Resistance to individual diseases is rated on a 1-9 scale and any breakdowns in resistance noted.

Prior to the 2000's, Recommended List rankings of vegetables were made available by NIAB, when untreated plots were included in replicated plot trials in which diseases were often facilitated to develop. There are now no independent replicated trials of vegetable varieties from a range of breeders where information can be reliably gained by growers (Bruce Napier, NIAB, pers.comm.). NIAB currently have replicated onion trials, but as they are within commercial fields they receive chemical pesticide treatments, and carrots are just grown as single plot demonstration trials (Bruce Napier, NIAB, pers.comm.). The Duchy College in Cornwall conduct some brassica variety trials for growers in the south-west of England. However, in general any disease resistance or susceptibility information on varieties is now held by the seeds companies for their own breeding lines, and not necessarily included in their seed catalogues, although growers may be invited to view demonstration plots. There has been breeding of clubroot resistant commercially available brassicas for the UK (Angela Huckle, ADAS pers.comm.). Gardeners have available to them a good choice of clubroot resistant / less susceptible varieties of cauliflower, Brussels sprout, cabbage savoy cabbage, red cabbage and swede [D229], but other characteristics and supermarket contract specifications can mean such varieties are not grown commercially.

The use of carrot varieties with resistance to cavity spot is well-established in the industry, however, resistance is incomplete and therefore additional control measures, particularly fungicides, are still used [D263]. One company has intentions to bring onion varieties with resistance to fusarium basal rot to the UK market (Angela Huckle, vegetable consultant pers.comm.)

*Bremia lactucae* has different pathotypes, with new ones continuing to be recorded. In Europe the strains are numbered Bl : 1EU (Bl for *B. lactucae*) and by 2021 the number had reached 37EU. Lettuce varieties are bred with resistance genes for particular strains and these are declared for growers to see when purchasing seed [D104].

Very few commercial varieties of vegetable brassicas show high levels of resistance against downy mildew (*Hyaloperonospora brassicae*), but varieties showing some level of downy mildew resistance can be found in seed catalogues described as having partial or intermediate resistance. The main risk of infection is to seedlings in propagation owing to the humid conditions and use of overhead watering [D217]. Downy mildew in salad rocket grown as baby leaf can cause total crop loss because the high plant density means the disease can spread rapidly. Varietal resistance is stated to be present, but trials found no difference between varieties, and there was a suggestion that the pathogen might have different races [D217].

Downy mildew resistant onion varieties are available and will become more important in the future as a result of the increasing constraints on the use of chemical fungicides [D217].

Spreadsheets of varieties of horticultural crops in seed catalogues to 2021 with any resistance to various pathogens are provided online for public access by Cornell University (USA). Crops and pathogens include Brussels sprouts (*Xanthomonas campestris*, downy mildew, fusarium wilt), cabbages (*X. campestris*, fusarium wilt), lettuce (downy mildew), onions (fusarium basal rot) and carrots (Alternaria leaf blight, cavity spot). These varieties may not be available in the UK.

Any selection of disease resistant varieties by growers can lead to a compromise being sought on some other varietal attribute. Disease resistance is seldom complete, so fungicide treatment is usually still required. However, fungicide programmes may be able to be delayed, or a bioprotectant substituted for a chemical, if weather conditions do not favour the disease and therefore quality reduction is unlikely. With vegetable crops, there is a low tolerance of blemishes, and there will be unmarketable yield if diseases cause leaf spots or rots. Thus, unless strong disease resistance is available and maintained in a variety to all key pathogens, and hygiene and crop growing conditions reduce pathogen infection risk, fungicides will still be required.

Varieties have been bred for generations by crossing plants with desirable traits and it can take years to obtain the hoped for transfer. Genetic engineering is a development that allowed insertion at random of DNA into a host genome but has proved controversial and the genetically modified organisms (GMOs) are put under severe release restrictions in the UK. It is now possible to not only determine where a specific DNA sequence believed to assist with producing a particular trait is on a gene but to use genome / gene editing to use enzymes to “cut” this out and potentially move it to a specific site in the DNA of another host. In 2021, the UK government carried out a consultation on genetic technologies regulation [D344] that did not produce any new evidence that gene edited organisms should be regulated as GMOs, with gene editing being likened to traditional breeding methods. In 2022 Defra has relaxed the rules on trials that investigate new traits that “could have occurred naturally or through traditional breeding" and has listed examples of applications such as sugar beet resistance to virus yellows and mildew-resistant tomatoes [D345]. There is thus potential for faster breeding of varieties that have fewer individual plants affected and/or less severe visible symptoms, which in particular is of benefit to bioprotectant microbes as these can be overwhelmed by a fast pathogen colonisation of a host plant.

*Seed health*

A number of vegetable diseases can be carried into an otherwise clean area on seed. Disease can spread outwards from a low number of infected seeds, particularly in closely spaced propagation areas. Infected seeds are unlikely to be detected at the point of sowing as the pathogen may not have caused any staining and mycelium can be under the seed coat. Resting spores can be carried in dust on the outside of seeds. The only way to have confidence in seed batches is for them to have certification from an official seed testing station, often alongside information on germination. Self-saved seed has a high chance of being infested, but this practice by farmers is not seen in vegetables in the way it is with cereal, oilseed and pulse crops.

Pathogens know to be carried on seed include the fungi *Alternaria dauci*, *Alternaria radicina* and *Phoma apiicola* on carrot and *Alternaria brassicae*, *Alternaria brassicicola* and *Leptosphaeria maculans* on brassicas / crucifers and *Septoria lactucae* of lettuce. *Xanthomonas campestris* bacteria can be carried on brassica seed [D101 D107].

Work within AHDB Project CP 184 reported for spinach seed the use of quantitative PCR (qPCR) using commercially supplied kits to assess the amount of total DNA (live or dead) of *Peronospora effusa,* and Reverse Transcription PCR (RT-qPCR) to establish the relative content of RNA (which being less stable than DNA can be used to estimate the amount of viable pathogen within a biological sample) [D329]. Seed-testing using conventional agar-plate culturing of seed-borne fungi (such as *A. brassicae* and *A. brassicicola*, *A. dauci* and *S. lactucae* [D101]) or bacteria (such as *X. campestris* [D101]) is not possible with downy mildews as they require host tissue to grow, therefore DNA testing of seed, and in particular the RNA assessment of viable pathogen contamination, is now a way to detect contaminated seed batches other than by microscopic examination for oospores. Seedborne infection may be possible but is not generally considered important in lettuce downy mildew (*B. lactucae*). Even a small incidence of infected seed in crops grown as transplants (such as brassicas and lettuce) can spread to kill or stunt a large number of seedlings because pathogen spread is favoured by the close host spacing frequently coupled with overhead irrigation.

Seed treatment is a method of cultural control of downy mildews, but as even 0.1% of infected seeds can cause significant loss further measures are needed [D284]. Seed treatment by hot water 48 - 50°C for 20 minutes and hot air 65°C for 10 minutes has been tested and found to reduce disease incidence caused by brassica and basil downy mildew respectively. Lamb's lettuce infection by the downy mildew *Peronospora valerianellae* was effective using hot water 50°C for 30 minutes, or heat at 40 - 55°C for 10 - 30 minutes, while with lower efficacy sodium hypochlorite gave better control than ethanol [D284].

*Sowing or planting date and harvesting*

Sowing or planting crops earlier or later to reduce disease risk is a possible IPM strategy. Increasing the interval between crops can decrease the potential for disease transfer from previous crops (as detailed in previous sections). Waiting for soils to warm in spring or for when rain is forecast can mean that crops establish strongly and can help with disease tolerance. In theory, avoidance of planting-out when pathogens are more likely to be dispersing spores and/or conditions are more favourable for infection could be done, however, delaying getting the crop into the ground is impractical with established production schedules, particularly where there is multiple cropping in a year, such as with lettuce, or when produce, such as onions, require conditions at harvest that are less likely later on. Delay may also not be possible where the sowing or planting period of the next crop is quite tightly defined, particularly if the field needs to be handed back to another farmer, the land having been rented from them to obtain a good rotation interval.

Growers need to be prepared that if cavity spot is detected in a carrot crop then harvest should be carried out promptly [D269].

*Soil/substrate amendments - organic matter incorporation*

Green composts (composed principally of windrow-composted garden and amenity horticulture waste [D243]) typically have a higher lignin content, which is more resistant to microbial breakdown, than farmyard manures and therefore tend to increase organic matter content more quickly (relative to the same amount of organic matter added). Farmyard manures tend to contain more fresh organic matter and are better at stimulating biological activity and increasing microbial biomass [D244]. Both can assist in the moisture-holding capacity of the soil and provide some nutrients [D245 D246]. Organic matter can also favour the development of communities of beneficial fungi and bacteria [D247] which can compete with soil-borne pathogens for resources and are also reported to stimulate plant host defence responses [D230]. There is a strong relationship between the total amount of organic carbon in soil and the degree to which pores are connected and have the capacity to hold water [D348]. Application of organic matter over a number of years may be needed to significantly improve soil health, as the amount applied per year has a regulation limit, leading to only a thin covering, to prevent excessive soil nitrogen.

 

A wide range of organic amendments have been examined for control of soil-borne diseases including composted green waste, animal manures, and various crop wastes [D257]. Onion waste was used to control white rot (*Sclerotium cepivorum,* now called *Stromatinia cepivora*) of onion in the UK [D258]. There is probably increased scope for greater use of organic waste products as components of disease control in the UK, but various problems need to be overcome including regular supply, bulk handling, product consistency, limited spectrum of activity, limited efficacy, operator safety (dusts, spores) [D132]. Work in Belgium reported lignin by-products improved control of *S. sclerotiorum* in lettuce crops when using the bioprotectant Contans WG [D259]. Soil incorporated biochar has been demonstrated to aid crop protection through effects on mycorrhizae and possibly induction of systemic acquired resistance (SAR) [D260 D261].

Work within the Soil Biology Soil Health Project [D349] investigated the addition to improve soil health of green compost incorporated before planting onion sets in spring. The soil had recently grown onions and was known to contain a high level of *F. oxysporum*, but no improvement in crop vigour was seen after green compost application that might otherwise have helped to resist infestation by *F. oxysporum*. However, this is a very aggressive disease attacking the basal plate of the onion bulb killing both foliage and roots. A recent review of Fusarium basal rot in *Allium* spp. concluded that although many studies have shown a great potential of compost amendments and organic matter in reduction of the disease, the effectiveness of this technique is inconsistent and unpredictable [D342].

A review [D248] seeking to identify the characteristics of organic soil amendments that suppress soilborne plant diseases found that the response of pathogen populations to organic matter amendments was a reliable feature only for some organic matter types (e.g., crop residues and organic wastes with C-to-N ratio lower than around 15) and for pathogens with a limited saprophytic ability, such as *Thielaviopsis basicola* and *Verticillium dahliae*. Instead, population responses of the pathogenic fungi *Phytophthora* spp., *Rhizoctonia solani* and *Pythium* spp. appeared unrelated to disease suppression. Fluorescein diacetate (FDA) hydrolysis assay can measure non-specific enzyme activity (e.g., esterases, proteases, lipases) and the results have been correlated with organic matter decomposition, with positive correlation with peat and compost suppressiveness. Enzymatic and microbiological parameters, rather than chemical ones, assist more in predicting suppressiveness, with the most useful being FDA activity, substrate respiration, microbial biomass, total culturable bacteria, fluorescent pseudomonads and *Trichoderma* populations. The integration of different parameters, such as FDA hydrolysis and chemical composition by Carbon-13 nuclear magnetic resonance (NMR), may be a promising approach for identification of suppressive amendments.

 

A review [D204] of biological control of soil-borne *S. sclerotiorum* in horticultural crops found evidence for the pathogen's reduction following the addition of organic amendments, but also population increase although incorporation of antagonistic microorganisms such as *Coniothyrium minitans* or *Trichoderma virens* within organic residues looked promising for pathogen elimination.

Organic materials such as, green compost, sewage sludge, manures and anaerobic digestate can produce benefits, there may also be some risks of introducing crop pathogens with these materials if they are not adequately pasteurised [D132].

Soil condition can greatly influence disease development. Notably moisture / drainage and soil pans, but also pH, conductivity and other factors. Guidelines on how growers can improve soil structure to optimise water and nutrient use efficiency have been provided following work within the GREATSOILS soils project [D104]. Manipulation of different soil features is likely to particularly influence soil pathogens favoured by wet soils, such as *Phytophthora* spp*.,* *Pythium* spp*.* and *P. brassicae* [D132].

Cover crops can improve crop yield, environmental quality and improve soil physical, chemical and biological properties [D550]. In addition to enhancing organic matter, they can increase nutrient release, suppress weeds, and control pests [D550]. The species selected, their termination stage and termination method all have a bearing on these benefits [D108]. Trials work by Agri-Tech Cornwall and Duchy College has identified phacelia and (where a break from brassicas is not required) oil radish as the most effective cover options for vegetable land, by improving soil organic matter [D346].

## In-crop

A review in 2015 for the AHDB summarised control measures, diagnostics and knowledge gaps for both root infecting oomycetes [D217] and another in 2016 covered aerial infecting oomycetes [D330]. Root infecting oomycetes included carrot cavity spot and phytophthora root rots of brassicas. Aerial oomycetes reviewed included vegetable brassica downy mildews, vegetable brassica white blister, onion downy mildew and white tip of leeks. Information from these reviews is incorporated into the following sub-sections.

A 2020 AHDB review [D284] of cultural control of aerial oomycetes in propagation and the protected environment reported the benefit of manipulation of the environment (humidity, light, temperature), seed treatment, early warning systems, water treatment, hygiene and decontamination, rotations, rogueing, avoiding overwatering, and modification of crop fertilisation. Most of these measures will already be in use to a greater or lesser extent by vegetable growers.

 

*Decision support*

Digital technology has resulted in numerous websites and smartphone applications (apps) designed for use in the field of plant health both within the UK and internationally, and these were reviewed by the Scottish Plant Health Centre in 2018 [D162] with those tabulated mainly targeted at arable and tree crops. They mainly provide facts on, and pictures of, pests weeds and diseases. The benefits of mobile applications could be extended to the receiving of alerts when new risks to plant health emerge, perhaps utilising location information to enable geographical mapping of developing threats, and the ability to directly report sightings to plant health officials, with instructions on control measures then promptly sent to the reporter [D162].

To be able to manage the pathogens that infect field vegetables and lettuce, monitoring is required as part of IPM. The AHDB has produced a series of free crop walkers' guides, some of which were latterly also published online, to aid the identification of diseases and other problems together with seasons and reasons for their occurrence including for brassicas [D158], outdoor lettuce and celery [D156], allium [D157], and carrot and parsnip [D161], together with a wide range of factsheets. Information available from the AHDB Horticulture has tended to be in the form of research reports and factsheets targeted at specific problems and require initial knowledge of their existence. There may be a need for a more-consolidated information source, perhaps resembling the Vegetable Management Guide 2020/21 funded by the United States Department of Agriculture and produced at the University of Massachusetts Extension Vegetable Program in collaboration with staff from New England Cooperative Extension programs [D105].

The comprehensive 2016 review for the AHDB of the aerial oomycetes assessing management or control options for UK production horticulture [D330] concluded that there are fundamental gaps in our understanding of this group of plant pathogens that need to be filled to help the further development of integrated disease management. A key area identified centred on the initiation of new epidemics and the role of overwintering inoculum such as oospores and systemic infections of structures such as seeds, their viability under field conditions, their capacity for germination and importance in initiating of new infections and epidemics. Also identified was a paucity of information on survival of airborne inoculum (sporangia, often referred to as 'conidia') as well as the possibility of water-borne disease spread.

A review of downy mildew management options in protected horticultural crops carried out for AHDB Project CP 184 [D284] concluded that integrated management is now essential for the effective management of downy mildews on horticultural crops and that advanced diagnostic studies need to be combined with knowledge on current treatments and the possibilities for using and adapting decision support systems.

 

In the first year report of AHDB CP 184 [D490], the lifecycle stages of downy mildew and late blight and the conditions optimum for each were tabulated as factors to be considered for developing IPM for their management. Details were given on the current state in the UK of decision support and diagnostics for *Bremia lactucae* on lettuce and *Peronospora destructor* in onions (summarised below), and some information gaps from the 2016 review addressed.

Downy mildew in lettuce rapidly builds up and is widely disseminated by asexual sporangia of *B. lactucae* generated in repeated cycles under favourable conditions and spread by wind and rain-splash [D309]. Under UK conditions it can produce abundant resilient overwintering oospores in infected tissues which can survive in soil and debris between crops and initiate epidemics in new plantings [D320 D321] although the importance of this relative to spread by sporangia is not always clear. A series of developments have sought to provide advice to growers on when there may have been an infection period so that sprays can follow, rather than spraying on a calendar basis. Leaf wetness duration (LWD) has a very strong impact whilst the temperature optimum for germination and subsequent infection is broad (5 - 20˚C at a LWD of ≥4h), with the most germination after ≥12h LWD at 5°C, and after ≥4h at 10 - 15˚C, poorest at 25C and no germination or infection at 30˚C [D322].

Analysis of downy mildew in lettuce crops in relation to weather variables in California identified morning LWD as the most important indicative variable, with a 4 hour median morning (between 06:00 and 10:00 hrs) LWD identifying infection days [D324], although later modified to a LWD of 3 hours [D323]. Using these parameters and numerical weather forecasts infection and non-infection days were predicted and spray advisories issued resulting in a significant reduction in the number of sprays applied in Californian field conditions with no drop in disease control [D325]. The biological validity of this model was supported by observations that infection could immediately follow sporulation on mornings with extended LWD and that spore release is initiated in the morning period [D325]. The BREMCAST model was subsequently developed and tested in Canada [D326 D327], supported by routine scouting for lesions in the crops. Advisories were triggered by the recording of a ‘sporulation-infection period’ of a LWD from 0300 -1000 hrs with a temperature between 5 and 20˚C, and sprays were applied just prior to expected symptom development based on day degrees. These models assume most spores are released in the morning, but spore trapping in Canada showed days when this might just be 75% of those released [D328]. Spore trapping may thus need to be combined with current decision support models and while this was unrealistic with traditional methods of counting trapped spores on slides, following the development of a *B. lactucae* primer set and qPCR assay [D331] and spore collection in California by rotating arm impaction traps this shows promise [D332], but other technical issues remain to be solved [D329].

 

*P. destructor,* causing onion downy mildew, has very similar surface wetness (LWD) and relative humidity requirements for sporulation and infection to *Bremia.* Sporangia are also mostly released under the influence of solar radiation and reducing humidity at daybreak [D333]. In addition to a longer latent (symptomless) period than *Bremia* (9 to 16 days, rather than 7-9 days) *P. destructor* infection and sporulation are optimal at slightly lower temperatures (8 to 12°C rather than 5 to 23°C) [D334]. The MILIONCAST system (see below) instruction video states that spore production is optimal during nights with a high humidity and temperature between 4 to 25°C and that following infection it is possible for new spores to be able to infect other plants or leaves every 11 to 15 days [D307].

The possibility of reducing the number of routine sprays or improving their timing by taking a bioclimatological approach to forecasting downy mildew disease in onion crops as part of an integrated control strategy resulted in the model DOWNCAST being developed in Canada [D335]. The model predicted a sporulation-infection period when environmental conditions were conducive to sporulation, dispersal, survival and infection and it was effective in predicting infection in Australian crops of onions, reducing the three sprays per crop to two [D336 D337]. Under the wetter and cooler North-Western European climates sporulation predictions by DOWNCAST were found to be inaccurate [D338 D339] and improved models were developed in Germany (ZWIPERO – German Weather Service model [D340]) and the UK MILIONCAST [D339]. These models improved the accuracy of sporulation, spore release, survival and infection predictions, although plant development, disease susceptibility and actual inoculum present in the field were not accounted for. The effectiveness of MILIONCAST was further improved by augmenting environmental disease risk predictions with low-cost detection with quantification lateral flow devices for use with aerial onion downy mildew spores [D308 D341], although further refinements were needed to allow for changes in infection efficiency [D343]. Since 2019, MILIONCAST was funded by AHDB Horticulture as part of the free CropMonitor information service provided by Fera [D307]. This tool allows UK growers to see for their individual field locations whether temperature and humidity had been, is currently, and is likely in the next three days to be suitable for the development of onion downy mildew spores. The risk of initial infection (not symptom expression) is shown as high, moderate or low, with the aim being to reduce how many times the crop needs to be sprayed. Growers have up to now registered their details via AHDB Horticulture, but this sector of the levy body will be shut down in March 2022.

A review of modelling in aerial oomycete-associated diseases was completed in 2020 [D284]. It was concluded that the mathematical models which summarise the effect of leaf wetness duration, temperature and spore density on infection by downy mildews of brassicas (*H. parasitica)* and lettuce, (*B. lactucae)* [D285] may help to model such diseases when multiple interacting factors are important and could be useful for predicting disease outbreaks and scheduling control approaches.

Downy mildew in brassicas is primarily of importance at propagation, rather than in the field. Little work has been done regarding forecasting because the short duration of moisture required (as little as 30 minutes) over frequently seen temperature ranges means that infection conditions occur in the crop canopy on most days or nights [D330].

A number of UK companies have developed decision support tools for growers which include weather data to assist spray timing. Details are available on their websites. These include Hutchinsons' "Omnia", Agrii and Bayer's FieldView. Fera run CropMonitor Pro [D312] which is a subscription service launched in September 2020 that uses a network of weather monitoring stations whose data is used with models to guide spray decisions for winter wheat, oilseed rape and potato.

Rothamsted Research provide a phoma leaf spot (*L. maculans*) forecast on the date that they expect 10% of oilseed rape plants to show symptoms of phoma leaf spot, this level is generally regarded as the threshold for spraying oilseed rape in autumn. Phoma can grow down petioles to form a stem canker of oilseed rape and lead to a dry rot in swedes [D158].

The AHDB utilise rainfall data to produce a regional forecast in autumn that shows the proportion of the oilseed rape crop estimated to have more than 25% of plants affected by light leaf spot (*P. brassicae*) in the spring with the aim of helping farmers to well-time and potentially omit fungicide sprays [D314]. These warnings could be utilised at particular locations to see the risk of light leaf spot in overwinter brassicas, in particular Brussels sprouts, where blemishes cause buttons to become unmarketable. There is also a sclerotinia infection risk alert service provides by the AHDB [D315] , but that is of little relevance to vegetable brassica growers as it relates to the pathogen infecting leaves and stems via dropped petals (in May) in warm humid conditions, however the forecast of ascospore release from apothecia growing from sclerotia in the soil could be of use against aerial *S. sclerotiorum* infection of lettuce such as for protectant use of Prestop biofungicide.

*Pathogen / dise*ase sampling

Molecular approaches to disease diagnosis were reviewed in detail for AHDB in 2015 [D217] including immunoassays (e.g., ELISA), on-site immunoassays (lateral flow tests), immuno-array tests (multiplex testing for more than one pathogen), and methods involving DNA amplification (LAMP, PCR and quantification of DNA using qPCR). There is also next generation sequencing (NGS) which can be used to analyse complex environmental samples. More recently a molecular procedure (PMAxx -qPCR) has been developed which can be used to determine if pathogen or biocontrol microbe molecular material is viable when sampled

 

[D206]. Lateral flow tests for phytophthora are able to be used by growers to obtain results on-site and as described in the review [D217], work has been ongoing, starting with using LAMP to enable growers to do their own molecular testing.

Molecular detection of different *Pythium* spp. important in carrot cavity spot in carrots and soil using PCR primers designed on the basis of Internal Transcribed Spacer (ITS) sequences was reported in 2008 [D279] but could not be used for threshold sampling pre-planting as it was not quantitative. Following work up to 2018 in the UK [D278], a quantitative PCR test (qPCR) for *P. violae* has been developed and validated for *P. violae* research, it has to date not been used to reliably predict disease. Accurate detection is hampered by the patchy distribution of *P. violae* in soil, meaning that testing of small soil samples may not represent the pathogen load over the entire field. Better levels of detection were achieved when disease pressure levels of cavity spot were high and the pathogen was multiplying.

In Australia, where *P. sulcatum* is the most common cause of cavity spot, real-time qPCR assays were developed by the South Australian Research and Development Institute (SARDI) and evaluated for assessing the risk of cavity spot in carrot crops [D280]. Although *P. sulcatum* presence was associated with a risk of cavity spot occurring, multiple soil samples were required within relatively small areas of crop, such as a couple of hectares, for adequate detection of this pathogen. After a test was developed for *P. violae* this species was found to be more widespread than previously thought. Results from the UK [D278] suggest the threshold for disease risk posed by *P. violae* in susceptible varieties may be below the level of detection of the DNA test.

Pre-plant tests for the soil DNA concentration of *Plasmodiophora brassicae* linked to the risk of yield loss to club root of susceptible brassica crops were made available in 2019 through SARDI's PREDICTA service [D280]. They caution that warm growing conditions, low soil pH, soil compaction and inadequate drainage can elevate the risk of clubroot and need to be taken into account when interpreting DNA soil testing results. In the UK, Fera receive soil samples from growers and carry out a soil bait test (to attract the living pathogen) followed by a molecular test (TaqMan) to determine if *P. brassicae* was baited, but this is only for presence or absence [D311].

Amplicon sequencing to quantify *F. oxysporum* and other microbe species in soil has been shown to be a useful technique, with detection of *F. oxysporum* f.sp. *cepae* by qPCR being consistent at levels ≥1 x $10^4$ colony forming units/g of soil, with ≥1 x $10^5$ c.f.u. /g of soil being associated with onion basal rot development [D350].

At least 50 different bacterial taxa were detected by metabarcoding of bacterial 16S rRNA barcodes in the soil of an onion crop as part of SBSH Project 5 [D349], with each plot presenting a different “pattern” of relative abundance of each species, but much more work will be needed to determine any relevance of this within the soil community, preferably where the treatments used are shown to have an effect on plant health.

Most detection methods require destructive sampling, however with hyperspectral imaging it is possible for various disease on plants to be detected based on changes in the wavelengths of light coming back off their leaves. This is a developing field of research with information being gathered to enable interpretation of readings from monitoring equipment and equipment being designed and tested for carrying the sensors into the crop. One study investigated the feasibility of using hyperspectral remote sensing imagery as a non-destructive method to identify grapevines inoculated with grapevine vein-clearing virus (GVCV) in the early asymptomatic stages [D356]. The exploratory analysis showed the importance of vegetation indices associated with pigment, physiological, and canopy water changes. Indices reflected changes in the chlorophyll degradation into pheophytin, the chlorophyll fluorescence, carotenoid and mesophyll cell structures, anthocyanin levels, and canopy water and temperature statuses. The ability to detect disease before it is visible (i.e., asymptomatic / latent) will allow management action to be taken before the chance of spread from that plant and to either not plant the affected plant, or if in a crop to treat or eliminate it. The not too distant future promise is of being able to detect diseases in a crop using sensors mounted on a tractor, drone or glasshouse gantry, including before symptoms are visible [D356].

*Environmental control*

Even if strict pre-crop hygiene measures have been put in place where plants are to be produced under glass or polythene structures, there is still the possibility of spores being brought into the protected area by various means; examples include if growing media is not kept covered, footwear/clothing is not changed or disinfected, irrigation water is inadequately treated or entry on air currents through openings. Various integrated management advice has been given for downy mildews which are valid across for most pathogens [D317]; with short heavy overhead watering rather than frequent light periods (if possible, substituting with underneath watering), good ventilation and good plant spacing all assisting to reduce humidity and make leaf surfaces less conducive to spore germination. Prompt removal of visibly diseased plants and all weeds (particularly cruciferous where brassicas are grown) is important, although this can be a challenge where rows of propagation trays are stood close together.

Management of environmental conditions by venting or heating in glasshouses has long been able to be computer controlled, however, logging equipment is now being used in some nurseries that record the temperature, humidity within the canopy and growing media moisture, with real-time readings being sent to a computer or mobile phone, so that growers can send instructions to the control computer if conditions are becoming conducive to disease development. Seeing the likelihood of dew formation, from warm humid air on cold leaves, is one benefit. Historical data storage “in the cloud” enables a review of the conditions to learn from past trends. The Zensie / 30MHz data platform [D281] is in use by several UK growers. Models have been developed for downy mildew forecasting on lettuce (see Decision support section of this report) utilising environmental records, but these need to be combined with spore detection (either by ELISA or qPCR), as the earlier an outbreak can be predicted the greater the chance of a bioprotectant being effective rather than requiring a systemic, curative active chemical such as the commonly used metalaxyl.

The review of cultural control of aerial oomycetes in protected production completed for the AHDB in 2020 [D284] noted the benefit of manipulating the crop environment. High relative humidity is needed for spore production and free moisture being needed for spore germination, but although light can trigger spore release in the morning, continuous broad- and narrow-band illumination can suppress sporulation and more work is needed on the potential utilisation of UV light. High temperature (above 35°C) can reduce downy mildew survival, but this may have less potential than seen in warmer countries.

*Precision irrigation*

Precision irrigation in this section of the report has been taken to include at its simplest; a change from overhead boom or rain-gun irrigation to drip / trickle tape whereby water is provided uniformly just to the crop row without wetting the foliage, and probably controlled by a timer. The resulting lower humidity, leaf wetness and water splash means that most foliar pathogens such as downy mildews, powdery mildews, botrytis, leaf spots and bacteria are less able to infect, and without over-wet soil and water run-off root pathogens such as pythium and phytophthora species are less able to spread. Mulches (organic, plastic sheet or horticultural fleece) over the trickle tape can reduce evapotranspiration and further reduce humidity around the leaves, while enhancing soil organic matter improves water-holding capacity [D508]. Information on soil type water holding capacity, and the requirements of shallow rooted leafy brassicas and lettuce and root, tuber and bulb vegetables including the critical growth periods of water need are available [D508]. Information on water management has been provided by the AHDB for potato crops where the main driver for early season irrigation in the UK has been its use for the reduction of common scab caused by *Streptomyces scabiei* and other pathogenic *Streptomyces* species that are widely distributed in most soils [D507] and also affect other root vegetables. Tables are available which take into account soil type and potato variety susceptibility to scab to show what soil moisture deficits should be maintained either by using scheduling and/or moisture probes [D507]. If susceptibility to common scab were determined for swede, turnip, carrot and beetroot varieties then the maximum soil water deficits (which range widely between potato varieties) could be determined and irrigation then be applied to the best level.

In recent years in the UK the mix of long dry periods and heavy, often patchily distributed, downpours makes irrigation by timer less than satisfactory. More-precise irrigation application for vegetables was investigated in a Hort LINK project to improve water efficiency and crop quality [D509]. The project reviewed the technical, agronomic and economic aspects of wireless sensor control drawing on published evidence form the US, Australia, New Zealand and Europe. The review determined that whilst a number of different types of wireless soil moisture sensing systems had recently emerged in the market (some of which had been evaluated) there still remained a noticeable lack of research and farmer guidance on the number of sensors required to provide optimal field coverage and to inform sensor placement. This was followed by research over three years comparing the use of a hose-reel fitted with a boom system or a solid set sprinkler rig when a wireless soil moisture sensing array was installed for the growing season in lettuce and onion fields at grower sites. One of the challenges in sensor placement was understanding the extent of spatial soil variability that exists within a field to enable informed decisions on where to install the sensor. A technique known as Electromagnetic Induction (EMI), being developed in the UK, was evaluated and how to use the EMI data to delineate Irrigation Management Zones (IMZ). The project concluded that development and uptake of precision irrigation would need to be justified in terms of the wider benefits to crop quality and the reduced environmental impacts associated with irrigation (reduced drainage and higher nitrogen efficiency) as at that time (2014) the potential economic benefits from precision irrigation for supplemental irrigation on field-scale crops in a humid climate such as England appeared modest. The benefit to the grower in the reduced cost of water and energy was estimated to be typically less than £25/ha that is over-irrigated. However, investment in equipment and technology to allow water application where and when really needed would be worth re-evaluation as there was no consideration of aspects such as minimised disease in precision-irrigated crops and issues (particularly in Eastern England) of restrictions on water usage due to low river or aquifer levels.

*Physical disease control*

Control measures include removal of weeds that can host crop diseases by cultivation, both before and during cropping. Inter-row hoes are available that can be positioned by guidance mechanisms including machine vision, with recent precision farming equipment even able to weed between plants within the row [D316]. Spot-treatment of plants with foliar disease to stop pathogen spread is the subject of research involving hyper-spectral vision whereby diseased plants can be “seen” because of their stress response [D355]. Currently intended to find targets for pesticide application, there is potential for robotic physical removal of single plants, particularly if the space can then be filled by a new plant.

*Amendments - soil mulches*

Plastic, straw, paper or other soil mulches, above which the plant foliage protrudes, are sometimes used in horticulture and can be effective in reducing certain diseases such as can arise from pathogens in debris and the soil splashing up onto stem bases and leaves e.g., rhizoctonia basal rot, or where basal leaves would otherwise create a humid microclimate favourable to the pathogen e.g., botrytis or sclerotinia rots. Planting through white plastic is increasingly used in protected soil-grown lettuce production to reduce rhizoctonia basal rot and sclerotinia [D132]. Although of limited scope, soil mulches are effective. However, recycling soiled plastic mulches has difficulties for which solutions are being sought [D249]. Several studies have looked into biodegradable alternatives, including spray-on-mulches using materials such as cotton waste and recycled newspaper [D132]. Information on biodegradable polyester and starch-based plastics and successful trials with them in crops in Spain has been provided for UK farmers [D250]. In lettuce crops although polyethylene and paper mulches were more effective than chopped up maize cobs and stalks and straw, the latter were also promising as organic mulch alternatives [D251].

*Biological control – bioprotection and low risk plant protection products*

Biological control, or biocontrol, technologies are defined as originating from nature – directly or identical to nature if synthetized. Biocontrol technologies include semiochemicals / communication chemicals and invertebrate biocontrol agents. The other two product categories, for pest, disease and weed control, are microbials and natural substances. Microbials are based on microorganisms including bacteria, fungi, protozoans, viruses, viroids and mycoplasmas and may include entire microorganisms, living and dead cells, any associated microbial metabolites, fermentation materials and cell fragments. Natural substances consist of one or more components that originate from nature, including but not limited to plants, algae/microalgae, animals, minerals, bacteria, fungi, peptides, protozoans, virus, viroids and mycoplasmas. They can either be sourced from nature or are nature identical if synthetized [D526]. Both microbial and natural substances require registration as plant protection products if some or all of their efficacy is by direct control of the pest (rather than, indirectly, by for example stimulating/eliciting plant defence responses). Microbial or natural substance based control products can be termed biofungicides or bioinsecticides, but more recently the term bioprotectant has been adopted for such disease and pest control products.

A range of bioprotectant products and other low risk plant protection products are either available for commercial purchase or have shown potential as alternatives to chemical control of pathogens. Products containing living beneficial bacterial or fungal propagules for spray or drench applications have become available in the UK this century but have been registered in considerably lower numbers than chemical fungicides. Published research on various microbial isolates (bacterial and fungal) against various pathogens is abundant. Many of these biocontrol agents are unlikely to become formulated as products. Most research on them has been laboratory and pot tests rather than field based, and often using artificial inoculation of the pathogen [D204 D221]. An EU review in 2007 [D214 & D543] searching for reports of significant biocontrol activity against botrytis, powdery mildews, rusts, downy mildews, late blights and *Monilinia* rot counted 157 microorganisms (36 genera of fungi or oomycetes, 13 yeast genera and 25 genera of bacteria), with the greatest number of research articles focussed on botrytis. For these aerial pathogens, and also *F. oxysporum*, 1791 references were found and all reported successful effect in controlled conditions. As common for scientific publications, reports showing poor control are perhaps less likely to be published. Few promising isolates make the step to formulation as a product and the large funds needed to produce dossiers on safety (environmental and human) and efficacy to enable registration are a further hurdle.

Biocontrol organisms should be applied preventatively so they can colonise the target leaf and / or root surface and reduce the ability of pathogens to find the space and nutrients they need to colonise. Enzymatic activity may also be used directly against the pathogen, and there are also indications that systemic acquired resistance can be induced within the host, priming the plant's defence mechanisms ready for any pathogen attack [D222 D223]. Bioprotectants need to be in contact with pathogens to be effective, and spray application techniques that lean heavily on the systemic movement of many chemical fungicides away from the site of deposition can be expected to give poor results. The AHDB AMBER Project [D199] has been evaluating the persistence of a selection of foliar applied bioprotectants, decision making on if and when to apply them, and how to improve spray applications. As further products come onto the market it will be necessary to determine how best to use these products and how to optimise their efficacy.

Growers and advisors can search the UK Health and Safety executive CRD website to determine which crops bioprotectants are authorised for and against which pathogens they have activity [D195] and any off-label authorisations (EAMUs) [D196]. Authorisation details change and so growers and advisors need to check their information is current before product use. The LIASON pesticide database [D202], updated daily by Fera, can be accessed by subscribers. Until recently it has not been easy for growers, if not aware of a product's existence, to know if it is available for a particular crop or problem, but a free online tool has been set up by CABI, their "BioProtection Portal", to enhance the awareness and uptake of biocontrol and biopesticide products by growers and advisors, specific to their country and with information on products around the world [D197]. The Portal includes both microbial and chemical bioprotectants. It is important that Portal users then check the status of these products in the UK with the regularly updated authoritative HSE website databases.

A number of bioprotectant products have been restricted by HSE to on-label use under permanent protection, such as is provided by glasshouses, thus for field vegetables and outdoor lettuce bioprotectants use may only be able be possible in propagation. However, as for chemical fungicides, EAMUS are often later granted for outdoors applications. Authorised, on-label, uses will have efficacy and crop safety data against the pathogens named on the product label. EAMUS do not need to have known efficacy, although AHDB funded efficacy trials, such as SCEPTRE [D198] and SCEPTRE plus [D200] for crops including alliums, brassicas, carrots and parsnips and leafy salads have frequently been used to support EAMU applications.

A factsheet was produced by the AHDB “Getting the best from biopesticides” [D207], following on from efficacy trials on vegetables under the SCEPTRE Project [D198]. The factsheet gives advice on application practices and environmental factors that can affect efficacy. The subsequent AHDB AMBER Project [D199] is producing further advice to growers. The beneficial organisms in bioprotectants usually require humidity (over 60% RH) while they colonise the plant surface. Conditions of high humidity are also those that favour many pathogens and so are likely to be a factor in deciding on the preventative bioprotectant application. Warmer temperatures (20 – 25°C) are usually optimum for the growth of beneficial organisms such as *Bacillus amyloliquefaciens* in Serenade ASO, *Gliocladium catenulatum* in Prestop and *Ampelomyces quisqualis* in AQ10 [D207], but this is also true for most plant pathogenic bacteria and fungi. The number of viable colonies of the beneficial organism on the plant can decline from the concentration applied, particularly if environmental conditions are unfavourable, but the number of colonies needed to manage the pathogen and hence re-application intervals is a grey area. Molecular quantification of viable colonies washed from leaves has been developed, PMAxx™ -qPCR, (as an alternative to colony counting on agar plates) [D206]. Viable DNA of *B. subtilis* QST 713 and *G. catenulatum* J1446 was retrieved from bioprotectant sprayed lettuce and strawberry plants grown under various temperature and humidity regimes, and population survival and reproduction at optimal and sub-optimal temperatures shown to be favoured by increasing relative humidity [D205].

Both Serenade ASO and Prestop drenches reduced club root severity in inoculated growth cabinet tests with a susceptible oilseed rape variety [D194], but a month of dry weather after field application was attributed to their poor performance in field. Serenade ASO has UK on-label registration for a wide range of diseases of protected crops (lettuce under full protection, against botrytis and sclerotinia), and there are extensions of use authorisations (EAMUS) including for outdoor brassicas, onions, carrot, parsnip, lettuce and baby leaf [D195 D196] Prestop is also on-label for protected edibles against *Botrytis*, *Pythium*, *Phytophthora*, *Rhizoctonia* and *Fusarium* spp. and has an EAMU for an extensive range of outdoor horticultural edible and non-edible crops [D195 D196]. Outdoor lettuce may however only get some control of *B. lactucae*, from Prestop and Serenade ASO and also Amylo X WG (*Bacillus amyloliquefaciens* subsp. plantarum strain D747), particularly when there is high disease pressure [D104].

The parasitic fungus, *Coniothyrium minitans*, is available in Contans WG in the UK for incorporation into affected soils prior to planting any edible or non-edible crop, against *S. sclerotiorum* and *S. minor*. The label list of vegetable hosts includes broccoli, cabbage, carrot, lettuce, onion, radish and turnip, with optimum efficacy stated to be in moist soil between 12 - 20°C. Under optimal conditions of 15 - 20°C and pH 4.5 – 5.6, *C. minitans* was shown highly effective at colonising and neutralising sclerotia [D203.] Applications of different antagonistic fungi (28 listed) and bacteria (11 listed) for the control of *S. sclerotiorum* in horticultural crops have been reviewed [D204]. The authors also noted applications of organic matter with either *C. minitans* or *Trichoderma virens* incorporated had proved effective. Following a review of microbial products, Contans together with *Trichoderma harzianum* Rifai race KRL-AG2 was incorporated into lettuce fields in Turkey before planting lettuce seedling and shown to be an effective alternative to chemicals in the control of *S. sclerotiorum* in lettuce [D208.] In the UK, *T. harzianum* is available as Trianum P and Trianum G (strain T22) but does not have on or off-label use for outdoor (only protected) lettuce other than baby leaf. It is also only permitted, under an EAMU, on brassicas and named other crops if they are under permanent protection and targeted at *Pythium*, *Rhizoctonia* and *Fusarium* spp., which are likely to cause root rot and collapse of seedlings [D195 D196]. Another product T34 Biocontrol, containing *T. asperellum* strain T34, can also only be used for brassicas and lettuce and other crops when they are under permanent protection [D196].

In UK trials, when a bioprotectant (only given a code) was applied seven days before drilling carrots and again four to six weeks after drilling, similar levels of carrot cavity spot developed to untreated plots [D263]. Carrot cavity spot control field trials in Southwest France [D276] (where *Pythium sulcatum* dominates) comparing the use of bioprotectant products Rhizocell (*Bacillus amyloliquefaciens* strain IT 45), Prestop (*Gliocladium catenulatum* strain J1446), Tri-Soil (*Trichoderma atroviride* strain I-1237), Xedavir (*Trichoderma asperellum* strain TV1) and Trianum-P (*Trichoderma harzianum*) with untreated and metalaxyl-M treated carrots found Tri-Soil was the most effective product tested, reducing the proportion of damaged carrots from 63% to 27%. Tri-soil is available in France for use against vegetable soil borne diseases (*Pythium* spp. on carrot and *Rhizoctonia* spp. on salads) including for use in organic farming, working mainly through spatial and nutritive competition (antagonism) but also via antibiosis and mycoparasitism.

Of the above products tested in France [D276] only Prestop and Trianum-P are authorised as plant protection products in Great Britain and Northern Ireland [D195 D196], and while Prestop has an EAMU for named outdoor vegetables the latter is only for use under an EAMU for under permanent protection with full enclosure ("PPFE") but Trianum-G (not the powder -P formulation) is the product for vegetables. Other products to those in France are available in the UK, but as different strains and so may not have the same efficacy. T34 Biocontrol, *T. asperellum* strain T34 has an EAMU for "PPFE" lettuce and named brassicas including propagating material. Amylo X WG, *B. amyloliquefaciens* D747, is authorised "PPFE" for a selection of crops including lettuce, with EAMUS for crops including named vegetable brassicas, lettuce, and protected and outdoor carrots advised for use against *Anthracnos*e spp, *Botrytis cinerea*, *Fusarium* spp, *Pseudomonas* spp, *Pythium* spp., *Rhizoctonia* spp., *Sclerotinia*, *Xanthomonas* spp., damping off diseases, downy and powdery mildews. Taegro *B. amyloliquefaciens* strain FZB24 can be used on lettuce "PPFE" on crops including lettuce, but not brassicas, with no EAMUs. Integral Pro is authorised in the UK for winter oilseed rape. This contains *B. amyloliquefaciens* strain MBI600 and the same strain is sold as Serifel for "PPFE" crops including lettuce, choi sum and oriental cabbages with an EAMU for outdoor lettuce against *Botrytis* spp. and *Sclerotinia* spp.. Numerous studies of a wide range of plant species have identified *Bacillus* spp. as potential biocontrol agents and plant growth promoters, with it acknowledged that more understanding is needed on factors that influence the successful application of *Bacillus* spp. and how the different strains function [D277].

*Botrytis cinerea* (causing rotting of lettuce and often enlarging the damage caused by biotic and abiotic causes across all vegetables) has been the focus of many research activities, and a recent review [D222] found these were mostly focused on *Trichoderma* spp., *Ulocladium* spp., *Bacillus subtilis*, and also plant extracts and their essential oils with some commercial products, such as Serenade ASO available on the UK market. The review concluded that different biofungicides have provided good disease control with some being comparatively effective as synthetic fungicides, especially when disease pressures are low to moderate. However, variability in the field efficacy of some indicates that the best outcomes are likely to be achieved by the combination of biofungicides with different modes of action and also in combination with "reduced risk" fungicides within integrated disease management.

Application of *Trichoderma viride* strain S17A gave significant white rot (*Stromatinia cepivora*) reduction in most of a number of onion field trials. In glasshouse trials with a salad-onion cultivar, *T. viride* combined almost emanated the disease.  An AHDB review in 2016 [D224] of biological control product use worldwide specifically against allium white rot (*S. cepivora*) found the only commercial product in use was Tenet (*Trichoderma atroviride* isolate C52) marketed in New Zealand and Australia. Field trials showed 70% incidence reduction under low disease pressure, 40% in high [D226]. An AHDB project in 2013 [D225] tested various biocontrol agents against onion white rot and found drenches of either Serenade ASO or Prestop gave good disease reduction under low disease pressure, with variable results at higher levels. Application method is important, with in-furrow treatments being the most effective for delivering products to the root zone [D224].

One of the difficulties with *S. cepivora* control by beneficial microbes is that the sclerotia only germinate (and thus become more susceptible to attack) in the presence of *Allium* stimulants. Natural and artificial stimulants such as garlic oils and their constituent chemical compounds such as diallyl disulphide (DADS) or diallyl sulphide (DAS) have been tested [D357]. A recently completed AHDB project [D357] has shown a commercially available product (NEMguard SC with 99.9% garlic extract) marketed for free-living nematode control is able to induce *S. cepivora* sclerotia germination in the field and significantly reduce white rot disease either alone or in combination with Tri-soil (*Trichoderma atroviride* I-1237). Tri-soil is a French biocontrol product for use on vegetables against *Pythium* spp. and *Rhizoctonia* spp.. In the UK, *T. atroviride* strain SC1 is registered as a plant protection product (Vintec) but only for use on outdoor grapes.

The 2013 Defra review of non-chemical control measures [D132] stated "There is potential for greater use of microbial biofungicides but uptake is likely to remain restricted in the medium term due to several features which generally disadvantage them compared with conventional fungicides – lower efficacy, greater cost, narrower spectrum of activity, shorter spray interval, need for a higher water volume and more variable results. They are generally used in alternation with fungicides or other crop protection measures as part of an integrated disease management programme". More research on timing, spray application and conditions that improve persistence are still required, but disease management with IPM is not beyond reach. There is, however, opinion that although increasingly innovative and sophisticated biological-based crop protection is emerging from research programmes, the regulatory system and on-farm knowledge of how to use such products are struggling to keep up. Indirect or augmentative control from biological systems (such as endophytes, elicitors, arbuscular mycorrhizae and bacteria and fungi species within the soil microbiome) is particularly challenging for regulatory systems [D358].

Bacteriophages are the viruses of bacteria and bacteriophage treatment of bacterial infections of crops, such as of xanthomonas leaf blights of brassicas carrots and beans and peas, pectobacterium soft rot of lettuce, or streptomyces scab of radish could be a future development as other plant protection products are lacking for bacteria. Experiments have been conducted with a number of different phages [D511]. Greenhouse trials showed that phage PP1 could significantly reduce disease development on lettuce plants by *Pectobacterium carotovorum* ssp. *carotovorum* [D513]. Radish seedlings treated by Phages Stsc1 and Stsc3 against *Streptomyces scabies* (common scab) had similar weight to uninfested controls, whereas the untreated weighed 30% less [D514]. A field trial with the non-UK pathogen *Xanthomonas axonopodis* pv. *allii* showed that weekly and biweekly applications of phage could reduce disease severity, a result which was comparable to treatments of weekly applications of copper-mancozeb [D515]. It would be possible to create “phage cocktails” with tailored host ranges and they can be combined with other chemical or biocontrol agents and could be produced in UV protectant formulations [D511]. They have been used on some foods such as lettuce and spinach against human pathogens which could contaminate them such as *Escherichia coli*, *Campylobacter* and *Salmonella* species [D512 D516]. At the University of Exeter “citizen science” is being used to collect water samples to isolate phages, whose genomes are then sequenced and they are tested against human pathogens on agar plates (effective ones produce holes in the bacterial culture) for potential use to treat multi-drug resistant infections. Such methodology could be used to find phages against plant pathogenic bacteria [D517].

Potassium hydrogen carbonate (potassium bicarbonate) has had long usage under the category of commodity substance with use to desiccate powdery mildew spores. The products Karma and Omex K50 containing this as the active ingredient are registered as plant protection products and can be used on some vegetable crops e.g., outdoor lettuce [D195].

*Nutrient management – micronutrients and biostimulants / elicitors*

Crops require nutrients for satisfactory growth and quality production. There is much interest currently in the role of macro and micro-nutrients and biostimulants in the control of diseases. A wide range of both non-microbial and microbial products, and combinations of the two, are available in the UK, with a multitude of different attributes given on their labels [D110]. Biostimulants can be, but are not necessarily elicitors i.e., stimulators of plant defence reactions. This section will consider the indirect effect of nutrients on disease through the correction of nutrient deficiencies, or ‘stimulation’ of the crop and changes in the nutrient status of the crop. The direct effect of nutrient salts and elements as biofungicides / bioprotectants was discussed separately in ‘Bioprotectants and Low Risk Plant Protection Products (PPP’s)’.

A recent AHDB review for arable crops concluded that there is currently little independent research to support the use of nutrients where they are not deficient, or bio-stimulants, in protecting crops from disease through effects on plant health [D110]. The types of products and their contents and the evidence base for positive biostimulant effects was also summarised in the associated factsheet [D215] with evidence of the non-microbial products, seaweed extracts and chitin or chitosan derivatives having indications of biotic stress tolerance promotion in cereals or oilseed rape, as did products containing plant growth promoting bacteria and arbuscular mycorrhizal fungi.

An AHDB review [D216] was carried out in 2019 to include the use of elicitors against aerial oomycete pathogens of selected horticultural crops. A table derived from this review of the different types of elicitor and the types of plant defence responses elicited as given in a recent review is given in the soft fruit section of this report. A wide range of biostimulants are also promoted to UK cereals and oilseed rape growers and a review to assist farmers' understanding of was also commissioned by the AHDB [D488]. Not all biostimulants have the potential to elicit or stimulate plant defence mechanisms. Published work on elicitor use on vegetable downy mildews including onion (*P. destructor*), *Brassica* spp. including baby leaf (*Hyaloperonospora parasitica* formerly *Peronospora parasitica*) and lettuce (*B. lactucae*) was found to be sparse. A number of existing reviews were referenced that gave information on the biochemistry and host genetics considered to be at work in plants' defence mechanisms and by extrapolation how externally applied elicitors may work. A summary of the nature of activity of elicitors of plant defence was previously given in a report on management options for aerial oomycetes in horticulture [D330]. Research on microbial, botanical and other agents was carried out by the EU between 1973 and 2008 during the ENDURE project [D213]. This has recently been followed up by the EU Bio4Safe Interreg project which has created a database allowing product searches by ingredient type, effects and the arable and horticultural crop types on which they are intended for use [D489].

Some biostimulant products are now acknowledged as biofungicides / bioprotectants i.e., with direct activity on the pathogen (although elicitor activity may also occur). One example, potassium phosphonates, have relatively recently been registered in the EU as an active ingredient for plant protection having shown efficacy against oomycetes. However, it is still currently available as a component in many products that are sold as fertilisers or biostimulants, not as plant protection products. Laminarin, a glucan, extracted from brown algae (*Ascophyllum nodosum*) is a biofungicide sold in the UK for the control of foliar diseases of wheat, but is a common component of biostimulant products [D216]. A table of biostimulant products available in the UK for arable crops that include label statements around improving resistance to disease / improving plant health was presented in the 2016 AHDB review [D110], however manufacturers are aware that they cannot claim disease control as this would require efficacy testing for registration as a plant protection product. Biostimulant products from at least one UK supplier to horticultural crop growers including fulvic acids or seaweed extract or tryptophan and other free amino acids are said to promote crop growth and improve crop resilience. Other non-microbial biostimulants include humic substances and chitin and chitosan derivatives. A number of vegetable growers in the UK do apply amino acid and/or fulvic acid (from organic matter) biostimulant products to their crops to promote health (Angela Huckle, pers. comm. ADAS vegetable specialist). There are also bacteria and fungi which can have some biostimulant activity such as plant growth promoting bacteria and rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF).

A worldwide ENDURE review [D214] noted the product Bion (acibenzolar-S-methyl) (at one time registered as a PPP in the UK) and phosphonate as giving success in field trials against downy mildew of brassicas, and *Trichoderma harzianum* in indoor tests. Phosphonate was also successful against *B. lactucae* in the field. When either Phytogard (potassium hydrogen phosphite) or beta-amino-butyric acid (BABA) were sprayed on two weeks old lettuce seedlings in a growth cabinet both gave good protection from *B. lactucae* [D218] at the higher concentrations tested. There is large body of work on the elicitor BABA, but toxicological as well as biodegradation studies will be required before registration as a plant protection product. A fungal elicitor was found highly effective against onion downy mildew *Peronospora destructor* in the field [D219].

Elicitors are best used preventatively and do not give 100% control [D211 D212] but can help in reducing the requirement for synthetic chemical pesticide usage. As with varietal resistance, there can be fitness costs to plants associated with the defence response perhaps resulting in reduced yield, and the secondary metabolites produced have potential to negatively affect the quality or taste of crops. There are significant uncertainties around elicitors, with further research needed on when, where and on what crops and pathogens each particular product could be used to give disease reductions.

Plant defense responses have a genetic basis, and the DRASTIC (Database Resource for the Analysis of Signal Transduction in Cells) gene expression database was set up in 2001 by the Scottish Crop Research Institute and the University of Abertay. The DRASTIC web site [D220] is a database of plant expressed sequence tags and genes up- or down-regulated in response to various pathogens (biotic stress), chemical treatments, and abiotic stress such as drought, salt and cold. There is a road map facility to enable the creation of look-up tables to find genes that are co-regulated by treatments. While primarily intended for use by researchers in plant breeding, understanding what genes are involved in defense responses could help with the selection of types of elicitors and gain an indication of whether then could be effective on different hosts.

 

*Mycorrhiza and plant growth regulating rhizobacteria*

Mycorrhiza products can provide a similar health promoting role to the indigenous rhizosphere microbes (which will include mycorrhiza) [D230]. There is evidence that through their symbiotic relationship with the plant roots, nutrient (in particular phosphorus and possibly nitrogen [D110]) and water uptake to the plant can be improved [D231 D232 D233]. AMF may assist host plants in the up-regulation of tolerance mechanisms to abiotic stresses such as drought [D232 D233]. The mycorrhizal fungi need to be able to contact and enter plant roots, so in vegetable crops would normally be applied at drilling or by broadcasting using a granular applicator, although they can be suitable for seed blending [D235].

Bacteria that colonize plant roots and promote plant growth are referred to as plant growth-promoting rhizobacteria (PGPR). There is also evidence of increased benefits to plant growth from co-inoculation of plants with arbuscular mycorrhizal fungi and plant growth promoting bacteria (PGPRs). Arbuscular mycorrhizal fungi establish symbioses with plant roots which help to improve nutrient uptake by the host plant and alter its physiology to withstand external abiotic factors and pathogens. Plant growth promoting bacteria promote plant growth either directly by aiding resource acquisition and controlling the levels of plant hormones or indirectly by reducing the inhibitory effects of phytopathogens. Co-inoculation of both organisms combined the benefits of each for increased crop productivity [D234].

Mycorrhizal products are available to growers and can contain a mix of arbuscular mycorrhizal fungi (AMF) such as *Claroideoglomus claroideum*, *Funneliformis mosseae* (syn*. Glomus mosseae*)*, Funneliformis geosporum*, *Rhizophagus irregularis (previously with Rhizophagus intraradices as Glomus intraradices)*, *Glomus microaggregatum* and *Diversispora* sp. (pers. comm. Natallia Gulbis, PlantWorks UK Ltd.). AMF products may also contain biostimulants; e.g., a UK produced product contains molasses and plant derived amino acids that are said to support mycorrhizal development and further enhance benefits [D235], and consequently any contribution by the AMF could be harder to affirm. The same UK manufacturer [D235] sells PGPR products aimed at particular horticultural and arable crop groupings having found that different plant types can benefit from different formulations.

A 2015 review [D231] gave an overview of the advances in the production of quality AMF inocula and in the biostimulant properties of AMF on plant health, nutrition and quality of horticultural crops (fruit trees, vegetables, flower crops and ornamentals). It has been shown that AMF symbioses are able to modify host plant metabolism, stimulating the production of phytochemicals in the roots and shoots of mycorrhizal plants, with such changes potentially ascribed to a transient activation of host defence reactions and the accumulation of antioxidant compounds. The authors conclude that further research, particularly under field conditions, is needed to integrate the use of AMF into horticultural crop production.

 

A 2012 review of PGPRs [D236] showed these highly diverse rhizobacteria to act as biocontrol agents via local antagonism to soil-borne pathogens and / or by induction of systemic resistance (ISR) against pathogens throughout the entire plant. Rhizobacteria belonging to the genera Pseudomonas and Bacillus are well known for their antagonistic effects and their ability to trigger ISR. Several substances produced by antagonistic rhizobacteria have been related to pathogen control and indirect promotion of growth in many plants, such as siderophores and antibiotics. Of relevance to vegetable seedling propagation, antibiotics produced by pseudomonads have prevented damping off by *Rhizoctonia solani*, and inhibited zoospores of *Pythium* spp. by causing membrane damage. ISR in plants resembles pathogen-induced systemic acquired resistance (SAR) under conditions where the inducing bacteria and the challenging pathogen remain spatially separated. Both types of induced resistance render uninfected plant parts more resistant to pathogens in several plant species. Rhizobacteria induce resistance either through the salicylic acid-dependent SAR pathway or require jasmonic acid and ethylene perception from the plant for ISR. There is potential for both resistance-inducing and antagonistic rhizobacteria to be formulated in new inoculants to benefit from combinations of different mechanisms of action, leading to a more efficient use for biocontrol strategies to improve cropping systems.

*Other substances used towards healthy plant growth*

A wide range of chemicals or animal or plant by-products can be purchased for application to crops to help growth. A list of over 40 are listed as able to be used (sometimes with stipulations) in the farm and growing standards for organic production [D310]. Examples are wool, wood ash, mollusc waste, eggshells, gypsum, elemental sulphur, magnesium sulphate and biochar.

There are indications that sulphur fertilisation, particularly in areas with low natural sulphur deposition enhances natural crop defences against disease. In oilseed rape, experiments have shown some reduction in light leaf spot severity due to sulphur application, but the effects are inconsistent and poorly understood [D132] and this could be extrapolated to its use in vegetable brassicas.

There is some evidence that autumn nitrogen applications can increase canker severity in oilseed rape [D132] and it may thus be the case in root brassicas. Excessive nitrogen will also exacerbate diseases such as powdery mildew and rusts in cereals. Where excess nitrogen is used, crops are more likely to lodge and this favours pathogens that develop under very humid conditions (e.g., botrytis, sclerotinia and alternaria). The effect of nitrogen form and level on plant diseases is complex and variable [D132].

## Field vegetables, pest control

 

## Crop planning

*Field history, rotation and break crops*

Knowledge of any previous field history can help to predict potential pest problems.

In carrots, carrot fly populations quickly build up where susceptible crops including carrot, parsnip, celery and parsley are grown close to previous crops in short rotations. Numbers of the pest can be reduced by separating successive crops and growing them less frequently in the rotation [P173].

Lengthening the rotation of carrot and parsnip crops will also reduce the risk of damaging populations of free living nematodes. Ideally, another carrot or parsnip crop should not be grown within seven years, rotating with poor host crops for the nematodes that damage carrot or parsnip. In Scotland, barley is often rotated with carrot but in East Anglia, carrot is often rotated with other good hosts for free living nematodes, such as potato, which allows numbers to increase [P174].

In AHDB review FV 232, it was reported that growing green manures as biofumigants, such as *Tagetes patula* may decrease numbers of root-lesion nematodes (*Pratylenchus* spp.) but increase numbers of stubby-root nematodes (*Trichodorus* and *Paratrichodorus* spp.) that can cause carrot 'fanging'. The effect of growing alternative crops or cover crops in the same rotation as carrot or parsnip in order to suppress nematode populations would need further research [P175].

In onions, stem nematode, *Ditylenchus dipsaci* can be a damaging pest, and depending on the nematode race, can also infest other crops including broad and field beans, peas, oats, carrot and parsnip. Crop rotation with non-host crops such as lettuce, leaf brassicas, wheat and barley can help to limit population build-up [P176].

In leafy and root brassicas, cabbage root fly,*Delia radicum* is a very damaging pest of both leafy and flowerhead brassicas including cauliflower, cabbage, Brussels sprouts and calabrese and also root brassicas such as radish, swede and turnip. The pest will also infest oilseed rape. The widespread occurrence of the pest, together with the long dispersal ability of the adult flies means that crop rotation and spatial separation of brassica crops is not a viable cultural control option [P177].

*Soil amendments*

In AHDB review FV 232, it was reported that soil additives such as chitin amendment (crab waste) can reduce numbers of plant-parasitic nematodes, but the practicalities of soil incorporation need to be assessed [P175].

 

*Decision support and monitoring*

For carrots, before sowing, the soil should be tested for free living nematodes that could cause damage. Traditional methods of confirming nematode genera and numbers using microscopic examination after extraction are usually used, but molecular methods are available for some species [P174.] If possible, avoiding growing carrots or using a nematicide in fields where estimated threshold numbers of nematodes are exceeded will reduce the risk of economic damage [P175].

However, shortage of land may limit the choice of where to grow carrots, and in addition, threshold numbers of different nematode genera and species for prediction of economic damage to carrots need reviewing [D263].

In leafy and root brassicas, forecasts and current pest activity reports for many horticultural pests including brassica aphids and cabbage root fly could be found on the AHDB Pest Bulletin hosted on the Syngenta website in association with the University of Warwick and also on the Warwick University blog [P178] [P179]. The future of the Pest Bulletin, due to the wind down of AHDB Horticulture, has yet to be determined.

The aphid forecast includes information from the Rothamsted Insect Survey which predicts the first migration of various aphid species including those that infest brassicas and gives information on aphid numbers caught in suction traps at various UK locations [P180]. Aphids can also be monitored using yellow water traps and regular crop monitoring.

The cabbage root fly forecast gives information on when adults of each generation will emerge from pupae and when they will lay eggs, which can help growers time planting out dates and applying crop covers. Growers and agronomists can also monitor adult fly activity using yellow water traps and monitor egg laying by floating the eggs in water from soil samples taken from around the base of the plants [P177].

For onions, before sowing or planting, the soil should be tested for stem nematode. There are no thresholds for numbers of stem nematodes for prediction of damage to onion; growers are advised to avoid growing onions on land where a soil sample has confirmed the presence of this pest [P181].

*Spatial separation/selection of low-risk locations*

Carrot fly adults do not fly far, therefore growing carrots at least 1km from a previous infested crop will reduce numbers attacking the new crop. Adults emerging from first generation pupae usually stay in the vicinity of the crop, therefore early and late drilled carrot crops should also be spatially separated in order to break the life cycle [P182].

 

As carrot fly adults spend much of the day sheltering in hedges and vegetation around the edges of fields, very sheltered fields should be avoided for growing carrots [P173].

For lettuce and endive, new crops should be isolated from older crops if possible to reduce the risk of aphids transferring to the new crops. As lettuce root aphid overwinters as eggs on Lombardy and black poplar, these trees should not be planted as a windbreak around lettuce fields, although existing trees should not be destroyed [P183]. Currant-lettuce aphid overwinters as eggs on currant and gooseberry, so lettuce crops should be sited away from soft fruit crops, however in the south of England and in mild winters it can overwinter as nymphs and adults on weed hosts (see weed control below).

## Pre-cropping

*Weed control*

In leafy and root brassicas, cruciferous weeds such as wild radish can act as alternative hosts for cabbage root fly. Hedgerows and tall weeds can also shelter the flies. Weed hosts for cabbage aphid include charlock, shepherd's purse and wild radish. Keeping hedges trimmed and controlling weeds around headlands may reduce the risk of infestation with both these pests [P184]. However, as cabbage root flies are so widespread and mobile, this is unlikely to have much effect on crop infestation. Adult turnip moths lay their eggs on tall weeds and other vegetation during May, so cutworms are more of a risk if crops are planted after May following heavy weed cover.

In lettuce crops in the south of England and in mild winters, currant-lettuce aphid can overwinter on weed hosts such as wall speedwell. Other weed hosts include chicory, common and spiked speedwell, hawkweed and nipplewort. Controlling weeds will reduce the source of aphids in the spring [P185].

Adult turnip moths lay their eggs on tall weeds and other vegetation during May/June, so cutworms are more of a risk if lettuce crops are planted after May following heavy weed cover [P184].

*Hygiene and prevention*

Any carrots badly infested with carrot fly should be lifted by November and the damaged carrots either fed to livestock or disposed of at a green waste or anaerobic digestion facility to prevent any larvae completing development. Ploughing in of infested carrots or dumping them near to other carrot crops should be avoided. Crops infested with willow-carrot aphid should not be left in over winter as aphids can hibernate on carrot crops in addition to overwintering as eggs on willow. These overwintering aphids on the crop may be carrying virus and are thus a particular risk [P184].

 

In brassicas, the cabbage aphid, *Brevicoryne brassicae* and the peach-potato aphid, *Myzus persicae* are the main two aphid pests of brassica crops. Both these species overwinter on cultivated host plants such as broccoli, Brussels sprout, cabbage and kale and the cabbage aphid can also overwinter as eggs on these plants. Destroying overwintered brassica crops before early May by cultivation or discing followed by ploughing to bury the plant debris will reduce the risk of winged cabbage aphids migrating to new brassica crops in the spring [P184]. However, peach-potato aphids can start migrating from March onwards [P186].

Onion thrips overwinter on the host crop including leek and onion but also on neighbouring crops such as brassicas and cereals. After harvest, removal or ploughing in of any plant debris and volunteers will reduce the source of thrips to the next onion or leek crop [P187].

Similarly, stem nematodes can survive for many years in a desiccated state in dried plant tissue. Careful removal and disposal of as much plant debris as possible after harvesting an infested crop will reduce this risk, together with appropriate disposal of any trash and soil left behind in onion stores after clearance [P184].

Two species of bean seed fly, *Delia platura* and *Delia florilega* can cause severe damage to onion and other crops including bean, pea, brassicas, lettuce, spinach, clover and cereals. The female flies are attracted to freshly disturbed soil to lay their eggs, particularly if there are high levels of organic matter, such as plant debris from a previous crop that was ploughed in shortly before drilling, or where farmyard manure has been used as a fertiliser. Feeding damage by the larvae in cotyledons causes poor emergence and plant death. Timely and thorough burial of crop debris before drilling and sowing when rapid germination is likely to take place will reduce the risk of damage [P184].

Although lettuce root aphid often overwinters as eggs on poplar, some may also overwinter on cut root stumps left in the ground after harvest, therefore infested autumn crops should be cleared of as much debris as possible to reduce the risk of infestation of crops planted the following spring. However, in practice growers plough in any debris so this may allow the survival of lettuce root aphids until the following year. If possible, rotation should be practiced to avoid spring planted crops following infested autumn crops [P184].

*Sowing or planting date*

Early season carrot crops emerging before mid-May are susceptible to egg laying by first generation carrot fly, whereas crops sown after mid-May are unlikely to be attacked by the first generation. However, in northern regions adults emerge later than in south-east and eastern England [P184]. Early season crops are also vulnerable to immigrant willow-carrot aphids which usually fly into carrot crops during May/early June, whereas crops sown in June may escape attack [P184].

 

Delaying sowing of carrots in a cold, wet spring will also help carrot crops to establish more quickly and make them less susceptible to damage by free living nematodes [P175].

Brassica crops planted out at different times to the predicted egg laying periods (see Decision support above) will be less liable to damage by cabbage root fly [P184]

*Variety choice*

Carrot variety choice is often driven by low susceptibility to disease and breakage at harvesting. Varieties with partial resistance to carrot fly such as Flyaway and Resistafly are available on the home garden market. However, these varieties are not grown commercially as they only reduce the pest and damage by about 50%, which is not effective enough when used as the only control method. However, using partially resistant varieties could play a role in the future in an IPM strategy alongside other control methods [P188].

In the USA, 49 onion cultivars were evaluated for resistance to onion thrips and 11 had very little leaf damage and were considered to be resistant. All the resistant cultivars had yellow-green foliage whereas the other cultivars had blue-green foliage [P189]. Resistance to onion thrips in UK-grown cultivars has not been tested [P190].

For lettuce crops, varieties were developed with resistance to lettuce root aphid e.g. Avoncrisp and Avondefiance, but there has not been any further development of modern resistant varieties [P191]. Lettuce varieties have also been developed with resistance to currant-lettuce aphid, but resistance-breaking aphids started developing in 2009 in the UK and other European countries and these are now widespread. Defra-funded research by seed companies in the Vegetable Genetic Improvement Network project is investigating different resistance mechanisms for the development of new resistant varieties [P188].

*Companion planting*

Companion planting can help with reducing cabbage root fly in brassicas. Bird's foot trefoil, red clover or yellow trefoil was sown into modules together with calabrese and planted out in a UK organic field, and the presence of any of the three companion plants reduced cabbage root fly egg laying by up to 48% and led to considerable reduction of larval damage to the roots [P192]. The method was cheaper than using crop covers to deter egg laying and avoided the weed control problems associated with using covers. However, survival of the companion plants was reduced by mechanical hoeing for weed control. It was concluded that further research would be needed to improve the survival of companion planting as a cultural control method for cabbage root fly [P192].

## In-crop

 

*Bioprotectants – natural substances*

The bioprotectant Nemguard DE is a granular formulation containing garlic extract, approved for use in the UK on carrot and parsnip in furrow at sowing, for reducing damage by nematodes. However, the label for use on carrot and parsnip warns that 'A single application of NEMguard DE at the recommended rate and in appropriate conditions may reduce the level of root malformations detected in the fully mature crop. The benefits of using NEMguard® DE granules can be variable and useful reductions of nematode damage or increases in marketable yield cannot be relied on [P193]'. Nemguard DE has been shown to give useful reductions in free-living nematode damage to sugar beet [P194]. However, in AHDB project FV 232, garlic granules did not reduce free living nematodes in carrots in pot and field experiments [P175].

In AHDB SCEPTRE plus trial SP 04, the fatty acids product Flipper gave good control of peach-potato aphid on Brussels sprout and the maltodextrose product Majestik gave some control of peach-potato aphid, however this trial did not test these products against willow-carrot aphid or on carrot. Majestik is currently approved for use on all edible crops for the control of spider mite and whitefly, with some reduction in aphids. Flipper has a current EAMU for use on carrot for aphid control.

*Bioprotectants – macrobiologicals*

In brassicas, naturally occurring carabid beetles e.g., *Bembidion lampros* were shown to be good predators of cabbage root fly eggs and larvae in the laboratory. However, subsequent work indicated that they have far less impact in the field as although they eat the eggs on the soil surface, those below the surface escape predation. UK research has also been done on the staphylinid beetle *Aleochara bilineata* which is both an egg predator and a pupal parasitoid. However, natural populations develop too late to control peak first generation CRF and mass-rearing for field release is too expensive due to the need for host flies for the parasitic life stage [P196]. Research in the UK showed that the commercially available predatory staphylinid beetle *Atheta coriaria* (now renamed *Dalotia coriaria*) predated both cabbage root fly eggs and larvae in the laboratory. 'Seeding' cauliflower modules with the predators in propagation led to reduced damage by cabbage root fly larvae in a semi-field pot test [P195]. A subsequent field trial showed that either 'seeding' the modules or releasing the predators into the field led to reduced cauliflower plant death caused by cabbage root fly [P196]. *Dalotia* (*Atheta) coriaria* is commercially available for control of sciarid and shore flies in protected crops. A cheap and easy grower 'DIY' method for rearing the predators using turkey feed as alternative food was developed [P197]. Commercial growers use this method for sciarid and shore fly control, for example in ornamental propagation houses. Although further research is needed, initial results indicated that *Dalotia* (Atheta*) coriaria* is a good candidate for cost-effective inundative release for biological control of cabbage root fly.

The entomopathogenic nematode (EPN) *Steinernema carpocapsae* e.g., Nemasys C and Capsanem is recommended as a foliar spray for the control of some caterpillars infesting brassicas including cabbage moth and silver Y. Various species of EPN are also commonly used for control of some soil-dwelling pests in horticultural crops including vine weevil, sciarid and shore flies. *Steinernema feltiae* was tested against cabbage root fly on cauliflower in a field trial in Belgium. Spraying the plants with the nematodes before planting out reduced the number of plants dying due to cabbage root fly larval feeding and were infective for five weeks after application. It was concluded that further research is justified on prolonging the infective period or testing more virulent EPN species or strains against cabbage root fly [P198].

Aphids on brassica crops are attacked by various naturally-occurring predators and parasitoids including hoverflies, lacewings and ladybirds and various species of parasitic wasps including *Diaretiella rapae* and *Praon volucre*. The former species is not commercially available in the UK and the latter species is only available in a mix with other species. These parasitoids, together with naturally-occurring entomopathogenic fungi can lead to an 'aphid crash' during the summer [P177].

In onions, biological control agents are widely used in protected crops for thrips control, including predatory mites, bugs and entomopathogenic nematodes. Naturally-occurring predators of thrips in field crops include mites, bugs, lacewings and predatory thrips. Entomopathogenic nematodes are successfully used in UK pot chrysanthemum for control of western flower thrips. The nematodes have been shown to be more effective against the ground-dwelling prepupae and pupae than against adults and larvae on the plants [P199].

Nematodes have been evaluated in the field against onion thrips on onion in Egypt. Application to the base of the plants and the soil led to reductions in thrips numbers [P200].

Research in Pakistan showed that application of nematodes together with entomopathogenic fungi were more effective against onion thrips than either nematodes or fungi alone and that control of prepupae was better than that of larvae or pupae. *Beauveria bassiana* was more effective than *Metarhizium brunneum* (*anisopliae*) [P201].

*Beauveria bassiana* (Botanigard WP) has an EAMU for use on outdoor onion, garlic and shallot in the UK for thrips control.

The entomopathogenic nematode *Steinernema feltiae* gave 50% control of bean seed fly larvae in a pot test on salad onion in the UK. Further research on the use of entomopathogenic nematodes as part of an IPM strategy against both onion thrips and bean seed fly are justified [P202].

A range of entomopathogenic fungi were tested in the UK in the laboratory against onion fly, *Delia antiqua* larvae and adults. Three isolates caused over 50% mortality of larvae, whereas 12 isolates caused over 50% mortality of adults. It was concluded that some of the isolates have potential for biological control of onion fly and related fly pests [P203].

Use of entomopathogenic nematodes and fungi against both onion thrips and bean seed fly on onion justify further research in the UK.

Foliar-feeding aphids that infest lettuce are attacked by various naturally-occurring predators and parasitoids including hoverflies, lacewings and ladybirds and various species of parasitoids including *Aphidius* species and *Praon volucre*. Aphid parasitoids are released into organic lettuce crops by at least one UK grower. *Aphidius* species are commercially available in the UK but *P. volucre* is only available in a mix with other species. These parasitoids, together with naturally-occurring entomopathogenic fungi can lead to an 'aphid crash' during the summer [P185].

The entomopathogenic nematode (EPN) *Steinernema carpocapsae* e.g. the commercial products Nemasys C and Capsanem is recommended as a foliar spray for the control of some caterpillar species including silver Y which is a common pest of lettuce.

*Bioprotectants – microbials*

*Bacillus firmus* is a bacterium effective against plant parasitic nematodes and the product BioNemWP is registered for control of root knot nematodes on various crops in Israel, although carrot is not included. Persistent control of root knot nematodes is reported [P204].
*Bacillus firmus* (Flocter) is approved for use on carrot in the UK and used to have an EAMU for use on carrot but this has now expired [P205].

Arbuscular mycorrhizal fungi (AMF) are root symbionts that can protect the host carrot plant from stresses such as infestation by plant parasitic nematodes. Mechanisms could include early root development to compensate for damage and induced systemic resistance (ISR) [P206].

In AHDB review FV 447, it was reported that adding AMF to carrots in a pot experiment reduced numbers of *Pratylenchus* sp. nematodes and compensated for yield loss [P174]. However, in AHDB project FV 232, it was suggested that more needs to be known about the rhizosphere in which these fungi are active before progress can be made in the potential of AMF for nematode control [P207].

 

In brassicas, the bacterium *Bacillus thuringiensis* subspecies *kurstaki* is approved for use against young caterpillars of most species infesting brassica crops, although only partial control of cabbage moth is given [P208]. *Bacillus thuringiensis* (Bt) products include DiPel DF and Lepinox Plus. After foliar application, the bacteria kill the caterpillars after they have eaten treated leaves, so young larvae need to be actively feeding to ingest the bacteria. The products are washed off leaves by rain, therefore application should be repeated after rainfall.

In AHDB project CP 092, the naturally-occurring entomopathogenic fungus, *Pandora neoaphidis* was shown to be a key natural enemy leading to the 'crash' of cabbage aphids on horticultural brassicas, together with predators and parasitoids. Infection of aphids was shown to be linked with temperature and this knowledge could lead to the development of a model predicting timing of the aphid 'crash' [P209].

In Defra-funded research, the entomopathogenic fungus *Beauveria bassiana* (Botanigard) reduced numbers of cabbage aphids on cabbage by 73% after two foliar applications in a field trial, although in a second trial there was no effect on peach-potato aphids [P210].

There are no current approvals for use of *B. bassiana* on outdoor field vegetable crops, although the product Naturalis-L is approved for use as a foliar spray for the control of whitefly on all edible crops under permanent protection (glasshouses), so could be used during propagation.

In addition to using EPF as foliar sprays, there is increasing interest in their action as root-associated EPF (R-AEF), when they can either be endophytic or soil saprophytic. These R-AEF can act as 'plant bodyguards' by increasing host plant resistance to pests by triggering plant induced systemic resistance or produce secondary metabolites that deter pest feeding. Laboratory and field experiments demonstrated the 'fatal attraction phenomenon' where *Metarhizium brunneum* associated with cabbage roots altered host plant traits used by cabbage root flies when selecting egg laying sites and increased the infection by the fungus. Two *Metarhizium brunneum* (*anisopliae*) products, Lalguard M52 GR and Met52 granular bioinsecticide have current EAMUs for control of cabbage root fly on vegetable brassicas. The latter product is currently unavailable and the availability of the former product is uncertain.

In lettuce, the bacterium *Bacillus thuringiensis* subspecies *kurstaki* can be used for control of young caterpillars. The product Lepinox Plus is approved for use on lettuce and the product DiPel DF has a current EAMU for use on lettuce. After foliar application, the bacteria kill the caterpillars after they have eaten treated leaves, so young larvae need to be actively feeding to ingest the bacteria. The products are washed off leaves by rain, therefore application should be repeated after rainfall. Caterpillars can also get infected with natural bacteria or viruses.

Aphids are often infected with naturally-occurring entomopathogenic fungi, particularly in warm, humid conditions such as on lettuce crops during the summer when they are regularly irrigated. The commercially available entomopathogenic fungus *Beauveria bassiana* (Botanigard WP) has a current EAMU for use on both outdoor and protected lettuce for control of various pests including aphids, so has potential for commercial uptake.

*Bioprotectants – natural substances*

In AHDB SCEPTREplus trial SP 04, the fatty acids product Flipper gave good control of both cabbage aphid and peach-potato aphid on Brussels sprout and the maltodextrose product Majestik gave some control of peach-potato aphid. Majestik is approved for use on all edible crops for the control of spider mite and whitefly, with some reduction in aphids. Flipper has a current EAMU for use on both outdoor and protected brassicas for aphid control and therefore can be used both in propagation and in the field.

In onions, the bioprotectant Nemguard DE is a granular formulation containing garlic extract, that has a current EAMU for use in the UK on bulb onion, garlic, leek and shallot at drilling or planting for the control of stem nematode and root-knot nematode. This product is reported to be more effective on damp, sandy soils, although control is likely to be variable due to the endoparasitic nature of these nematode species.

In AHDB SCEPTREplus trial SP 04, the fatty acids product Flipper gave good control of peach-potato aphid on Brussels sprout and the maltodextrose product Majestik gave some control of peach-potato aphid on Brussels sprout but poor control of currant-lettuce aphid on lettuce. Majestik is approved for use on all edible crops for the control of spider mite and whitefly, with some reduction in aphids. Flipper has a current EAMU for use on both outdoor and protected lettuce for the control of various pests including aphids and therefore can be used both in propagation and in the field.

*Elicitors*

AHDB-funded project FV 364 investigated the potential of using plant defence elicitors to induce broccoli resistance to cabbage root fly. The experimental elicitor methyl jasmonate (MeJa) combined with reduced rate insecticides or entomopathogenic nematodes showed partial efficacy but MeJa was phytotoxic at some of the concentrations and volumes tested [P211].

Recent research in the UK has investigated the effect of another plant defence activator, cis-jasmone (CJ) to help to protect brassica plants against aphid attack. Plants sprayed with CJ were less attractive and suitable as a host for the peach-potato aphid but were more attractive to the naturally-occurring aphid parasitoid Diaretiella rapae. It was concluded that CJ could be used in brassica crops as part of an IPM strategy [P212].

*Intercropping*

Research in the US showed that intercropping collards with spring onion led to reduced numbers of cabbage aphids. High nitrogen inputs increased the numbers of aphids but also increased collard yields. High numbers of aphids decreased yield. It was concluded that soil nitrogen level could be increased using a spring onion-collard intercrop and this would increase yield [P213].

*Weed control*

In brassicas, weeds can be a source of aphids. Willow carrot aphid can overwinter as adult or young aphids on umbelliferous crops and weeds in addition to on willow as eggs. However, most umbelliferous weeds die down over winter. Peach-potato aphid can overwinter on brassica weeds or volunteers and many other weed species.

In onions, many common weeds can harbour pests so good weed control will reduce the availability of alternative hosts. Stem nematodes can infest bindweed, chickweed, cleavers, knotgrass, mayweed, scarlet pimpernel and speedwell [P183].

*Early harvest*

Early lifting of a carrot crop prevents second generation carrot fly damage and avoids overwintering of carrot fly larvae in the crop. The carrot fly forecasting model used for predictions in the AHDB Pest Bulletin provided predictions of when damage will start to occur and helped growers to time lifting. As funding for the Pest Bulletin ceased with the wind down of AHDB Horticulture, the future of this service hosted on the Syngenta website and also on the Warwick University blog, is currently unclear [P188 P178 P179].

*Decision support and monitoring*

For carrots, the AHDB Pest Bulletin hosted by Syngenta in association with the University of Warwick and provided forecasts and current pest activity reports for many horticultural pests including carrot fly and willow-carrot aphid (see above). The carrot fly forecast gives information on when adults of each generation will emerge and when they will lay eggs, which helps growers to time control measures [P178 P179].

Orange sticky traps can be used to monitor numbers of carrot flies but these are not reliable for predicting whether or not a crop should be treated with an insecticide. The carrot fly forecast should be used to predict first egg laying as research has shown that insecticides applied one week before egg laying commences are more effective than those timed using the first adults being caught on traps. However, sticky traps can be useful for monitoring whether any control measures have been effective, as few or no flies should be found on traps if an effective insecticide has been timed well [P188].

The willow-carrot aphid forecast on the AHDB Pest Bulletin uses weather data to predict when winged aphids are likely to migrate into carrot crops from willow trees, where they overwinter as eggs [P217]. The Rothamsted Insect Survey monitors winged aphids in suction traps and gives information on the activity of many aphid species at various UK locations including two other species that can infest carrots and transmit viruses, the parsnip aphids *Cavariella pastinacea* and *Cavariella theobaldi* and the peach-potato aphid, *Myzus persicae* [P218].

In brassicas, regular crop monitoring should be done to detect the first sign of pests including aphids and caterpillars. Adult moths and butterflies can be monitored using water or sticky traps or pheromone traps for species such as cabbage moth, diamondback moth, garden pebble moth, silver Y moth and turnip moth (cutworm). There is also a forecasting system for cutworm, based on weather and rainfall data, as rain can wash young caterpillars off the plants [P214].

In onion crops, Blue or white sticky traps can be used for monitoring the presence of adult thrips in the field in order to time control measures. However, other thrips species may be caught on traps and species cannot be identified in the field. Numbers of thrips on traps do not reliably predict the severity of infestation or damage. Monitoring the plants for onion thrips damage to young leaves is likely to be more useful. A day degree model developed in America to forecast onion thrips populations proved to be inaccurate in the UK [P215].

Bean seed fly adult activity can be monitored using sticky traps or water traps, but numbers cannot be used to predict damage severity and there is no available forecasting model [P216].

An app developed by PGRO includes a section in which growers and agronomists can record the incidence of bean seed fly larvae in any crop, which provides information on the pest's distribution in all UK affected crops [P219]. Information on activity of bean seed fly is also available in the AHDB Pest Bulletin hosted on the Syngenta website and also on the Warwick University blog [P179] [P178].

For lettuce crops, the AHDB Pest Bulletin (see details above for carrots) has information for both peach-potato aphid and potato aphid that can attack lettuce, but currant-lettuce aphids and lettuce root aphids are not included. However, day-degree forecasts are available for both currant-lettuce aphid and lettuce root aphid and these give early warning of when crops may be infested. Lettuce root aphids migrate from poplar in June and July so there is a limited window when crops can be infested. Similarly, currant-lettuce aphid is more common during the autumn, whereas other species tend to peak in June and July [P185].

 

Regular crop monitoring should be done to detect the first sign of pests including all aphid species and caterpillars. The main two caterpillar pests in outdoor lettuce are those of the turnip moth (cutworm) and the silver Y moth. Silver Y moths are migrant species, flying into the UK from the continent in spring, whereas cutworms spend the winter underground and emerge as adults in spring, usually in late May/early June. The adult moths of both these species can be monitored with pheromone traps which can alert growers and agronomists to monitor more carefully for the first sign of caterpillars or damage. There is also a forecasting system for cutworm, based on weather and rainfall data. Rain or overhead irrigation can wash the young cutworm caterpillars off the plants, therefore as most outdoor lettuce crops are irrigated regularly it is unlikely that pesticides will be needed for cutworm control [P185].

*In-field non-cropped areas*

Adult carrot flies spend much of the day sheltering around the edges of fields in hedges, ditches and weeds, with females flying into the crop to lay eggs in the late afternoon, so any sources of shelter should be kept well-trimmed [P184].

*Intercropping*

Intercropping onion or leek with undersown clover has shown good potential for reduction in onion thrips damage. Competition between the crop and the intercrop and potential yield loss needs to be considered when planning this strategy [P190].

For example, in Slovenia, intercropping onion with *Phacelia*, buckwheat, white clover and orchard grass was evaluated for reduction of onion thrips. *Phacelia* and buckwheat were the most attractive to onion thrips but were not suitable for intercropping with onion as they out-competed the crop. White clover was considered the most suitable intercrop [P220].

Further research in Slovenia showed that intercropping leek with bird's foot trefoil and summer savoury reduced onion thrips damage to the crop. There was some associated yield loss but this was considered acceptable due the benefit of intercropping in thrips control [P221].

For lettuce, research in California has demonstrated that intercropping organic lettuce with sweet alyssum led to higher numbers of hoverflies and higher yields due to improved aphid control. Alyssum is a good source of nectar and pollen for the hoverfly adults [P222].

Defra-funded research in the UK showed that planting wildflower strips around lettuce crops led to fewer aphids in the lettuce during June and July, although the benefit was greater nearest to the strips [P223].

*Physical exclusion of pests*

Carrot fly adults fly low to the ground, therefore infestations can be reduced by using vertical barriers up to 2m high. These were investigated in AHDB project FV 312 and gave some reduction in damage to early season carrots but they did not exclude all flies and gave inadequate protection, particularly after subsequent fly generations. Mesh or fleece crop covers can also be used over the whole crop to exclude carrot flies. To be effective they should be used from sowing or before first egg laying. Application at the start of second generation fly activity is risky as any flies surviving from the first generation may be trapped under the covers. Disadvantages of using crop covers include costs and management time, risks of increased disease development and reduced options for weed control [P182].

Covering the crop with fine mesh netting is widely used on organic brassicas and on radish, swede and turnip crops to exclude cabbage root fly adults. The covers should be applied before egg laying starts, but after emergence from any pupae that may be in the soil from the previous crop, as otherwise emerging adults could get caught under the covers. Using crop covers can lead to problems with weed control [P224]. Crop covers used to exclude cabbage root fly might also exclude winged aphids, but if the mesh size is not small enough or if a tear or hole in the mesh allows aphids to enter, numbers can increase quickly under the protection of the mesh [P223].

Crop covers can also exclude butterflies and moths, but it is possible that eggs might be laid through the mesh where it touches the plants, thus allowing caterpillars such as those of diamondback moth to develop under the covers [P214].

Mesh netting is used on some organic lettuce crops to exclude winged aphids. However, if there is a tear in the mesh or if the mesh size is too large, aphids can enter the crop and breed under the covers [P185]. Crop covers can also exclude butterflies and moths, however their use can lead to problems with weed control.

*Precision irrigation*

In brassicas, well-timed irrigation can wash young cutworm off plants before they descend to the soil to feed. Using pheromone traps to monitor for adults and the cutworm prediction model (see Decision support above) will help to time irrigation if insufficient rain falls [P225].

Overhead sprinkler irrigation has been shown to reduce thrips populations on onion plants in the United States, where it is considered that the thrips are washed from the plants and the water droplets on the leaves are detrimental to thrips which thrive in warm, dry conditions [P187].

However, a trial in the UK to evaluate the effect of overhead irrigation on onion thrips numbers in salad onion gave inconsistent results [P215].

In addition, in AHDB-funded trials, water has frequently been applied as an overhead spray as an ‘untreated’ control to compare the efficacy of bioprotectants and chemical insecticides against western flower thrips in protected ornamentals and the water has allowed high numbers of thrips to develop. However, the water volume used for spray application is much lower than that used in overhead irrigation [P138 P226].

In onion fields, overhead irrigation or rainfall would also increase soil moisture and this might also lead to increased natural infection with entomopathogenic fungi. Before the arrival of western flower thrips in the UK in 1986, onion thrips was the main thrips species infesting protected crops. Before the adoption of covering glasshouse floors with polythene and using growing media such as rockwool slabs, cucumber crops were grown in straw bales stood on the soil. Growers were advised to damp down the soil paths to increase natural fungal infection of onion thrips once larvae had dropped to the ground to pupate. The naturally-occurring entomopathogenic fungus *Entomophthora thripidum* was confirmed to be infecting the ground-dwelling stages of onion thrips in Dutch glasshouses [P227].

The fungus *Beauveria bassiana* also occurs naturally in many soils as well as being a commercially available microbial bioprotectant and is known to infect onion thrips. Research in Egypt showed that survival of *B. bassiana* spores was shown to be higher in soil at 20% moisture content than at 10% or 30%, when evaluated as a soil-applied control agent for WFT in protected aubergine. This suggests that too dry or too wet soil moisture inhibits natural fungal infection of the ground-dwelling life stages of onion thrips [P228].

For lettuce, damage caused by lettuce root aphid is worse when plants are dry at the roots, leading to wilting and if severe, plant death. Irrigation can reduce damage if applied when plants are showing symptoms of damage or where the pest is known to occur. Irrigation can also wash young cutworm caterpillars off the plants (see DSS and monitoring above), therefore if the cutworm forecasting service is used together with regular irrigation if insufficient rain falls, pesticides are rarely needed for cutworm control on lettuce [P176 P185].

## Field vegetables, weed control

### Crop planning

*Fallow*

A fallow is a period without a crop, traditionally multiple cultivations were used during the fallow period to reduce perennial weeds. Reduction of the seedbank in a single year fallow is difficult to achieve because there are few weed species with a life of less than one year [W101]. A fallow would only be introduced where weed infestations are so high that they would compromise the economical integrity of the crop where land rents are high and crop margins low.

 

*Field history,* rotation and break crops

Field history and rotation are important to prevent the build-up of particular weed species. Rotating vegetable families will aid in reducing the predominance of one type of weed species. The inclusion of autumn sown cereals would further reduce the weed burden. Field history will help to evaluate the risk of volunteers. Many growers use rented land for vegetable production and this can help to extend the rotation. However, this can give growers minimal time to control crop volunteers, with potato volunteers being a potential problem on lighter soils. The integration of grass/clover leys and other cover crops can reduce the weed seedbank but the economic return would need to be factored in.

*Select low-risk locations*

The selection of lower risk locations can help to reduce weed infestations in the crop. Rotations should be planned to avoid fields with high broad leaved weed burdens and a history of potatoes. Control of weeds in earlier parts of the rotation is essential to reducing the weed burden in horticultural crops.

## Pre-cropping

*Hygiene and prevention*

Preventing weed seed from re-infesting the same field, infesting new areas within the farm or between farms is a key strategy in IWM systems.

*Contaminated straw*

Straw can be used to protect carrots from frost during field storage. This is a potential source of weed seed infestation and care should be taken to use straw from weed free sites.

*Forage, feed and livestock*

Weed seeds can be moved around a farm by passing through the digestive tract of livestock, attaching to their coats, and via livestock transportation vehicles [W110].

Manure can be a source of weed seeds either directly from the bedding straw, or through seeds in forage being ingested and passing though the animal. It has been demonstrated that 17% of green foxtail (*Setaria viridis*) and between 0 - 88% of wild-oat (*Avena fatua*) seeds survived digestion in the rumen [W111]. Grass weed seeds are less likely to survive ensiling and/or rumen digestion than broadleaf species [W108].

*Composting*

Weed species with hard seed coats like field bindweed (*Convolvulus arvensis*) and docks (*Rumex* spp.) present the greatest risk of surviving composting [W112]. However, if the compost is moist, reaches the desired temperature, and completes its full-cycle of decomposition, even seeds of these species are killed. If the turning and heating process is incomplete then there is likely to be some survival of seeds and wind-blown species can enter if the compost is not covered.

*Sown seed*

The UK seed certification scheme ensures that purchased seed reaches a minimum quality standard with a maximum 1.0% (by weight) content of seeds of other plant species allowed [W109].

*Transfer on machinery*

Weed seeds can be transferred by vehicles and farm machinery. In Australia, on inspection of 110 vehicles and plant machinery 250 species were recorded, predominantly in the cabins of passenger and four-wheel drive vehicles, with the engine bay being the next most frequent location [W113]. Up to 397 weed seeds per vehicle were recorded on vehicles used to install powerlines in Southeast Queensland, Australia [W114].

*Primary cultivations (crop residue burial)*

Cultivations prepare the soil for the next crop. These can be classified in to four main groups: plough, non-inversion tillage, no-till / direct drilling and strip tillage. Different cultivation techniques will affect the placing of weed seeds in the soil profile.

*Ploughing*

Ploughing inverts the soil, burying 86% of freshly shed seed to 15 - 20cm and bringing up 35% of old seed from the lower soil profile. Subsequent secondary cultivations to establish the crop generally do not disturb the buried seed. Weed seeds that germinate post ploughing are mostly seed shed in previous seasons and generally have lower levels of emergence and herbicide resistance. Roberts [W115] compared shallow ploughing and rotary cultivations at the same depth of cultivation and found fewer weed seeds in the shallow ploughed plots.

The NIAB Star project has shown ploughing can reduce herbicide costs by around £70/ha when compared to non-inversion continuous wheat treatments [W116]. Results from the same trial show grass weeds increased in the non-inversion treatments with grass weeds absent in the continuous plough treatment [W117].

Annual meadow grass (*Poa annua*) seeds were 70% lower after 9 years of ploughing compared to shallow rotary tillage [W194]. Perennial weeds can also be kept at manageable levels for annual vegetable crops by ploughing.

 

*Non-inversion tillage*

Non-inversion tillage mixes the soil in the upper layers to the working depth of the implement. The weeds that germinate are a mixture of freshly shed seed and those from previous seasons. A cultivation 11cm deep will bury approximately a third of newly shed seed below germination depth (6 cm) and 9% of old seed returns to the surface [W155].

Shallow non inversion tillage puts most of the weed seeds in to top 5cm layer of soil, promoting the growth of annual grass weeds when used with winter cereals [W156]. Shallow burial of seed will promote germination due to availability of light, alternating temperatures and decreasing soil moisture [W157]. Mixing of soil by cultivating will place seed at varying depths and cause emergence to be staggered.

The use of non-inversion tillage has led to fewer broad leaved weeds and an increase in the level of grass weed [W158 W139], particularly bromes (*Anisantha* spp., *Bromus* spp.), Italian ryegrass (*Lolium multiflorum*) and black-grass (*Alopecurus myosuroides*) [W160] in arable production.

*Secondary cultivations - Minimum tillage/No-till*

The only soil movement that occurs during no-till/direct drilling is that done by the drill. The freshly shed seed from the previous season remains on the soil surface, covered by the mulch that reduces weed growth. Direct drilling can decrease the weed seedbank density but increase weed diversity particularly for perennial and biennial species that have the chance to thrive due to the lack of cultivation [W119].

Minimum tillage is currently not practised in field vegetables as the reduced establishment costs might not outweigh the potential financial risk of reduced crop yield and quality if establishment is reduced in minimum tillage systems. A German farmer has pioneered a system where mulch is applied to cover crop stubbles and then vegetable transplants are directly planted through the mulch with no tillage [W118]. However, this is not suitable for direct drilled crops and would need 3ha worth of grass to produce enough mulch for 1ha of vegetable production. Similar systems have been developed where cover crops are killed by crimper rolling and then vegetables transplanted directly through the in-situ mulch [W120].

*Strip Tillage*

Strip tillage cultivates narrow bands of soil to produce a tilth, leaving the remainder of the field undisturbed. The Conservation Technology Information Centre [W171] defines strip tillage as a modification to direct drilling with disturbance of less than one third of the total area. UK Growers are trialling strip tillage in cover crops for brassica production to aid with weed suppression [W121] and to create better soil drainage and reduce compaction. Trials in the USA comparing strip tillage, no tillage, and conventional tillage showed intra row weed density was highest in the conventional and strip tillage systems. Inter-row weed density was highest in conventional tillage. The study concluded that there is potential for strip tillage, alongside the use of stale seedbeds, to be used in organic vegetable production whilst maintaining yield potential [W122]. Previous studies in the USA showed strip tillage in cabbage crops to produce high yields, albeit slightly lower than plough/disced treatments [W123].

*Seedbed quality*

A firm fine seedbed is key to good crop establishment, quick canopy closure and improving the activity of pre-emergence herbicides. Rolling after drilling ensures good seed to soil contact and absence of large clods ensures good coverage of the herbicide and consistent crop germination. Many pre-emergence herbicides have a requirement for seed to be covered with a minimum depth of soil.

*Sowing / planting date*

Delaying sowing or planting date allows for extra time to control weeds via stale seedbeds. However, planting dates are often dictated by the scheduled marketing window for the produce. Spring drilled crops offer the least amount of flexibility of control beforehand, with weeds often germinating post emergence of the crop. With limited post-emergence weed control options for many field vegetable crops and reduced efficacy of pre-emergence herbicides in dry conditions growers need to carefully select fields for early drilling and planting.

*Hand weeding / roguing*

Weeds can be severely detrimental to both yield and production efficiency. Limited herbicide options and the high value of crops make hand weeding an essential approach to weed control in carrots. It is very expensive and can be up to £2,500/ha in organic carrots where the use of a flat-bed hand weeder is used. One thorough hand weeding pass early in the crop lifecycle should be sufficient to give the crop a good head start, with hand rogueing later on if there is potential for weeds to interfere with harvest [W126]. Hand weeding is rarely practised in conventional field brassica and salad production.

*Undersowing and companion crops*

Undersowing and companion crops could help to suppress weeds in vegetable crops. Most of the work has looked at the effects of pest reduction so work would need to be carried out to ascertain the benefits of weed suppression. Trials looking at under sowing brassicas with clover to reduce pest infestation suggested the companion crop would need to be sown after transplanting to avoid any negative impact on crop yield [W125].

 

*Use of cover crops*

Cover cropping is becoming more popular with growers for the benefits to soil quality. It can fit in to annual crops where land would otherwise be left fallow over winter. Cover crop trials in baby spinach showed some suppressions of weeds, however the trial was unreplicated and had no untreated control. The trial showed cover crops need to have good ground coverage as weeds will grow in any gaps. Buckwheat and the buckwheat/red clover mix gave the best overall weed suppression in the following crop [W124]. Cover crop residue can interfere with machinery and reduce establishment of fine seeded crops, such as carrots, if the cover crop isn't broken down well enough. Cover crop trials prior to kale production in Turkey showed hairy vetch (*Vicia villosa*) suppressed weed density and biomass whilst doubling the kale yield compared to the no cover crop treatment [W163].

*Mechanical*

Mechanical weeding kills weeds by burying, cutting or uprooting. Plant spacing and dry weather are critical to the success of mechanical weeding. Weeders can be mounted at the front or rear of a tractor, either powered or ground driven. They can be steered from the tractor, have a second operator (by vision guidance), or by GPS, or GIS.

The type of physical damage needed to kill a seedling weed has demonstrated that burial to 1 cm depth was the most effective treatment, closely followed by cutting at the soil surface [W101, W102].

Mechanical weeding should take place in dry weather to provide effective control. Wet weather at the time of weeding can lead to regrowth of weeds. The most effective time to control weeds is at the white thread stage, when the root emerges from the seed. Weed seed can germinate over many weeks, so multiple passes may be needed and soil disturbance can also trigger germination of further weeds. Timing needs to be carefully balanced so it is carried out when the crop is large enough to withstand damage but the weeds are still small enough to provide adequate control. Hoeing can disturb residual herbicides so should only be used where required. Mechanical hoes are often used in salad crops and can also be used in brassica crops.

Pre crop emergence weed control can be carried out by blind harrowing if the crop is sown below the working depth of the harrows. Blind harrowing is a technique where a harrow passes through the top 2 - 3cm of soil before the crop emerges to kill off any weeds. This can reduce weed levels once the crop emerges and can be beneficial with slow germinating crops (carrots) or if the crop can be sown below the depth at which weeds emerge [W127].

Post emergent options range from inter-row weeders to vision guided weeders that can control inter and intra row weeds.

 

*Inter-row weeders*

Inter-row weeders work between the crop rows and can be front or rear mounted. Rear mounted options can be controlled via a second operator to get as close to the crop as possible. Recent advancements in technology, such as the Garford Robocrop Baby leaf hoe, have led to vision guided hoes that can get even closer to the crop. Other inter-row options include duck's foot hoes, cage weeders, brush weeders and powered rotary cultivators. Equipment choice depends on crop and soil type/conditions, and the adjustment of the implement can often be more important than the choice of equipment [W154]. Brush weeders are best used in friable soil conditions and are best suited to carrot and lettuce production [W129].

*Intra-row weeders*

Weed control in the row is difficult to achieve with mechanical options. Precise set up of inter-row equipment can provide a level of intra row control by covering smaller weeds. The use of finger and torsion weeders can provide adequate control, but these need a well-established crop with small weeds and ideally a loose soil structure for optimum efficacy. The finger weeder has made a significant impact in organic production, with crops such as brassicas being controlled exclusively with mechanical weeding [W161].

Garford Robocrop InRow weeder is capable of inter- and intra-row weeding in crops such as lettuce and cabbage using video image analysis techniques. Accuracy of 8mm from the plant stem is possible. Tillet *et al.* found a computer guided in-row and inter-row cut-out disc cultivator removed 80% of weeds with low crop damage and no plant kill when performed within normal commercial weed levels [W162].

*Thermal*

Thermal weed control involves the use of heat to kill weed seeds. Techniques include electrical, flaming, infrared, hot water/foam, steaming and dry heating, radiation, freezing and ultraviolet and lasers. Flame weeding is currently the only technology ready for use in field scale horticulture and is widely used in organic vegetable production as a stale seedbed technique. It has been shown to be effective when used as a band applicator in transplanted cabbage crops [W146]. Two flame weeding applications were shown to be as effective as two herbicide or two mechanical weed passes at controlling weeds in white cabbage trials [W144]. It can be associated with slow application speeds and high energy consumption leading to higher costs. However high value horticultural crops can justify the high cost of flame weeding [W145].

 

## In-crop

*Bioprotectants natural substances*

Bioherbicides are crop protection products usually based on organics acids or plant essential oils / extracts and other natural compounds. They are generally less persistent than synthetic herbicides. Biopesticides (more-recently sometimes termed bioprotectants) are regulated as plant protection products under EU plant protection Regulation 1107/2009. Although "biopesticides" do not exist as a regulatory category, the pesticide categories "basic substances" and "low risk substances" were introduced in August 2017, as defined in Regulation 2017/1432, amending Regulation 1107/2009. A list of low-risk active substances can be found here: https://www.hse.gov.uk/pesticides/pesticides-registration/applicant-guide/low-risk-active-substances.htm

A range of essential oil and plant compound based bioherbicides were tested on annual and perennial weeds in the SCEPTRE project and showed that although they initially scorched annual weeds, there were signs of recovery within a few days of application [W165]. Bioherbicides often give reduced weed control compared to synthetic herbicides and require repeated applications at high rates, as they are not systemic and leave the plant meristem intact [W148]. Manuka oil has shown the potential for systemic activity that could help overcome the lack of systemic activity of pelargonic acid [W147].

Due to the initial scorching symptoms and 'knock-down' there is potential for bioherbicides to be used as part of an integrated weed management programme [W149 W150].

Pelargonic acid is a contact broad-spectrum bioherbicide that disrupts cell membranes and the phytotoxicity effects are visible a short time after application. It can provide adequate weed control, has no residual activity, and low toxicity and environmental impact [W148]. Pelargonic acid was the only bioherbicide tested in the SCEPTRE project that provided good control for fat hen (*Chenopodium album*), groundsel (*Senecio vulgaris*), and dock (*Rumex* spp.) after repeat applications, although some other weeds were not controlled [W165]. Pot trials in Greece showed sufficient weed control of broadleaved weeds, even at low pelargonic acid concentrations. However, higher concentrations were required to increase the control of grass weeds [W147]. It was also shown that lemongrass and pine oil also act as burn-down herbicides.

Acetic acid (vinegar) is a bioherbicide that causes non-selective, foliar burn down that kills most annual broad-leaved weeds at early growth stages (1-2 leaves), but only results in leaf scorching on grass weeds and larger broad-leaved weeds. Multiple applications of concentrations up to 20% gave 28 - 45% weed control [W168]. Other work has shown concentrations of 5%, 20%, and 30% were effective at reducing weed levels to a rating of zero within 48 hours but required three (2016) and five (2017) retreatments to maintain zero weeds when compared to glyphosate [W166].

*Physical mulches*

Mulches are commonly used for weed control in organic production and in conventional cucurbit crops such as courgettes where herbicide options are limited. This method is very effective in controlling annual weeds; however weeds can grow through the holes and in inter-row areas not covered by the mulch. Growers are investigating alternative methods of weed control between rows such as living mulches and straw. Mulches have proved effective but the cost alongside finding efficient methods of applying the mulch in different cropping situations needs to be factored in.

Plastic mulches have the advantage of suppressing weed growth throughout the entire lifecycle of the crop. However, it is expensive so only economical in high value crop and perennial crops [W151] and being non-renewable creates a large amount of waste with associated disposal costs.

Woven textile mulches such as Mypex are available that can last between eight and 12 years [W167]. However, due to the high cost, they are mainly used where a crop may be grown on the same site year on year such as rhubarb.

Growers are seeking alternative options to plastic based mulches but implementing biodegradable plastics has proved more challenging than anticipated for some. Growers aim to achieve 100% replacement in the future, but it is a challenge to get the longevity of the plastic right. It can break down too fast and does not last for the life of the crop.

Biodegradable mulches are available that are made from natural materials such as corn starch and completely biodegrade so can be tilled back into the soil, eliminating waste and disposal costs. However, growers have experienced difficulties in finding biodegradable mulches that suit the crop lifecycle with thinner mulches breaking down before the end of the crop and some thicker mulches taking several months to biodegrade. This can pose a threat to wildlife and can be blown or washed into neighbouring environments [W164]. Living mulches can be grown in-season alongside the cash crop. Other types of mulches that are being tested are straw, compost, woodchip and wool. All of these options have the advantage of being natural resources that are fully biodegradable and can provide habitats for seed predators [W151]. However, long breakdown times can inhibit germination of further crops and effective solutions are needed to lay the mulch material as up to 20t/ha of straw is required to provide effective weed control [W152]. Innovative Farmer group trials on an organic farm in Wales showed arborist woodchip can be used as an effective mulch in horticultural crops grown from transplants, avoiding the cost of hand hoeing. Crop vigour was maintained; however incorporation of the mulch would compete with following crops for nitrogen. Further alternatives to plastic film mulches are currently being investigated by the Innovative Farmer group.

*Decision support*

Thresholds are available for weeds tolerance within the current crop, however thresholds often do not allow for the impact of seed return on subsequent crops which can cause populations to build quickly over seasons. There are many factors that influence the effect of weeds on crop yield, however weeds can also slow crop ripening, delay or impact harvesting, spoil crop quality, harbour pests and diseases but also attract beneficial insects and pollinators. The competitiveness of the weeds can be affected by weed density, distribution crop density and vigour and the weather. Decision support systems need to include relevant IPM strategies (including rotation) as well as herbicides. IPM Decisions is a five year project started in 2019 to create an online platform to enable farmers and agronomists easy access to DSS, data, tools and resources to monitor and manage pests by region.

# Opportunities to develop non-chemical control strategies

## Scoring system for KE and research priorities

As part of this project, each circumstance where a non-chemical control strategy could be considered appropriate for a given crop adversity has been scored (see appendix 1) on a 1 – 5 scale for:

a) Effectiveness
b) Strength of evidence
c) Inexpensive to implement
d) Economic importance of pest
e) Ease of implementation
f) Speed of Impact
g) Current use
h) Potential use

For all factors, high scores represent a positive effect. For example, a score of 5 for “inexpensive to implement” would mean the strategy had a low implementation cost, whereas a score of 1 would have a high cost.

All factors are scored for their relevance to the farmer or end user. For example, a strategy may be scored a 5 if it is very cheap for a farmer to implement. However, this does not mean that the further research or knowledge transfer required to prove effectiveness, develop tools, or increase uptake are low-cost endeavours. For example, a new decision support tool will have a low cost of implementation to the farmer (so a high score) but will likely require significant research and expenditure to develop. We have not considered the cost applicable to the researcher or knowledge exchange investor in this scoring system.

For each relevant pest-strategy combination, a priority score was calculated using the following equation (letters refer to above list):

$$\text{P-score} = (a + d) + ((c + e + f + (h - g))/4)$$

We considered potential value to the industry, effectiveness (a) and economic importance of the pest (d) to be the most important consideration for any given strategy, so were given a higher weighting in our calculation. Factors which were considered to be of lesser importance were given a lower weighting, and we considered these as factors of feasibility and scope of implementation. The difference between current and potential use was included to give higher weighting to those factors that have the highest scope for increased use from present levels.

To identify priorities for attention, each crop group has been filtered to include only those where there is potential for an increase in use of a given strategy ($h - g > 0$). All economic importance scores of 1 and 2 ($d < 3$) were also excluded so that pests that are not considered to be of great economic importance were not included in our priority's lists. The remaining pests and strategies were then split into the cases that:

1. Have a significant body of evidence proving their effectiveness ($b \geq 4$). Strategies in this situation may require increased knowledge transfer of existing information.
2. Have a less conclusive or complete body of evidence that proves their effectiveness ($b \leq 3$). Strategies in this situation require more primary research to better prove the case for effectiveness and further future uptake.

The following tables list the top 40 factor and strategy combinations for knowledge exchange and research priorities based on our scoring system. Where scores are tied for the final position in the table, all factors with that score have been included, so the table may exceed 40 factors.

The full data sets will be made available separately as excel files, one for each of the four main crops groups: soft fruit, arable, top fruit, field vegetables.

The data in these tables be sorted or filtered in other ways as required, for example, to look at scores for one crop type only, or by pest, or by strategy type, etc.

Tables to be read in conjunction with the text

Table 13. Soft fruit: priority ranking table, top 40 strategies all pests,

| Ranking | Crop | Disease, Pest or Weed | Pest name | Non- chemical control strategy | Economic importance | Current use | Potential use | P-C | Effectiveness | Speed of impact | Inexpensive to Implement | Ease of implementation | Strength of evidence | P-SCORE (ALGORITHM) | KE or Research priority (Threshold >=3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Grape Vine | P | Spotted winged drosophila | Sterile male technique | 5 | 1 | 5 | 4 | 5 | 5 | 2 | 4 | 3 | 13.8 | **Research** |
| 2= | Raspberry | P | Raspberry cane midge | Variety choice/Breeding | 5 | 3 | 5 | 2 | 5 | 3 | 4 | 5 | 5 | 13.5 | **KE** |
| 2= | Raspberry | P | Blackberry leaf midge | Variety choice/Breeding | 5 | 3 | 5 | 2 | 5 | 3 | 4 | 5 | 3 | 13.5 | **Research** |
| 4= | Strawberry | D | Phytophthora spp | Test & treat irrigation water | 5 | 3 | 5 | 2 | 4 | 5 | 4 | 4 | 5 | 12.8 | **KE** |
| 4= | Raspberry | D | Phytophthora spp | Test & treat irrigation water | 4 | 3 | 5 | 2 | 5 | 5 | 4 | 4 | 5 | 12.8 | **KE** |
| 4= | Grape Vine | P | Spotted winged drosophila | Hygiene and prevention | 5 | 3 | 5 | 2 | 4 | 5 | 3 | 5 | 5 | 12.8 | **KE** |
| 7= | Strawberry | D | Powdery mildew | Clean stock | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Powdery mildew | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Botrytis | Clean stock | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Botrytis | Control volunteers & weeds | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Botrytis | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Botrytis | Bioprotectants microbial | 5 | 2 | 4 | 1 | 4 | 4 | 4 | 4 | 3 | 12.5 | **Research** |
| 7= | Strawberry | D | Phytophthora spp | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Phytophthora spp | Pre-plant soil tests | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 3 | 12.5 | **Research** |
| 7= | Strawberry | D | Phytophthora spp | Seed and young plant testing | 5 | 2 | 5 | 3 | 4 | 5 | 3 | 3 | 4 | 12.5 | **KE** |
| 7= | Strawberry | D | Phytophthora spp | Substrate | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Phytophthora spp | Hand weeding/roguing | 5 | 3 | 5 | 2 | 4 | 4 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | D | Phytophthora spp | Plant sauna | 5 | 1 | 4 | 3 | 4 | 5 | 3 | 3 | 4 | 12.5 | **KE** |
| 7= | Strawberry | D | Phytophthora spp | Precision irrigation | 5 | 2 | 5 | 3 | 4 | 4 | 4 | 3 | 4 | 12.5 | **KE** |
| 7= | Raspberry | D | Botrytis (cane & fruit) | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Raspberry | D | Botrytis (cane & fruit) | Bioprotectants microbial | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 3 | 12.5 | **Research** |
| 7= | Raspberry | D | Botrytis (cane & fruit) | Environmental control (including overhead protection) | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 7= | Strawberry | P | Spotted winged drosophila | Sterile male technique | 5 | 1 | 5 | 4 | 4 | 4 | 2 | 4 | 3 | 12.5 | **Research** |
| 7= | Strawberry | P | Thrips | Variety choice/Breeding | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 2 | 12.5 | **Research** |
| 7= | Raspberry | P | Spotted winged drosophila | Sterile male technique | 5 | 1 | 5 | 4 | 4 | 4 | 2 | 4 | 3 | 12.5 | **Research** |
| 7= | Raspberry | P | Aphids | Nutrient management | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 2 | 12.5 | **Research** |
| 7= | Raspberry | P | Raspberry cane midge | Biennial cropping | 5 | 1 | 3 | 2 | 4 | 4 | 4 | 4 | 4 | 12.5 | **KE** |
| 28= | Strawberry | D | Powdery mildew | Defoliation (incl. pruning, mowing, grazing) | 5 | 3 | 4 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Powdery mildew | Environmental control (including overhead protection) | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 4 | 12.3 | **KE** |
| 28= | Strawberry | D | Powdery mildew | Hygiene | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Powdery mildew | Precision irrigation | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 3 | 4 | 12.3 | **KE** |
| 28= | Strawberry | D | Powdery mildew | UV-C | 5 | 1 | 4 | 3 | 4 | 4 | 3 | 3 | 4 | 12.3 | **KE** |
| 28= | Strawberry | D | Botrytis | Defoliation (incl. pruning, mowing, grazing) | 5 | 3 | 4 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Botrytis | Environmental control (including overhead protection) | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Botrytis | Hygiene | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Botrytis | Precision irrigation | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 3 | 4 | 12.3 | **KE** |
| 28= | Strawberry | D | Phytophthora spp | Drainage | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Phytophthora spp | Environmental control (including overhead protection) | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Strawberry | D | Phytophthora spp | Hygiene | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Raspberry | D | Botrytis (cane & fruit) | Hygiene | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Grape vine | D | Downy mildew | Select low-risk locations | 4 | 4 | 5 | 1 | 5 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Grape vine | D | Downy mildew | Spatial separation | 4 | 3 | 4 | 1 | 5 | 4 | 4 | 4 | 3 | 12.3 | **Research** |
| 28= | Grape vine | D | Powdery mildew | Select low-risk locations | 4 | 4 | 5 | 1 | 5 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 28= | Grape vine | D | Powdery mildew | Spatial separation | 4 | 3 | 4 | 1 | 5 | 4 | 4 | 4 | 3 | 12.3 | **Research** |
| 28= | Strawberry | P | Aphids | Physical exclusion of pests | 4 | 4 | 5 | 1 | 5 | 5 | 3 | 4 | 5 | 12.3 | **KE** |

More than 40 pests included as several crop-pest-strategies had the same priority score

 

Table 14. Arable crops: priority ranking table, top 40 strategies all pests.

| Ranking | Crop | Disease, Pest or Weed | Pest name | Non- chemical control strategy | Economic importance | Current use | Potential use | P-C | Effectiveness | Speed of impact | Inexpensive to Implement | Ease of implementation | Strength of evidence | P-SCORE (ALGORITHM) | KE or Research priority (Threshold >=3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1= | Rye & Triticale | D | Yellow rust | Variety choice | 4 | 2 | 4 | 2 | 5 | 5 | 4 | 5 | 5 | 13.0 | **KE** |
| 1= | Rye & Triticale | D | Brown rust | Variety choice | 4 | 2 | 4 | 2 | 5 | 5 | 4 | 5 | 5 | 13.0 | **KE** |
| 1= | Fodder crops | D | Clubroot | Pre-plant soil tests | 4 | 1 | 5 | 4 | 5 | 5 | 3 | 4 | 5 | 13.0 | **KE** |
| 4= | Fodder crops | P | Flea beetle | Stubble management | 5 | 1 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 12.8 | **KE** |
| 4= | Rye & Triticale | W | Annual grasses | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 5 | 4 | 12.8 | **KE** |
| 4= | Peas, dry & fresh | W | Annual grasses | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 5 | 4 | 12.8 | **KE** |
| 4= | Beans, dry & fresh | W | Annual grasses | Hygiene and prevention | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 5 | 4 | 12.8 | **KE** |
| 4= | Rye & Triticale | D | Ergot | Primary cultivations (crop residue buria | 4 | 3 | 5 | 2 | 5 | 5 | 4 | 4 | 4 | 12.8 | **KE** |
| 4= | Fodder crops | D | Clubroot | Hygiene and prevention | 4 | 2 | 5 | 3 | 5 | 4 | 4 | 4 | 4 | 12.8 | **KE** |
| 4= | Fodder crops | D | Rhizoctonia | Hygiene and prevention | 4 | 2 | 5 | 3 | 5 | 4 | 4 | 4 | 4 | 12.8 | **KE** |
| 4= | Fodder crops | D | Rhizoctonia | Pre-plant soil tests | 4 | 2 | 5 | 3 | 5 | 5 | 3 | 4 | 5 | 12.8 | **KE** |
| 12= | Peas, dry & fresh | W | Annual grasses | Primary cultivations (crop residue buria | 5 | 3 | 5 | 2 | 4 | 5 | 3 | 4 | 4 | 12.5 | **KE** |
| 12= | Beans, dry & fresh | W | Annual grasses | Primary cultivations (crop residue buria | 5 | 3 | 5 | 2 | 4 | 5 | 3 | 4 | 4 | 12.5 | **KE** |
| 12= | Rye & Triticale | D | Ergot | Control volunteers & weeds | 4 | 3 | 5 | 2 | 5 | 5 | 3 | 4 | 4 | 12.5 | **KE** |
| 12= | Rye & Triticale | D | Ergot | Seed and young plant testing | 4 | 1 | 4 | 3 | 5 | 5 | 3 | 3 | 4 | 12.5 | **KE** |
| 16= | Rye & Triticale | D | Yellow rust | Control volunteers & weeds | 4 | 3 | 5 | 2 | 5 | 5 | 3 | 3 | 4 | 12.3 | **KE** |
| 16= | Fodder crops | P | Flea beetle | Undersowing & Companion cropping | 5 | 1 | 4 | 3 | 4 | 4 | 4 | 2 | 2 | 12.3 | **Research** |
| 16= | Rye & Triticale | W | Annual grasses | Primary cultivations (crop residue buria | 5 | 4 | 5 | 1 | 4 | 5 | 3 | 4 | 4 | 12.3 | **KE** |
| 16= | Peas, dry & fresh | W | Annual grasses | Fallow | 5 | 3 | 4 | 1 | 4 | 4 | 4 | 4 | 3 | 12.3 | **Research** |
| 16= | Beans, dry & fresh | W | Annual grasses | Fallow | 5 | 3 | 4 | 1 | 4 | 4 | 4 | 4 | 3 | 12.3 | **Research** |
| 21= | Fodder crops | P | Flea beetle | Field history, rotation & break crops | 5 | 3 | 5 | 2 | 4 | 4 | 2 | 4 | 4 | 12.0 | **KE** |
| 21= | Fodder crops | P | Flea beetle | Seed rate (incl. variable seed rate) | 5 | 2 | 4 | 2 | 4 | 4 | 2 | 4 | 4 | 12.0 | **KE** |
| 21= | Rye & Triticale | W | Annual grasses | Secondary cultivations (drilling method) | 5 | 4 | 5 | 1 | 4 | 4 | 3 | 4 | 4 | 12.0 | **KE** |
| 21= | Peas, dry & fresh | W | Annual grasses | Secondary cultivations (drilling method) | 5 | 4 | 5 | 1 | 4 | 4 | 3 | 4 | 4 | 12.0 | **KE** |
| 21= | Beans, dry & fresh | W | Annual grasses | Secondary cultivations (drilling method) | 5 | 4 | 5 | 1 | 4 | 4 | 3 | 4 | 4 | 12.0 | **KE** |
| 21= | Rye & Triticale | D | Brown rust | Control volunteers & weeds | 4 | 3 | 5 | 2 | 5 | 4 | 3 | 3 | 4 | 12.0 | **KE** |
| 21= | Beans, dry & fresh | D | Rust | Control volunteers & weeds | 4 | 3 | 5 | 2 | 5 | 4 | 3 | 3 | 3 | 12.0 | **Research** |
| 21= | Beans, dry & fresh | D | Sclerotinia | Microbial bioprotectants | 4 | 1 | 5 | 4 | 5 | 3 | 2 | 3 | 4 | 12.0 | **KE** |
| 21= | Fodder crops | D | Clubroot | Variety choice | 4 | 3 | 5 | 2 | 5 | 4 | 2 | 4 | 5 | 12.0 | **KE** |
| 30= | Rye & Triticale | W | Annual grasses | Precision irrigation | 5 | 1 | 4 | 3 | 4 | 4 | 2 | 2 | 2 | 11.8 | **Research** |
| 30= | Peas, dry & fresh | W | Annual grasses | Precision irrigation | 5 | 1 | 4 | 3 | 4 | 4 | 2 | 2 | 2 | 11.8 | **Research** |
| 30= | Beans, dry & fresh | W | Annual grasses | Precision irrigation | 5 | 1 | 4 | 3 | 4 | 4 | 2 | 2 | 2 | 11.8 | **Research** |
| 30= | Rye & Triticale | D | Ergot | Hygiene and prevention | 4 | 2 | 4 | 2 | 4 | 5 | 4 | 4 | 4 | 11.8 | **KE** |
| 30= | Fodder crops | D | Clubroot | Decision support, incl. monitoring | 4 | 2 | 5 | 3 | 5 | 3 | 3 | 2 | 4 | 11.8 | **KE** |
| 30= | Fodder crops | D | Rhizoctonia | Decision support, incl. monitoring | 4 | 2 | 5 | 3 | 5 | 3 | 3 | 2 | 4 | 11.8 | **KE** |
| 36= | Rye & Triticale | D | Yellow rust | Sowing or planting date | 4 | 2 | 4 | 2 | 4 | 5 | 4 | 3 | 4 | 11.5 | **KE** |
| 36= | Rye & Triticale | W | Annual grasses | Undersowing companion crops | 5 | 2 | 4 | 2 | 4 | 4 | 2 | 2 | 2 | 11.5 | **Research** |
| 36= | Peas, dry & fresh | W | Annual grasses | Undersowing companion crops | 5 | 2 | 4 | 2 | 4 | 4 | 2 | 2 | 2 | 11.5 | **Research** |
| 36= | Beans, dry & fresh | W | Annual grasses | Undersowing companion crops | 5 | 2 | 4 | 2 | 4 | 4 | 2 | 2 | 2 | 11.5 | **Research** |
| 36= | Peas, dry & fresh | P | Pea moth | Bioprotectants Semiochemical | 4 | 1 | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 11.5 | **Research** |

 

Table 15. Top fruit: priority ranking table, Top 40 strategies all pests.

| Ranking | Crop | Disease, Pest or Weed | Pest name | Non- chemical control strategy | Economic importance | Current use | Potential use | P-C | Effectiveness | Speed of impact | Inexpensive to Implement | Ease of implementation | Strength of evidence | P-SCORE (ALGORITHM) | KE or Research priority (Threshold >=3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1= | Apple | D | Apple scab | Field history, rotation & break crops | 5 | 5 | 5 | 0 | 4 | 5 | 3 | 5 | 5 | 12.3 | **KE** |
| 1= | Apple | D | Apple scab | Pruning/canopy management | 5 | 4 | 5 | 1 | 4 | 5 | 3 | 4 | 4 | 12.3 | **KE** |
| 1= | Apple | P | Aphids | Bioprotectants Macrobiological | 5 | 2 | 5 | 3 | 4 | 3 | 3 | 4 | 5 | 12.3 | **KE** |
| 1= | Apple | P | Aphids | Pruning/canopy management | 5 | 4 | 5 | 1 | 4 | 2 | 5 | 5 | 4 | 12.3 | **KE** |
| 1= | Apple | P | Fruit tree spider mite | Bioprotectants Macrobiological | 4 | 3 | 5 | 3 | 5 | 3 | 3 | 4 | 5 | 12.3 | **KE** |
| 1= | Apple | P | Lepidopterous caterpillars | Bioprotectants Microbial | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 5 | 12.3 | **KE** |
| 1= | Pear | P | Pear sucker | Physical exclusion of pests | 5 | 1 | 3 | 2 | 4 | 5 | 3 | 3 | 3 | 12.3 | **Research** |
| 1= | Pear | P | Lepidopterous caterpillars | Bioprotectants Microbial | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 9 | Apple | D | Apple scab | Defoliation - urea sprays | 5 | 4 | 4 | 0 | 4 | 4 | 4 | 4 | 5 | 12.0 | **KE** |
| 10= | Apple | D | Apple scab | Decision support, incl. monitoring | 5 | 4 | 5 | 1 | 4 | 4 | 3 | 3 | 4 | 11.8 | **KE** |
| 10= | Apple | D | Apple scab | N management | 5 | 2 | 3 | 1 | 3 | 4 | 5 | 5 | 5 | 11.8 | **KE** |
| 10= | Apple | D | Apple scab | Forecasting | 5 | 4 | 5 | 1 | 4 | 4 | 3 | 3 | 4 | 11.8 | **KE** |
| 10= | Apple | P | Aphids | Nutrient management | 5 | 2 | 4 | 2 | 3 | 3 | 5 | 5 | 4 | 11.8 | **KE** |
| 10= | Pear | P | Pear sucker | Nutrient management | 5 | 1 | 3 | 2 | 3 | 3 | 5 | 5 | 4 | 11.8 | **KE** |
| 15= | Apple | D | Apple scab | Hygiene and prevention | 5 | 3 | 3 | 0 | 3 | 5 | 3 | 5 | 5 | 11.3 | **KE** |
| 15= | Pear | D | Pear Scab | Field history, rotation & break crops | 4 | 5 | 5 | 0 | 4 | 5 | 3 | 5 | 5 | 11.3 | **KE** |
| 15= | Apple | P | Lepidopterous caterpillars | Physical exclusion of pests | 5 | 1 | 3 | 2 | 4 | 5 | 1 | 1 | 2 | 11.3 | **Research** |
| 15= | Apple | P | Lepidopterous caterpillars | Pruning/canopy management | 5 | 4 | 5 | 1 | 3 | 2 | 5 | 5 | 3 | 11.3 | **Research** |
| 15= | Pear | P | Lepidopterous caterpillars | Physical exclusion of pests | 5 | 1 | 3 | 2 | 4 | 5 | 1 | 1 | 2 | 11.3 | **Research** |
| 15= | Pear | P | Lepidopterous caterpillars | Pruning/canopy management | 5 | 4 | 5 | 1 | 3 | 2 | 5 | 5 | 3 | 11.3 | **Research** |
| 21= | Apple | D | Canker | Field history, rotation & break crops | 4 | 5 | 5 | 0 | 4 | 4 | 3 | 5 | 5 | 11.0 | **KE** |
| 21= | Pear | D | Pear Scab | Hygiene and prevention | 4 | 3 | 4 | 1 | 4 | 4 | 4 | 3 | 5 | 11.0 | **KE** |
| 21= | Apple | P | Aphids | Undersowing & Companion cropping | 5 | 1 | 3 | 2 | 3 | 2 | 4 | 4 | 3 | 11.0 | **Research** |
| 21= | Apple | P | Aphids | Bioprotectants Microbial | 5 | 1 | 3 | 2 | 3 | 4 | 3 | 3 | 4 | 11.0 | **KE** |
| 25= | Apple | D | Canker | N management | 4 | 2 | 3 | 1 | 3 | 4 | 5 | 5 | 5 | 10.8 | **KE** |
| 25= | Pear | D | Pear Scab | Decision support, incl. monitoring | 4 | 3 | 4 | 1 | 4 | 4 | 3 | 3 | 3 | 10.8 | **Research** |
| 25= | Pear | D | Pear Scab | N management | 4 | 2 | 3 | 1 | 3 | 4 | 5 | 5 | 5 | 10.8 | **KE** |
| 25= | Apple | P | Aphids | Variety choice / root stock choice | 5 | 2 | 5 | 3 | 4 | 2 | 1 | 1 | 4 | 10.8 | **KE** |
| 25= | Apple | P | Aphids | Physical exclusion of pests | 5 | 1 | 2 | 1 | 3 | 4 | 3 | 3 | 3 | 10.8 | **Research** |
| 25= | Apple | P | Lepidopterous caterpillars | Bioprotectants Semiochemical | 5 | 3 | 5 | 2 | 3 | 4 | 2 | 3 | 4 | 10.8 | **KE** |
| 25= | Pear | P | Lepidopterous caterpillars | Spatial separation | 5 | 4 | 4 | 0 | 4 | 1 | 3 | 3 | 4 | 10.8 | **KE** |
| 25= | Pear | P | Lepidopterous caterpillars | Bioprotectants Semiochemical | 5 | 3 | 5 | 2 | 3 | 4 | 2 | 3 | 4 | 10.8 | **KE** |
| 33= | Apple | D | Apple scab | Variety choice & rootstock | 5 | 3 | 3 | 0 | 3 | 4 | 4 | 2 | 4 | 10.5 | **KE** |
| 33= | Apple | D | Canker | Hygiene and prevention | 4 | 4 | 4 | 0 | 4 | 4 | 3 | 3 | 5 | 10.5 | **KE** |
| 33= | Apple | D | Canker | Pruning/canopy management | 4 | 4 | 4 | 0 | 4 | 4 | 3 | 3 | 4 | 10.5 | **KE** |
| 33= | Apple | D | Replant disease | Field history, rotation & break crops | 4 | 2 | 4 | 2 | 4 | 4 | 2 | 2 | 5 | 10.5 | **KE** |
| 33= | Apple | D | Replant disease | Select low-risk locations | 4 | 2 | 4 | 2 | 4 | 4 | 2 | 2 | 4 | 10.5 | **KE** |
| 33= | Apple | P | Lepidopterous caterpillars | Bioprotectants Macrobiological | 5 | 1 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 10.5 | **Research** |
| 33= | Pear | P | Lepidopterous caterpillars | Bioprotectants Macrobiological | 5 | 1 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 10.5 | **Research** |
| 40= | Apple | D | Apple scab | Microbial bioprotectants | 5 | 2 | 3 | 1 | 3 | 3 | 2 | 3 | 4 | 10.3 | **KE** |
| 40= | Pear | D | Canker | Field history, rotation & break crops | 3 | 5 | 5 | 0 | 4 | 5 | 3 | 5 | 5 | 10.3 | **KE** |
| 40= | Apple | P | Fruit tree spider mite | Undersowing & Companion cropping | 4 | 1 | 3 | 2 | 3 | 2 | 4 | 5 | 4 | 10.3 | **KE** |
| 40= | Pear | P | Pear sucker | Variety choice / root stock choice | 5 | 2 | 4 | 2 | 4 | 1 | 1 | 1 | 4 | 10.3 | **KE** |

More than 40 pests included as several crop-pest-strategies had the same score (10.0).

 

Table 16. Field vegetables: priority ranking table, Top 40 strategies all pests,

| Rank | Crop | Disease, Pest or Weed | Pest name | Non- chemical control strategy | Economic importance | Current use | Potential use | P-C | Effectiveness | Speed of impact | Inexpensive to Implement | Ease of implementation | Strength of evidence | P-SCORE (ALGORITHM) | KE or Research priority (Threshold >=3) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1= | Carrot | D | Cavity spot | Hygiene | 5 | 4 | 5 | 1 | 5 | 5 | 5 | 5 | 5 | 14.0 | **KE** |
| 1= | Onion | D | Fusarium basal rot | Seed and young plant testing | 5 | 3 | 5 | 2 | 5 | 5 | 4 | 5 | 5 | 14.0 | **KE** |
| 3 | Endive /Lettuce | D | Sclerotinia sclerotiorum | Select low-risk locations | 5 | 4 | 5 | 1 | 5 | 5 | 4 | 5 | 5 | 13.8 | **KE** |
| 4= | Onion | D | Fusarium basal rot | Pre-plant soil tests | 5 | 1 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 13.0 | **KE** |
| 4= | Onion | D | White rot | Pre-plant soil tests | 5 | 1 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 13.0 | **KE** |
| 6= | Carrot | D | Cavity spot | Pre-plant soil tests | 5 | 1 | 5 | 4 | 4 | 4 | 3 | 4 | 3 | 12.8 | **Research** |
| 6= | Onion | D | Fusarium basal rot | Alternative seed treatments | 5 | 3 | 5 | 2 | 4 | 5 | 4 | 4 | 4 | 12.8 | **KE** |
| 6= | Onion | D | Fusarium basal rot | Variety choice | 5 | 1 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 12.8 | **KE** |
| 6= | Endive /Lettuce | D | Rhizoctonia bottom rot (*R. solani*) | Select low-risk locations | 4 | 4 | 5 | 1 | 5 | 5 | 4 | 5 | 5 | 12.8 | **KE** |
| 6= | Carrot | P | Carrot fly | Variety choice | 5 | 1 | 4 | 3 | 4 | 4 | 4 | 4 | 2 | 12.8 | **Research** |
| 6= | Lettuce & Endive | P | Aphids | Variety choice | 5 | 1 | 5 | 4 | 3 | 5 | 5 | 5 | 3 | 12.8 | **Research** |
| 12= | Carrot | D | Alternaria | Fallow | 4 | 1 | 5 | 4 | 5 | 4 | 1 | 5 | 5 | 12.5 | **KE** |
| 12= | Carrot | D | Cavity spot | Growing in substrate not soil | 5 | 1 | 2 | 1 | 5 | 5 | 2 | 2 | 5 | 12.5 | **KE** |
| 12= | Onion | D | Downy Mildew | Variety choice | 5 | 3 | 5 | 2 | 4 | 4 | 4 | 4 | 5 | 12.5 | **KE** |
| 12= | Root brassicas | D | Clubroot | Fallow | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 4 | 12.5 | **KE** |
| 12= | Root brassicas | D | Clubroot | Field history, rotation & break crops | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 5 | 4 | 12.5 | **KE** |
| 12= | Root brassicas | D | Clubroot | Select low-risk locations | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 5 | 4 | 12.5 | **KE** |
| 12= | Root brassicas | D | Clubroot | Alternative seed treatments | 5 | 1 | 3 | 2 | 4 | 4 | 4 | 4 | 3 | 12.5 | **Research** |
| 12= | Root brassicas | D | Clubroot | Seed and young plant testing | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 12= | Root brassicas | D | Phoma leaf spot / canker | Fallow | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 4 | 4 | 12.5 | **KE** |
| 12= | Root brassicas | D | Phoma leaf spot / canker | Field history, rotation & break crops | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 5 | 4 | 12.5 | **KE** |
| 12= | Root brassicas | D | Phoma leaf spot / canker | Select low-risk locations | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 5 | 4 | 12.5 | **KE** |
| 12= | Root brassicas | D | Phoma leaf spot / canker | Alternative seed treatments | 5 | 1 | 3 | 2 | 4 | 4 | 4 | 4 | 3 | 12.5 | **Research** |
| 12= | Root brassicas | D | Phoma leaf spot / canker | Seed and young plant testing | 5 | 4 | 5 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 12= | Endive /Lettuce | D | Grey Mould | Select low-risk locations | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 5 | 4 | 12.5 | **KE** |
| 26= | Endive /Lettuce | D | Sclerotinia sclerotiorum | Growing in substrate not soil | 5 | 3 | 4 | 1 | 4 | 5 | 4 | 4 | 5 | 12.5 | **KE** |
| 26= | Carrot | D | Cavity spot | Variety choice | 5 | 3 | 5 | 2 | 4 | 4 | 4 | 3 | 5 | 12.3 | **KE** |
| 26= | Carrot | D | Cavity spot | Precision irrigation | 5 | 2 | 5 | 3 | 4 | 4 | 3 | 3 | 4 | 12.3 | **KE** |
| 26= | Carrot | D | Powdery Mildew | Commodity substances/salts | 3 | 2 | 5 | 3 | 5 | 5 | 5 | 4 | 5 | 12.3 | **KE** |
| 26= | Onion | D | Fusarium basal rot | Decision support, incl. monitoring | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 12.3 | **KE** |
| 26= | Onion | D | White rot | Decision support, incl. monitoring | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 12.3 | **KE** |
| 26= | Root brassicas | D | Clubroot | Spatial separation | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 3 | 4 | 12.3 | **KE** |
| 26= | Root brassicas | D | Clubroot | Decision support, incl. monitoring | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 12.3 | **KE** |
| 26= | Root brassicas | D | Phoma leaf spot / canker | Spatial separation | 5 | 2 | 4 | 2 | 4 | 4 | 4 | 3 | 4 | 12.3 | **KE** |
| 26= | Root brassicas | D | Phoma leaf spot / canker | Decision support, incl. monitoring | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 12.3 | **KE** |
| 26= | Endive /Lettuce | D | Grey Mould | Decision support, incl. monitoring | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 12.3 | **KE** |
| 26= | Endive /Lettuce | D | Grey Mould | Hygiene | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |
| 26= | Endive /Lettuce | D | Sclerotinia sclerotiorum | Decision support, incl. monitoring | 5 | 3 | 5 | 2 | 4 | 4 | 3 | 4 | 4 | 12.3 | **KE** |
| 26= | Endive /Lettuce | D | Sclerotinia sclerotiorum | Hygiene | 5 | 4 | 5 | 1 | 4 | 4 | 4 | 4 | 5 | 12.3 | **KE** |

 

## Summary and recommendations

### Identifying where to focus KE and research effort.

IPM consists of multiple interventions to control multiple pests in multiple crops, resulting in hundreds of crop-pest-control method combinations. This creates two challenges:

1. Identifying where to focus research and knowledge exchange effort.

2. Structuring IPM guidance for farmers and advisers.

This review considered the available evidence for IPM. Despite reviewing hundreds of published sources of evidence there remain many crop-pest-control method combinations for which there is a sparsity of published evidence on their efficacy or implementation. These cases have been identified by a low score for 'strength of evidence' and are all potential cases for further research. However, there are far more such cases than resources available to investigate them, so the task remains to prioritise without adequate published evidence on which to base the priorities. Our approach was, therefore, to prioritise control methods firstly by the economic importance of the pest that they address, then to use expert judgement of ADAS crop protection specialists to estimate their likely effectiveness. The scoring system was then devised to give a high weight to the economic importance of the pest and estimated efficacy of the strategy, and a lower weighting to scores related to practical implementation. Priorities were then filtered to exclude those control methods where increased implementation was unlikely, because: (i) implementation is already high and there is little additional scope, (ii) the benefits of increased implementation would be limited, or (iii) there are substantial practical or cost impediments.

Crop-pest-control method combinations with high strength of evidence scores are candidates for knowledge exchange. The scoring system described above was applied, to identify effective control methods against economically important pests, where there is good potential for increased implementation.

The large number of crop-pest-control method combinations means that a small difference in individual scores can result in large changes to the priority ranking. The scores are necessarily subjective and other experts could reach alternative conclusions and scores based on the same evidence. The priority score equation combines the various scores to arrive at a priority ranking. The weightings given to each score are designed to reflect the importance of economic benefits to farmers and the potential for increased implementation to achieve those economic benefits. Hence, the efficacy of the control method and the economic importance of the pest are given the highest weighting in the prioritisation equation, then factors related to the likelihood of increased uptake are considered in the equation. This approach is logical, but other methods of calculation are possible. To address this, we will provide the data files of scores are also appended to this report to enable others to explore different prioritisation approaches.

The priority tables in section 8 should be self-explanatory to extract the detail, but certain themes emerge repeatedly, either within or across crops. In particular, decision support comes out as a high priority across all crops for both research (where further evidence for the value of DSS is required) and knowledge exchange (where existing DSS use could be increased).

## Trade offs

The implementation of non-chemical control measures can sometimes have negative effects that counterbalance the benefits they bring. These trade-offs, require careful consideration. References tables at the start of this document provide a point for cross checking the impact of specific strategies on other pests, weeds and diseases. The direction of the impact on each of these can be found within the main body of the report. Clearly in some cases some trade offs may have far reaching effects on the economic and/or agronomic aspects of crop production, and these also require careful consideration with cropping experts to ensure there is a net benefit of any new approach.

The tables below summarise some of the main trade offs in the implementation of strategies for each crop group.

Table 17. Soft Fruit (Raspberry, strawberry and grape) Trade-offs. Measures are not all inclusive and some are at an early development stage. Measures arranged in approximate order of management.

| Non-chemical control strategy | Approach | Positive effect (reduction, unless specified) | Negative effect (increase, unless specified) |
|---|---|---|---|
| **Meristemming** | Use of technique in early stages of propagation. | Diseases including viruses. | Poor plant output success. Micro-propagated plants can lose trueness to type. |
| **CATT (controlled atmosphere treatment)** | Treatment of propagation material (not for fruiting) | Tarsonemid, nematodes. | Treatment cost. |
| **Hot water treatment** | Treatment in propagation | Tarsonemid. | Plant pathogenic bacteria via spread in the water. |
| **Plant sauna** | Treatment in propagation | Xanthomonas. Colletotrichum. | Cost of buying & running unit. |

 

| | | | |
|---|---|---|---|
| | | Phytophthora. | |
| **Clean stock** | Biosecurity & hygiene – start clean-stay clean. | All diseases & pests. In-field pesticide use. | Higher costs for propagators from increased cleaning, monitoring. |
| **Varietal choice** | Select disease & pest resistant / tolerant varieties. | Phytophthora of raspberry & strawberry.<br>Powdery mildew.<br>Raspberry cane blight.<br>Grape downy mildew<br>Large raspberry aphid. | Strawberry & raspberry growers do not have free choice of cultivars when they are tied into production and marketing contracts. Large raspberry aphid populations have broken resistance. For winemakers, the types of wine produced are linked to the particular grape varieties used.<br>Greater resistance can be counter-balanced by lower yield, shelf life, flavour or appearance. |
| **Growing out of soil** | Strawberry & raspberry grown in peat, coir or other substrate in containers. | Phytophthora.<br>Verticillium. | Cost of substrate & pots and non-sustainable.<br>Phytophthora, as if plants become infested it spreads easily.<br>Weeds can grow on compost surface & may harbour aphids. |
| **Rotation** | 3 to 5 year interval in both propagation & fruiting fields. | Weeds.<br>Verticillium<br>Phytophthora.<br>Free-living nematodes. | Need for land - may require renting or rent-out agreement<br>Distance from field to packhouse likely.<br>Requirement for utilities & tunnel structures.<br>Profit loss due to less-valuable interim crops. |
| **Spatial separation** | New & old crops apart, perhaps by biennial cropping in raspberry. | Most foliar diseases.<br>Most pests, e.g., vine weevil, aphids, western flower thrips, raspberry cane midge, blackberry leaf midge. | No fruit every other year with biennial cropping, so more land required.<br>Access to water & electricity needed at a separate site, so can limit take-up. |
| **Pre-plant soil test** | Soil sample taken before finalising site or variety. | Nematodes.<br>Verticillium.<br>Use of qPCR can reduce time for result return. | Sampling & analysis cost. 1-2 month for Verticillium & nematodes by extraction.<br>qPCR gives DNA content but more research needed on likely disease level resulting. |
| **Pre-plant irrigation water test** | Sample water source & storage or bait test. (Test even if water is being treated) | Phytophthora.<br>Pythium. | Labour cost to sample.<br>Cost for analysis. |
| **Organic amendments** | Anaerobic digestate solids or FYM. | Improved soil health.<br>Increased water holding. | Transport costs; but needs to be available locally as bulky.<br>Risk of pathogens if digestate not PAS 110 certified. |
| **Planting timing** | Annual planting raspberry & strawberry crops.<br>Planting not delayed too long of cold-stored plants. | Pest & disease carry-over.<br>Fewer losses to root pathogens / better establishment when | Labour cost for clearing old crop & establishing new.<br>Cost of new plants.<br>Carbon-footprint from annual need for cold-stored canes & runners. |

 

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| | | plants have lost less energy during storage. | |
| **Physical mulches** | Plastic covers over roots.<br>Woven ground-cover under pots.<br>Straw between strawberry beds. | Weeds.<br>Herbicide usage.<br>Soil-splash onto fruit. | Labour & material costs.<br>Problems of disposal if plastic.<br>Pests, which use mulches for daily or seasonal shelter e.g., Voles, Vine Weevils.<br>Blackgrass if present in straw. |
| **In-field non-cropped areas** | In-field strips or margins containing wildflowers | Increased biodiversity e.g. pollinators and natural enemies of pests, e.g., hoverflies.<br>Possible increased birds. | Associated costs.<br>Weeds, from blown seeds.<br>Capsid & thrips may breed in some species of flowers.<br>Wildlife, which may eat fruit. |
| **Hygiene** | Debris-free growing areas.<br>Waste fruit removal. | Weeds.<br>Botrytis.<br>Cane & stem diseases.<br>SWD. | Labour costs. |
| **Environment control** | Tunnel-polythene lifting in strawberry & raspberry. | Diseases, due to humidity & temperature lowering. | Problems of labour availability & cost. |
| **Precision irrigation** | Drip irrigation controlled by need not timers. | Phytophthora.<br>Symptoms of Verticillium wilt. | Cost of probes & problem of likely variability across the field / variable plant needs. |
| **Nutrient management** | Reduced N fertiliser. | Aphids. | Yield loss possible. |
| **Defoliation** | De-leafing of everbearers.<br>Removal of lower raspberry cane leaves. | Powdery mildew & Botrytis, due to reduced humidity & old leaf removal.<br>Increased pesticide spray penetration.<br>Faster cane hardening. | Labour availability & cost.<br>Removal of predators / parasitised pests on mature leaves.<br>Botrytis and cane blight, due to entry via wounds. |
| **Pruning** | Removal of excess primocane / strawberry runners.<br>Cutting back vine shoots.<br>Removal old vine-wood & old floricane. | Powdery mildews & Botrytis, due to reduced humidity & selection of healthy tissue.<br>Downy mildew in vines.<br>Reduction in cane and stem disease spread with pathogen removal in old tissue. | Labour availability & cost.<br>Diseases, due to spread of spores on pruning equipment and pathogen entry via cut ends. |
| **UV-C** | Treatment of strawberries at night. | Powdery mildew. | Hire cost of equipment.<br>Treatment needs to start early in crop or may not be managed.<br>UV-C is hazardous to humans. |
| **Physical exclusion pests / crop covers** | Tunnel covers during flower / fruiting.<br>Fleecing or netting strawberries for warmth. | Botrytis.<br>Fruit spoilage from hail.<br><br>Exclusion of SWD, thrips.<br>. | Cost; erection time & materials.<br>Plastic disposal.<br><br>Time needed to raise fleece to spray pesticides, or release predators.<br>Greater warmth or humidity can increase pests / diseases<br>Netting can exclude natural beneficial insects. |
| **Mass monitoring** | Roller traps in strawberry | SWD.<br>Thrips. | Labour & cost of traps. |

 

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| **Sterile male technique** | Release in strawberry & raspberry | SWD. | Labour & cost. |
| **Decision support – to include one or more measures** (see also sampling/trapping) | Monitoring in crop at least weekly.<br>Pheromone traps weekly checks.<br>Utilisation of on- or off-site MET data in relation to pathogen epidemiology & pest life cycles.<br>Use of models and forecasts. | All Weeds, Pests, Diseases by assessing in the crop & controlling before increase.<br>Strawberry Botrytis & Powdery mildew.<br>Grape Powdery & Downy mildews.<br>Raspberry cane midge.<br>Strawberry blossom weevil. Better awareness of pest and disease incidence in crop and of how well biological control agents are establishing.<br>Reduced pesticide sprays (good environmental benefit & saves costs).<br>Increased evidence to show need for sprays on produce. | Training/skill/extra payment for staff to monitor & identify pests and diseases.<br>Increased management skill & time to use models / forecasts.<br>Any online forecasts need to be funded to be kept running. |
| **Biostimulants** | Foliar or root treatment. | Improved crop vigour. | Cost of product & application.<br>Uncertain benefits. |
| **Bioprotectants; invertebrate bio-controls** | Release or application at appropriate rate & timing. | Aphids.<br>Thrips.<br>Vine weevil.<br>Two-spotted spider mite.<br>Reduced use of pesticides overcomes pesticide resistance. | Cost of product e.g. aphid parasitoids can reduce uptake.<br>Increased knowledge of product / pest needed. |
| **Bioprotectants; natural substances** | Application before (pathogens) or early in infestation. | Powdery mildew.<br>Pests e.g. aphids, thrips, spider mites.<br>Increased plant priming / eliciting of defence responses.<br>Pesticides of non-natural origin & residues. Low risk to beneficials. | Ineffective if application situation inappropriate.<br>Increased knowledge is needed on how to gain optimal performance. Frequent applications often necessary.<br>Contact in action so may not reach target pests. |
| **Bioprotectants; microbial** | Application at low pest or disease levels to foliage or roots. | Thrips.<br>Aphids.<br>Vine weevils.<br>Caterpillars.<br>SWD<br>Beneficials survive<br>Botrytis.<br>Powdery mildew.<br>Phytophthora.<br>Pythium.<br>Increased plant priming / eliciting of defence responses.<br>Pesticides of non-natural origin & residues. | Product cost.<br>Pests & diseases - incomplete / no control if application situation e.g. relative humidity inappropriate.<br>Multiple applications at short interval may be needed.<br>Require specific conditions for use e.g., climatic control – more information needed.<br>Can be target-specific so some other pests / diseases survive.. |

 

Table 18 Arable crops trade offs. Measures are not all inclusive and some are at an early development stage. Measures arranged in approximate order of management.

| **Non-chemical control strategy** | **Approach** | **Positive effect (reduction, unless specified)** | **Negative effect (increase, unless specified)** |
|---|---|---|---|
| Sowing date (autumn) | Delay drilling | Reduce risk of many diseases (mildew, septoria, yellow rust) | Reduced yield from reduced biomass<br>Risk of poor crop establishment |
| Variety choice | Selecting resistant varieties | Reduced pest and diseases (brown rust, yellow rust, Rhizoctonia, pea downy mildew, pea leaf spot, flea beetle, cabbage root fly) | Reduced yield<br>Crop not sold for a quality premium |
| | | Reduced clubroot | Clubroot resistant varieties have a selection pressure on the pathogen. Should not be used unnecessarily |
| Primary cultivation | Crop residue burial | Cultural control of annual grasses<br>Reduce Ergot/ sclerotinia spores | Reduced soil structure (plough pan)<br>Greater carbon loss higher operational costs e.g., fuel labour |
| Undersowing companion crops | | Greater competition for weeds to establish | Cost. Crop competition |
| | | Reduce Flea beetle damage | Harvest compatibility |
| Secondary Cultivation | Successive passes | Reduce weeds | Cost, poorer soil structure, capping<br>Carbon loss/ GHG emissions<br>Loose soils free drainage capacity. Greater likelihood of soil run-off /erosion |
| Stubble management | Leaving taller stubbles | Reduce Flea beetle damage from crop disguise | Potentially more material to enable disease carry over |
| Seed testing | Disease testing | Reduced Ergot | Cost |
| Soil testing | Clubroot | Reduced clubroot | Cost |
| Fallow | Uncultivated fields | Breaks disease/ weed lifecycles by removal of crop host | Problem weeds could seed if mismanaged<br>Economic losses from absence of production outside subsidised schemes e.g., 2-year legume fallow |
| Seed rate | Increase seed rate | Increase competition with weeds | Cost of extra seed |
| | Increase row spacing | Allows for interrow hoeing | Potential for more disease with higher density crop canopy |

 

Table 19 Top Fruit (Apple and Pear) Trade-offs. Measures are not all inclusive and some are at an early development stage. Measures arranged in approximate order of management.

| Non-chemical control strategy | Approach | Positive effect (reduction, unless specified) | Negative effect (increase, unless specified) |
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| **Field history** | 5 year or more rotation.<br>Inter-row planting. | Apple replant disease. | Requirement for suitable land.<br>Complications of management if plant inter-row trees |
| **Variety choice** | Select resistant material. | Apple scab.<br>Apple canker.<br>Apple powdery mildew.<br>Pear scab.<br>Pear canker.<br>Aphids.<br>Caterpillars.<br>Pear sucker.<br>Increased benefit for use in organic production. | Decrease in sales where varieties are not of known names and contracts often preclude grower choice.<br>Increase in tree breeding activity & variety acceptance required. |
| **Undersowing / cover crops** | Mixed swards, mown close to fruit harvest, to provide refuges for predators.<br>Nettles to establish aphids for predators.<br>Sow e.g., French marigolds | Aphids.<br>Spider mites.<br>Weeds.<br>Increase in late spring of Typhlodromus mite, Anthocorids & Earwigs.<br>Increase Ladybirds, Hoverflies, Lacewings. | Competition with fruit trees.<br>Hiding place for voles<br>Dampness around tree may increase canker.<br>Grass-apple aphid.<br>Pest species that host on companion plants. |
| **Spatial separation** | Site new orchards away from established trees. | Caterpillars. | Aphids will still fly in, but so may predators. |
| **Pruning** | Removal of diseased tissue. | Apple & pear scabs.<br>Apple & pear cankers.<br>Powdery mildew.<br>Aphids.<br>Caterpillars. | Canker can spread via pruning tools in wet weather.<br>Labour cost of removal. |
| **Hygiene** | Destruction of fallen leaves & pulverising of pruning wood.<br>Urea applied to old leaves.<br>Removal of dropped fruit – potential for animal grazing<br>Weed control. | Apple scab<br>Pear scab.<br>Apple canker.<br>Primary mildew.<br>Caterpillars entering soil from fruit.<br>Weeds. | Labour time & cost.<br>Damage to trees possible if using grazing of dropped fruit. |
| **Physical pest exclusion** | Insect – mesh netting (not just hail netting) | Aphids.<br>Caterpillars.<br>Pear sucker.<br>Bird damage.<br>Pesticides | Labour & materials costs.<br>Humidity rise increases powdery mildew.<br>Reduced pollination due to exclusion of pollinators if used during flowering.<br>Reduced ease of inspection / spray access |
| **Microbial bioprotectants** | Spray application to foliage or ground. | Apple scab.<br>Caterpillars.<br>Aphids.<br>Some mite species. | Costs of products.<br>Spray rounds may increase. |

 

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| | | | Knowledge of optimum conditions & development stage needed.<br>Research needed before commercial use for canker. |
| **Botanical bioprotectants** | Regular spray application | Apple scab.<br>Pear scab.<br>Pear canker.<br>Weeds.<br>Harvest interval. | High costs of products.<br>Uncertain efficacy, potential use only in low disease levels. |
| **Macrobiological bioprotectants** | Withhold / reduce conventional pesticides to maintain natural populations of predators.<br>Supplement with predatory mites / parasitic wasps.<br>Apply entomopathogenic nematodes.<br>Earwig nests. | Aphids.<br>Spider mite.<br>Caterpillars.<br><br>Increased beneficials. | Management time to observe effectiveness of natural populations to aid reducing pesticide use.<br>Awareness of pesticides which will do beneficials least harm.<br>Labour to put out beneficials & earwig nests |
| **Semiochemical bioprotectants** | Set up pheromone dispensers.<br>Dispensary sachets methyl salicylate | Caterpillars.<br><br>Increased hoverflies, lacewings, ladybirds, *Orius.* | Mainly used for detecting males / mating disruption rather than trapping-out as insufficient numbers trapped. |
| **Biostimulants / elicitors** | Alternation or early application within pesticide spray programmes. | Apple & pear cankers.<br>Powdery mildew.<br>Increased yield.<br>Fungicides. | Disease multiplication if application at too high a disease level. |
| **U-V light** | Robotic use at night. | Powdery mildew. | Risk to humans.<br>Further development costs.<br>Disease, unless used at low disease levels only. |
| **Nutrient management** | Use of nitrogen according to variety & growth stage, not in excess. | Apple & pear scabs.<br>Apple & pear cankers.<br>Powdery mildew.<br>Aphids.<br>Pear sucker. | None. |
| **Organic amendments** | Amendments to increase beneficial microbes. | Apple replant disease. | Cost, particularly as long-term effectiveness not proven. |
| **Mowing & mechanical or thermal weeding** | Weed control | Weeds. | Cost of thermal weeding.<br>Number of passes compared with herbicide use. |
| **Physical mulches** | Green compost.<br>Straw.<br>Woven mulches. | Weeds. | Only short-term benefit as unable to maintain compost cover due to soil nutrient regulations.<br>Blackgrass in straw.<br>Voles, which hide in straw.<br>Cost, for woven ground-cover. |
| **Decision support** | Routine monitoring.<br>Recording local MET data.<br>Models & Forecasting. | Apple & pear scabs.<br>Powdery mildew.<br>Fungicides.<br>Caterpillars. | Potential increased infestation / infection after a decision to delay treatment. |

 

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| | | | Training/skill/extra payment for staff to monitor & identify pests and diseases.<br>Increased management skill & time to use models / forecasts.<br>Any online forecasts need to be funded to be kept running. |

Table 20. Trade-off Table for Field Veg (Carrots, Onions, Vegetable Brassicas & Lettuce) (measures are given in approximate order of use in the crop year). The list does not claim to be totally inclusive, further measures are given in the text or in the score tables. Some measures are novel or require further development in commercial crops.

| Non-chemical control strategy | Approach | Positive effect (reduction, unless specified) | Negative effect (increase, unless specified) |
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| **Low-risk location** | Avoid proximity to oilseed rape & other brassicas | Alternaria.<br>Light leaf spot.<br>Ringspot.<br>Phoma. | Costs associated with greater distance of brassicas to pack-house. |
| **Fallow** | One or more seasons without a crop & kept bare. | Some weeds.<br>Aphids.<br>Trash-borne pathogens - Alternaria,<br>Light leaf spot,<br>Ringspot,<br>Phoma. | Cost of cultivations.<br>Loss of income from growing a crop. |
| **Rotation** | 4-year rotation with non-host plants. | Weeds.<br>Carrot fly.<br>Stem nematode.<br>Free living nematodes.<br>Alternaria.<br>Light leaf spot.<br>Ringspot.<br>Phoma.<br>Increased fertility. | Lower gross margin with inclusion of lower-value crops.<br>Costs associated with greater distances to pack-house. |
| **Primary and secondary cultivations** | Plough & harrow. | Grassweeds.<br>Sclerotia buried.<br>Slugs.<br>Aphids, onion thrips.<br>Compaction. | Sclerotia brought to surface. Fine tilth/ seedbed reduces slug problems. Burial of crop debris reduces other pests. Can expose pests to predators.<br>Reduction of "soil health" reduction with worm & beneficial mycelium destruction.<br>Loss of soil moisture. |
| **Pre-plant soil test** | Extraction / isolation for identification & quantification &/or infectivity | Free-living nematodes.<br>Stem nematode.<br>*Verticillium dahliae.*<br>Club root. | Cost of sampling & analysis.<br>Delay of weeks while waiting for results of field infestation.<br>Risk of low numbers of stem nematodes being undetected. Thresholds for free living nematodes in carrot need reviewing. |

 

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| **Pre-plant soil test** | Molecular identification & quantification of organisms' DNA. | Detection of various microbial and invertebrate pests and beneficial species. | Speed of result receipt. Uncertainty of correlation between DNA presence & potential damage / benefits. |
| **Varietal choice** | Select disease / pest resistant / tolerant varieties. | Carrot fly.<br>Lettuce root aphid.<br>Currant-lettuce aphid.<br>Onion thrips.<br>Club root.<br>Light leaf spot.<br>Ringspot.<br>Phoma.<br>Xanthomonas.<br>Brassica, onion & lettuce downy mildews.<br>Brassica & carrot Alternaria leaf spots.<br>Carrot cavity spot.<br>Onion Fusarium basal rot. | Risk of poor results because of a lack of performance trials. Currant-lettuce aphid populations that break resistance now widespread. No commercial varieties with resistance to carrot fly available. Research needed on newpest- resistant varieties.<br>Opportunity for sales where less pesticide use is valued.<br>Decreased market for non-mainstream varieties, particularly if taste, shape, shelf-life etc. is not as good as previous susceptible choice. |
| **Hygiene & control in propagation** | Keep clean – stay clean: Clean seed, debris-free growing areas, clean water, environmental condition control, weed control. monitoring & swift remedial action. | Weeds in modules<br>Aphids.<br>Downy mildew.<br>Powdery mildew.<br>Alternaria.<br>*Xanthomonas* sp..<br>*Pythium* sp..<br>*Rhizoctonia* sp..<br>In-field pesticide use. | Staff time to keep areas clean & requirement for staff training in crop monitoring. |
| **In-field non-cropped areas** | In-field strips or margins containing wildflowers | Most pests.<br>Increase in biodiversity & natural enemies.<br>Increase in birds, rabbits & other mammals. | Weeds in crop from dispersed seed.<br>Seed & establishment costs.<br>Pests & diseases including virus from cruciferous plants.<br>Botrytis.<br>Bird & rabbit damage. |
| **Organic amendments** | Incorporation of FYM, PAS 100 green compost or PAS 110 anaerobic digestate solids in the field | Increase in moisture retention but decrease in waterlogging with opened soil structure.<br>Potential increase beneficial microbes. | Potential introduction of soil-borne pathogens e.g., *Plasmodiophora, Phytophthora, Pythium* spp. if Certified products not used. |
| **Undersowing, intercropping or companion crops** | Reduction in bare ground. Sowing companion crops in brassica modules. | Weeds.<br>Increased natural enemies eg hoverflies leads to better aphid control. | Weeds.<br>Humidity in crop leading to increase in pathogen infection.<br>Potential yield loss due to intercropped plants competing with crop. Mechanical hoeing |

 

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| | | Reduction of cabbage root fly egg laying. | reducing survival of companion crops. |
| **Hygiene in the field** | Avoiding movement of soil or plant debris between fields on equipment or footwear. Burial of plant debris or disposal from site. | Weeds. Aphids. Stem nematodes. Carrot fly. Bean seed fly. Trash and soil-borne pathogens. | Cleaning-down time. Travel and costs of disposing waste away from new crops. Staff training in how plant diseases & pests spread. |
| **Physical exclusion pests** | Mesh or other covering sealed over the crop. | Caterpillars. Cabbage root fly. Carrot fly. Aphids. Bird damage. Pesticides (environmental & cost benefit) | Cost of material, managements & cleaning or disposal. Labour to set-up, check for breaches & remove. Any pests inside as warmer & predator-free. If any tears in netting or mesh size too small, pests can enter. Foliar diseases favoured by humidity. Problems with weed control. |
| **Mechanical / thermal weeding** | Non-chemical control, potentially utilising GPS / machine vision guided equipment | Herbicide use. Weeds. Non-crop hosts of pests & diseases. Competition for water. | Cost of new technology. Weeds if soil surface is disturbed. Potential for damage to crop plants or roots. |
| **Decision support** | In-crop monitoring. Utilisation of models & forecasts. | Aphids. Caterpillars. Cabbage root fly. Carrot fly. Onion thrips. Downy mildew. Alternaria. Light leaf spot. Ringspot. Phoma. Xanthomonas. Reduced use of pesticides (environmental & cost benefit). Better awareness of pest and disease incidence in crop leads to better decision making in IPM. | Management of decisions & scouting time rather than routine pesticide application. But this is offset by improved awareness of pest & disease risks and incidence. Uncertainty over future availability of forecasting information. |
| **Invertebrate bio-controls** | Conservation of naturally occurring biocontrol agents. Limited release of aphid biocontrols in organic lettuce. | Cabbage root fly. Aphids. Caterpillars. Onion thrips. Bean seed fly. | Need for more research. |
| **Biostimulants / plant defence elicitors** | Application to disease / pest-free crops, particularly if showing abiotic stress. | Aphids possibly. Cabbage root fly. Plant stress & increased plant defence elicited. | Cost of product & application. Uncertainty of benefits. Potential phytotoxicity. Need for more research. |

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| **Bioprotectants: natural substances** | Prophylactic applications, or at low levels of disease / pest.<br>Use in propagation & / or in field | Weeds.<br>Aphids.<br>Nematodes.<br>Increased plant defence elicited. | Risk of increase if missed / small levels increase soon after an omitted non-bioprotectant spray. Frequent applications may be needed. Inconsistent results. |
| **Bioprotectants; microbial** | Prophylactic applications, or at low levels of disease / pest. Use in propagation & / or in field. | Caterpillars.<br>Pythium.<br>Rhizoctonia.<br>Club root.<br>Sclerotinia.<br>Botrytis.<br>Powdery mildew.<br>Beneficials survive.<br>Increased plant defence elicited.<br>Reduces use of pesticides of higher environmental risk or lower specificity. | *Bacillus thuringiensis* only effective against young caterpillars so timing critical. Washed off by rain/irrigation so repeat application may be needed.<br>Need more research on commercial entomopathogens for aphid/thrips control.<br>Risk of increase if missed / small levels increase soon after an omitted non-bioprotectant spray.<br>Risk of efficacy failure if conditions are unsuitable for the microbe.<br>Other diseases / pests remain if using a target-specific product.<br>Knowledge acquisition needed to gain optimum performance. |

## Soft fruit KE & research priorities

In soft fruit, the top 40 priorities identified here are exclusively on pests and diseases. The control of spotted winged drosophila (SWD) in grape vine, strawberry and raspberry is of particular interest. Several non-chemical approaches such as decision support, hygiene, and mass monitoring on strawberry and raspberry are well understood and might benefit from further KE. Additionally sterile male techniques had high priority scores for SWD control on all crops, and have big potential for increase in use, however strength of evidence indicated further research is necessary to support its uptake.

Also highlighted was the potential for using variety choice and breeding to control raspberry cane midge and blackberry leaf midge in raspberry, and thrips in strawberry. Based on differences in strength of evidence, KE may help broaden the use of varietal resistance to raspberry cane midge, whereas more research may be required to develop greater uptake of blackberry leaf midge resistance in raspberry and thrips resistant varieties of strawberry. A limiting factor in grower variety choice in soft fruit is that marketing groups stipulate which varieties to grow.

Powdery mildew and botrytis in strawberry were identified as the main diseases where non-chemical control strategies could have a greater role. Several approaches are clearly well known and used, such as the use of clean stock, hygiene and prevention, the control of volunteers and weeds, and environmental control, however these still have the potential for wider use. For powdery mildew control, other less commonly used approaches with potential include seed and young plant testing, defoliation, and the use of UV-C. These are supported by good evidence and with suitable KE could be more widely applied.

## Arable KE & research priorities

For the non-broadacre arable crops considered in this review, a range of non-chemical control strategies were identified as having the potential to assist in the control of weeds, pests and diseases.

Choosing to grow rust resistant varieties of rye and triticale was highest on the priority list. These are significant pathogens, and there is potential for greater use of less susceptible varieties. It should be noted this may narrow varietal choice and could result in growers having to accept other agronomically less favourable features. The control of volunteers in preceding crops or weeds that may act as a host can reduce yellow and brown rusts and also prevent pathogens bridging between old and new crops.

For fodder crops, soil testing and stubble management could be more widely used in the control of clubroot and flea beetle. Decision support and monitoring was also highlighted for clubroot and rhizoctonia control as an approach that could be more widely used to good effect. There may also be the potential to control flea beetle through undersowing or companion cropping, however strength of evidence is on this is low, and this area may require more research to fully understand its role and how it can be most effectively implemented.

Hygiene and prevention featured extensively as an approach that could assist in the control of annual grasses in cereals and pulses, but also in the control of clubroot and rhizoctonia in fodder crops. For annual grass weed control the use of primary and secondary cultivations was also identified as non-chemical strategies that could be used more.

For the control of ergot, a particular problem of rye and to a lesser extent triticale, a range of non- chemical control strategies were prioritised. These included primary cultivations, grass weed control, seed testing and hygiene and prevention.

In peas, beans, rye and triticale the use of precision irrigation for the control of annual grasses was highlighted as an area that could be used more but strength of evidence was low, so this may require more supporting evidence from research to initiate further uptake.

 

## Top Fruit KE & research priorities

In top fruit, this analysis indicated that greater uptake of non-chemical control strategies would be possible for a number of pests, weeds and diseases. Strategies for invertebrate pest management were highlighted particularly, accounting for 8 of the top 10 priority strategies as scored. The potential for increased use of microbial or macrobiological bioprotectants for the control of pear sucker, caterpillars and aphids on apples and pears, and fruit tree spider mites was identified. The strength of evidence for their use is high, so more knowledge exchange could initiate greater uptake.

The control of caterpillars in apples and pears, and pear sucker by physical exclusion or pruning / canopy management was also considered as strategies that could be more widely adopted. Here strength of evidence was more limited, and research may be required to encourage further uptake.

A number of non-chemical control strategies for apple scab were highlighted as having potential for wider use. Strategies such as pruning / canopy management, forecasting and decision support / monitoring are already commonly practised, there is good evidence that they are effective and could be more widely adopted. Microbial bioprotectants and N management are currently less widely used for scab control but also have good evidence of efficacy and the potential for greater use.

Several strategies were identified for the control of aphids in apples, in addition to the use of bioprotectants, as previously mentioned. These included nutrient management, and variety or root stock choice, where evidence is strong. The use of undersowing or companion cropping or the physical exclusion of aphids from the plant may also have potential but less is known, so these approaches may initially require more research to improve understanding and subsequently uptake.

The control of perennial grasses and broad leaved weeds in apples and pears are highlighted here also. Non-chemical control strategies of hygiene and prevention are widely practised but could be used more. The use of mechanical weeding is less common but also effective and could be more widely implemented.

## Field vegetables KE & research priorities

The top priority scores mainly highlight the potential of non-chemical strategies to control diseases and pests. Weed control did feature but these strategies tended to have lower priorities scores, as they were generally already being widely implemented, and there was less scope for greater use. Strategies prioritised to control some of the most economically important diseases generally focused on pre-cropping approaches. For the control of cavity spot of carrot and sclerotinia, for example, there is strong evidence of the value of hygiene, and although current use is quite high, measures to reduce infested soil movement between crops on equipment could be implemented more widely.

Pre-planting soil tests and growing in substrate not soil, were also identified as alternative approaches to its control, although the use of pre-planting soil tests may require more research to strengthen the evidence for its value. Effective strategies that could be used more widely for Fusarium basal rot control in onions included set testing and pre-plant soil tests using molecular assays, alternative seed treatments, and choosing more resistant varieties. Good evidence exists for further development of all of these approaches and more knowledge exchange could improve uptake.

Within the root brassicas, prioritised approaches to clubroot and phoma leaf spot / canker focused on pre-cropping, with fallowing, the use of rotation, or simply using lower risk locations being well understood to improve control. The use of alternative seed treatments was considered valuable but not sufficiently well understood. Spatial separation from previous fields and monitoring / decision support were also viewed positively.

Some ‘in crop’ strategies did also feature as priorities, these included precision irrigation in the control of cavity spot in carrots, and the use of commodity substances / salts for powdery mildew.

Decision support and monitoring was widely identified as an approach that should be prioritised for the control of many pests and diseases of field vegetables. There is much that is already known in this area, and more KE could help uptake.

For pests, more research on the role of varieties to control both carrot fly in carrots, and aphids in endive / lettuce, was considered a high priority, as this approach has good potential for further research and development, leading to greater uptake as currently uptake is limited due to lack of recent research.

In addition, the current thresholds used for predicting damage to carrot by free living nematodes need reviewing.

## Structuring IPM guidance for farmers and advisers

A huge quantity of IPM information is available through the AHDB website, but the information is not always in a form that allows the relevant bits of information to be found quickly and interpreted to guide decisions on IPM implementation. In some cases, there are short articles or guides, clearly signposted, which provide the information needed. In other cases, the information is contained in lengthy project reports or reviews which farmers and advisers are unlikely to have time to read to extract what they need. This inconsistency of presentation is partly the legacy of previously separate levy bodies, but the main underlying issue is that there are many options for how IPM information could be structured for delivery to levy payers.

Within each crop there are a range of pest species. There are also a range of specific IPM interventions, each of which is relevant to one or more pest species. Some of those interventions fit within broad themes, such as 'varieties' or 'decision support'. Hence, there are various options for sub-dividing and structuring IPM guidance, so that the relevant information can be found and each piece of information can be short. The information can be sub-divided by:

- Individual pest - including information on all the key IPM methods to control it (e.g., Managing Weeds in Arable Rotations).
- Individual IPM control method – listing the pests to which it is applicable.
- Individual pest by control method combination (e.g., guidance on managing dumps for potato blight management).

Or by grouping together:

- Groups of pests and their control measures within a particular crop (e.g., the Wheat Disease Management Guide).
- Types of intervention against multiple pests (e.g., disease and pest resistance scores in the RL).

There are pros and cons of each of these methods of sub-division, particularly as many aspects of IPM are interrelated. Any of these approaches to structuring information could probably be made to work, if applied consistently. Currently, AHDB's IPM information is in a mixture of the above structures, making it difficult to navigate.

An alternative structure is proposed here which could make use of existing resources and simplify navigation for users, based on a crop management decision timelines.

Each crop species has a timeline of crop management decisions during the year. At any particular time in the year, decisions about management of a sub-set of specific pests are relevant and a subset of particular control methods for those pests are relevant. An IPM dashboard for each crop could show the circular seasonal timeline by calendar and crop stage. Each pest and IPM intervention would be shown at the relevant points along the timeline, so for example Fusarium basal rot of onions would appear at relevant time points, with links to information guiding variety choice, seed and plant testing, soil tests and alternative seed treatments.

The information provided at any given time point to guide a particular IPM decision would be short and may take the form of:

 

- Text describing the factors to be taken into account in making the decision.
- A decision guide in the form of a flow chart.
- Decision support (e.g., a pest forecast, monitoring information or treatment threshold).

Much of this could be achieved by providing links to the appropriate parts of existing KE resources. And it fits with the AHDB's IPM themes of Prevent, Detect, Control - with particular pests being in Prevent, Detect or Control phases at different times of the year.

## Aligning AHDB IPM information with ELMS IPM Land Management Planning

The priorities identified and recommendations from this review should be considered in the context of parallel work being conducted on IPM for Defra. Implementing IPM has benefits to farmers and 'public good' benefits. The latter has not been rewarded to date. Defra has signalled an intention to encourage uptake of IPM through the Environmental Land Management Scheme (ELMS). An ELMS Test and Trial project has been investigating how IPM Land Management Plans might be incentivised and supported by advice and guidance. Two of the recommendations from the report of the IPM Test and Trial were:

- Bring the evidence up to date for effectiveness of specific IPM practices for key pests in those crops.
- Ensure IPM guidance is available online for each crop, so the Tool [an online tool for creating IPM Land Management Plans] can provide context sensitive links to support user decisions on which IPM practices to implement.

This review relates to these recommendations.

The IPM ELMS Test and Trial project has developed an IPM Land Management Planning (IPM LMP) tool for farmers. This has been tested by farmers and their feedback has shown that the tool provides an achievable, quick and effective process for farmers to: (i) create IPM land management plans, (ii) record their current IPM practices, and (iii) record their intention to increase implementation of IPM. 88% of farmer users stated that they would recommend the process to others.

The IPM LMP Tool has been created in Excel and contains IPM guidance in the form of 'pop-up' notes and links to the relevant AHDB IPM KE resources for each pest and IPM intervention. The tool provides a structure for presenting IPM guidance. Where pests and IPM interventions in the tool do not have a link, it is because the developers of the tool could not find relevant guidance – this identifies KE gaps. Where links take users to disparate forms of information, these disparities should be addressed. Making these changes would require substantial effort.  The result would justify the effort, as there is now a unique opportunity for ELMS to incentivise IPM and AHDB to enable IPM, to benefit levy payers.

 

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## Appendices

A complete list of the IPM strategies identified and scored through the course of this review can be found within the file attached below. For each crop group there are two tables, one which contains all scores for each strategy pest combination, and another which just looks at strategies that were judged to have the potential for wider use (were Potential use was scored higher than Current use (P>C)).

NB Tables to be read in conjunction with the text.

IPM%20strategy%20
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