December 2021

Research Review No. 98

Enabling the uptake of integrated pest management (IPM) in UK arable rotations

(a review of the evidence)

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This review is the final report of a four-month project (21120205) that started in May 2021.
The work was funded by AHDB (£19,350).

1. Abstract

Integrated pest management (IPM) methods are an integral part of the production of cereals, oilseeds and potatoes in the UK. However, there is considerable scope for increased uptake.

IPM uses non-chemical control methods (for example, through choice of resistant varieties and appropriate agronomy) to reduce the need for pesticides (preventative measures). Following this, IPM targets pesticide inputs according to need (for example, through use of decision support tools, such as treatment thresholds or pest forecasts).

In this review, ‘pests’ include weeds, invertebrate pests and diseases. For the major pests of each crop considered – cereals (wheat and barley), oilseeds and potatoes – this review identified the IPM methods growers have at their disposal. Non-chemical approaches to control lodging were also considered.

The review identified and considered 40 IPM control strategies and 80 of the most significant crop pests. In total, 642 situations were identified where IPM control strategies could have a role. 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 with increased scope for further adoption were also identified. As the implementation of some strategies have undesirable consequences in other ways, the ‘trade-offs’ of advantages and disadvantages were also considered and tabulated.

A review of hundreds of sources of information revealed inadequate evidence on the efficacy and/or implementation of many IPM methods. For such methods, scores were assigned by ADAS specialists in pathology, entomology, weed science and crop physiology.

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).

2. Introduction

The production of cereals, oilseeds and potatoes the UK currently relies 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 details the non-chemical crop protection strategies that are, or could be used in growing cereal, oilseed and potato crops 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 and for the control of lodging in cereals and oilseeds. 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, diseases and crop lodging.

The tables below indicate the specific crop adversity (pests, weeds, disease and lodging) and the relevant nonchemical control methods of value. Look up tables in the appendix go further and rate the performance of each nonchemical 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 implementation of a non-chemical control method to control one crop adversity can sometimes have a direct negative effect on the control of other pests or problems. These trade-offs affect the value of the strategy and as such are included in the review.

The review also identifies the non-chemical control strategies that could increase in usage either through a focus on the knowledge transfer 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.

2.1. Objectives

1. Establish the baseline evidence for non-chemical interventions in wheat, barley, potatoes and oilseed rape against the most economically significant weeds, pests and diseases for each crop.
2. Rank each control measure based on its effectiveness, cost, the strength of evidence, ease of implementation, and impact following adoption.
3. Summarise recommendations for each crop in terms of most effective measures, providing road maps to adoption.

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

Table 2.1. Wheat and Barley, the key pests, diseases and weeds and type of lodging, and the non-chemical control strategies applicable to prevent them.

Point of use	Non- chemical control strategy	Diseases										Pests											Weeds						Lodging	
		Brown rust (*P. hordei, P recondita*)	Ear blight (*Fusarium* spp)	Eyespot (*Tapesia yallundae*)	Leaf & glume blotch (*Phaeosphaeria nodorum*)	Mildew (*Blumeria graminis*)	Ramularia (*Ramularia collo-cygni*)	Seed borne diseases (bunt, smut, leaf stripe)	Septoria leaf blotch (*Septoria tritici*)	Take-all (*Gaeumannomyces graminis*)	Yellow rust (*Puccinia striiformis*)	Barley yellow dwarf virus vectors	Frit fly	Gout fly	Leatherjackets	Saddle gall midge	Slugs	Summer aphids	Wheat blossom midge (Orange)	Wheat blossom midge (Yellow)	Wheat bulb fly	Wireworms	Annual grasses	BLW - fibrous root	BLW - tap root	Perenial grasses	All weeds (Pre-emergence)	Volunteer potatoes	Stem lodging	Root lodging
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 testing		✓				✓	✓																						
	Seedbed quality									✓					✓		✓					✓	✓	✓	✓					
	Sowing date	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓							✓	✓	✓				✓	✓
	Stubble management																						✓	✓	✓	✓	✓	✓		
	Trap crops																													
	Undersowing & Companion cropping											✓																		
	Use of cover crops																				✓		✓	✓	✓	✓	✓	✓		
	Variety choice	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓							✓		✓		✓	✓	✓			✓	✓	✓
	Variety mixtures								✓		✓																		✓	✓
In-Crop	Bioprotectants and low risk PPP's	✓	✓			✓		✓	✓		✓												✓	✓	✓		✓		✓	✓
	Biostimulants																												✓	✓
	Decision support (incl. thresholds)	✓	✓	✓		✓			✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓
	Defoliation (incl. mowing and grazing)																						✓	✓	✓					
	In-field non-cropped areas											✓						✓	✓				✓	✓	✓					
	Nutrient management	✓		✓		✓			✓	✓	✓																		✓	✓
	Organic amendments																													
	Rolling soil post-planting												✓				✓					✓							✓	✓
	Hand weeding/roguing																						✓					✓		
	Mechanical weeding																						✓	✓	✓					
	Thermal control																						✓	✓	✓		✓			
	Physical mulches																													
	Precision application																						✓	✓	✓	✓			✓	✓
	Undersowing companion crops																						✓	✓	✓		✓	✓		
	Intercropping																						✓	✓	✓		✓	✓		

Table 2.2 Oilseeds, the key pests, diseases and weeds and type of lodging, and the non-chemical control strategies applicable to prevent them.

Point of use	Non- chemical control strategy	Diseases						Pests											Weeds					Lodging	
		Clubroot (*Plasmodiophora brassicae*)	Light leaf spot (*Pyrenopeziza brassicae*)	Phoma stem canker (*Leptosphaeria maculans*)	Sclerotinia stem rot (*Sclerotinia sclerotiorum*)	Turnip yellows and other virus diseases	Verticilium wilt (*Verticillium longisporum*)	Brassica pod midge	Cabbage root fly	Cabbage seed weevil	Cabbage stem flea beetle	Cabbage stem weevil	Mealy cabbage aphid	Pollen beetle	Rape winter stem weevil	Slugs	Turnip sawfly	TuYV vectors	Annual grasses	BLW - fibrous root	BLW - tap root	Perenial grasses	All weeds (Pre-emergence)	Stem lodging	Root lodging
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 testing																								
	Seedbed quality										✓					✓			✓	✓	✓		✓		
	Sowing date	✓	✓	✓		✓			✓		✓	✓		✓										✓	✓
	Stubble management										✓								✓	✓	✓	✓			
	Trap crops										✓			✓											
	Undersowing & Companion cropping										✓														
	Use of cover crops																		✓	✓	✓	✓	✓		
	Variety choice	✓	✓	✓	✓	✓	✓											✓	✓	✓	✓			✓	✓
	Variety mixtures																							✓	✓
In-Crop	Bioprotectants and low risk PPP's				✓														✓	✓	✓		✓	✓	✓
	Biostimulants																							✓	✓
	Decision support (incl. thresholds)		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓			✓	✓
	Defoliation (incl. mowing and grazing)																		✓	✓	✓				
	In-field non-cropped areas									✓		✓	✓	✓	✓		✓	✓	✓	✓	✓				
	Nutrient management	✓																						✓	✓
	Organic amendments										✓														
	Rolling soil post-planting															✓								✓	✓
	Hand weeding/roguing																		✓						
	Mechanical weeding																		✓	✓	✓				
	Thermal control																		✓	✓	✓		✓		
	Physical mulches																								
	Precision application																		✓	✓	✓	✓			
	Undersowing companion crops																		✓	✓	✓		✓		
	Intercropping																		✓	✓	✓		✓		

Table 2.3 Potatoes, the key pests, diseases and weeds and type of lodging, and the non-chemical control strategies applicable to prevent them.

Point of use	Non- chemical control strategy	Diseases												Pests						Weeds				
		Black dot (*Colletotricum coccodes*)	Common scab (*Streptomyces scabies*)	Dry rot (*Fusarium* spp.)	Early blight (*Alternaria solani*)	Gangrene (*Boeremia foveata*)	Late blight (*Phytophthora infestans*)	Potato blackleg (*Pectobacterium atrosepticum*)	Powdery scab (*Spongospora subterranea*)	Silver scurf (*Helminthosporium solani*)	Stem canker and black scurf (*Rhizoctonia solani*)	Storage diseases	Viruses (soil borne eg PMTV, TRV))	Cutworms	FLN & spraing	Potato cyst nematode	Slugs	Viruses (aphid borne eg POTY)	Wireworms	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						✓								✓	✓		✓	✓	✓	✓	✓	✓	✓
	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 testing	✓			✓	✓		✓	✓	✓	✓		✓					✓						
	Seedbed quality	✓	✓				✓	✓	✓		✓									✓	✓	✓		
	Sowing date						✓				✓													
	Stubble management																			✓	✓	✓		
	Trap crops																							
	Undersowing & Companion cropping																							
	Use of cover crops																			✓	✓	✓	✓	
	Variety choice	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓		✓			✓		✓	✓	✓	✓	
	Variety mixtures																							
In-Crop	Bioprotectants and low risk PPP's																			✓	✓	✓		
	Biostimulants																							
	Decision support (incl. thresholds)	✓			✓		✓	✓			✓			✓	✓	✓	✓	✓	✓	✓	✓	✓		
	Defoliation (incl. mowing and grazing)																							
	In-field non-cropped areas																			✓	✓	✓		
	Nutrient management				✓		✓																	
	Organic amendments																							
	Rolling soil post-planting																							
	Hand weeding/roguing																			✓				
	Mechanical weeding																			✓	✓	✓		✓
	Thermal control																			✓	✓	✓		✓
	Physical mulches																			✓	✓	✓		
	Precision application																✓			✓	✓	✓	✓	
	Undersowing companion crops																			✓	✓	✓	✓	✓
	Intercropping																							

3. Weed control

This section reviews the non-chemical control strategies that may have a role in controlling weeds. Rather than identify a wide range of specific weeds against each IPM technique, weeds have been grouped by their growth habit and / or lifecycle (Table 3.1).

Table 3.1 Weed group and example species

Weed group	Example species
All weeds (pre-emergence)	All weeds
Perennial grasses	Couch (*Elymus repens*), perennial ryegrass (*Lolium perenne*), Cocksfoot (*Dactylis glomerata*)
Annual grasses	Black-grass (*Alopecurus myosuroides*), annual meadow grass (*Poa annua*), brome (*Bromus* spp., *Anisantha* spp.)
Broad-leaved weeds - tap root	Thistles (*Cirsium* spp), Sowthistle (*Sonchus* spp.), Dock (*Rumex* spp).
Broad-leaved weeds - fibrous root	Chickweed (*Stellaria media)*, Cleavers (*Gallium aparine)*, Speedwells (*Veronica* spp.)
Volunteer potatoes	-

3.1. Current status

Loss of key herbicide active ingredients in cereals, oilseed rape and potato crops due to changes in legislation has been compounded by resistance to many of the remaining herbicides in a range of grass and broad-leaved weeds. Herbicide resistance in black-grass (*Alopecurus myosuroides*) is widespread but populations of wild-oats (*Avena sterilis*), ryegrass (*Lolium* spp.), poppy (*Papaver* spp.) and chickweed (*Stellaria media*) and mayweed (*Tripleurospermum inodorum*) have all been found to be resistant to a range of herbicides in some locations. Resistance issues are also emerging in bromes (*Anisantha* spp. and *Bromus* spp.) and are increasing in frequency. For individual farmers, this can present serious problems, with associated additional costs of control. Cultural control is generally more effective for grass weeds, but for the broad-leaved species' long lived seedbanks, extended germination periods or other biological or agronomic features limit cultural options.

3.2. Crop planning

3.2.1. Fallow

A fallow is a period without a crop. Traditionally, in organic systems, a fallow would be used during the drier summer months when multiple cultivations can take place to reduce infestations of perennial weeds, particularly common couch (*Elymus repens)*. The continuous cultivation of rhizomes and roots combined with the dry weather exhausts the plant, ultimately reducing the population[565]. Fallow can also refer to one or more seasons where no crop is grown.

A single-year fallow will not significantly reduce the soil seed bank of the majority of weed species. A two-year fallow may reduce the weed seed bank further but will have limited impact on some broad-leaved weeds[127]. A fallow for part of the year can be useful, achieving similar effects to a full fallow. Incorporating a spring crop into a winter dominated rotation would allow for a fallow period and can achieve similar effects to a full fallow, without the potential detrimental effects to whole farm margins. The term active fallows, used to describe cover crops in fallow periods, is discussed under 'Use of cover crops'.

3.2.2. Field history, rotation and break crops

Crop choice and rotation are the essential building blocks of any weed management strategy. The choice of crop affects the type and timing of both cultivations and drilling with some crops being more competitive against weeds (Table 3.2).

Table 3.2: Competitive ability of autumn and spring drilled crops[11]

	Competition with weeds	
Crop	Autumn sown	Spring sown
Wheat	+++	+++
Barley	++++	++++
Oats/rye	++++	
Oilseed rape*	+ to ++++	+ to ++++
Potatoes	N/A	++++

Range ++++ high to + low,
**depends on level of crop establishment*

Varied crop rotations are a fundamental aspect of good weed management systems. Similar numbers and species of weed seeds may be present in the seed bank but the frequency of their occurrence as growing plants varies with respect to the crop sown at the time[90]. It is not just the number of different crops but also the sequence of the crops that can play a role in affecting weed seed populations[374]. Herbicide usage also influences the weed species populations. Cropping sequence is the most dominant factor influencing species composition in the seedbank. This can be partly attributed to herbicide use in each cropping sequence, producing a shift in the weed seedbank in favour of species less susceptible to applied herbicides[57]. For example, introducing grass and herbal leys into an arable rotation may lead to a reduction in the population of black-grass and wild-oats (*Avena sterilis*)[148] but a build-up in the population of couch grasses (*Elymus* sp.)[368]. Additionally, the integration of leys can help control weed species by breaking the weed life cycle, minimising seed return and reducing the numbers of weeds in the soil seed bank. One-year leguminous cover crops have been shown to reduce the weed seed bank in subsequent crops, with up to 65% reduction at the termination of the cover crop and still showing substantial reductions three year after cover crop termination[369]. Crop rotation provides an extra level of weed control and when used in combination with herbicides is an effective integrated weed management tool[179].

The dominant weed species will have a similar life cycle to the crop. A selection of spring germinating weeds will occur in spring crops; likewise, a selection of autumn germinating weeds in autumn sown crops[500]. Weeds commonly associate themselves with crops that have similar lifecycles, such as black-grass which is commonly found in winter cereals. Simplified rotations of continuous autumn sown wheat, established by minimal tillage, has led to the predominance of black-grass[391], whilst spring cropping has been shown to reduce black-grass populations[567]. Diverse crop rotations avoid particular weed species becoming dominant[358]. Disrupting these crop/weed associations discourages the growth and reproduction of certain weed species. Crop volunteers can also be attributed to rotations[149].

Rotations containing spring crops reduced black-grass densities by up to 98% when compared to rotations with winter only crops[247]. A five-year rotation containing a two-year green manure crop showed a 54% reduction in the weed seed bank compared to a five-year crop rotation containing only annual cash crops, with reduced above ground biomass and weed level reduction still seen three years after cover crop termination[369].

However, despite the importance of crop rotation for weed control, few attempts have been made to quantify the level of weed control gained by changing the rotation due to its complexity.

Overall, rotations tend to increase the diversity of weed species present[179,330,331,494]. Cover cropping increases weed diversity but doesn't affect weed density[257]. More diverse weed communities have been hypothesized to be less competitive, reducing the likelihood of occurrence for one dominant, highly adapted weed species[507].

The field history needs to be taken in to account when planning future cropping as the soil contains many weed seeds from previous years. The seeds vary in the number of years they remain viable within the soil seed bank with rates of annual decline, both with and without annual cultivation (Table 3.3)[127]. Previous years cultivations will dictate where the weed seeds are located within the soil profile. Cultivations can move seed within the soil profile, both downwards to a depth where seed can no longer germinate or up in to the top 5cm of soil where most weeds emerge from. Competitive crops can help to reduce the weed seeds in crop, thereby reducing the seed burden in the following year. Competitive wheat cultivars have been calculated to decrease black-grass head number/m² by 20%[343]. Hybrid barley can significantly reduce black-grass heads compared to 2-row barley and winter wheat[133]. Where seedbank levels in the top 5cm of the soil profile are estimated to be high, then the techniques outlined in this review should be used to avoid a high weed burden on the following crop.

Table 3.3 Rate of annual decline (%) of seeds with and without annual cultivation. Taken from data recorded between 1933 and 2006[127].

Common name	Species	Under cultivation	No cultivation
Sterile brome	*Anisantha sterilis*	100	100
Meadow brome	*Bromus commutatus*	No information	
Italian ryegrass	*Lolium multiflorum*	96-99 (plough)	95
Black-grass	*Alopecurus myosuroides*	67.9	54.3
Wild-oats	*Avena fatua*	66.8	19-70
Annual meadow grass	*Poa annua*	44.8	34.5
Scentless mayweed	*Tripleurospermum inodorum*	43.0	19.9
Chickweed	*Stellaria media*	47.6	34.3
Green field-speedwell	*Veronica hederifolia*	62.0	19.0
Common field-speedwell	*Veronica persica*	51.4	37.3
Field Pansy	*Viola arvensis*	41.1	28.0
Cleavers	*Galium aparine*	74.7	18-100
Fat hen	*Chenapodium album*	32.0	13.3
Poppy	*Papaver rhoeas*	30.8	21.7

3.2.3. Select low-risk situations

There are some high-risk situations for weeds, where herbicide choice is limited and specific weed are unable to be controlled, such as black-grass in oats, charlock in conventional oilseed rape and bolters in sugar beet. Rotations should be planned to avoid these wherever possible.

3.3. Pre-cropping

3.3.1. Drainage

Poorly drained fields can encourage the development and persistence of certain weeds, such as rushes. Black-grass is known to frequently occur in fields where drainage was described as fair or poor; though occurs just as frequently in well drained fields; however' improving field drainage will improve crop establishment and the competitive ability of crops[59,423].

3.3.2. Use of cover crops

Cover crops can be used to manage weed populations through direct competition for light, water and nutrients, allelopathic effects, residues blocking light or physical competition[141]. Often, it is difficult to quantify the exact mechanism of weed suppression by cover crops.

Cover crops have been shown to supress weeds compared to a bare soil control. The effect of cover crops on weed control is not just due to biomass production smothering weeds, but also to the cover crop species selected. Weed suppression could be due to early soil cover (shading)[378] and/or allelopathic effects, for example rye (*Secale cereale)* has been shown to have consistent allelopathic potential[277,278]. Some cover crops have been shown to induce germination of weed seeds, causing a depletion of the weed seed bank[379].

In regard to whether cover crops reduce weeds in following crops, a meta-analysis of data from 46 field studies showed that cover crops can provide satisfactory weed suppression from termination of the cover crop up to 7 weeks after planting of the main crop. The cover crops were terminated either chemically or mechanically[410]. The trials were located predominantly in the USA, where the main crops were planted 1 to 3 weeks after termination of the cover crops. Some studies have presented no effects on weed levels in following crops where cover crops were incorporated mechanically into the soil[5], whereas other work has shown benefits, but this could be due to the method of cover crop termination, chemical, mowing or crimping where residues are left on the soil surface or soil incorporation.

Cover crops can also control weeds by providing a break in the rotation. An example of this is the rotational switch to spring cropping to target the control of black-grass, this offers the opportunity of a large window in which to grow a cover crop. It has been noted that in a rotational context, the direct effects of cover crops on grass weeds are small[147]. Almost all of the effects on black-grass populations were explained by the underlying cultural control approach. The authors concluded through the combined approaches of pot experiments and field trials, the effect of cover crops on modifying the population dynamics of grass weeds should not be overstated. Field experiments in Maine and Pennsylvania (2003 – 2006) which evaluated five different cover crop and cash crop systems, demonstrated that soil disturbance associated with cover cropping encouraged weed germination and establishment reducing the density of terminable seed in the weed bank[381]. It is the cultural control provided by a break in the rotation (and other measures employed during this time) which results in weed control, rather than the cover crop itself.

The method of destruction of the cover crop may also have an effect on weed control, for example destruction by incorporation, may stimulate the germination of weed seeds. Whilst destruction by crimping provides a thick cover crop residue, which prevents germination. Glyphosate is widely used for cover crop destruction and as a weed management tool.

The effect of cover crops on seed bank density, and therefore, weed burden in main crops can vary dramatically depending on the cover crop used and the target weed species and tillage system[385]. This highlights the importance of varying cover crop species selection depending on target weed species and farming system, and that the whole system (cover crop species and cultivations) must be tested in a practical context[365].

Cover crops can also have undesired consequences. They can themselves become weeds. They are not always effective at supressing weeds, and they may occasionally have a positive effect on germination or seedling growth of weeds[5,315]. High levels of biomass production can impinge on the establishment of the crop itself[315,380]. Allelopathic chemicals from the cover crops can also negatively affect the germination and seedling growth of the main crop[315].

There is some evidence that, as a result of early light interception, cover crops can suppress the development of smaller weed species, such as annual meadow grass and common chickweed, which are often found in cereal and oilseed crops. Larger weeds such as fat hen (*Chenopodium album*) are less affected as they outgrow the height of cover crops[314]. However, recent research has shown that the main impacts 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].

There is interest in the use of cover crops prior to potatoes in the UK, primarily to improve soil structure and take up nitrogen (N) which would, otherwise, be lost via leaching over-winter when ground is bare. In Italy, rapeseed and ryegrass (*Lolium spp.*) cover crops were the most efficient weed suppressors in potato crops, with weed biomass less than 1% of the total biomass produced by the cover. The cover crops also reduced weed emergence in the following potato crops[105].

3.3.3. Early harvest

Where grassweeds are problematic in cereals, it is becoming increasingly common for growers to remove arable crops early to prevent high levels of black-grass seed return. The resultant offtake can be conserved by crimping, or whole crop ensiling, before being fed directly to cattle. Although black-grass is not particularly palatable, it can be composted, made into silage, or put in an anaerobic digestor (AD).

Ensiling crops has been shown to render seeds of black-grass (*R. Hull*, *pers. comm*), great brome (*Bromus diandrus*), *Vulpia* spp., Wild-oat (*Avena fatua*) and wild radish (*Raphanus raphanistrum*) unviable after a minimum of 3 months[425]. Black-grass can survive in an anaerobic digester, after pasteurisation (up to 1 hour), mesophilic anaerobic digestion at 37.5°C (five days) or storage in digestate at 7-11°C (still viable at 10 days)[557].

Crimped grain - freshly harvested grain, between 35% and 45% moisture, is processed through crimping machine (to expose the carbohydrate and/or protein), a preservative is applied, and the resulting feed is ensiled in airtight storage being ready to feed in three weeks[296]. After one month of the crimping process, black-grass germination was zero[297].

3.3.4. Flooding

Flooding is a method of control that requires the area being treated to be saturated at a depth of 15 to 30 cm for a period of 3 to 8 weeks. The saturation of the soil reduces the availability of oxygen, killing the weed roots or seed. Some weeds can be controlled completely by flooding for six weeks, including the perennial weeds creeping thistle (*Cirsium arvense*), coltsfoot (*Tussilago farfara*) and couch (*Elymus repens*)[536]. The practicalities of using this approach on a field scale in the UK are limited.

3.3.5. 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[241].

Contaminated straw

At harvest, some weeds are retained on the plant, incorporated into baled straw and removed from the field. The straw is transported to livestock farms or used on farm, for example to protect carrots from frost. Transport of straw has been highlighted as the primary source of black-grass seed in Scotland and the West and Southwest of the UK

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[258].

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[79].

Composting

Weed species with hard seed coats like field bindweed and docks present the greatest risk of surviving composting[294]. However, if the compost is moist, reaches the desired temperature, and completes its full-cycle of decomposition, even seeds of these species are killed. Black-grass does not survive composting if temperatures reach around 60°C, but if the turning and heating process is incomplete then there is likely to be some survival of seeds.

Sown seed

The UK seed certification scheme ensures that purchased seed reaches a minimum quality standard. The standard for C2 seed is detailed in (Table 3.4).

Table 3.4 UK seed standards for certified seed to the second generation (C2), all species except maize[36]

Weed species		**Maximum number of seeds**
Wild-oat	*Avena fatua*	0
	Avena ludoviciana	
	Avena sterilis	
Darnel	*Lolium temulentum*	0
Wild Radish	*Raphanus raphanistrum*	3
Corn Cockle	*Agrostemma githago*	3
Couch	*Elymus repens*	Not applicable
Sterile Brome	*Bromus sterilis*	Not applicable
Total of all weed species		7

Certified wheat seed to Higher Voluntary Standard may have up to two black-grass seeds per kg, or one black-grass seed and one sterile brome seed per kg and still pass the official seed test as HVS[347].This means that at a seed rate of 200 kg/ha, a farmer sowing certified C2 HVS seed can still be sowing up to 400 black-grass seeds per ha. In 2021, black-grass was found in wildflower seed in the Republic of Ireland[514].

Home saved seed is at greater risk of containing weed seeds than purchased weed and should be checked and cleaned thoroughly before sowing to avoid transfer of weed seeds between fields and farms.

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[383]. 397 weed seeds per vehicle were recorded on vehicles used to install powerlines in Southeast Queensland, Australia[302].

Burning off

Destroying patches of black-grass in winter wheat during the first week of June with non-selective herbicides, or mowing will significantly reduce viable seed return.

Harvest weed seed control

Harvest weed seed control (HWSC) methods have been developed over the past 20 years in Australia in response to widespread development of herbicide resistance. The technology is currently being trialled in the UK by Frontier, and as part of the H2020 IWMPraise project[275].

At harvest, any weed seeds left on the plant usually end up in the chaff after combining. HWSC methods prevent seeds being added to the weed seedbank. Weeds are not controlled in the current season, but the aim is to decrease the weed pressure in the future by preventing seed return to the soil seedbank.

There are three methods used that could be applicable to the UK:

Chaff collection

Chaff is collected in a large wheeled bin that follows the combine. The Australian Herbicide Resistance Initiative (AHRI) tested chaff carts on several commercial harvesters and found that they collected between 73-86% of rigid ryegrass (syn. annual ryegrass; *Lolium rigidum*) seeds that entered the combine during harvest[545]. Chaff is then emptied off the field and burnt or composted. Difficulties with management of large volumes of chaff have meant that, to date, there is limited uptake of this technique[546].

Weed seed destruction

The chaff is passed through a rotary mill so that weed seeds are ground into dust. It has been shown to destroy over 95% of a wide range of weed seeds[548]. However, a large amount of horsepower is required to run the destructor.

Chaff lining and chaff tramlining

Attachments on the rear of the combine catch and channel chaff into narrow rows, 20-30 cm wide. The concentrated rows of chaff provides weed seeds with an environment that is unsuitable for germination and emergence. To be most effective, the chaff lines need to remain undisturbed; the greater the amount of chaff, the lower the level of weed germination.

In Australia, the technique has been used in wheat, barley, oilseed rape and lupins reducing weed emergence from 65% to under 10% at the highest chaff rate[547]. In the UK, trials have shown 95% of seed taken in by the combine header ends up in the chaff.

3.3.6. 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.

Ploughing is an effective means of controlling black-grass populations in winter wheat and has been shown, on average, to reduce populations by 69% when compared to non-inversion tillage[343]. Ploughing, together with false seedbed preparation, has shown to reduce black-grass by up to 70% compared to conservation tillage with a chisel plough[568].

The NIAB Star project has shown ploughing can reduce herbicide costs by around £70/ha when compared to non-inversion continuous wheat treatments[404]. Results from the same trial show grass weeds increased in the non-inversion treatments with grass weeds absent in the continuous plough treatment[388].

Annual meadow grass (*Poa annua*) seeds were 70% lower after 9 years of ploughing compared to shallow rotary tillage[453]. Perennial weeds can also be kept at manageable levels for annual 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[384].

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[238]. Shallow burial of seed will promote germination due to availability of light, alternating temperatures and decreasing soil moisture[187]. 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[208,388], particularly bromes, rye grass and black-grass[240].

3.3.7. Secondary cultivations (drilling method)

No-till/direct drilling

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, with a few weed seeds lowering down the soil profile through cracks in the soil. The use of no-till /direct drilling relies heavily on herbicides to control weeds and has led to an increase in umbellifer and grass weeds in rotations. Direct drilling in winter wheat increases black-grass (*Alopecurus myosuroides*) populations by 16% when compared to non-inversion tillage[343]. 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[401].

Oilseed rape is often established with minimal cultivation in order to retain moisture, subcasting drills are often used, using widely spaced tines or subsoiler legs each fitted with a seed distributor or coulter. This technique causes limited movement of the soil at the surface, but some weed seeds will move down the soil profile due to soil disturbance from the tines. The effect is similar to no-till or direct drilling, but some weeds germination from depth will occur where the subsoiler leg has moved the soil.

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 (CTIC, 2002) defines strip tillage as a modification to direct drilling with disturbance of less than one third of the total area. Strip tilling combines the benefits of a high proportion of crop residues in the soil surface but improved conditions for crop establishment through cultivation[389]. A popular technique for establishing oilseed rape, strip tillage allows the seed to be placed accurately and most systems have the facility to put a band of fertiliser underneath the seed. The method is quick and keeps costs down. Drill technology has improved in recent years, increasing the consistency and reliability of the system as well as allowing wide or conventionally spaced rows.

3.3.8. Seed rate

Increasing seed rate has been shown to suppress weeds in cereals. Increasing seed rate from 100 plants/m^2 to 200 or 300 plants/m^2 has been shown to have no effect on black-grass plant numbers, but the number of heads per m^2 was decreased by 17% and 32%, respectively[343].

The growing of ‘competitive’ crops after a potato crop helps limit both the emergence of volunteer potato plants and their capacity to produce tubers. Sprout emergence is considerably delayed by crops that have a high light interception at their early stages of growth such as winter barley and winter wheat[1].

Increasing oilseed rape seed rates can also increase crop competition, with seed rates of 81 plants/m^2 compared to 16 plants/m^2 able to decrease Italian ryegrass head densities to 245 heads/m^2 from 539 heads/m^2. Black-grass heads were reduced by 9% when increasing oilseed plant populations from 29 to 51 plants/m^2[483]. In the absence of herbicides, increased seed rates coupled with narrow rows could reduce weed populations and increase yields, but it was not possible to increase oilseed rape seed rates to account for increased row width, as yield decreased with more than 17 plants/m in the row[132]. Plant density increases had a small effect on in weed competition, but a vigorous crop was of greater importance[342].

In potatoes, the development of a dense canopy is key to preventing weed development. Crop uniformity and density is largely determined by the variety, market outlet, seed size and seed spacing. High density plantings for salad or seed crops result in faster canopy closure and, therefore, a less likelihood of late germinating weeds proving to be troublesome. The planting of large potato seed has the same effect. Plant misses as a result of diseased seed, poor planting conditions, Rhizoctonia, FLN (free living nematodes) or a malfunctioning planter will reduce canopy development and, therefore, competitiveness with weeds. Bed planting can also be used to provide earlier canopy cover that will increase competitiveness with weeds.

3.3.9. Seedbed quality

A firm fine seedbed is key to 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.

Many pre-emergence herbicides have a requirement for seed to be covered with a minimum depth of soil.

3.3.10. Sowing date

Later sowing dates increase the time to carry out weed control but delaying sowing date in cereals increases emergence time and reduces crop vigour, so seed rate has to be increased. Delaying the drilling of winter wheat from September to October reduced black-grass populations by an average of 50% over 19 experiments[343]. In oilseed rape, yield loss tends to increase with increasing numbers of barley volunteers, delaying drilling exaggerates this effect as the crop becomes less comptetitive[340]. One hundred barley plants/m² would result in a 5% yield loss for a crop sown on 26 August, whereas 10 plants/m² would give the same yield loss for a sowing date of 9 September. Further work showed the base temperature for dry matter accumulation to be higher for oilseed rape than for volunteer cereals and chickweed, so oilseed rape is at a disadvantage in later sowings if temperatures are low [343,127].

Delaying drilling is a key part of IPM strategies to control black-grass resulting in 31% reduction in the level of black-grass[343]. An AHDB-funded project on sustainable winter cropping under threat from herbicide resistant black-grass investigated the effects of delaying drilling in field trials over a period of 3 years (2010-2013)[390]. One of the key findings was increased robustness of black-grass control, achieved by pre-emergence herbicides (flufenacet + diflufenican + prosulfocarb) when applied in later sown crops. The benefit was an additional 26% control of black-grass where sowing was delayed by 3 weeks from 16-21 September to 3-11 October, with a smaller additional benefit when drilling was delayed to late October/early November. To reinforce this result, a review was done on a herbicide performance trials dataset (NIAB) between 2012-2015, two drilling dates, three weeks apart, September (7-20 September) and October (14-28 October). Herbicides were applied at pre-emergence (within 48 hours of drilling), the herbicide applied was flufenacet + pendimethalin + diflufenican. At this timing, there was a 25% improvement in control of black-grass at the later drilling date compared to the early drilling date. The control from the herbicide was not only improved, but the level of control was more consistent between years. The improvement in control from the herbicide has been attributed to increased levels of soil moisture and lower temperatures at the later application dates. Potatoes, being a spring crop, allow a large window which allows more time for weed control and the ability to create a stale seedbed prior to the crop.

Stale seedbed

A stale seedbed is a technique to encourage a flush of weeds prior to crop establishment and then using cultivations or non-selective chemical applications to control them. This technique depletes the seed bank in the upper layers of the soil, reducing weed emergence within the crop[83]. In six field trials over three years, stale seedbeds have been reported to reduce black-grass by an average of 25%[371].The use of cultivations can be detrimental if not used correctly; too deep risks a further flush of weeds, and too damp can result in movement of established weeds rather than death. Temperature and moisture determine the emergence of the main flush of weeds and any delay in drilling must be weighed up with the potential effects of late crop establishment.

3.3.11. Stubble management

Stubble cultivations immediately after harvest can both stimulate weed seed germination or induce greater seed dormancy, depending on the weed species present. The use of cultivations improves seed to soil contact and emergence of weeds but only when conditions are moist. Seeds on the soil surface are buried which reduces predation. Emerged weeds can be controlled via cultivation or non-selective chemistry before drilling the following crop.

Freshly shed oilseed rape seed has no dormancy and will germinate when moisture is available. Therefore, to reduce the chance of oilseed rape becoming a volunteer in the following crop, seeds should be left on the soil surface and cultivations delayed for two to four weeks depending on soil moisture[13]. It has been reported that post-harvest dispersal losses from the soil surface could be as great as 68% for black-grass and 76% to 85% for wild-oat[391,393]. Similarly, seedbank decline of oilseed rape has been found to be slowest when stubble is cultivated immediately after harvest with 14% to 17% of seed remaining after a year, compared to 0.1% to 2.2% with delayed tillage[237].

Volunteer potato plants can grow from tubers or true seed. When harvesting potatoes, some of the tubers will remain in or on the soil. These tubers will survive if not sufficiently exposed to freezing temperatures during winter. Tubers as small as 10 mm in size may sprout and start growing in the succeeding crop(s), producing volunteer potato plants[502]. Volunteers occurring from true seed is considered to be less significant. Seed can remain viable for 7 years[47]. The vast majority of volunteer potato plants would originate from tubers[82]. Reductions in the return of outgrade potatoes can be achieved by crushing implements on the rear of the harvester. Leaving tubers exposed over winter will increase the chances of them being frosted or predated. Likewise, cultivations if done, should be shallow so volunteers emerge quickly and thus, improve conditions for and optimum timing of herbicide applications.

3.3.12. Varietal choice

Competitive crop cultivars have been identified in cereal crops but breeding for competitive varieties has not been a priority[38]. Interim results from farm based organic wheat variety trials show varietal differences in weed abundance[19]. A review of eight experiments involving competitive wheat cultivars showed a potential 20% decrease in black-grass heads/ m² when compared to the mean of all cultivars tested[343]. It has been suggested that the development of a simple ‘competitive potential' assessment for new cultivars is required based on multiple traits[38]. Three aspects to cultivar competitiveness were identified during the work:

1. Reducing the fitness of the weed species through competition for resources such as light and water (suppression)
2. Resisting yield loss (tolerance)
3. Producing chemical exudates that reduce growth (allelopathy).

Tolerant cultivars will maintain yield but may not reduce weed levels. This could lead to increased weed levels to the point where they cannot be tolerated. Suppressive cultivars will reduce weed seed production and could be part of a long-term integrated weed management strategy. Field experiments using wheat cultivars with high levels of allelopathy have been shown to reduce black-grass biomass by 50% compared to low level cultivars[76].

It has been argued that allelochemicals with benefits in multiple aspects of plant defence could be developed into naturally-derived chemistries, maximising benefits to weed, insect and pathogen control[254]. However, the development of an agronomic output would require substantial interdisciplinary work, hence, the reason why allelopathic products are rare.

Hybrid barley has been shown in trials to be more competitive against black-grass and sterile brome than standard 2-row or 6-row barley[133]. Hybrid winter barley is taller, has more planophile leaves, greater tillering and a higher growth rate, it commences growth earlier in the season than conventional barley and is most competitive between growth stages 39 to 55 due to its plant architecture (Syngenta, pers comm). The dense crop canopy reduces light availability to the base of the crop resulting in black-grass with 43% fewer fertile tillers and 65% less seed per plant than those in winter wheat[131].

Currently in UK cereals, oilseeds and potatoes, the only herbicide tolerant crop available is imidazolinone tolerant Clearfield® oilseed rape. The use of ALS tolerant oilseed rape can increase weed control options, particularly for hard to control broad-leaved weeds in the crop including charlock, hedge mustard, runch and shepherds purse[62].

Although, as ALS inhibitor herbicides are usually used in cereal crops to remove oilseed rape volunteers, one issue surrounding the use of herbicide tolerant oilseed rape is the removal of volunteers in the following crop. Therefore, in systems where ALS tolerant oilseed rape is grown, herbicides with other modes of action will need to be used to remove volunteers in the following crops, potentially increasing herbicide usage[312]. There is also a risk of the development of ALS resistant weeds in ALS-tolerant cropping systems as ALS inhibitors are a high risk herbicide mode of action for resistance and there are already a number of ALS-resistant weeds in cereal and oilseed cropping systems and this has been complicated with the introduction of Conviso® sugar beet[323]. Growers using Clearfield® oilseed rape are advised to follow strict stewardship guidelines to help manage herbicide resistance and crop volunteers[63].

The competitive ability of potatoes has been associated with the development of a dense canopy and its maintenance for a long period during the growing season[384]. Differences have been reported among ten potato cultivars in their ability to tolerate weeds and retain tuber yield in the presence of weeds[125]. Crop cultivars with fast developing canopies, large leaf area index, and tall height generally suppress weed growth and tolerate weeds better than less competitive cultivar[111].

3.3.13. Varietal mixtures

Research on varietal mixtures has to date been predominantly disease focused, so information on the effects of varietal mixes on weed control is lacking. As stated in Section 3.3.12, farm based organic wheat variety trials have shown varietal differences in weed abundance[19]. However, this work has not included varietal mixtures. The suggestion that the development of a simple 'competitive potential' assessment for new cultivars is required based on multiple traits could be extended to explore the competitive potential of specific varietal mixtures[38].

3.3.14. Precision application

The lack of introduction of new modes of action in combination with the development of herbicide resistance and the tightening toxicological and environmental restrictions, such as the EU Regulation 1107/2009, has reduced the number of herbicides available for weed control. It is, therefore, important to optimise the use of existing chemistry through precision application.

GPS

GPS uses satellite navigation and works with many types of precision technology. Weed patches can be mapped, usually when heads are visible above the crop. Soil characteristics such as organic matter pH, and soil texture were found to be indicators of weed patches[375]. This approach has potential; however, some concerns over the spread of weed seeds via combines and other farm machinery may have limited uptake of this technique to control black-grass.

Spot treatment

Weeds are not heterogeneously spaced in a field and often occur in patches through a field; therefore, spot spraying herbicides on patches of high density weeds instead of a whole field can be effective in reducing herbicide use and consequently reducing costs and environmental impacts whilst still providing adequate weed control[217,344].

Spot spraying is commonly practised through growers manually selecting spray booms on tractor mounted or self-propelled sprayers. This boom or nozzle selection may also be guided by GPS or camera imagery (aerial or mounted). It can also be done by field walking and spraying patches using a backpack sprayer, mapping weeds in a field, by field walking, or by using robots with weed identification technology[217]. Herbicides such as glyphosate are often applied to patches of weeds such as creeping thistle.

Weed wiping

Weed wiping is used in arable crops and grassland to control volunteers like weed beet and general weed populations like bracken, rushes, thistles and ragwort in grassland. Weed wiping can be used in any growing crop or in non-cropped areas, providing the herbicide (glyphosate) does not touch the crop. For safe application, weeds should be a minimum of 10 cm above the height of the crop. Weeds not touched by the herbicide will not be controlled, and two passes in opposite directions may be needed where weeds are dense.

Spray application

Precision spraying is required to a) improve drift control, b) maximise spray deposition, and c) reduce pesticide usage. Efficiency of spraying and reduction of drift is dependent on multiple factors including the weather, equipment used, crop growth stage, herbicide product formulation, and operator parameters. Optimisation of spray setting can lead to reduced drift and increase the precision of herbicide application. Typically, the smaller the nozzle orifice and the greater the sprayer pressure, the smaller the droplet size produced and the greater proportion of driftable droplets[142]. Much work has been done by manufacturers on appropriate nozzle selection and design of nozzles for different applications to improve coverage of the target whilst minimising drift.

3.3.15. Bioprotection and low-risk plant protection products (PPPs)

Biopesticides are generally safe crop protection products based on micro-organisms, plant extracts and other natural compounds. The use of bioherbicides differs from biological control, as it is based on the production of natural products or pathogens under controlled conditions that are subsequently spread by growers, rather than the release and natural, uncontrolled spread of biological agents. Biopesticides 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:

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 UK and showed that, although they initially scorched annual weeds, there were signs of recovery within a few days of application[249]. These compounds are non-selective, and several are currently approved for use on natural surfaces not intended to bear vegetation and permeable surfaces overlying soil (Table 3.5).

Pelargonic acid is a contact broad-spectrum bioherbicide that disrupts cell membranes. It can provide adequate weed control, has no residual activity, and low toxicity and environmental impact[159]. Pelargonic acid was the only bioherbicide tested in the SCEPTRE project that provided good control for fat hen, groundsel (*Senecio vulgaris*), and dock after repeat applications, although some other weeds were not controlled[249] (Figure 3.1).

Table 3.5 Examples of commercially available bioherbicides available in the UK

Example product	Active ingredient	Type	Target	Reference
Katoun Gold	Pelargonic acid	Organic acid	Non-selective	BCPC, 2018
New way weed spray	Acetic acid	Organic acid	Non-selective	BCPC, 2018
Barrier H	Citronella oil	Essential oil	Ragwort	BCPC, 2018

Reference: BCPC (2018) The UK pesticide guide 2018. Products approved for use in agriculture, amenity, forestry, pest control and horticulture. 31st Edition. Lainsbury MA eds. Hobbs and Printers Ltd, UK. Available: www.ukpesticideguide.co.uk

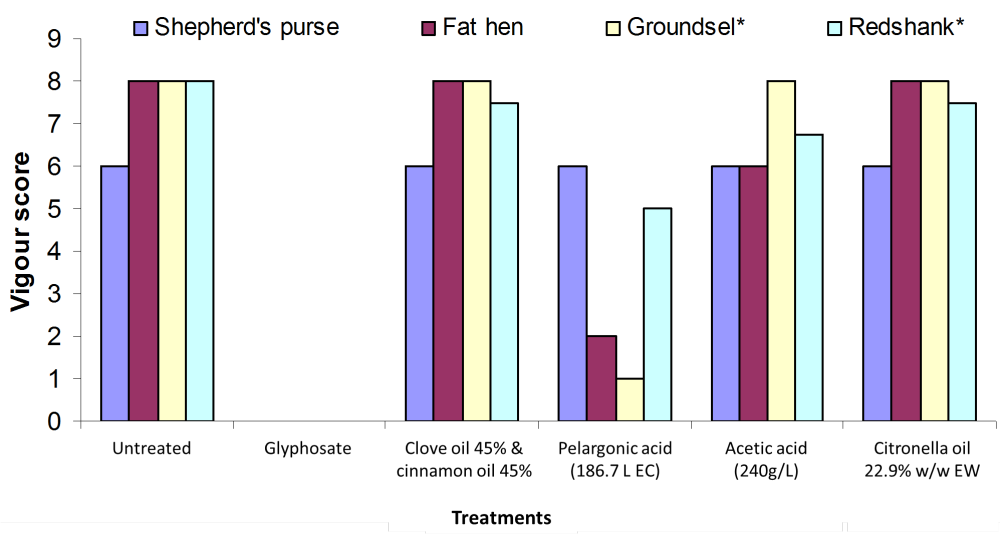

Figure 3.1 Vigour score (9= healthy, 0=dead) of shepherd’s purse, fat hen, groundsel, and redshank 6 weeks after treatment and *3 weeks after treatment with bioherbicides or glyphosate[249].

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 of up to

20% have been found to give 28-45% weed control[490]. Other work has shown concentrations of 5%, 20%, and 30% were effective at reducing weed levels to a rating of 0 within 48 hours but required three (2016) and five (2017) retreatments to maintain zero weeds when compared to glyphosate[178]. Bioherbicides 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[159]. Due to this initial scorching symptoms and 'knock-down', there is potential for bioherbicides to be used as part of an integrated weed management programme[137,138].

3.3.16. Decision support (including thresholds)

Thresholds for weeds are available which indicate the degree of tolerance within the current crop. These can be useful where weeds can be controlled elsewhere in the rotation; however, this approach can be problematic with more difficult to control weeds such as black-grass, as thresholds often do not allow for the impact of seed return on subsequent crops which can cause populations to build quickly over seasons. Table 3.6 contains the competitive index and the number of weeds that cause an average 5% yield loss of a range of species in winter wheat[354]. A 5% yield loss is often used as a threshold at which the cost of control very roughly equates with the cost of both the herbicide and application.

There are many factors that influence the effect of weeds on crop yield, but yield is not the only parameter affected. Weeds can slow crop ripening, delay harvesting and spoil crop quality. They can harbour pests and diseases but also beneficial insects and pollinators. The density of the weed, distribution within a field, crop density, crop vigour and weather all influence the competitiveness of weeds. Decision support systems should include relevant cultural control strategies (including rotation) as well as herbicides.

Table 3.6 Relative competitive ability of 26 weed species in winter wheat crops

Common name	Latin name	Competitive Index(CI) (% yield loss/ weed plant/m²)	No of weed plants/m² that result in a 5% yield loss (= 5 ÷ CI value)
Severely competitive			
Cleavers	*Galium aparine*	3.0	1.7
Wild-oats	*Avena spp.*	1.0	5.0
Italian rye-grass	*Lolium multiflorum*		
Sterile brome	*Bromus sterilis*		
Black-grass	*Alopecurus myosuroides*	0.4	12.5
Highly competitive			
Charlock/mustard	*Sinapis* spp.	0.4	12.5
Oilseed rape	*Brassica napus*		
Scentless mayweed	*Tripleurospermum inodorum*		
Common Poppy	*Papaver rhoeas*		
Moderately competitive			
Black bindweed	*Fallopia convolvulus*	0.3	16.7
Chickweed	*Stellaria media*	0.2	25.0
Field Forget-me-knot	*Myosotis arvensis*		
Fat-hen	*Chenopodium album*		
Redshank	*Polygonum maculosa*		
Knotgrass	*Polygonum aviculare*	0.1	50.0
Annual meadow-grass	*Poa annua*		
Sow thistles	*Sonchus* spp.		
Fumitory	*Fumaria officinalis*	0.08	62.5
Speedwells	*Veronica* spp.		
Red Dead-nettle	*Lamium purpureum*		
Crane’s Bill	*Geranium* spp.		
Groundsel	*Senecio vulgaris*	0.06	83.3
Fool’s Parsley	*Aethusa cynapium*		
Weakly competitive			
Scarlet Pimpernel	*Anagallis arvensis*	0.05	100.0
Field Pansy	*Viola arvensis*	0.02	250.0
Parsley Piert	Aphanes arvensis		

3.3.17. Defoliation

Defoliation of any weed during its life will delay maturity in the first instance but depending on the weed type and the point in its lifecycle it can prevent flowering and the production of viable seeds.

Mowing can be very effective in the control of weeds such as black-grass. Plants react to mowing by producing new heads on shorter stems which leads to repeated treatment for control. Three cuts were needed to reduce black-grass seed return by 99%[122], but in set-aside (fallow) seven cuts were required to prevent black-grass from setting seed[115].

Weed surfing is a technique that can be used to remove extended weed growth above the canopy of arable crops (black-grass, charlock, wild oats, thistles) and for the control of weed beet. The Weed Surfer™ is available up to 9m wide and the cutting blades are powered from the tractor power take off. The aim is to remove heads before seed set, although the majority of the yield reduction in the crop has already occurred. Farm trials have reported around 80% of black-grass heads being severed in this way[34]. The CombCut has blades that comb through a narrow stalked cereal crop taking out larger weeds. It operates in established crops, preventing weed seed dispersal, by cutting the flowers and seed head of weeds above the crop. It is used for thistles, nettles, charlock, docks and black grass. It is also available up to a 9m width. Patches or whole fields of black-grass and other weeds are sometimes mowed off prior to seed set. This prevents or reduces the amount of viable seed return.

3.3.18. In-field non-crop areas

Encouraging predators

Weed seeds can be consumed or destroyed by predators such as birds, rodents, insects, and soil microorganisms, which can substantially decrease the amount of seed returning to the soil and deplete the seedbank over time[468]. Predators can be split into two groups those which feed on seeds prior to their shedding from the parent plant (pre-dispersal) and those that feed on seed on the soil surface (post-dispersal).

Different patterns for seed predation by birds and other granivores have been observed in winter wheat (*Triticum aestivum* L.) crops in the South-East of England. Birds removed 6.7% of seeds compared to 51% from non-avian predators[261].

Crop management practices such as stubble cultivations, use of pesticides or disturbance can cause a reduction in predators and a reduction in foraging behaviour. Predators can be encouraged through maintenance of their preferred habitats around fields (margins) and within fields (beetle banks) and through delaying stubble cultivations after harvest[370,468]

Management of non-cropped areas

Weed infestations often begin from a source either on or off farm, non-cropped areas are becoming more common and need to be managed to prevent spread of wind-blown seed such as sowthistle, ragwort and groundsel. For example, with rosebay willowherb (*Chamerion angustifolium*) it has been estimated that 20 to 50% of seeds could be carried 100 m and some seeds could potentially travel over 100 km[95]. Weeds such as black-grass and brome can be taken from the field margin into the centre of fields via the combine harvester.

3.3.19. Hand weeding/roguing

Hand weeding is a slow, time consuming method of weed control, generally used only for small areas or where weed density is very low. It can be done by walking through the crop removing weeds by hand or by a team of individuals lying on a purpose built flat-bed weeder[358]. Often, hand weeders will follow a pass of a mechanical weeder to clear-up missed weeds.

Small patches of weeds or individual plants can be pulled or rogued from crops by groups moving methodically through the field. Pulling/roguing usually refers to the removal of large weeds that appear above the crop canopy such as black-grass (*Alopecurus myosuroides*) wild-oats (*Avena* spp.), ragwort (*Senecio jacobaea*), weed beet, docks (*Rumex* spp.) and thistles (*Cirsium* spp.).

Perennial weeds can be directly dug or pulled. Specialised handheld tools have been developed to remove specific weeds e.g. prongs or forks to remove tap rooted weeds such as docks or ragwort and billhooks to remove weeds not easily dug or pulled. Powered strimmers or mechanically driven devices can chop or macerate larger weeds *in situ*.

Braw, push and stirrup/oscillating hoes are used to cut weeds and move soil which then dislodges or buries weed seedlings. They can be used with long or short handles[157].

3.3.20. Mechanical weeding

Mechanical weeding kills weeds by burying, cutting or uprooting. Plant spacing is critical to the success of mechanical weeding, Crops need to be sown in rows or ‘on the square’. 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[286,288]. Total burial is required for control of weeds, but plant size, angle and growth habit influence the depth of covering required[52].

The success of mechanical weeding is weather dependant, its effectiveness is dependent upon soil type and moisture levels, the number of days without rain before and after weeding, weed size and species and the type of equipment including adjustment and speed.

Weed control prior to crop emergence

The most effective time to control weeds is at the white thread stage, when the root emerges from the seed, but weed seed germination can occur over two to six weeks or longer, so multiple passes may be needed. The action of moving the soil can also trigger germination of other weeds.

Pre-crop emergence weed control can reduce weed levels at a low density during early crop development.

Harrowing can be done during this phase but only if the crop is sown below the depth at which the harrows are working. The crop also needs to be sown below the depth at which weeds emerge, generally 5cm[532].

Inter-row and intra-row weeders

To avoid crop damage, mechanical weeding is best delayed until the crop is large enough to withstand damage, but often the weeds are too large to be controlled effectively. Traditional methods are based around spring-tine harrows and cultivators, but new devices have emerged, such as finger-weeders, torsion-weeders and intelligent weeders[532,533]. Brush weeders, and torsion-weeders tend to be used in low density crops, while spring-tine harrows are mainly applied in narrow-row high-density crops[422]. Table 3.7 contains a summary of the options.

Table 3.7 Weeder type, optimum growth stage for use, risks, capacity and speed[532]

Weeder type	Row spacing (min)	Optimum crop growth stage	Optimum weed growth stage	Risks	Capacity and speed
Harrows, tine	any	Between sowing and emergence when cultivation depth is less than sowing depth Well rooted crops from the 2 leaf stage	Cotyledon to 2 leaves	2-5% loss of plants damage to broad-leaved crops	2.5 ha/ha with a 6 m width, speed 3-12 km /ha
Fixed or sprung	15 cm or above	Protect crops from cotyledon to 4 leaves, continue until crops are damaged or crop	Cotyledon to 4 leaves, also well rooted weeds and grasses	Risk to small crop plants by soil covering. Root damage can be caused by delaying hoeing. Regular	0.5 to 2 ha per hour, 4-7 km/hr, with steering up to 15 km/hr.

		covers the soil completely		hoeing will prevent growth of surface roots.	
Rotary	30 cm	From seedling stage until damage caused to the plants	Cotyledon to 3 leaves	Root damage can be caused when cultivations are too deep <4 cm from the row	0.75 ha per hour (3 m width), 3-7 km/hr
L shaped	30 cm	From seedling stage until damage caused to the plants	Cotyledon to 15 cm	Root damage can be caused when cultivations are too deep <4 cm from the row	0.75 ha per hour (3 m width), 3-7 km/hr
Straight tines	50 cm	From seedling stage until damage caused to the plants	Cotyledon to 4 leaves	Risk of crop damage is low, some soil coverage occurs	0.75 ha per hour (3 m width), 3-8 km/hr
Finger	25-35 cm - >35 cm	When properly rooted from the 2 leaf stage	Cotyledon to 2 leaves	Well planted or rooted crops to prevent uprooting	1 ha per hour, 2-12 km/hr
Torsion	25cm	Cotyledon to 2 leaves	Well rooted crops until the crop plants meet in the row.	Relies upon well rooted crops to avoid uprooting	1 ha per hour, 2-12 km/hr
Cage	20cm	cotyledon		Cultivation between the row	1 ha per hour, 3-12 km/ha

Specialist weeders such as the Kvik-up harrow can be linkage mounted or semi-mounted and its working width is up to 6.4m[320]. The harrow comprises large tines with goose feet ends which loosen the soil to a depth of 10 to 15 cm and rotating spring-tines working at a depth of 5 to 7 cm that grab soil and plant material, throwing it backwards. Due to gravity, all the light weed roots remain at the soil surface where they can be desiccated in the sun or wind or exposed to frosts. This method is particularly successful for controlling common couch (*Elymus repens*).

Cereals and oilseeds

Mechanical weeding can be very effective in cereals. Spring-tine weeders are the most commonly used form of mechanical weeding used in UK organic cereals, with weeding often done in the spring reducing weed densities by 5% to 90% depending on the species present[156]. Two to four harrowings using stiff tines can give 69-95% weed control in winter wheat[83]. Mechanical weeding with spring-tine weeders in winter oats is most effective when done early (e.g. November), when the crop is strong enough to withstand the weeding, but before weeds have become established[10]. Weeds that develop tap roots are also better controlled by mechanical weeding in the autumn. However, autumn harrowing of wheat and oilseed rape can thin crops compared to spring harrowing[83].

The Royal Agricultural University trialled an Opico harrow comb weeder, Garford RoboCrop inter-row hoe, TRP Rotanet, and the Combcut weeder in winter wheat[106]. However, none of the mechanical weed control options used gave yield advantages over the untreated control plots, a finding supported by other studies [156]. Reasons for a lack of differences in yields could range from weed infestations being below competitive levels, poor levels of weed control, late timing of weed control after competition has already occurred, and damage to the crop[156].

Mechanical weeding using inter-row hoes is used in oilseed rape crops, on 50cm rows, in Denmark with the first pass done in August as the crop emerges (1-2 leaves) getting the hoe close to the plants in the row. Hoe blades are usually configured in a ducks foot or A-width shape and mounted on S-tines or shanks [367]. A second pass in early October aims to ridge the soil around the row to prevent weeds growing between the plants. A final pass in early April controls later germinating weeds[132]. Increasing the row width to 50cm to allow for mechanical weeding does not compromise yield. In addition, with new technologies inter-row hoes can now be automatically steered with cameras reducing potential crop damage [366].

Mechanical weeding in cereals and oilseeds can be hindered by a number of issues that can prevent use. These include high weed abundances; in particular, grasses, being more tolerant to the physical process of mechanical weeding, crop residues blocking implements, and poor crop competition after weeding [366].

Potatoes

In organic potato crops, and traditionally in many conventional crops, fields are raked over post-planting and when weeds are at the cotyledon stage. Weeds are removed from the top of the ridge and buried, the work rate is high, and a 12 m rake can weed 80 ha per day in good conditions. A cultivator/ridger is then used between two and four times post-emergence and is a very effective strategy. Due to the generally lower nutrient status in organic potato crops (compared to those grown conventionally), the crop is less competitive and multiple passes are sometimes needed to control post planting weed growth. The earlier passes are faster due to less top growth being present; however, later passes of a two-row cultivator may only cover around 7ha /day to avoid canopy damage. Large six-row equipment requires RTK GPS-controlled equipment with a large tractor to provide sufficient weight and stability for the cultivator/ridger. In wet springs, finding suitable weather windows to cultivate to remove weeds is a significant problem, so control is often less than ideal. Mechanical weeding can cause moisture loss from the soil, and this loss can be significant for the crop. In addition, mechanical weeding can damage crop root systems

Despite the issues raised above, mechanical weeding in potato crops is generally effective. In the UK, three years of experiments with one, two or three passes were done[306]. A single pass reduced weed biomass by 59-87%, two passes by 85-87% and three passes by 70%. There were no major differences in yield between chemical and mechanical weed control. In Denmark, one, two and four passes with a rolling cultivator were done at pre-emergence of the weeds and at the cotyledon and true-leaf stage. Annual weed biomass was reduced by 80%, even with one or two passes. The efficiency was independent of the weed size and weed species. The perennial weeds couch (*Elymus repens*) and creeping thistle were less well controlled, with only a 50% reduction in weed biomass.

3.3.21. Thermal control

Thermal weeding refers to methods of weed management, whereby heat is applied to destroy weeds. There are many different methods of thermal weeding, and many are commonly used today, mainly in organic farming. The most common thermal techniques include direct heating methods such as flaming, hot water, steaming and dry heating and electrical weeding. Less common techniques include infrared weeding, radiation with microwaves, ultraviolet and lasers, and conversely, control by freezing. Advantages of thermal weed control include no chemical residues, no disruption to soil surface, no risk of resistance development, and a wide spectrum of control. Disadvantages include potentially higher cost and slower application times, lack of residual weed control, higher energy consumption and in some cases, applicator safety or a requirement for expert application only.

Flame weeding

Flame weeding was once considered crude and dangerous, having nearly disappeared in the 1970s. It then became one of the most common methods of direct weed control used in organic agriculture through the 1980's and 1990's[41,83,114,391]. Flame weeders use liquefied petroleum gas (LPG) burners (predominantly propane), although hydrogen has also been evaluated as a possible fuel to produce an intense heat which, rather than burning the weeds, causes the plant cells to rupture and causes the weed to wither and die within 2 to 3 days[37].

Flame weeding is generally applied pre-emergence of the crop; however, it can also be used for some situations post-emergence depending on the crop[41]. For heat-tolerant crops, intra-row weeding is achieved at certain crop growth stages by angling the burners to the base of the crop[43]. For heat-sensitive crops, inter-row weeding is achieved by shielding the crop from the flames or lowering the dosage to a tolerable level[41,386]. For best control, pre-emergence flaming is delayed as long as possible to allow the maximum number of weeds to be exposed; however, flame weeding does not appear to reduce subsequent weed emergence and may even increase the germination of some weed species[41].

Several studies have evaluated the efficacy of flaming in various situations. Developmental stage of the weed significantly affects the effectiveness of flaming and the dose required for control; however, weed density appears to have no effect[114,45]. To achieve 95% control on various target weed species, the propane required ranged from 10-40 kg/ha for weeds with 0-4 true leaves to 40-150 kg/ha for weeds with 4-12 leaves[41]. Efficacy also varies with type of weed. In general, flaming is more effective on broad leaved weeds than on grasses[114] and more effective on annuals than biennials and perennials[41,43]. Fuel pressure and application speed have also been evaluated and may also affect the success, or otherwise, of this technique[41,421]. The pros and cons of this technique have been previously outlined, including data from dose-response experiments highlighting the importance of dose for optimum control of target weeds at certain growth stages[154].

A range of flaming equipment is available in the UK and a number of studies have been conducted to determine the best design[42,180,291,413,414]. The initial purchase of the flaming equipment can be expensive; nonetheless, it has been concluded that treating 6-20 hectares keeps costs at an acceptable level and that this area can be much smaller in certain crops[403].

Suitability of flame weeding is dependent on crop type and typically horticultural crops offer more opportunities than arable crops. The high value of vegetable crops also justifies the high machinery cost[83]. Efficacy of flame weeding and its potential for crop damage has been evaluated on several crops such as maize[526,527] and wheat[528]. More recent research investigating the benefits of flame weeding in vegetable systems has been investigated in a European H2020 funded project IWMPraise (2019)[275]. A thermal flame spot weeder has been developed and trialled in Denmark[433], on board cameras identify weeds and small burners are activated to control weeds identified by the cameras. Table 3.8 contains a summary of flame weeding.

Table 3.8 Summary table for the use of flame weed control

Suitable crops	Pre-emergence: all crops, post-emergence: maize, onions, flames can be directed at small weeds in tall crops such as maize, brassica, onions.
Optimum crop growth stage	Pre-emergence, between rows; depends on crop, broadcast; depends on crop
Optimum weed growth stage	Depends on type of weed- generally between 0-12 leaves. Annuals better than perennials, broad-leaved better than grass. More difficult weeds (and larger weeds) require more heat to kill.
Crop damage and losses	For post-emergence use only suitable on some crops – shields enable flame to be directed at weeds and not crop. Crop damage can range from 0-75%
Not suitable for	Perennials, large scale
Machinery available	Yes, but limited choice for field-scale
Currently used	In vegetable crops, and organic situations
Overall assessment	Equipment is expensive as is fuel to run, cost is justified in high value crops grown intensively.

Hot water

The application of hot water for weed control has been investigated in both field and laboratory trials. In orchards, water heated to 85-95°C and applied at a working speed of 6 km/h provided sufficient control of foliate weeds without causing damage to the apple trees[319]. A series of papers aimed at controlling weeds on urban hard surfaces, were published examining some factors required for optimum control of test weed *Sinapis alba* using hot water[241,242,243]. Further studies indicate that hot water treatment is less energy efficient and less effective on various broad-leaved weed species than other thermal control methods[48]. There have been no further developments in hot water treatments for weed control and it is not available for arable use in the UK.

Hot foam

Hot foam has been developed as a way of improving hot water weed control and results with new equipment have demonstrated it is more effective and requires fewer treatment applications. The foam can be made from a mixture of coconut sugar and corn sugar and reduces heat dissipation during application[437]. Hot foam has been tested and found effective at controlling weeds on hard surfaces[298]. Over the past decade in the UK, hot foam has been developed and patented with a system 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 the weeds by Weedingtech™ (2018) called Foamstream. Trials on the weed control efficacy of the hot foam technology from Foamstream by ADAS (as part of the EMT/HDC/HTA Weeds Fellowship project 2013/2014)[249] tested the system in three different horticultural situations including hardy ornamental nursery stock, strawberries and organic field vegetables. The results showed the wide spectrum of weed control, including of perennial weeds, that this method can provide; however, multiple applications were required. Hot foam should always be applied with care due to crop phytotoxicity issues. For example, 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[4]. To date, there has been relatively few trials carried out in cropped environments in soil, with only limited data available to demonstrate in-crop efficacy. This type of system is most suited to urban and amenity areas such as pavements, car parks and other harder surfaces.

Steam

Steam has been used to sterilize soil and control weeds and diseases in glasshouses prior to crop establishment for many decades[83]. Research then further developed steaming methods for use outdoors in fields and in polytunnels. Pressurized steam applied to the soil surface for 3-8 minutes can heat the soil to 70-100°C and kill most weed seeds to depths of at least 10 cm[83]. The disadvantages of this application of steam weeding are the high energy consumption, the amount of time needed for treatment (40-100 hr/ha), the risk of injury to those operating the equipment, and the drastic effects that it has on other organisms in the soil.

The use of low temperature-short duration soil steaming has been examined and found that 100% control of tested weeds, diseases and nematodes could be achieved by steaming to heat the soil to 50-60°C for three minutes[535]. Both temperature and duration of heating impact weed control, however, studies show that temperature is more important [363,518]. Band-steaming is a method of steaming developed for row-grown vegetable crops, whereby only the soil corresponding to the intra-row area is steamed[362]. Compared to flame weeding, band steaming provides a longer lasting reduction in weed seedling emergence[44]. To achieve >90% control, it has been reported that a soil temperature of 60-80°C is required [363]. Many soil factors have a significant effect on the effectiveness of soil steaming[150,426]. Weed control was greater in sand than in sandy loam soil and greater in fine soil than coarse [364]. The efficacy of band steaming is improved if performed on moist soil [364] Although significantly less costly than mobile pressurized steaming, band steaming is still expensive and operational time is around 8h /ha[363].

The effects of steam weeding on nitrogen and carbon dynamics have reported findings of no significant affects[193], but that there was a large increase in ammonium concentrations. It is believed that the ammonium surplus would be of benefit to the crop, but further research is needed in this area[193]. Steam weeding has been studied and considered effective in onions[362,487], strawberries[467], apple orchards[322,447], carrots and leeks[363]. A revised method of steam weeding was designed in New Zealand. It is a 'direct-fired steam weeder' and is more efficient at producing steam and therefore, more cost-effective[372]. Products are available for amenity, vineyards, orchards and horticultural row crops from WeedTechnics, in New Zealand, USA, Canada and Australia. Their machines use a unique system called Satusteam™, which is a form of saturated steam which can reach higher temperatures for a more effective plant kill. It is currently not available commercially in the UK.

Electrical weed control

The historical use of electric currents as a method of weed control has been previously reviewed [176]. This review outlines methods of weed control by high voltage electric shock dating back to 1970. Two methods are considered: direct contact, and pulse discharge; the former being considered the best method. The direct contact method involves simple electrodes which span the crop rows and, upon contact with a range of types, delivers a shock (12-20 kV) which kills the living plant tissues. Electric shock weeding is suggested for late weed outbreaks[176]; however, studies show that high numbers of weeds can be missed with this method. In two studies within sugar beet crops, it was reported that 47%[557] and 25%[175] target weeds missed, respectively.

The energy aspects of electric current weed control have been reviewed and it was concluded that it would not be suitable as primary control methods for high density weed populations and that even with densities of 15 plants/m^2 [(538)], the energy input required is very high. Unpublished data suggests that electrocution can be an effective method of controlling perennial weeds, although re-growth is a concern in some species. Tractor mounted machinery has been developed in the US[83], but in the UK applications in the field are strictly experimental at this stage. There are vehicle-mounted small machines for sale and used in the amenity sector.

The key advantages of electrical weeding are that it is chemical free, systemically kills the plant roots and does not disturb the soil. A UK-based company Rootwave™ has been developing this technology over a number of years and in 2018, launched a professional hand-held device for amenity use. A recent research project in bush and cane fruit, with a small tractor mounted system, demonstrated good control of perennial weeds such as creeping thistle (*Cirsium arvensis*), with a minimum of two application timings; however, this technology is currently not commercially available[511]. The technique has the advantage of being useable on windy days when herbicide applications would not be possible. It could also be used in areas that are required to be pesticide-free, or in conjunction with herbicides as an integrated weed management strategy. The energy consumed by a static electrical weeder with a single probe was relatively high compared with that of the standard weed control method (glyphosate application using either a knapsack or tractor mounted spray equipment)[4, 408]. However, with the tractor-mounted electrical weeding system evaluated for efficacy in blackcurrants between 2017-2019, it was shown that the electrical weeding system used an equivalent amount of fuel compared to other mechanical control methods such as mowing[511].

The key benefits of electrical weeding:

- Non-toxic to micro-organisms in the surrounding soil
- No naked flames or need for propane gas such as with a flame weeder
- No need for large water tanks and high fuel use such as with a foam weeder
- No soil disturbance, therefore, no further weed seed from the seedbank stimulated to germinate
- Quicker and cheaper than hand weeding
- Amenity kit lance can be very precise for spot treating

There are other methods of thermal weed control that are not widely practiced or that are still at an experimental stage. These include dry or direct heat, infrared radiation, microwaves, lasers, solarisation, ultraviolet irradiation and freezing. There is limited new information available on these methods and it appears that there has been no further progress with their development or uptake in over a decade.

3.3.22. Physical mulches

Mulches include the use of black plastic film or biodegradable material, such as straw. These are laid on the soil surface to physically suppress weeds. They reduce the germination of light-responsive weed seeds and cause the death of any other germinated weed seedlings by blocking light. Mulches are more effective against weeds germinating from seed but are not generally effective against existing perennial weeds[84]. Although physical mulches can offer weed control, they are not used in winter wheat or oilseed rape.

In the potato crop, clear plastic or white “fleece” is sometimes used to promote crop earliness, with residual herbicides applications prior to it being laid. The fleece is removed soon after crop emergence, but the dry soil surface promoted by these covers often means weed control is poor. Black plastic could be used as an alternative to clear plastic removing it as crops emerge. Any emerging weeds would be killed due to lack of light and any survivors would be weak and easily killed by cultivation or with a gas burner. The cost of laying down and taking up plastic is expensive, and disposal/recycling are additional issues[58]. Therefore, this technique is only applicable to small areas of niche high value crops.

3.3.23. Undersowing/companion crops

Companion cropping (also called living mulches) are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season.

There are two different types of companion crops:

- Perennial companion crops, typically white clover, where main crops are sown without complete destruction of the companion crop canopy. This type of cropping system is known as *"bicropping"*.
- Annual companion crops, sown together with the main crop and used only for one season, including use of the regrowth of the companion crop after harvest as forage or green manure.

The choice of species is key for a successful companion crop to minimise yield losses from the main crop. The companion crop should not compete for light, nutrients and water.

The suppressive ability of living mulches against weeds and their impact on cereal grain yield has been investigated in several studies[100,164,216, 247,318]. Weed densities were equal to or up to 55% lower with than without living mulch. Grain yields with living mulch were in the range of 14% less to 22.0% greater compared to the treatments without living mulch[216,246,539]. Densities and biomass of perennial weed species such as *Elymus repens*, *Sonchus arvensis* and *Cirsium arvense* were not affected by living mulch[255].

In the UK, an Innovative Farmers field lab are investigating the potential for establishing no-till organic/low input arable farming systems using a permanent living mulch understory of clovers[270]. Where the clover established well, there was evidence that weeds were suppressed, in particular, perennial weeds and grasses. The time of establishment is key and where clover is established late, it may not provide enough competition against weeds. There is lower risk in establishing clover in the Autumn, but there will be more competition from autumn germinating weeds. A spring established clover going into a spring crop is more favourable as weeds will experience more competition from the cereal crop, and it allows the opportunity for mechanical weeding prior to establishing clover in spring.

Companion cropping in oilseed rape is being trialled for cabbage stem flea beetle control but the effect on weeds is not being measured. Companion crops have also been trialled in the UK by commercial companies to reduce soil compaction and slug damage but not weeds[140]. In a review of legume-oilseed intercrops, significant weed suppression was reported, due to the complementary use of resources between the intercrop components [181]. Legume-oilseed mixtures were more readily able to utilise available resources, such as light, space and nitrogen compared with sole crops. There was increased use of resources by the crop components which suppresses weed growth and vigour, and reduces weed biomass, abundance and reproductive vigour compared with weeds growing in monocultures. Future work needs to consider herbicide management within these mixtures.

In potatoes, the potential of ridging was evaluated, in combination with intercropping cover crops, to control weeds[441]. Vetch (*Vicia dasycarpa*), oats (*Avena sativa*), barley (*Hordeum vulgare*), red clover (*Trifolium pratense*), or a combination of oats and hairy vetch (*Vicia villosa*), were intercropped following ridging three, four, or five weeks after planting. Ridging and interseeding treatments were compared to a no-cover treatment and an herbicide treated control. Cultivation associated with the intercropping operation and cover crops reduced weed density by 20 to 27%, three weeks after interseeding. The intercrops were treated with herbicides to prevent excessive competition. Control of cereals resulted in a dead mulch that provided 0 to 95% weed control, whereas legumes regrew after herbicide application and provided 45 to 70% weed control.

3.3.24. Intercropping

Intercropping is ‘the growing of two or more crop species where part or all of their crop cycle overlaps temporally and/or spatially, where one or more of the component species is taken to harvest[264]. The term companion cropping can be defined as the close planting of different plants that enhance each other’s growth or protect them from pests[264].

Inter and companion crops compete for space, water and nutrients more efficiently than cropping with no companion crop so provide better competition against weeds. Potential disadvantages of companion crops are the limitation of herbicide choices as some active ingredients may damage or kill the intercrop.

Winter wheat intercropped with white clover (*Trifolium repens*), subterranean clover (*Trifolium subterraneum*), and birdsfoot trefoil (*Lotus corniculatus*) had significantly fewer weeds than standard plots[255].

Companion cropping in OSR is increasing in the UK, initial efforts showing the same weed control as a pre-emergence herbicide, less herbicide use and reduced the biomass of cranesbill[264]. Trials in France between 2011 and 2014 showed the use of frost sensitive legumes as a companion crop in oilseed rape contributed to weed control, compensating for the reduction in herbicide use to preserve the legume intercrop[104].

4. Disease control

4.1. Current status

The majority of the most economically important diseases of cereals, oilseed rape and potatoes are caused by pathogenic fungi. A large range of different fungicides are available to treat disease epidemics, with varying levels of product efficacy and pathogen resistance.

In cereals, *Septoria tritici* (septoria leaf blotch or septoria) of wheat is the most economically important foliar pathogen in the UK and is found in all regions of the country. Septoria has a significant capacity to evolve resistance to the different modes of action found in fungicides; however, new chemistry is constantly being developed and control currently relies on currently three single site Modes of Action (MoA) (triazoles (DMIs), succinate dehydrogenase inhibitors (SDHIs) and quinone inside inhibitors (QIIs), alongside multisite chemistry (folpet and mancozeb). Many of the SDHI and triazole fungicides are now ineffective against septoria. With the rate of discovery and development of new chemistry for control slowing, increasing integrated management of the disease is essential. The rusts of wheat and barley specifically *Puccinia striiformis* (yellow rust of wheat), *P. hordei* (brown rust of barley) and *P. recondita* (brown rust of wheat) are significant foliar diseases in the UK. A range of chemistry is available for control including the triazole and strobilurin classes of fungicides. Some SDHIs also appear to have useful activity. Of the other foliar diseases, only limited chemical control options are available for *Blumeria graminis* (powdery mildew), and *Ramularia collo-cygni* (ramularia of barley) as both these pathogens have developed resistance to many existing MoAs. Whilst a problem in the past, *Phaeosphaeria nodorum* (leaf and glume blotch in wheat) is rarely seen in the UK currently[524]. A number of species from genus *Fusarium* cause ear blight, for which there are chemical control options; however, these are generally only partially effective.

Of the soil borne diseases, *Gaeumannomyces graminis* (take-all of wheat and barley) is a highly significant pathogen which affects yield in most circumstances where susceptible crops are grown sequentially. Although some fungicides can reduce symptoms, their control is only partial at best. *Tapesi yallundae* (eye spot of wheat and barley), although much less widespread than take all, can cause significant yield loss where conditions favour it, and again conventional fungicides are only able to reduce symptoms. Barley Yellow Dwarf Virus (BYDV) is vectored by aphids, and as such, this is considered under ‘Pests’.

A range of azole and non-azole chemistry is available to control oilseed rape diseases. *Pyrenopeziza brassicae* (light leaf spot) is the most important foliar disease of oilseed rape, with most areas of the country considered to be at a high risk of infection. Strains with decreased resistance to azoles have been identified; however, both azole and non-azole chemistry currently performs similarly in terms of disease control in the field against these strains[307,449]

Oilseed rape is at risk from a number of stem diseases which increase the risk of canopy collapse and pod shatter. *Leptosphaeria maculans* (phoma stem canker or blackleg) and *Sclerotinia sclerotiorum* (sclerotinia stem rot) are both well-established stem diseases present in the UK. No issues regarding fungicide insensitivity have been reported in the UK to azoles; however, decreased sensitivity to fluquinconazole has been reported in Australian populations[530]. Fungicides are available to control sclerotinia, though timing is key as they are effective only as protectants, with no curative activity. Sclerotinia isolates with decreased sensitivity to boscalid have been reported in the UK; however, these appear to be infrequent as they are not detected every year and no issues with field control using boscalid have been reported[265]. *Verticillium longisporum* (verticillium wilt or stem stripe) is a more recent arrival to the UK and outbreaks have occurred sporadically; there are no chemical control options.

Plasmodiophora brassicae (clubroot) is a critically important soil borne pathogen of oilseed rape that also effects all other cruciferous plants. There are no options available for the chemical control of clubroot. Turnip Yellows Virus (TuYV) is vectored by *Myzus persicae* (peach potato aphid), as such this is considered under 'Pests'.

Cultural control always been important for potato disease management as chemistry is not available for many pathogens or it has been withdrawn. For example, the control of common scab and blackleg is reliant on non-chemical control measures in the UK. An extension of authorisation for minor use (EAMU) was obtained for the application of fluazinam to seed crops only and allows a maximum dose of 1.5 kg a.i./ha via tractor mounted drench in 200 l/ha water, applied to the ridge prior to destoning of bed tilling[93]. This allows the product to be thoroughly incorporated into the soil. Fluazinam works to decrease the severity of powdery scab on progeny tubers rather than the incidence and is predominately effective against soil-borne inoculum sources[93]. Zinc has been associated with reductions in powdery scab on tubers when soil inoculum levels were low; however, it is usually less effective than fluazinam[93]. There are twelve modes of action available for the control of late blight (*Phytophthora infestans)* in the UK. A potato crop in the UK on average receives around 10 fungicide applications primarily for the control of late blight; however, products come with restrictions on the number of times they can be applied in a single season, the mixture partners and spray intervals[213]. Strains with resistance to metalaxyl and fluazinam are present in the UK, so there are fewer modes of action than those available to include in late blight fungicide programmes[231]. Some products are likely to be withdrawn as a result of changes in legislation.

Chemicals are also used on stored potatoes; however, disease levels of tubers, the store environment and the resilience of the variety to disease development (e.g. resistance/skin set) are also factors in whether disease develops or not[146]. Imazalil and thiabendazole can be applied to tubers prior to storage to manage potato storage diseases. In-furrow applications of azoxystrobin (stem canker/black scurf and black dot) and fluxapyroxad (black scurf) are available to reduce or provide moderate control of those diseases. Seed treatments to manage black scurf, silver scurf and black dot include flutolanil and fludioxinil.

Active ingredients in products that control alternaria include fluxapyroxad, difenoconazole, prothioconazole and fluopyram. Pseudomonas SP. (DSMZ 13134) is registered for the control of *Rhizoctonia solani* on potatoes and is suitable for organic farming. Fosthiaziate is a nematacide that offers a reduction in spraing transmitted by free living nematodes (FLN).

4.2. Crop planning

4.2.1. Field history, rotation and break crops

Many rotations are devised to avoid the effects of take-all in cereals by alternating between cereals and take-all break crops. Second wheat yields are typically 1.0-1.5 t/ha less than first wheat yields[29], though in trials losses as high as 3.0t/ha have been recorded due to take-all[499]. On light soils, barley is often chosen as the second cereal as its yield tends to be less affected[499]. Oats may be grown as a take-all 'break' crop, as, although oats do get take-all, they are affected by a different strain. Fortunately, take-all declines quite rapidly in the absence of susceptible host crops and a one-year break is usually sufficient to maintain first wheat yields. On organic soils, take-all can be very severe, and cereals are often grown only as single 'break' crops in a root crop rotation. As take-all is a root disease, any factors that adversely affect root develop such as soil compaction, acidity, poor drainage, low nutrients or trace element deficiencies will aggravate the yield impact.

Where the same crop is grown in successive seasons, foliar and stem disease carry over from trash and volunteers can be significant. Most seed-borne diseases are exacerbated by repeat cropping, as many can also infect crops via the soil or crop debris from the preceding crop[14,16]. Foliar diseases such as yellow and brown rust, *P. nodorum*, powdery mildew as well as rhynchosporium and net blotch can also be introduced early into the following crop where there this a lack of cropping rotation[16]. 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[14].

The growing of oilseed rape frequently within the rotation can increase the risk of yield loss due to disease. Most diseases of oilseed rape are trash borne, and so avoiding fields with a history of infection is an effective strategy for reducing the risk of most diseases and using longer rotations of four years or more is effective for reducing the incidence of many diseases; especially soil borne diseases. For example, the soil borne disease clubroot, caused by the fungus *Plasmodiophora brassicae*, tends to occur in patches within fields, particularly in damp areas, and can survive for up to 15 years in soil[269] with a half-life estimated at 3.7 years[544]. 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[359]. Implementing rotations of four years or more will be beneficial for reducing the viable inoculum of clubroot in soil. A wide range of brassica plants can be affected by clubroot and can exacerbate the problem. Where it is known to be a problem, rotational planning to avoid other brassicas in the rotation may also improve control.

Sclerotinia disease in oilseed rape, caused by the fungus *Sclerotinia sclerotiorum*, has a soil-borne phase in its life cycle, with resting bodies (sclerotia) which can survive in soil for five years or more depending on soil conditions, and rotations of five years or longer are effective for reducing control[167]. A history of sclerotinia infection in fields on the farm is a key factor increasing the risk of infection in current fields[525].

Verticillium stem stripe in oilseed rape, caused by the fungus *Verticillium longisporium*, was first reported in the UK in 2007[221], Verticillium has a soil phase in its life cycle of microsclerotia which can survive more than ten years in soil[D66]. It can also survive on plant debris in soil. Rotations of four years or more are likely to be helpful for reducing the disease risk, but there are few studies focused on rotation effects for control of Verticillium in oilseed rape[165].

Lengthening the rotations of oilseed rape crops is effective at reducing the incidence of many diseases, particularly those with soil borne inoculum, but it is important to ensure that other crops in the rotation are not also hosts of the same diseases. For example, sclerotinia infects crops including potatoes, peas, green beans, and lettuce, and if infected, all of these will contribute to inoculum build-up in the soil which is likely to increase the risk of sclerotinia incidence in the next oilseed rape crop[512].

For potatoes, a substantial number of diseases can persist in soil or on crop debris and volunteers; therefore, field history and rotation can impact on risk. Control of many potato diseases, such as common scab (*Streptomyces scabies*) and blackleg (*Pectobacterium atrosepticum*) are already reliant on non-chemical control strategies for management and are not included here. In general, evidence that demonstrates the effectiveness of non-chemical strategies directly with chemical strategies is limited. At present, identifying risks associated with field history, rotation and break crops and the effect on pathogen survival and disease development is the only way to evaluate the potential of such strategies to reduce disease risk. Some diseases, such as black dot, occur on both on the seed and in the soil; however, each differ in their impact on final disease levels. Soil-borne sources of *Colletoctrichum coccodes* have been shown to significantly increase tuber disease compared to seed sources in the UK[327]. Rotation studies in the USA found that years out of potatoes and the number of preceding potato crops accounted for 71% of the variability associated with black dot incidence, with black dot risk reduced with rotations greater than 5 years[285]. For *Rhizoctonia solani,* which causes stem canker and black scurf on potato, both seed and soil-borne inoculum can cause disease, with disease more severe where both are present[522].

Sclerotia have been shown to decline in viability after two years burial, however, around 20% were still viable after this period[450]. For silver scurf, progeny tubers derived from disease-free early generation seed stocks became infested when grown in fields where potatoes had never been grown and had been grown up to 4 years earlier[88], suggesting a role for soil-borne inoculum in infecting seed stocks. Clean land is important for potato mop top virus (PMTV) management. Studies have found that there was a strong association between the incidence of PMTV on progeny tubers and soil inoculum, but not with infected seed tubers[155].

Foliar disease management can be affected by rotation and field history. The onset of early blight, caused by *Alternaria solani*, has been found to be influenced by field and rotation[2]. It was found that an interval of at least two years between potato crops was required to delay the onset of early blight in subsequent potato crops. Given that potato crops are recommended to be grown a maximum of 1 in every 3 years (with no alternative host plants grown)[39], and rotations are usually in excess of this, sufficient time will have passed for this to be a factor for early blight control. Long rotations are more important for the management of late blight (*Phytophthora infestans)*, particularly, to allow the degradation of oospores, which can act as primary inoculum for epidemics and are a source of novel genotypes. Outbreaks caused by oospores have not been reported in the UK. However, they are suspected in some regions of GB[135]. Novel clones compromise both chemical and non-chemical control strategies, with the latter demonstrated by the downgrading of variety resistance ratings when exposed to the genotype 13_A2 [329]. Powdery scab (*Spongospora subterranea*) is known to survive at least 5 years in the absence of a potato crop[332], with little understood about the relative contribution of soil inoculum to disease development[326]. In general, Soil and pH are not considered factors that affect powdery scab development substantially if the field pH is within the normal range for arable cropping, and soil type is free draining,. *Phoma exigua* var. *foveata*, which causes potato gangrene, was found to persist in the soil, with effective control only achieved through a combination of tuber disinfection after harvest and a 1 in 5 crop rotation[337].

4.2.2. **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.

Epidemics of yellow rust 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[14]. Brown rust thrives in higher summer temperatures, so is a greater threat in the south[14.] There is also anecdotal evidence also that powdery mildew tends to favour sheltered, low lying fields where humidity tends to be higher during the late autumn and spring. It is not practical to completely avoid growing cereals in high risk locations in the UK. The selection of lower risk locations for cereal pathogens is best considered as part of a holistic approach to disease control, as it may affect the degree that other strategies (e.g. varietal choice and sowing date) are employed to control disease. For example, eyespot favours heavy soils that retain water. These sites may also have high yield potential. Such locations could still be used with the eyespot risk reduced by later planting, use of a resistant variety and/or ensuring the crop was proceeded by a break crop[16] .

Selection of lower risk locations is an effective strategy to reduce the incidence of some oilseed rape diseases, e.g. the incidence of sclerotinia stem rot is likely to be reduced by avoiding lower lying damp fields, such as those by rivers. If there are sclerotia in the soil, damp conditions will encourage germination of sclerotia in spring and subsequent production of airborne spores which infect the crops[117]. For clubroot, drier, well-drained soils will be lower risk for clubroot[177].

A preliminary analysis of 17 years of late blight outbreaks by the James Hutton Institute for AHDB identified that the closer a site is to intensive potato production, the higher the risk from late blight. This is perhaps unsurprising; however, the analysis also concluded that risk is high in all areas and that the threat of spread depends in part on the risk in neighbouring areas[18]. For aphid-borne viruses, cooler areas are often considered to be lower risk as they are less favourable for vector proliferation and survival.

4.2.3. Spatial separation

In cereals, the proximity of a susceptible crop to one that is already infected can significantly increase the risk of infection, where the disease is wind dispersed. This is true for the foliar rusts and bunt. Previously, the use of crop diversification strategies to limit the spread of yellow rust (should one resistance gene be overcome), by identifying appropriate neighbouring varieties was promoted in the 1990s and early 2000s[7]; however, the changing diversity of yellow rust isolates since the introduction of the Warrior Race in 2011, and the ability to control the pathogen with fungicides has limited the value of this approach and meant other factors have taken precedence over varietal positioning on farm. Some seed borne diseases such as loose smut and bunt can also infect crops from nearby or neighbouring fields, so where these proliferate, spatial separation may effectively reduce the risk of infection[14].

Ensuring that fields designated for oilseed rape are not adjacent to fields with known clubroot patches will be effective at reducing incidence, as clubroot tends to be confined to localised patches, with the caveat that good hygiene is essential for preventing spread of the disease to other fields (see 3.3.3). Spatial separation to reduce the incidence of sclerotinia 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[549], although some exceptions have been found. However, even if no other infected host crops are nearby, many wild plants are hosts of sclerotinia, e.g., buttercups, and shepherds' purse which can be sources of sclerotinia inoculum[116]. For a disease such as phoma, separating the next year's oilseed rape crops from fields with infected stubble will be beneficial; 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 phoma severity[353].

Spatial separation of new oilseed rape crops as far away as possible from previous fields is advised as effective at reducing the risk of diseases which have carry over from one year to the next on infected crop debris, for example, light leaf spot[19] and for phoma[20,49].

Phytophthora infestans, which causes late blight on potato, has been demonstrated to travel from a point source (potato outgrade piles) up to 900m away[573]. This study also found that the majority of inoculum that affected potato fields was derived from outgrade piles. New strains of *P. infestans* have been found to spread as quicky as ~14km per week, although this appeared to vary depending on the year[18]. Recent modelling studies considering landscape planning and the consequences of spatial separation have confirmed the capacity for long distance dispersal of *P. infestans* sporangia[488]. Interestingly, the model appeared to suggest that geographical separation of regions and use of resistant cultivars has benefits in preventing spread between distinct regions.

Early blight on potatoes is caused by *Alternaria solani,* with brown spot caused by another species, *Alternaria alternata,* on potato leaves. Aerial conidia concentrations and dispersal have been measured and it was found that atmospheric spore concentrations for *A. alternata* was greater at height and in both upwind and downwind directions in a field[173]. *A. solani* tended to be found downwind, suggesting that *A. solani* conidia were derived from within crops whereas *A. alternata* was generated from more diverse sources across the landscape.

4.3. **Pre-cropping**

4.3.1. Alternative seed treatments

The common seedborne diseases of cereals, such as bunt and smut, are currently effectively controlled with standard fungicide seed treatments; however, alternatives are also available, including mustard powder products for the control of bunt, thermal treatment, and use of mechanical brush cleaners that remove spores from seeds[356].

Hot water treatment has been shown to provide control of black leg and some control of powdery scab, with a thermal death point after submersion of 10 min at 55°C[93]. Steam treatment in packing houses has been experimentally tested and found to decrease development of black leg, silver scurf, common scab, powdery scab, *Fusarium* spp, black scurf and black dot on tubers[6]. Proradix (Pseudomonas SP DSMZ 13134) is approved for use in the UK for the control of *Rhizoctonia solani* on potato tubers.

4.3.2. Control weeds and volunteers

In all crops, volunteers and weeds can act as a source of infection for following crops 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[14]. Ideally, these volunteers should be destroyed prior to the emergence of new crops. Weed or volunteer control can be achieved chemically or by cultivations in many cases. Ploughing is effective in removing volunteers and many weeds that may be sources of air-borne pathogens and viruses. In practice, this is not always easily achieved as volunteers often emerge over several weeks and in fields sown with other crops such as oilseed rape. The impact of removing volunteers is, therefore, likely to be small. Common grass weeds, such as rye grasses, can act as virus reservoirs for BYDV and influence disease incidence in cereals[562].

Where volunteer wheat plants are left to grow in break crops, on fallow land or in conservation covers, they can significantly increase in the risk of take-all in following cereal crops. Early destruction of volunteers on fallow ground was shown to be effective at reducing damaging take-all levels in succeeding wheat crops[281]. The control of ergot in wheat is also often linked to the presence of grassweeds, particularly, black-grass and ryegrass, either in the crop or in the field margins. The control of these grassweeds can be effective in reducing the level of infection[14].

In oilseed rape, the control of weeds and volunteers reduces the prevalence of numerous diseases. Some soil-borne pathogens such as *V. dahliae* and *S. sclerotiorum* have a very wide host range and can, therefore, be maintained by many different plant species. Sclerotinia is able to complete its lifecycle on more than 400 host species, including common weeds like sow-thistle (*Sonchus arvensis*), dandelion (*Taraxacum officinale*), and shepherds' purse (*Capsella bursa-pastoris*)[167]. Early removal of oilseed rape volunteers has been shown to significantly reduce clubroot in succeeding crops compared to later removal[566]. Even under favourable conditions for the pathogen, incidence of phoma stem canker has been shown to be reduced by a combination of mechanical weed removal and application of bio-stimulants (e.g. amino acids)[352]. Incidence of verticillium stem stripe was also shown to be reduced by non-chemical weed control[352]. Weed and volunteer management are essential to include alongside crop rotations for the prevention of verticillium wilt to break the green bridge that can occur despite avoiding successive plantings of oilseed rape[251]. Turnip mosaic virus and other oilseed rape viral pathogens can be hosted in related brassica species, such as wild radish (*Raphanus raphanistrum*)[139].

The value of the destruction of volunteer plants and weeds is difficult to quantify but the impact of their control has been related to the numbers of volunteer plants involved in crops following fallow periods[283,560,561].

Many studies have focussed on determining the susceptibility of weeds to potato diseases, rather than their relative contribution to the persistence and proliferation of the pathogen in fields, and subsequent infection of host crops. *Colletoctrichum coccodes*, which causes black dot on potatoes, has been found to infect many species including common amaranth, fat hen, creeping thistle, field bindweed, shepherd's purse, common couch, large crabgrass, autumn millet, yellow foxtail, velvetleaf, common yellow wood sorrel and black nightshade[440]. *Spongospora subterranea* (powdery scab) has been found to infect a wide range of weed species, and this was determined using qPCR[523]. The same study investigated the potential for other crops to act as an alternative following inoculation with *S. subterranea* and found oats, radish, barley, alfalfa and tomato all tested positive.

Alternative hosts exist for many of the key potato diseases such as dry rot [87] and late blight [204]. There are complications when trying to understand the implications of alternative hosts. For example, for dry rot, there is variation in the susceptibility of alternative hosts to the different strains implicated in causing the disease [87]. There are concerns that ineffective management of alternative hosts could lead to undesirable changes in pathogen populations. In Sweden, it was demonstrated that *Phytophthora infestans* strains retrieved from hairy nightshade had short latent periods and greater capacity for spore production, suggesting that alternative hosts could affect populations negatively[235]. Although effective weed management is recommended as part of an IPM strategy for diseases, research to support why and how this should be done, is limited for both chemical and non-chemical control strategies.

Volunteer potatoes can act as hosts or reservoirs for black dot, *Rhizoctonia solani*, powdery scab, spraing and aphids/aphid-borne viruses [53]. Much of the work done on the cultural management of volunteers is now over 40 years old, however, is still relevant[439]. For example, potato volunteers act as a reservoir for many diseases and require at least 50 frost hours equivalent at or below –2°C for tuber kill (e.g. -2°C for 25 hours)[338]. Tubers at or near the surface are likely to be frosted and killed during winter than those left deeper in the soil[341]. It has been demonstrated previously that this is less effective if there is crop cover, likely due to higher temperatures at soil level[110]. Potato volunteers can be very numerous for several years after a potato crop and therefore, enable potato pathogens to survive despite 'break' crops. On lighter soils, outdoor pigs are sometimes used to clean up tubers left after potato harvesting and hence, contribute to disease control. Volunteers are also a risk factor for black leg[9]. Research is underway to determine whether there is a link between blackleg incidence and free living nematodes. *Helminthosporium solani,* which causes silver scurf, is thought to be short lived in soil; however, it can survive on volunteer potatoes, maize and wheat. Potato mop top virus is known to affect a range of weed species including those in the Solanaceae and Chenopodiaceae[245]. Tobacco rattle virus infection has been confirmed in many weed species, including *Viola arvensis* and *Stellaria media*[136].

4.3.3. Early harvest

The development of many potato diseases, particularly those causing surface blemishes, is associated with the duration of time the crop remains in the field after desiccation. Early harvest for potatoes is defined as harvesting as soon as is possible after skin set is complete. Harvest decisions are often dictated by external factors rather than disease risk; for example, if weather or soil temperature are unsuitable. Black dot, a skin blemish disease caused by *Colletoctrichum coccodes*, is known to be more severe when harvest is delayed. Delaying harvest by two weeks can cause significant increases in the proportion of unmarketable tubers and risk was found to be greater where a high level of soil inoculum was detected[94]. An updated AHDB guidance document is available for black dot[12]. Harvesting during unfavourable conditions or too early to have allowed skin set can increase the risk of many diseases through bruising and damage. Tuber infection caused by *Alternaria solani* is often associated with tuber damage and tuber infection has been shown to decrease where tubers are allowed to fully mature prior to harvest[537].

It was demonstrated nearly 100 years ago that tuber blight, caused by *Phytophthora infestans*, can be caused at lifting[397]. Desiccating the haulm prior to lifting substantially reduces this risk, as tuber infection is associated with foliar blight that is still active on green tissue[398,399]. Substantial infection by *P. infestans* is associated with wet soils, high numbers of zoospores and where potatoes have damage[394]. Crops should not be lifted until at least 14 days after the haulm is dead to minimise tuber infection [53].

Early harvest has been associated with lower incidence of silver scurf (*Helminthosporium solani*) and later harvest with more disease, suggesting that exposure time to inoculum is a factor[202,373]. Early harvest is beneficial for black scurf management (*Rhizoctonia solani*), as severity of this disease increases the longer the potatoes remain in the ground after desiccation[551]. Gangrene is associated with injuries to the tuber periderm[337]. For blackleg, lifting early once skin set is complete, and in dry conditions is recommended[470] as well as minimising damage at harvest[9]. The impact of early harvest was dependent on the infection levels of the original seed stocks. For example, where bacterial seed loading was low, only small increases in infection were observed when harvest was delayed. When levels were intermediate or high, delays in lifting resulted in larger increases in infection[9].

4.3.4. Drainage

Good drainage is effective for managing clubroot infection and the spread of clubroot in oilseed rape fields. Soils which are compacted, poorly drained or even prone to flooding will encourage proliferation of clubroot zoospores, especially in a warm autumn (>15°C)[177]. In addition, the zoospores are motile: they have flagellae and can move through wet soil, attracted by host root exudates[D93]. They can also be spread by water flow.

Some guidance recommends good drainage, along with good air movement within the canopy, to help reduce moisture levels in the crop canopy and decrease the risk from late blight[448]. Wet soil conditions favour blackleg development on tubers[419]. There is limited evidence that drainage affects powdery scab, with anecdotal evidence from the 1980s suggesting this. There is a link, however, between free moisture in soil and infection, and it has been suggested that manipulation of the soil environment during crop growth can reduce the likelihood of the disease developing on potato tubers[198]. Previous work has shown that the crop is highly susceptible from around a week prior to 50% tuber set to 3 to 4 weeks later, with withholding irrigation water during this time reducing the severity of powdery scab by up to 75%; however, this effect was not always repeatable year on year[513]. Anecdotal reports from commercial potato production suggests that powdery scab severity is increased on free draining, light sandy soils and where wet and dry soil conditions are more frequent. Similarly, less powdery scab was reported on Scottish farms in 1985 where soil inoculum was known to be high and remained water-logged throughout the season[93]. Blackleg and soft rot risk increases after excessive rainfall and is exacerbated by poor drainage; therefore, addressing waterlogged/compacted areas as well as avoiding poorly drained fields and areas prone to flooding is recommended[9].

4.3.5. Hygiene and prevention

Maintaining good farm hygiene is the first defence against the introduction of soil-borne diseases into clean land. Growers that are farm saving wheat or barley seed, should not do so from fields that have had infections of bunt[14], fusarium or ramularia[97].

In oilseed rape, hygiene is important for diseases such as clubroot and verticillium. 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 local transfer may have occurred. Hygiene and restrictions on cropping are important measures where diseases are subject to statutory control.

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 oilseed rape. 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[268].

Outgrade piles are an important source of potato late blight. Controlling haulm growth on dumps or covering the dumps is an essential part of the national guidance on late blight control[53]. Small quantities of tubers discarded on fields can have the same impact, if not more, given their proximity to the current crop[53]. For blackleg, it is recommended that rots are removed early when grading seed and grading equipment is cleaned if there were obvious signs of rots in a previously graded stock[9]. As many blighted tubers as possible should be removed during harvesting to prevent issues in store [53]. The presence of volunteers is known to increase the level and persistence of soil inoculum for powdery scab [93].

4.3.6. Lime

For take-all in cereals, the relationship between severity and soil pH is not well understood. Acid patches in fields, where soil pH is lower than ideal for cereal crop growth have been associated with more severe take-all symptoms in cereals, so correcting these situations may improve control. However, take-all is also understood to favour high pH environments, so overcorrecting for acidity may also have a deleterious effect.

Application of lime to raise soil pH and calcium levels is a method used for the control of clubroot in oilseed rape, as the disease favours acidic soil with low calcium levels. 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. However, liming does not provide complete or consistent protection in short rotations and is particularly ineffective where levels of clubroot infection are very high[231]. Liming should be used as part of a wider management strategy that includes varietal resistance[359,405].

4.3.7. Primary cultivations (crop residue burial)

Many growers have adopted no-till practices for the benefits provided in improving soil organic matter content, water holding capacity, and reduction in fuel costs[563]. However, this method involves drilling crops directly amongst the stubble and debris of preceding crops. The burial of crop debris by ploughing can reduce inoculum for some necrotrophic pathogens (which kill host tissue) which produce inoculum on plant debris. In cereals, ploughing has been shown to effectively reduce the prevalence of *Fusarium* spp. in the soil, seeds, seedlings and freshly harvested grain, with deep ploughing being more effective than shallow[55,503]. However, for eyespot, ploughing has been associated with higher levels of infection due to the infected debris having a suppressive effect on the pathogen, possibly due to the presence of antagonistic microflora[56,282].

Deep ploughing will bury sclerotia of sclerotinia to depths where germination and spore production are limited[167]. 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.

Cultivations that reduce the survival of volunteers will aid in managing blackleg, as fields with volunteer problems are considered to be high risk[9]. For late blight, soils should be cultivated deep enough to ensure there is sufficient tilth to adequately cover the tubers later in the season, to decrease the risk from tuber blight [53]. Cultivations that manage weed populations, bury overwintering crop debris and reduce volunteers can substantially decrease the risk of black dot development. Soil borne inoculum has been identified as the key source of tuber infection by *Colletotrichum coccodes*, which causes black dot[327]. Between 9 and 92% of black dot sclerotia have been found to survive at least 8 years when buried at 10 to 20 cm depth compared to 55% when they were left on the surface[172]. Current guidance notes that overwintering crop debris, volunteers and weed hosts can substantially increase the risk[12].

4.3.8. Secondary cultivations (drilling method)

The interaction of cultivations and take-all is a complex one, and despite its importance, it is poorly understood, with little conclusive work to be found. It is considered that primary cultivations can bury the previous crop debris, and this may reduce the risk of take-all, whilst also tending to leave a looser less consolidated seedbed which encourages the pathogen. As a result, secondary cultivations may be more important in determining the impact on take-all progress. Take-all in cereals is understood to favour loose seedbeds, so it is likely that secondary cultivations which consolidate the soil, whilst maintaining good soil structure for drainage, may help to control the damaging effects of this pathogen in second and subsequent cereals[262]. The effect of cultivations and drilling method on eyespot is considered under primary cultivations.

4.3.9. Seed rate

Lower seed rates have been shown to reduce incidence of take-all and eyespot in situations where infection is severe, such as in second or third wheats[226]. Lower seed rates can also reduce the severity of septoria infection, though the effect is likely to be small and inconsistent and may also risk poor plant establishment[387].

4.3.10. Seed testing

The use of certified seed is important for most crops to ensure that heavily infected seed stocks are not used and can be an effective approach to reducing some diseases. Seed testing of home-saved seed should be used to identify common seed-borne diseases such as *Fusarium spp*., bunt and loose smut[14]. Contaminants such as ergot that would introduce the disease into new crops can also be identified. There are numerous providers of seed testing services. If seeds are determined to be free of seed borne diseases, particularly bunt and smut, then seed may not need to be chemically treated. One route for Ramularia to infect barley is understood to be from seed borne infection. The selection of uninfected seed, following seed testing may help in its control.

For potatoes, seed certification is vital to contain virus diseases and eliminate stocks where there may be bacterial pathogens or high levels of tuber-borne diseases. The Seed Potato Classification Scheme (SPCS) is administered on behalf of the Department for Environment, Food and Rural Affairs (Defra) by the Animal and Plant Health Agency (APHA) in England and Wales, and SASA[470] in Scotland to provide assurance that seed potatoes meet specified minimum health and quality standards. Standards for blackleg, Virus A, Y and leaf roll and other mosaic viruses are included in field inspections for Pre-Basic, Basic (S, SE and E) and Certified seed (A and B). In addition to statutory testing, crop assessments and supplier information can be useful, and seed inspection prior to planting necessary to understand seed specific risks. For late blight, supplier inspection reports and wash up tests and after receiving seed can indicate the late blight risk in the seed growing area [53]. Molecular seed testing is available; however, its use is not widespread, and most testing organisations offer a visual examination of seed to determine fungal disease levels. The lack of molecular diagnostic testing may be due, in some cases, to a poor relationship between levels on the seed tuber and disease on progeny tubers or a lack of information on which to base crop management decisions on. For blackleg, seed testing can only give an indication of pathogen levels on tubers at the precise time of testing, as storage and handling in general can cause bacterial numbers to fluctuate on seed stocks[9]. Seed infection by *Alternaria solani* is relatively unusual in the UK; however, affected tubers should not be planted. Powdery scab can be seed or soilborne, with both contributing to disease on progeny tubers[198]; however, the relative importance of the two sources is unknown, with soil type, temperature and moisture also thought to influence disease development[93].Research has demonstrated previously that using nuclear seed tubers generally results in good disease control, but there are exceptions[214]. Infected seed is the major source of soil infestation for *Helminthosporium solani* (silver scurf) in soil and levels increase with every seed generation[88]; however, soil inoculum is thought to survive no more than one season. *H. solani* DNA has been detected on progeny tubers and stolons suggesting movement from seed tuber to progeny tubers via stolons[355].

After harvest, testing of seed stocks can be conducted in two ways: standard on growing test (GO) or direct tuber testing (DTT). The former uses a sprout growth promoter, gibberellic acid, and tests the resulting leaves using ELISA to identify viruses present. DTT uses RT-PCR to detect the presence of viral DNA in a tuber sample. They are currently considered to be comparable when used up to 10 weeks after harvest, with the DNA-based test more effective after this time[207]. Guidance linked with seed testing for viruses is considered to be driven by commercial needs; however, up to 4% tubers affected has been suggested as acceptable for further production and over 10% should not be planted[112]. In Switzerland, seed stocks are regulated and cannot exceed 10% of tubers affected[478].

There is some evidence that planting potato mop top virus (PMTV) affected seed stocks could increase the risk of introducing the virus to land unaffected by PMTV[155].

4.3.11. Seedbed quality

Severity of some diseases can be worsened by seedbed management practices. In wheat, take-all infection can be encouraged by poorly consolidated seedbeds[253], other effects of cultivation on take-all are covered under primary and secondary cultivations.

For control of clubroot in oilseed rape, 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 (see section on Lime)[252]. Minimum and no-till practices can increase the incidence of verticillium wilt in oilseed rape, so tillage is recommended to bury the microsclerotia remaining on stubbles[571].

For late blight, seed bed quality is important as beds can be eroded during the season via irrigation or rainfall. Quality, therefore, includes bed formation as well as tilth, to ensure adequate soil coverage for tubers. The latter will help to prevent zoospores being washed down and infecting progeny tubers [53].

4.3.12. Sowing date

Sowing crops earlier or later to reduce disease risk is a commonly used practice in IPM strategies of growers. In general, later sowing decreases the potential for disease transfer from previous crops, though there is often a yield penalty associated with sowing later. Additionally, wet autumns are also more likely to impede or prevent a later sowing. The risk of not establishing crops pre-winter can cause farmers to drill earlier whilst they have appropriate soil conditions, rather than delaying and potentially risk not being able to sow at all. This is especially the case on heavier soils, which are less likely to dry out once wet, and less well suited to spring cropping[8].

Later sowing (mid-October) has been shown to reduce the severity of Septoria in winter wheat[387], take-all of wheat and barley[239], eyespot[123], and BYDV in winter wheat and winter barley. However, late sown spring barley tends to be more prone to BYDV than early sown[24]. Late sown winter barley tends be less susceptible to ramularia[97], particularly where crops are being planted near to where spring barley crops were grown in the preceding season. Spring epidemics of yellow rust in winter wheat have been found to increase in severity with later sowings[220]. This may be due to younger plants being more susceptible to severe rust infection[199]. Powdery mildew epidemics are also often more severe in late sown crops of wheat and other cereals[27]. 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.

Incidence and severity of fusarium head blight has been shown to be worse in late sown crops [229,290]. Infections of common bunt that can be more severe when sown into colder soils, is likely later in the autumn[430]. However, the interaction between bunt and the weather is complex, and unlikely to be as simple as earlier sowings reducing risk. For example, heavy frosts and thin snow cover have been associated with low infection level, whilst heavy frosts and thick snow cover associated with higher levels of infection[336]. Later sowings are also often associated with higher rates of fusarium seedling blight[14], where seeds are infected and not treated.

In winter oilseed rape, early sowing in late-August or early-September into warm, moist soils encourages epidemics of clubroot in fields where the pathogen is present[412]. However, care must be taken in Scotland and northern England to avoid winter kill of young seedlings that may result if sowing is too late. Transfer of light leaf spot spores from recently harvested stubbles nearby can also be reduced by later oilseed rape drilling[509]. Early sowing of oilseed rape can reduce the severity of phoma stem canker epidemics, as the plants are larger by the time leaf spotting occurs so that the pathogen has further to grow down the petioles to reach the stem base[50]. Consequently, the pathogen reaches the stem base later, and the resulting stem cankers are less severe. Conditions that favour rapid emergence reduce the risk of stem and stolon cankers caused by *Rhizoctonia solani*[280].

4.3.13. 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 Recommended Lists published by AHDB and by other levy-funded projects[29]. 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. The diseases for which resistant scores for winter and spring wheat varieties are available are mildew, yellow rust, brown rust, septoria leaf blotch, fusarium ear blight and eyespot. No rating is provided for glume blotch as the disease is now present at such low levels in the UK that it is not possible to effectively measure through field trials. No true resistance has been identified for take-all, though research through the Wheat Genetic Improvement Network (WGIN) has demonstrated that there may be varying levels of variety ability to tolerate infection, i.e., to maintain yield despite disease pressure[65]. Barley varieties are available which are resistant to powdery mildew, yellow rust, brown rust, rhynchosporium, net blotch and mosaic virus. There is currently no genetic resistance rating for ramularia on the spring or winter barley recommended lists due to the significant effect environmental factors have on disease development and the difficulty in correctly identifying disease symptoms[160]. AHDB resistance ratings are not included for the recommended varieties of spring oilseed rape. The economic case for choosing resistant varieties is not always clear cut. In wheat, there is often a trade-off between yield and disease resistance, with the most resistant varieties yielding less. A range of other criteria are deemed important by growers, including standing power, sprouting, specific weight and quality characteristics that can affect the value of the end crop. The selection of disease resistant varieties constrains grower choices and usually leads to a compromise being sought on some other varietal attribute. Disease resistance is also seldom complete, so fungicide treatment is usually still required.

For oilseed rape, AHDB Recommended List resistance ratings are given for light leaf spot and stem canker[29]. Resistance score for light leaf spot range from 5 to 7, which represents a reduction in both the maximum and range of available resistance over the last 10 years. Resistance scores for stem canker range from 4 to 9, indicating that some varieties contain very effective genetic resistance and so are strong candidates for high-risk sites. Ongoing research is aimed at improving the level and durability of genetic resistance to the pathogens responsible for phoma[99] and light leaf spot[171,424,550]. There are also attempts to improve the utilisation of resistant varieties to delay or prevent resistance breakdown[49], which often occurs within a few years of a new resistance gene being commercialised[353]. Phoma canker resistance based on the resistance gene Rlm7 is available, although resistance has been shown to breakdown if not properly rotated[382]. In France, 50% of the oilseed rape sown is with cultivars containing the Rlm7 resistance gene, and this over reliance has resulted in 20% of *Leptosphaeria maculans* populations being virulent against this gene.

Three oilseed rape varieties are recommended to be grown on sites known to be infected with club root[29]. Currently, the varieties with effective resistance to clubroot are Crome, Crocodile and Croozer. These varieties should not be used to shorten oilseed rape rotations or be grown repeatedly at infested sites as this could lead to resistance breakdown. A previously recommended variety, Mendel, underwent resistance breakdown at sites where it was repeatedly grown[102].

Oilseed rape varieties are not ranked for resistance to sclerotinia in the UK AHDB Recommended Lists, but research has indicated that significant levels of resistance exist in oilseed rape and other, closely related species[174,212,361,486]. Potential resistance can be found at different stages of crop development, including cotyledon resistance where inoculum build up can be prevented, limiting later stem damage[303]. Differences in varietal susceptibility have been reported in the UK, but these usually reflect differences in their timing of flowering, relative to rainfall events or differences in canopy architecture. Verticillium wilt of oilseed rape has been formally recognised in England since 2007[221] but is now thought to have been present unnoticed or latent for much longer[165]. It is a persistent soil-borne disease for which crop rotations and resistant varieties appear to be the main management options. Research has now shown that there are significant and reproducible differences in resistance to verticillium between varieties[166,516]. However, there is still no national list testing for verticillium resistance and the two varieties found by the previously mentioned study to be the most resistant, Mentor and SY Harnas, are no longer on the Recommended List. Breeders are working on developing tolerant or resistant varieties, and some research effort is focused on understanding and developing resistance genes[196,197,464].

Information is available for potato varieties on the AHDB Potato Variety Database[23]. Resistance is provided for a range of individual pathogens on a 1-9 scale, with 1 the most susceptible score and 9 the most resistant score. For some pathogens, such as late blight and powdery scab, resistance scores are available for almost all varieties. Scores are limited to fewer varieties for dry rot, skin spot, silver scurf, black dot and PVY^N. Although not included on the variety database, differences in the susceptibility of varieties to black scurf (*Rhizoctonia solani*) and early blight (*Alternaria solani*) have been reported previously[113,321]. For early blight, there was a strong association between maturity and susceptibility, with earlier maturing varieties typically more susceptible[559]. Variety resistance can be used to substantially reduce fungicide inputs for late blight control[118,209,210, 54, 451]. Using a variety with good resistance in combination with fungicide can substantially decrease late blight risk, with the variety also offering some flexibility for fungicide timing[53]. Varieties, however, are usually selected for the market rather than their disease resistance profile and those with resistance ratings of between 3 and 5 are most commonly grown due to their consumer and industry desirable characteristics. A greater number of varieties with better resistance to late blight are becoming available e.g., Agrico's Next Generation varieties. Evidence exists for the benefits of varietal resistance for many skin blemish and rot diseases including black dot[541], dry rot[87] and blackleg[9]. For powdery scab, variety had the biggest impact on its control. Switching from a susceptible to moderately resistant variety substantially reduced disease incidence and severity[542]. Differences in variety susceptibility to potato mop top virus (PMTV) has been identified, with most susceptible varieties identified as Rooster, Cara and Saturna. The rankings were similar regardless of whether infection was derived from seed or soil, suggesting that resistance could be screened using either method[108].

4.3.14. Variety mixtures

Most crops are grown in varietal monocultures to ensure ease of planting and harvesting, and to maximise uniformity of the final product for sale to buyers. However, this approach to growing increases vulnerability to disease, and resistant crop varieties often experience rapid breakdown as new disease races emerge due to variety overuse.

Meta-analysis of varietal mixture studies in winter and spring wheat has shown that mixtures averaged an over yield of 6.2% under high disease pressure compared to single variety controls[29]. Growing a four-way wheat variety mixture has been shown to decrease septoria severity by an average of 17% compared to untreated plots of individual cultivars[313]. Disease reductions and yield increases were greater in untreated than in treated trials. Additionally, the varieties chosen were not specifically bred for resistance to septoria, so a mixture of resistant varieties could be expected to produce greater control. Meta-analysis on varietal mixture studies on yellow rust have shown that an average of 28% reduction in disease severity can be achieved in mixtures compared to pure stands[266]. Effects were also greater where disease pressure was higher, and disease was not fully controlled. Three-way mixtures of spring wheat varieties have been shown to provide up to 69% control in the presence of high levels of brown rust[35]. Observations on the effect of mixtures on eyespot are varied. Small reductions in eyespot (mean of 13%) were observed in 3 of 7 mixture combinations. Though in the presence of another disease (yellow rust), eyespot severity increased by 10%[396]. Other work has shown little or no effect of varietal mixture on eyespot[395,471].

Use of varietal mixtures in spring barley have been shown to provide significant control of powdery mildew. The most significant reductions in mildew severity were observed when the cultivars used in the mixture had intermediate levels of resistance[520]. Growing susceptible winter barley varieties in mixtures has been shown to reduce severity of brown rust compared to the susceptible varieties alone[143].

4.4. In-crop techniques

4.4.1. Bioprotection and low-risk plant protection products (PPPs)

A range of biofungicides and other low risk plant protection products are either available for commercial purchase or have shown potential as alternatives to chemical control of pathogens.

In cereals, biofungicides currently available include a range of elemental sulphur products, with protectant activity on powdery mildew and septoria tritici, and Laminarin (IODUS^{TM}) through its activity as an elicitor of the crops self-defence mechanism[194]. Laminarin is a storage carbohydrate extracted from seaweed and has been shown to reduce the severity of Septoria tritici when applied to leaves prior to infection occurring.

In addition to this, there are a range of other biofungicides that have potential to be of value in controlling diseases in wheat and barley. These includes essential oils and acids, salts, and microbial biocontrol agents.

Essential oils, including orange, spearmint and rosewood oil have all been shown to have activity on fusarium strains in wheat under laboratory conditions[417]. Ascorbic acid has also been found to have activity on septoria tritici[493].

In cereals, several naturally occurring salts have been found to have fungicidal some activity. Sodium chloride (NaCl and copper Sulphate ($CuSO_4$)) were used as early and as the 1600s and 1800s, respectively for the control of bunt (T. caries) infection in wheat[163]. There are a range of other inorganic salts which have shown fungicidal effects, including bicarbonates, phosphates, silicates and chlorides[163]. Bicarbonates have been shown to have good activity on brown rust in wheat[292]. Potassium Chloride have been shown to prevent a wide range of wheat diseases such as septoria tritici[350] and has been shown to reduce the severity of yellow rust when applied to the soil or leaves[463]. Chlorides and Silicate salts have also been shown to reduce symptoms of powdery mildew and glume blotch in wheat[292]. The degree to which inorganic salts can replace conventional fungicides or be a cost effective addition to a fungicide strategy is poorly understood, due to limited commercial interest (possibly due to salts being unpatentable).

A range of microbial biocontrol agents have also been shown to have either direct effect on pathogens or indirect effects via the plant. For septoria tritici in wheat these include *Bacillus spp.*[305], *Pseudomonas putida*[203], *Triochderma spp.*[418]. *Gliocladium spp*, have also been shown to reduce the severity of fusarium seedling blight in wheat[515].

Control of sclerotinia stem rot is possible with biological control agents. Numerous fungi have mycoparasitic activity against the sclerotia structures that build up in the soil. Most well understood is the parasitic fungus, *Coniothyrium minitans*, which is available as a commercial product for application to affected soils[491]. Application of *C. minitans* has been shown to be effective for the control of sclerotinia in a range of host crops, including oilseed rape, beans and sunflower. Whilst highly effective at colonising and neutralising sclerotia under optimal conditions of 15-20°C and pH 4.5 - 5.6, control is expected to be less effective as conditions deviate from the optimum[569]. Other fungi have also been studied for their efficacy in controlling sclerotinia, but these have predominantly been horticultural experiments in greenhouse conditions[491]. Bacteria have also been studied for control of sclerotinia. *Pseudomonas chlororaphis* and *Bacillus amyloliquefaciens* have both been shown to provide effective control of stem rot in field trials when applied at the 30-50% flowering stage[200]. When bacteria were applied at the same time as inoculation with sclerotinia, 100% control was achieved, highlighting the importance of application timing[472].

4.4.2. Decision support, thresholds and monitoring

Decision support systems (DSS) use meteorological and other data to model the risk of a disease and provide a recommendation on whether it is necessary to apply a treatment spray to a crop. DSS that are produced in one country may often be applicable to another, though they should be validated with local data to account for regional variation in pathogen biology and interactions with the abiotic factors included in the model. There are a range of subscription services available that provide DSS to farmers (for example, see CropMonitor Pro at: https://chap-solutions.co.uk/capabilities/cropmonitor-pro/) but information on the models used by these platforms is usually not freely available. An EU Horizon 2020 project is currently ongoing to build an open access platform of DSS available across Europe (https://www.ipmdecisions.net/) and documentation is available that lists many of the DSS available around Europe for different diseases, including those in paid-for subscription services (see IPM Decisions Deliverable 4.9). Thresholds also enable decision support by providing a set level of disease observed at which point treatment would be recommended.

DSS are available for a range of diseases on subscription farm management software, such as CropMonitor Pro. On this platform, DSS are available in wheat for septoria, yellow rust, brown rust, powdery mildew, fusarium, eyespot, tanspot and BYDV.

DSS for fusarium have been developed in Italy for durum wheats, with the model including considerations of weather, growing area, host species and resistance of cultivar, previous crop, and soil tillage[459]. AHDB produce a risk assessment document for fusarium mycotoxin levels that can be filled in with information including region, previous crop, cultivation, and rainfall to produce a risk score for presence of mycotoxins[30]. However, this risk assessment is primarily for use on grain passports and not designed for aiding decisions on application of a treatment spray.

Models for septoria of wheat have also been developed that use rainfall data to determine risk of a severe epidemic. Septoria transfer from lower to the upper, yield forming leaves occurs by rain splash, so wetter periods in spring are more favourable to disease severity. In Europe, the Crop Protection Online service provides a model that uses number of days with precipitation above 1mm, with treatments being recommended after 5 days over the rainfall threshold. A Danish 'humidity' model uses hourly values for percent relative humidity, leaf wetness, or rain events. The models have been validated in several countries across the Baltic region and have been shown to reduce fungicide inputs whilst providing effective disease control[289]. These models could also be validated for UK conditions. Similarly, models are available in Europe for the prediction of risk of glume blotch (*P. nodorum*), particularly on the VIPS platform in Norway (https://www.nibio.no/en/services/vips). Whilst glume blotch is not currently a disease of great concern in the UK, the availability of DSS in other countries provides an option for IPM in future should the pathogen return to prominence.

A DSS model has been developed and validated in Luxembourg for the optimisation of fungicide timing for the treatment of brown rust in wheat. The DSS has enabled effective control of brown rust with a single, well-timed fungicide spray, and yields did not differ significantly from plots treated with two or three treatment sprays[186].

AHDB provide a risk assessment tool for eyespot in wheat that allocated points to various agronomic factors to produce an overall risk score[25]. Pre-sowing factors considered include region, soil type and tillage, and this score is combined with a spring disease assessment to provide a recommendation on whether to treat for eyespot[D1].

DSS models are available for barley diseases in Denmark (Crop Protection Online), Norway (VIPS), and Finland (WisuPrognose). The Danish CPO service provides the greatest range of disease models, covering net blotch, brown rust, mildew, and scald.

There is growing interest in development of DSS for ramularia, and recent work in Ireland has looked at minutes of leaf wetness in the 2 weeks prior to GS49 to determine risk of ramularia development[17]. The study used two adaptive fungicide programmes that changed based on disease risk. One treatment in which fungicide rates increased or decreased, compared to a reference treatment, and another in which products were added or removed based on predicted risk. In high-risk situations, the reference treatment was sufficient to provide good control of ramularia. There were no low-risk situations predicted by the model against which to test the two adaptive fungicide programs. Additionally, the study highlighted the importance of weather after the key spray timing for control of ramularia. The model predicted 2018 to be a high-risk year due to high pre-GS49 precipitation, but a very dry period following this resulted in no ramularia developing. The authors note that if favourable environmental conditions for ramularia are important right up to symptom development, then the value of a DSS for this pathogen would be questionable as it would not be possible to make accurate predictions at the appropriate time.

Soil analysis can be conducted for the detection of clubroot of oilseed rape, the resting spores of which can remain in the soil for many years. A soil bait test will provide information on the presence of active clubroot in the soil and is available to purchase as a service from commercial laboratories.

AHDB produce a forecast for phoma that accounts for temperature and rainfall information between July and September. The forecast is published in October and predicts the date when 10% of oilseed rape plants could be showing symptoms of phoma leaf spot, at which point a fungicide treatment should be considered[28].

A seasonal risk forecast is released by AHDB for light leaf spot of oilseed rape[26]. A preliminary forecast is released every autumn, followed by an updated version in the spring that incorporates winter rainfall. The forecast shows the proportion of oilseed rape crop estimated to have greater than 25% of plants effected by light leaf spot in the spring of the current season. The forecast uses previous season pod incidence data and deviation from the 30-year mean summer (July and August) temperature. It also uses historic average winter rainfall data. The forecast is updated in spring to reflect deviation in actual winter rainfall data from the 30-year mean[26].

Any observed light leaf spot in oilseed rape is considered to be over the tolerable threshold and should be sprayed as soon as seen. Light leaf spot releases spores continuously and spreads rapidly, making early identification important. Incubating leaves at ~16°C can draw out symptoms early and maximise value of spray by treating for the pathogen early[64].

AHDB also produce daily updates during oilseed rape flowering for weather-based sclerotinia infection risk alerts, available for multiple locations across England and Scotland. These alerts include current and forecast times (next 72 hours) and are based on temperature and relative humidity thresholds of 7°C and 80%, respectively[309] which must be reached for at least 23 continuous hours for a sclerotinia infection alert to be issued[21]. Sclerotinia infects crops during flowering, mainly via infected petals, at times when flowers senesce and falling petals adhere to damp leaves. If the temperature and humidity thresholds are reached at these times, infection is likely to occur, and it is essential that fungicides must be applied beforehand, i.e. as protectants. The occurrences of forecast weather alerts have tended to be sporadic during flowering, i.e. not continuous, and have been a useful guide for farmers to justify delaying or omitting foliar fungicide treatments, or to achieve optimal timing of treatments ahead of infection[564]. In 2021, the forecast weather alerts were 91.5% accurate when comparing forecast to actual weather[21].

For powdery scab of potatoes, there is variability in the reports investigating the link between soil-borne inoculum and disease on progeny tubers. The relationships between types of inoculum (seed and soil), inoculum level, and environmental factors are not well understood[93]. Some studies have identified a positive link between soil-borne inoculum levels and disease incidence/severity[92,103], whereas, others have not[436,531]. It is possible to quantify soil inoculum accurately using standard PCR and qPCR tests[349]. It has been suggested that presence rather than quantity of sporeballs in soil is the relevant measurement to assess risk, as favourable conditions will encourage proliferation of high zoospore numbers regardless of initial inoculum levels[93]. The project DeS-BL (Building a Decision Support tool for Potato Blackleg Disease) is developing decision support tools for farmers, agronomists and policymakers to aid disease management[168]. Soil thresholds of between 50 and 1000 pg DNA/g soil were identified in field experiments for black dot to identify low and high risk sites[327,355].

PCR and RT-PCR assays have been developed for many potato seed and soil-borne pathogens, including *Rhizoctonia solani* which causes stem canker and black scurf on potato[328]. It is less common for this type of test to be accompanied by specific guidance on crop management strategies as a result of the test outcome.

Many decision support systems have been developed for the prediction of late blight epidemics, with many reassessed in the last 10 years in response to new, more aggressive strains of *Phytophthora infestans* including in GB[488]. More sophisticated DSSs that take into account varietal resistance and weather-based risk are available in other countries[402]. Free to user information to identify weather risk in GB includes BlightSpy, Blight CAST and Crop Monitor Pro. Some commercially available systems have both a late blight and early blight DSS, such as Dacom.

4.4.3. Nutrient management

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 in cereals. 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 is discussed separately in ‘Bioprotectants and Low Risk Plant Protection Products (PPPs)’.

Deficiency in nitrogen (N) and manganese can result in a higher susceptibility to take-all[91], especially, where N applications are delayed in the spring. Potash and sulphur deficiencies have also been linked to increased take-all severity. However, severe take-all sometimes occurs even when supplies of these nutrients are adequate[253].

Foliar diseases of cereals can be increased or decreased by nutrient applications to correct for deficiencies. Nitrogen is widely considered the most deficient nutrient in UK soils, and N fertilisation to correct this increases the prevalence of rusts[452] and Septoria[484] in wheat. It is also more likely to create a large crop canopy more conducive to the development of powdery mildew and eyespot.

Powdery mildew in wheat and barley, however, is exacerbated by manganese deficiency, and the correction of this, can reduce symptoms[126].

As previously stated, some nutrients may have direct effects on pathogen; however, 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[504].

There is some evidence that autumn N applications can increase canker severity in oilseed rape[D11]. Similar observations have been made in other studies where fertiliser was applied at different rates, though results have been inconsistent[244]. Increasing rates of N application have also been shown to increase severity of rust epidemics in wheat[46,153]. In the presence of excess N application, rusts have also been shown to reduce export of N to grains during filling, reducing grain protein content[169]. Excessive N application also favours eyespot[121] and powdery mildew[339].

There are indications that sulphur fertilisation, particularly in areas with low natural sulphur deposition, such as Scotland, 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[81,465,510]. However, given that adequate sulphur nutrition is required for optimal yield, it is recommended that sulphur applications should be made to oilseed rape in most areas.

Application of calcium can be used to control clubroot in oilseed rape (see section 4.3.5).

Crop nutrition has been associated with increased and decreased disease risk on potato. For late blight, increasing rates of NPK fertiliser or nitrogen fertiliser alone increased the lesion size and lesion growth rate linearly on potato leaves[107]. High availability of N significantly increased the susceptibility of three out of four potato cultivars; however, better N nutrition appeared to allow plants to invest more in biological defence pathways[457]. For early blight, it appears that the converse is true, with nitrogen fertilisers applied to ensure a high N content associated with a lower severity of *Alternaria solani* infection on potato leaves[3]. Potassium has also been implicated in decreasing early blight on potato as dose (applied as K_2O) increases[492].

5. Pest control

5.1. Current status

Invertebrate pests in wheat, oilseed rape and potatoes cause damage to the crop 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), slugs and wheat bulb fly (WBF, *Delia coarctata*). In oilseed rape, cabbage stem flea beetle (CSFB, *Psylliodes chrysocephala*), the TuYV vector (peach-potato aphid, *Myzus persicae*), slugs and pollen beetle (*Brassicogethes* spp.) are the most important pests. In potato, potato cyst nematode (PCN, *Globodera* spp.), aphid and nematode vectors of viruses (e.g., peach-potato aphid vectoring PVY, and free-living nematodes vectoring tobacco rattle virus, which is a causal agent of spraing) and wireworms are the most important pests.

Control of invertebrate pests in these crops remains highly dependent on using seed treatments and applications of insecticides/molluscicides, but reductions in available chemistry and increasing resistance issues have increased the need to make use of integrated pest management. Currently, some of the most important pests in these crops are those for which resistant populations exist. In cereals, grain aphid (*Sitobion avenae*) populations with moderate levels of resistance to pyrethroids are present in the UK[271]. In oilseed rape, pests with resistance to pyrethroids include peach-potato aphid, pollen beetle and CSFB[272]. In potato, peach-potato aphid and grain aphid are resistant to pyrethroids[273]. Peach-potato aphid is also resistant to organophosphates and carbamates, but these insecticides are no longer available for use in oilseed rape[274].

The lack of effective chemistry for economically important pests has increased uptake of non-chemical control options for pest management in recent years. There are a number of potential non-chemical control options for invertebrate pests. These range from approaches to reduce risk, for example by avoiding the pest (e.g., by growing crops in areas at low risk from the pest or selecting sowing dates that allow the crop to emerge after pest migration has passed), through maximising crop tolerance to the pest, to novel treatments and methods to targeting improve timing of treatments (e.g., decision support systems). Few of the non-chemical methods are likely to be 100% effective (except for OWBM resistant wheat varieties). However, they do reduce the requirement for chemical control, which in turn reduces the risk of current insecticide resistance spreading and new cases of resistance appearing. Combinations of one or more non-chemical control technique are likely to be most effective. Also, in many instances the presence of some pest damage will not necessarily impact on yield. A lot of information is available in Encyclopaedia of Pests and Natural Enemies in Field Crops[22] and Crop pests in the UK (Collected edition of MAFF leaflets[170,232]). Unless otherwise specified, much of what is described in the following sections is taken from these sources.

5.2. Crop planning

5.2.1. Field history, rotation and break crops

Field history can be used to assess risk particularly for those pests that are relatively immobile and unable to migrate long distances. This can be particularly important in rented land where a good understanding of field history will help to highlight potential pest problems.

It is well known that slugs are more or less confined as serious pests to heavy soils and are most numerous where drainage is poor and where the soil contains abundant organic matter. Light mineral soils hold less moisture than heavy soils and because of their texture and tendency to dry out quickly, are generally unsuitable for slugs. Although infestations of saddle gall midge (*Haplodiplosis marginata*) can occur in a range of soil types damaging populations of the pest are mostly restricted to heavy soils. In contrast, nematodes tend to be most numerous in light sandy soils. Both free-living and cyst nematodes are relatively immobile and tend to build up over time in particular fields in the absence of any control measures and if there is a host crop or weeds on which to feed.

Pests such as potato cyst nematode (PCN, *Globodera* spp), orange wheat blossom midge (OWBM, *Sitodiplosis mossellana*), saddle gall midge (*Haplodiplosis marginata*) and wireworms (*Agriotes* spp.) can persist in soil for several years, so any knowledge of previous infestations can help when planning pest control strategies. Tobacco rattle virus, which causes spraing in potatoes and is transmitted by stubby root nematodes (*Trichdorus* and *Paratrichodorus* spp), will persist in a wide range of weed species so it is important to know if has been previously recorded in a particular field.

Knowing when a field was last in grass is also important as it can indicate whether there is likely to be any carry over of ley pests to subsequent crops. Pests such as frit fly (*Oscinella frit*), leatherjackets (*Tipula* spp.) and wireworms can build up under long-term leys. These will potentially feed on any crop following a grass ley. The need for pesticide use can be avoided if crops that follow the ley are not vulnerable to the pests that thrive in it. For example, wireworms (*Agriotes* spp.), develop in grassland and populations can persist for several years after it is ploughed up. Vulnerable crops such as potatoes should not be grown after leys until the risk of damage has diminished, which can take five years.

Some pests are relatively immobile and increase in numbers only when their host crop is grown too frequently in the same field. Examples include orange wheat blossom midge, saddle gall midge, and potato cyst nematode (PCN, *Globodera* spp.) Growing alternative, non-host crops for appropriate periods can avoid the build-up of these pests whilst remaining economically viable[454]. The time period needed to grow break crops depends on the pest. One or two years is usually enough for saddle gall midge populations to decline to low levels, whereas up to eight years is needed before PCN numbers decline, depending on the population density in the field. Populations of leatherjackets take 3-7 years to reach peak levels in a grass ley[295]. Using these data and predictions from simulation modelling[78], it has been suggested that limiting leys to two years would help prevent leatherjacket damage in subsequent crops. Effects on the fertility-building value of a short ley and other unforeseen costs would also need to be considered in choosing this strategy.

Anecdotal evidence from the UK suggests that crops in fields where continuous wheat or barley had been grown are at greater risk from saddle gall midge than those grown in rotation with other crops. This was confirmed in Czech studies where first-year barley was reported to have 12% of tillers infested, but this rose sharply to 37% and 62% when successive barley crops were grown, and there were more galls per infested tiller[489]. Similar observations were made on successive crops of wheat. Very heavy infestations of cereals were recorded in Romania when the preceding crop was wheat (66%) or barley (44%) but infestation was much less following maize (11%), sunflower (11%), flax 8%), beans (7%) or peas (3%)[432]. The use of rotations that include no more than one or at most two successive cereal crops (at least of wheat and/or barley) may help keep numbers of midge larvae below damaging levels. To limit the potential risk from saddle gall midge, it has been suggested that winter-sown oats could be grown as a break crop/trap crop. Eggs are laid on oats, but damage is slight[489].

Wheat bulb fly (*Delia coarctata*) can theoretically be controlled by changing crop rotation. The pest will only lay its eggs in bare ground, so after a fallow, a rowed crop such as potatoes or sugar beet where the flies can access bare soil between the rows or where a crop is harvested early such as vining peas. If the following crop is not wheat or barley, the risk of WBF attack is eliminated. However, there are practical limitations to this approach as on light or heavy land where this pest is troublesome, wheat is the traditional and most suitable crop to grow after early harvest.

5.2.2. Select low-risk locations

Seed potatoes are commonly grown in locations where aphids are not frequently found in order to reduce the risk of virus transmission to the seed crop. This is why the majority of the British seed potato crop is concentrated in Scotland. BYDV risk is higher in fields close to the sea and in fields in which the surrounding land use is dominated by arable land[206]. 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. Selecting low risk locations is also important for wireworm, PCN and FLN management in potatoes, particularly in relation to soil sampling (see sections 5.1.1 and 5.3.2 for further details).

5.2.3. Spatial separation

Some pest species are relatively immobile and do not travel long distances between host crops in a single season. Wide spatial separation between host crops in successive years can make it difficult for the pest to find the crop. For example, brassica pod midge (*Dasineura brassicae*) is a relatively weak flyer so rotating oilseed rape around the farm can reduce the impact of the pest. A similar approach can also help to reduce the risk from both OWBM and yellow wheat blossom midge (YWBM, *Contarinia tritici*). It is also recommended that spring sown oilseed rape be situated away from sites where turnip sawfly (*Athalia rosae*) can overwinter, such as autumn sown oilseed rape, to minimise damage from this pest.

The main virus of concern for seed potato growers and industry is PVY, in particular the strain PVY^{NTN}. This virus causes direct yield losses as well as tuber blemishes and cracking. Effective virus management requires an understanding of the relationship between vector and virus, with control of the vector being the primary target for management strategies. Current guidance for PVY management recommends high grade seed crops to be isolated and away from fields with volunteers and to plant away from fields where volunteers have not been controlled[40].

5.3. Pre-cropping

5.3.1. Control volunteers and weeds

Volunteer potatoes can act as hosts or reservoirs for PCN, spraing and aphids/aphid-borne viruses [53]. Control of volunteer potatoes are unlikely to have a significant effect where PCN infestations are high but may help to maintain infestations at a low level from one crop to the next. A wide range of weed species can also act as alternative hosts for tobacco rattle virus which causes spraing in potatoes.

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[562]. Ensuring a clean stubble before preparing the seedbed can help minimise this risk as can leaving at least five weeks between ploughing and sowing the new crop. If the period between cultivation and sowing is less than five weeks, then applying a desiccant herbicide is likely to be beneficial (HGCA, 2003).

5.3.2. Biofumigation

Biofumigation is the suppression of soilborne pests, pathogens and weeds by toxic gases emitted from organic material. In the UK, this typically involves growing brassica green manure crops. The most common species are Indian mustard (*Brassica juncea*), rocket (*Eruca sativa*) and oil radish (Raphanus sativus). The usual growing period is 8–14 weeks within a mid-July to early November window. Biofumigant crops are then macerated and incorporated as they reach early to mid-flowering[15]. Most work on biofumigation in arable crops has concentrated on nematode control in potatoes particularly PCN where alternatives are being sought to broad spectrum soil-applied nematicides. Results have been inconsistent and a lack of detailed information on how to get the best results from biofumigation have led to limited uptake of this technique, although some of these issues have been previously addressed[529]. Biofumigation is also a potential control measures for other soil pests such as wireworms.

5.3.3. Early harvest

Early harvest can reduce the severity of pest damage in some crop/pest complexes but may result in reduced yield. For example, wireworms feed voraciously in potatoes throughout the autumn. Harvesting potato crops at risk from damage as soon as the crop is mature has been shown to reduce the level of damage[474]. Similarly, if potatoes are being attacked by slugs, early harvest can prevent further damage.

5.3.4. Flooding

It has been demonstrated that flooding soils can reduce populations of soil-borne pests[51,293]. The technique has rarely been adopted in the UK as it is only suitable for use in very flat terrain where water levels can be controlled but it has been used against PCN in potatoes[496]. Flooding has also been investigated for control of wireworms, where flooding during summer months has been shown to provide more effective control of the pest than flooding in winter. Greater soil salinity may also increase the effectiveness of flooding as a wireworm control strategy[534].

5.3.5. Hygiene and prevention

Potato seed production in the UK is undertaken under the strict regulation of the Seed Potato Classification Scheme. The SPCS is administered by SASA[470] in Scotland, and by APHA in England and Wales and these two authorities work together to ensure seed crops are multiplied under the official classification for each generation of seed. This scheme ensures that seed potatoes are guaranteed to be free of potato viruses which are transmitted by aphids and also of PCN. Outgrade piles are an important source of aphid-borne viruses in potato. Controlling haulm growth on dumps or covering the dumps is an essential part of the national guidance for virus management[40]. Small quantities of tubers discarded on fields can have the same impact, if not more, given their proximity to the current crop[53]. Early sources of virus should be removed before they can contribute to virus spread[40].

5.3.6. Primary cultivations/crop residue burial

Undisturbed trash or crop residue can provide shelter and food for pests such as slugs[325]. Prompt destruction of crop residues can prevent such materials aiding the survival of pests between crops. Primary cultivations can reduce numbers of soil pests but are less effective than secondary cultivations which are designed to produce a good seed bed. It is possible that some pests, such as the larvae of frit fly, will be buried by ploughing and subsequently be unable to migrate up from soil depth to feed on developing crops.

Soil cultivation kills slugs directly, but also increases opportunities for predation by vertebrates, exposes their eggs to desiccation, and removes organic matter from the soil surface, which can encourage their feeding[223,438].

Leatherjacket numbers are reduced significantly by cultivations. In cropping systems that use fertility-building grass leys, the ploughing up and cultivation of the ley prior to drilling with a spring cereal can reduce populations by up to 70% but it is advisable to plough as early as possible (July) and bury herbage well to limit carry-over and prevent egg laying by the current year's generation of adults[77]. With repeated annual cultivation, populations are reduced to low levels within two years[77].

5.3.7. Secondary cultivations (drilling method)

The mechanical action of cultivations can reduce soil populations of pests such as leatherjackets, slugs, wireworms and chafer grubs (e.g. *Melolontha* spp.)[431,570].

This can happen in a number of ways:

- Physically damage pests so that they die or bury them so that they find it difficult to access the crop
- Bring them to the soil surface where they can dehydrate and die
- Bring them to the soil surface where they are easily preyed upon by birds

In general, the more violent the cultivation method the more effective it is at controlling pests.

Cultivations also reduce soil moisture and thus reduce pest mobility and reproduction. However, increased tillage increases carbon footprint[182] and may harm natural enemy populations[406].

A number of factors associated with drilling can reduce slug damage. Direct drilling in dry conditions can maintain a consolidated soil and limit slug damage by limited access to the seed. However, the same strategy in wet conditions may produce slots in the soil that give slugs easy access to seeds. In general, direct drilling will help to maintain soil moisture which will in turn benefit germination and establishment. Crops that establish and grow away quickly are most likely to be sufficiently robust to tolerate some level of pest attack.

Depth of drilling can also have an impact on slug damage. Winter wheat seeds should ideally be drilled at a depth of about 30–40 mm to minimise slug damage[224,225]. Sowing deeper than this has been found to increase the risk of damage because deep drilling has a generally deleterious effect on establishment and so will tend to result in greater susceptibility to pest attack.

Establishment methods that minimise soil disturbance have been anecdotally reported to result in low levels of CSFB damage (L. Cotton, pers. comm.). Robust trial data is sparse; however, in an unreplicated trial, it was found that establishment methods with the lowest soil disturbance had lower adult CSFB damage and higher plant counts during establishment and fewer larvae in the autumn[239]. It has been suggested that the benefits of low soil disturbance establishment methods are due to the retention of soil moisture, which improves crop establishment, that CSFB are attracted to disturbed soil (for which there is no evidence currently), and because cultivations can harm ground beetles populations[260,263,407,435].

Recent comparisons of the effect of different tillage practices on occurrence of OWBM show that the most aggressive tillage methods cause the greatest reductions in OWBM numbers[570].

5.3.8. Seed rate (including variable seed rate)

Increasing cereal seed rates can compensate for the loss of plants to pests such as slugs, wheat bulb fly or wireworms[61,446]. The relative cost effectiveness of increasing seed rate or applying slug pellets to combat slugs in winter wheat and oilseed rape has been investigated[299]. For wheat sown at a typical commercial rate of 300 seeds/m^2 (or more), increasing seed rate did not give a greater gross margin than either treating the crop with slug pellets or leaving it untreated. For wheat sown at lower seed rates of 200 seeds/m^2 after September, increasing seed rate by 40 to 60% was best for slug pressures causing up to 40% plants lost, after which it was best to use a combination of greater seed rates and slug pellets.

For hybrid oilseed rape sown at 40-100 seeds/m^2, increasing seed rate never gave a greater gross margin than either slug pellets or leaving the crop untreated. For open pollinated commercial oilseed rape sown at 40 seeds/m^2, increasing seed rate by 80-100% was as, or more, cost effective than using slug pellets for low to moderate slug pressure (20 to 50% plants lost to by slugs). There was no benefit at 60 seeds/m^2 or more. For open pollinated home-saved oilseed rape sown at 40 to 60 seeds/m^2, increasing seed rate was as, or more, cost effective than to use slug pellets for low to moderate slug pressure (20 to 60% plants lost to slugs). There was no benefit at 100 seeds/m^2 or more.

For open pollinated commercial or home-saved seed sown at 60 seeds/m^2 with high slug pressure (>60% plants lost to slugs) the best gross margins were achieved by increasing seed rate by 40-80% and using a single application of slug pellets. At 40 seeds/m^2, it was best to double the seed rate and use slug pellets. It was also interesting to note that up to about 40% loss of plants to slugs it was equally cost effective to do nothing than apply molluscicide pellets or increase seed rate suggesting an inherent tolerance to loss of plants.

Seed rate can also be used to combat wheat bulb fly by calculating a seed rate sufficient to account for some loss of plants due to the pest[334,505]. This is covered in more detail in section 4.3.4 Decision Support Tools.

The potential to use seed rate to combat cabbage stem flea beetle (CSFB, *Psylliodes chrysocephala*), has also been investigated[553]. It was hypothesised that increasing seed rate would reduce CSFB damage by diluting the number of pests over an increased number of plants. However, while there was some suggestion that damage from adult CSFB was lower at high seed rates, this was not consistent across the trials. Further, increasing seed rate had little effect on the proportion of plants lost to adult CSFB. It was concluded that to ensure optimal plant populations are achieved, small increases in seed rate could be used in high CSFB pressure situations or when moderate CSFB pressure coincides with dry conditions at establishment.

Seed rate had no effect on larval damage or populations, with similar larval numbers found regardless of seed rate or plant population (Figure 5.1). This is surprising as, assuming that each plot experienced similar levels of adult CSFB pressure and in turn egg-laying, it would be expected that higher larval numbers would be recorded in plots with fewer plants. It has been suggested that larval infestations are regulated in a density-dependent fashion, either through higher levels of mortality in over-infested plants or by larvae dispersing to less infested plants[521]. Alternatively, adult CSFB may choose to avoid laying eggs around plants that already have high numbers of eggs around them or have high larval infestations. Increasing seed rate did increase the numbers of larvae/m^2 so potentially increases the pest risk for the subsequent season (Figure 5.2).

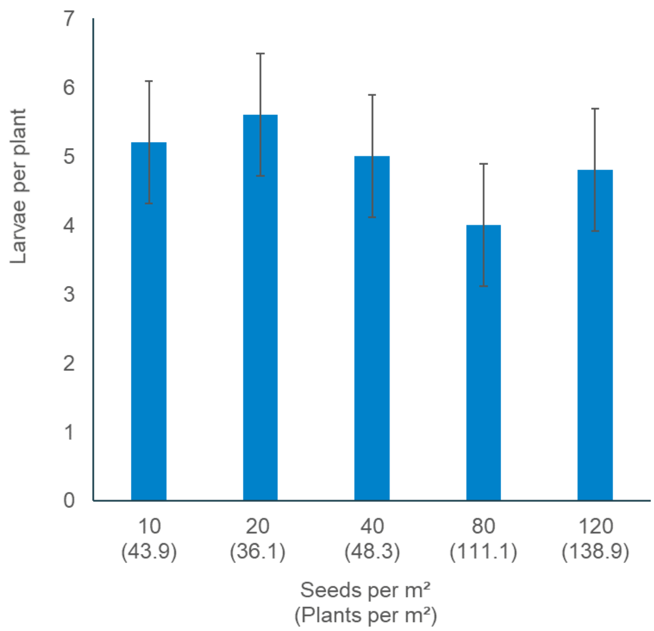

Figure 5.1 Impact of increasing seed rate on numbers of CSFB larvae per plant

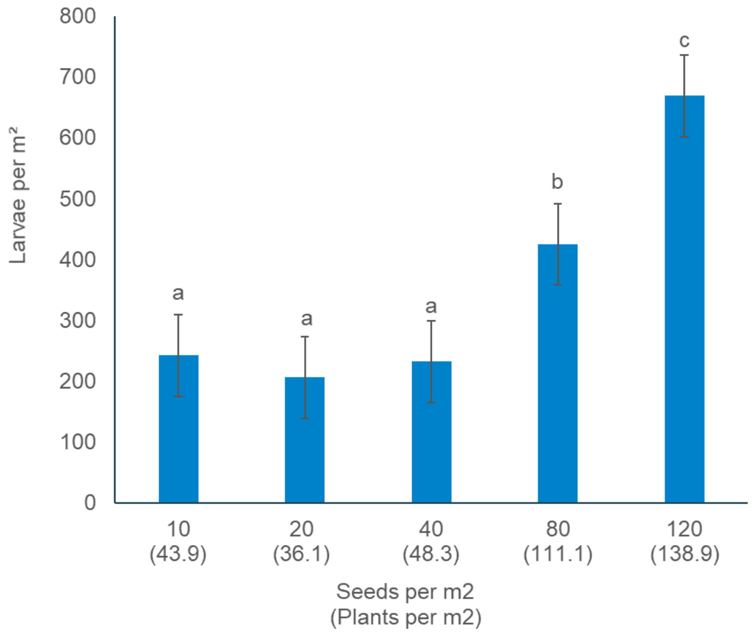

Figure 5.2 Impact of increasing seed rate on numbers of CSFB larvae/m^2

There is anecdotal evidence to suggest that reducing seed rate can help to combat CSFB larval infestations. Sowing oilseed rape to achieve about 20 plants/m^2 has produced very robust plants which are able to yield well even in the presence of substantial larval infestation. Research is underway to determine if this is a real affect or attributable to other factors.

5.3.9. Seed testing

As discussed under section 4.3.11, the Seed Potato Classification Scheme (SPCS) ensures that seed potatoes are guaranteed to be free of potato viruses that are transmitted by aphids and also of PCN.

5.3.10. Seedbed quality

Seedbed quality can have an important impact on pest damage. In poor seedbeds, there is poor seed/soil contact which can delay germination and make wheat and oilseed rape more susceptible to slugs[324,389]. Rough, cobbly seedbeds also allow slugs to access seeds underground. Firm, fine seedbeds avoid both problems and also encourage rapid germination and crop establishment, thus decreasing susceptibility to pest attack[225]. The importance of a quality seedbed containing sufficient moisture has been recognised as critical in CSFB management [553]. Dry conditions can result in oilseed rape emerging slowly and unevenly, making the crop highly vulnerable to adult CSFB damage. Dry seedbeds resulting in slowly emerging oilseed rape crops are also at greatest risk from turnip sawfly[234].

5.3.11. Sowing date

Early sowing of autumn-sown cereals and oilseed rape can allow more rapid plant establishment, which in turn can increase the tolerance to some types of pest damage. The early sowing of winter wheat can increase the tolerance of the crop to slug damage[225] and WBF [334,505]. This pest lays its eggs in bare soil from late July until early September but they do not hatch until January/ February of the following year. By sowing early, the crop will be tillering before the eggs hatch so can tolerate the loss of some tillers to WBF larval attack and still achieve its yield potential (see also 4.3.4 Decision support tools). However, early sowing of winter cereals can also increase the risk of infection with barley yellow dwarf virus (BYDV). This is simply 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 (usually about the second week of November).

Early sowing of spring oats is advised to ensure the crop has reached the resistant GS13 or beyond by mid-May when egg-laying by frit fly generally begins[80]. Early sowing of autumn crops can also reduce damage by frit fly. In a Bulgarian study on triticale, late September and early October sowings had fewer frit fly than late October sowings[316].

Early-sown winter crops and late-sown spring crops are most at risk from gout fly. In areas where damage is prevalent, coincidence of the most susceptible growth stages with the peak oviposition period can be avoided by sowing spring cereals as early as possible and before mid-April, and by sowing winter cereals as late as possible and after mid-September.

Studies in the UK in the 1970s showed that damage from saddle gall midge was greatest when cereals were at the stem extension stage (GS 31-39) at the time of egg laying and least when at or past the boot stage (GS45)[227]. It has been reported that crops sown in September had less damage than those sown in October and attributed this to the growth stage of early sown plants being less favourable at the time when the larvae hatched[489]. Thus, backward winter-sown or spring-sown cereals are usually at greatest risk. Early sowing of cereals in high-risk areas may, therefore, help crops get past the susceptible stages before the adult midges emerge[227].

Early sowing of oilseed rape can increase tolerance to slug damage as it gives the crop chance to establish quickly before slugs start to feed[162]. Sowing early will also reduce damage from adult CSFB[61]. This was confirmed with early drilling defined as before mid-August[553]. By sowing early, crops are able to establish early, and are then sufficiently robust to withstand feeding by adult CSFB when the main period of migration occurs, usually mid-August to mid-September. However, sowing early also increased infestation of crops with CSFB larvae (Figure 5.3) as the plants are exposed to beetle oviposition for longer than late sown crops (Mid-September onwards). As a result, more eggs are laid, and hatch and the larvae develop more quickly during the warm temperatures experienced in August compared with those in mid-September.

Sowing oilseed rape early can also limit damage from pollen beetle (*Meligethes aeneus*) in the spring as plants are often beyond the susceptible green/yellow bud stage before migration of the pest begins[480].

Delayed sowing can also have an impact on pest infestation. The migration of the aphid vectors of BYDV into the growing cereal crop usually ends by about mid-November. Delayed sowing delays emergence and thereby, reduces the exposure of the crop to the risk of BYDV, particularly if emergence is after the aphid migration is over[360]. However, it may not always be practical to delay sowing. If there are large areas to drill, delaying sowing can lead to some crops not being sown at all as the soil is too wet to permit cultivations and/or drilling. In addition, delaying sowing can increase the risk of WBF damage on the east side of the England and Scotland as crops may not have started to tiller before WBF egg hatch in January or February. Cereals sown soon after the destruction of a grass ley are susceptible to the direct transfer of frit fly larvae, but if a gap of at least six weeks is left between sward destruction and drilling the following cereal crop, the larvae do not survive, and this risk is removed[225].

Delayed sowing of oilseed rape in the autumn, so that crop emergence does not occur until September, can minimise the risk of cabbage root fly (*Delia radicum*) damage because egg-laying by this species usually ceases by the beginning of September[33]. However, in recent years cabbage root fly egg laying has extended into September due to warm late summer/early autumn temperatures. Sowing oilseed rape in late August or September can also reduce risk from turnip sawfly in years where only two generations of the pest appear (a third generation is associated with a warm summer followed by a warm autumn)[170]. During warm autumns, early sown crops of oilseed rape tend to be at greatest risk from TuYV[31].

Delayed sowing reduces the risk of infestation of oilseed rape by CSFB larvae (see above & Figure 5.3). Less eggs are laid than earlier in the season, these hatch more slowly as temperatures drop and the larval development is also slower. Late sowing of oilseed rape (from mid-September) would reduce CSFB larvae pressure and may also result in lower adult CSFB damage as the crop is likely to emerge after the peak of adult CSFB migration has passed [553].

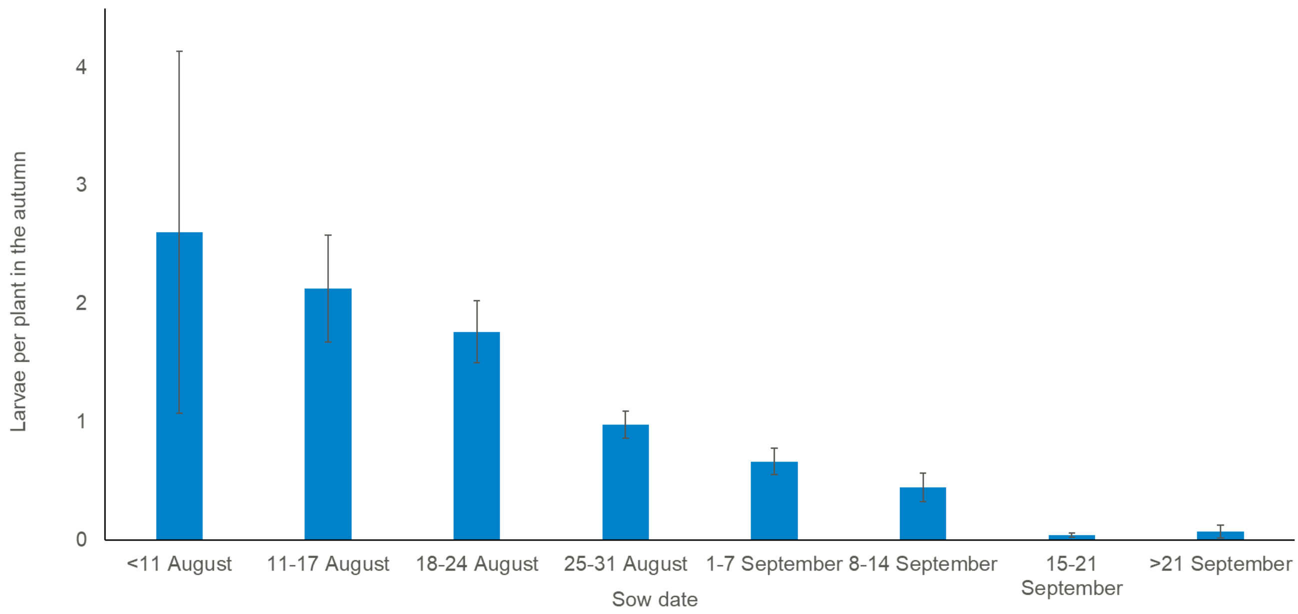

Figure 5.3 Impact of sowing date on infestation by CSFB larvae in the autumn

5.3.12. Stubble management

Limited trials work suggests that straw length influences pressure form CSFB adults on emerging oilseed rape. In general, % leaf area lost due to adult beetle feeding was less where the straw was left long (>30 cm) instead of short (<15 cm). This effect was consistent across three sites in England (F. Pickering, pers. comm.). The reason for this is unclear but it is thought that the long stubble makes it more difficult for the beetles to find oilseed rape seedlings. Also, spiders are able to spin webs between the lengths of stubble which might increase predation of CSFB adults.

5.3.13. Trap crops

Trap cropping is a method of reducing pest damage by attracting pests away from a susceptible crop and toward a trap crop. The trap crop is usually a plant stand (sown or otherwise) that is more attractive to the pest than the susceptible crop. This approach has been successfully implemented to reduce damage in commercial crops in a number of countries, including to reduce pollen beetle damage in oilseed rape in Estonia[469].

Volunteer OSR (vOSR) can be utilised as a trap crop by delaying its destruction until after the bulk of CSFB migration is complete[553]. Using this approach resulted in significant reductions in adult CSFB infestation (up to 88%) and damage (up to 76%), significant increases in plant population (up to 56%), and significant reductions in CSFB larvae (up to 69%) in newly sown WOSR in adjacent fields. An area of at least 2 ha of volunteers was required for the technique to be effective. Delaying the destruction of vOSR until late September (or later) is thought to reduce CSFB pressure in WOSR crops in nearby fields by i) being more attractive to migrating CSFB and ii) discouraging CSFB (that emerged in the previous crop) from leaving the vOSR. Additionally, as

CSFB wing muscles are thought to gradually atrophy once the beetles have arrived in a crop and mated[85], adults may have limited ability to move into WOSR crops in nearby fields when the vOSR is destroyed. Any eggs or larvae present in the vOSR at this time are very likely to die as they will not be able to complete their life cycle without finding another host.

Other brassicas are also attractive to CSFB and so brassica cover crops could also act as a trap crop[60] and, as long as these are removed before the CSFB larvae complete their life cycle (around March), would likely provide the same benefits in reducing CSFB populations. Trap crop borders consisting of sown non-OSR Brassicaceae have also been shown to reduce CSFB infestation in the neighbouring WOSR crop[60].

Use of turnip rape (*Brassica rapa*) as a trap crop, which flowers up to three weeks earlier than the oilseed rape crop, can reduce the number of pollen beetles to below threshold levels within spring oilseed rape until it is past the vulnerable pre-flowering stage. However, the success of the strategy was variable with winter oilseed rape, probably because the growth stage differential between the rape crop and the trap crop was not always sufficient[130,134 128, 129].

Trap crops are a potential non-chemical control method for PCN in potatoes. These are crops that trigger the hatch of PCN in soil but prevent the completion of the pest's lifecycle. The use of PCN trap crops dates back to at least 1939[109]. Early research focused on the use of potatoes as trap crops and limiting the length of the growing season, so that PCN juveniles invaded the roots but failed to complete their life cycle. More recently, research has also included other *Solanum* species[476]. A reduction of up to 80% of the soil population of PCN could be achieved using *S. sisymbriifolium* as a trap crop but that the severity of the initial PCN population affected the level of reduction achieved[477]. In one year of study, the reduction by *S. sisymbriifolium* in moderately to severely infested soils (2-19 juveniles/ml soil) was 77%, whilst the reduction in very severely infested soils (110-242 juveniles/ml soil) was only 52%. Black nightshade (*S. nigrum),* a native UK species, has long been known as a potential PCN trap crop. Two separate populations of *S. nigrum* showed complete resistance to *G. rostochiensis* and high resistance to *G. pallida* and also performed well under Dutch growing conditions but were not as effective as potato and *S. sisymbrifolium*[476]*.* In pot experiments in the UK, *S. nigrum* and an unspecified *Solanum* spp. showed good potential as trap crops over a three-year project and gave best control of PCN[191]. *S. nigrum* reduced PCN egg numbers by between 76% and 45% and the unspecified *Solanum* spp by between 65% and 45%. Recent work with *S. sisymbrifolium and S. scabrum* has shown problems with establishment in UK conditions[236]. In the UK, *S. sisymbriifolium* is available commercially as a PCN trap crop and is sold as Foil-sis by Branston and DeCyst by Greenvale. However, commercial uptake has been very limited due mainly to the loss of a profitable crop in the year of the trap crop[119].

5.3.14. Undersowing/companion cropping

A system was developed at IGER[287] to grow cereals, especially winter wheat, in a permanent understorey of white clover. At first, a pure sward of white clover is established, given a year's growth to build up fertility and then grazed hard during the autumn. The cereal crop is then direct-drilled into the clover. A standard Hunter Rotaseeder is particularly suited for this purpose. The cereal is grown with minimal or no nitrogen fertiliser and harvested conventionally. After harvest, the clover is allowed to recover, grazed down hard and re-drilled with cereal in the autumn or spring to repeat the cycle. The continuous presence of a crop minimises the loss of nitrogen through leaching because the roots of cereal and clover absorb any mineralised nitrogen. The presence of leaf area for the full period of growth maximises the use of solar energy.

Pest problems using the clover understorey system were much reduced, although the reasons for this are not clear. Populations of aphids were low or below the level of detection in plots where the clover was present and did not need control with insecticides. Although there is no objective evidence, it is believed that the dense year-round cover of vegetation offers a refuge for many species of predatory invertebrates. The most important of these are probably spiders, carabid and staphylinid beetles which feed on cereal aphids. Studies in Denmark recorded higher numbers of linyphiid spiders in a wheat-clover bi-crop system where winter wheat was grown in an under-storey of white clover compared with web densities estimated in conventional wheat-growing systems[233]. Also, it is known that alighting cereal aphids tend to select particular patterns of vegetation[120]. The continuous ground cover achieved with the system could reduce the number of aphids colonising the cereal crop.

Companion cropping shows potential for reducing pest pressure from adult CSFB. Companion cropping frost-sensitive legume crops with rapeseed helped to reduce damage of CSFB and rape winter stem weevil in France (RWSW, *Ceutorhynchus pictarsis*) when the biomass of the legume crop exceeded 200 g/m^2[462]. Similar results have previously been demonstrated[104]. Trials in Germany found two companion crop mixes resulted in significant reductions in adult CSFB damage compared to oilseed rape grown on its own[89]. Trials are currently underway in the UK to determine the effectiveness of companion crops for CSFB management in this country.

5.3.15. Use of cover crops

On bare fallows, a crop of mustard sown to cover the soil by mid-July will reduce egg laying by wheat bulb fly.

5.3.16. Varietal choice

Varietal resistance to pests has been found in some conventionally bred crops[458]. If agronomic/market factors allow, these varieties can be selected to avoid the use of chemical control[96]. For example, an increasing number of wheat cultivars are resistant to OWBM (Table 5.1).

Table 5.1 Recommended List varieties of wheat showing resistance to OWBM

Crop	Group	Variety
Winter wheat	UKFM Group 1	Skyfall
	UKFM Group 2	LG Detroit
	UKFM Group 3	LG Prince, LG Illuminate, LG Quasar, KWS Firefly, Merit, LG Astronomer. KWS Barrel, Elicit
	Soft Group 4	LG Skyscraper, RGT Saki, LG Spotlight, Elation. Swallow, KWS Jackal, LG Sundance
	Hard Group 4	SY Insitor, KWS Cranium, KWS Kinetic, Gleam, RGT Gravity, KWS Kerrin
Spring wheat	UKFM Group 1	Mulika
	UKFM Group 2	KWS Cochise, KWS Chilham

It is possible that using varieties resistant to OWBM might allow YWBM to increase in numbers, although there is no evidence of this to date.

A winter wheat variety RGT Wolverine is now available that is resistant to BYDV and two six-row barley varieties Rafaella (Limagrain) and Amistar (KWS) are tolerant of BYDV. This means that, although they might show some yellowing symptoms associated with BYDV infection, they are able to grow normally and suffer minimal yield loss.

An increasing number of winter oilseed rape varieties now show resistance to turnip yellows virus (TuYV, Table 5.2)

Table 5.2 Recommended List varieties of winter oilseed rape showing resistance to TuYV

Hybrid/Conventional variety	Variety
Hybrid	Ambassador, LG Aviron, Aurelia, Artemis, Temptation, LG Antigua, DK Expectation, Darling, Dazzler
Conventional	Acacia, Aspire

The AHDB Recommended Lists are a good source of information on pest resistance in both cereal and oilseed rape[29].

Information is available for potato varieties on the AHDB Potato Variety Database[23]. Resistance is provided for a range of individual pathogens on a 1-9 scale, with 1 the most susceptible score and 9 the most resistant score. For some viruses, including PVY and PLRV, resistance scores are available for almost all varieties. There are a number of potato varieties available that are resistant to PCN, spraing (transmitted by stubby root nematodes), PVA, PVY, and PLRV. These are listed on the AHDB Potato Varieties database https://varieties.ahdb.org.uk/varieties. The number resistant to the yellow PCN (*G rostochiensis* Ro1) are much greater than are resistant to the white PCN (*G pallida* Pa 2/3,1), although the latter is the most common PCN species in the UK. Some potato varieties are tolerant of PCN attack, which allows them to yield well in the presence of PCN, but the pest is still able to develop and multiply on the roots.

Varietal tolerance has also been investigated as a means of reducing reliance on pesticides for control of pests such as pollen beetle, and WBF. Much of this work is based on the understanding that OSR produces more buds or flowers, and wheat produces more tillers than are required to achieve potential yield. These excess buds or flowers or tillers can then be sacrificed to pests without affecting the crop's ability to achieve potential yield. Also, the ability of both OSR and wheat to compensate for loss of green leaf area have been investigated as a means of reducing reliance on chemical control[189,190]. The use of excess bud, flowers or tillers to develop robust pest thresholds are covered further in section 5.3.2. Decision Support (inc. thresholds). Tolerance to loss of green area and plants has the potential to limit unnecessary applications of molluscicide pellets and insecticides. However, methods of predicting which crops can tolerate leaf damage and plant loss by pests will be required before this can be used by farmers and agronomists.

Selecting varieties based on their characteristics can be useful in managing CSFB risk [553]. For example, choosing a variety that establishes quickly so that the crop rapidly reaches a stage from which it can tolerate adult feeding damage (typically four true leaves) will help to mitigate against CSFB. Varieties with good spring vigour may also be better able to grow away from larval feeding. There is anecdotal evidence that some varieties exhibit increased tolerance to CSFB. The importance of varietal tolerance, resistance and characteristics for CSFB management is currently being investigated in AHDB Project 21120185.

5.4. In-crop techniques

5.4.1. Bioprotection and low-risk plant protection products (PPPs)

Biological control agents include entomopathogenic fungi, entomopathogenic nematodes, bacteria and invertebrate 'macro-organisms' that are mass-produced or reared and then applied or released for the control of specific pests[185].

Biopesticides include micro-organisms e.g. fungi, bacteria, protozoa or viruses and plant extracts that can be used as substitutes for chemical pesticides. Examples of entomopathogenic fungi approved for use in Britain include *Metarhizium anisopliae* for the control of vine weevil larvae in ornamentals and strawberry[41] and *Beauveria bassiana* for the control of various foliar pests in protected crops[348]. The bacterium *Bacillus thuringiensis*[519] is widely used for the control of caterpillars in Britain, particularly within IPM programmes in protected crops. An example of a plant extract product used for pest control is one containing maltodextrins, which acts physically by smothering the target pest, e.g. two-spotted spider mite (*Tetranychus urticae*). Biopesticides have considerable potential for increased use, but currently, only represent approximately 5% of the world agrochemical market[455], and the cost of registration is considered prohibitive by small biopesticide suppliers. While biopesticide registration has improved in many parts of the world, far fewer are registered in Europe, mainly due to the complex and lengthy registration process[152]. In general, there has been very limited if any use of biopesticides in cereals, oilseed rape or potatoes. However, recent research is investigating the potential for biopesticides for control of CSFB[256]. Work to date has concentrated on laboratory studies and encouraging results were achieved with both entomopathogenic fungi and nematodes. Highly refined paraffinic mineral oils have been shown to reduce virus acquisition and transmission of potato virus Y in potatoes[481].

There is an increasing range of commercially available invertebrate ‘macro’ biological control agents, including predatory mites e.g. for the control of mites and thrips[218], parasitoids, e.g. for the control of whiteflies and aphids[161,400] and entomopathogenic nematodes for the control of vine weevil (*Otiorhynchus sulcatus*)[41], sciarid flies (*Bradysia difformis*)[230], thrips[101] and slugs[248]. Although in Britain, introduction of biological control agents has been widely adopted in protected crops with some use outdoors, there has been limited uptake in arable cropping. This is probably because of the availability of relatively inexpensive pyrethroid insecticides which have been the mainstay of chemical pest control for several decades. However, resistance to pyrethroids is now becoming much more widespread in a range of pest species (e.g. grain aphids (*Sitobion avenae*), CSFB, pollen beetle, peach potato aphid (*Myzus persicae*) so interest in biological control is likely to increase, although the cost in broad acre crops will remain an issue.

The nematode, *Phasmarhabditis hermaphrodita*, is a lethal parasite of many slug species[225,445] and has been available as a commercial molluscicide (Nemaslug, from Becker Underwood and now BASF) since 1994[438]. However, it is expensive and, therefore, more commonly used in high-value vegetable crops rather than in arable agriculture, not least because it has to be kept refrigerated[222]. Applications at lower rates would reduce costs, and still inhibit feeding by slugs[225]. Improved targeting (e.g. through identifying field areas with slug populations – see section 5.3.6. Precision Application) would also reduce costs.

Irrigation for pest control can be considered a low-risk PPP. The best-known example of using irrigation for pest control is for the control of cutworms, the larvae (caterpillars) of various moth species but mainly the turnip moth (*Agrotis segetum*). Juvenile cutworms feed on the foliage of potatoes (and other vegetable crops) but are washed off by heavy rainfall or irrigation and then die as they cannot climb back onto the plants. The 'cutworm model' is a computer programme that uses weather data to predict the rate of development of turnip moth eggs and caterpillars[86]. It also predicts the level of rain-induced mortality among the early instar caterpillars. If heavy rainfall does not occur, the model will predict when irrigation can be used instead of a chemical pesticide to control young turnip moth caterpillars before they reach the underground-feeding stage, when they are invulnerable to control measures[351].

5.4.2. Decision support (including thresholds)

Decision Support Systems (DSS) can assist on-farm decisions to implement IPM against invertebrates. They comprise treatment monitoring, thresholds and computer models.

Pest monitoring is an essential component of any pest management programme. The most widely used method is to walk through the crop and check the plants for the presence of pests or pest damage. As visual crop inspection does not always detect pests at low densities, trapping techniques are often used to monitor for pests in both field and protected crops in addition to crop walking. Types of monitoring traps include sticky traps (with or without pheromone lures), water traps and bait traps. Sticky traps are used to monitor several pests, including OWBM, aphids and saddle gall midge. Pheromone traps with specific lures for individual pest species can be used for early detection, with the best example in arable cropping being the pea moth system[543]. Other pheromone traps are available for detection of OWBM[98] and saddle gall midge[461] in cereals and for turnip moths to predict cutworm risk in potatoes. Water traps are used to monitor a range of pests including aphids, CSFB and saddle gall midge. Pests monitored with bait traps include slugs and wireworm. For some soil-dwelling pests, soil samples can be taken to estimate the size of the population and assess the risk of economic damage to the following crop. Common examples are PCN, free-living nematodes and wireworms. For PCN, if populations do not reach action thresholds, then pre-cropping pesticide usage may be avoided[195]. It is also possible to use soil sampling to assess levels of OWBM, YWBM, saddle gall midge, brassica pod midge and leatherjackets.

The Rothamsted Insect Survey (RIS) operates a network of suction traps, comprising 16 traps across England and Scotland. These 12.2 m suction traps catch flying insects, and these are counted weekly throughout the growing season. Numbers of particular species, especially aphids, are disseminated to the industry through a text service (which can be subscribed for https://insectsurvey.com/aphid-alert .This text service replaces AHDB's Aphid News from 2021[23]. This information is also available through the RIS website (https://insectsurvey.com/aphid-bulletin) and can be used to gauge when important pest species are migrating and inform in-field monitoring effort. In potato, in addition to the suction trap network, the FERA water trap network assesses the presence of potato virus vectors in crops. This information is disseminated via https://aphmon.fera.co.uk/index.cfm or by signing up the text service (at https://insectsurvey.com/aphid-alert). Information from water trap network can be used to inform virus management decisions in potatoes, such as insecticide treatments and timing of crop burn down.

Monitoring can avoid the use of routine pesticides e.g., if no pests are found, or if numbers are below the current treatment threshold. However, the thresholds for many UK pests of arable crops lack scientific provenance and require review[443]. Some work has been done on pollen beetle thresholds in OSR. A dynamic threshold scheme in which the treatment threshold is no longer a single value for all crops has been suggested[192]. This was based on the understanding that OSR produces more flowers than it needs to achieve its potential yield. These so-called excess flowers can be sacrificed to pollen beetle without affecting crop yield. The pollen beetle threshold varies in relation to the number of excess OSR flowers produced by different varieties in different seasons. This is an important change in the developmental approach to thresholds which has potential for application to other pest/crop interactions.

Currently, there are very few simulation models in use that predict risk and inform IPM interventions in cereals oilseeds and potatoes. Exceptions include the cutworm model in potatoes[86], the pea moth model[420], a pollen beetle model[128] and a day degree model for use in BYDV management. The pollen beetle DSS is based on a German model that was validated over several years in the UK[128] and was freely accessible through the AHDB and Bayer websites[170] but appears to be no longer available. For control of BYDV vectors (*Sitobion avenae*, grain aphid, and *Rhopalosiphum padi*, bird cherry-oar aphid) with insecticides, the current advice is to target the second-generation offspring of the aphids in the crop as these are associated with secondary spread of the virus within the crop and greater levels of infection. The second generation appears after approximately 170 'day degrees' have accumulated (using daily average air temperatures above 3°C). In 2018, AHDB developed a BYDV management tool that incorporated this day degree model to help time sprays more effectively against cereal aphids in the autumn[24]. The same tool is available through other websites e.g., Syngenta and Bayer. However, as the tool advises calculations to start on the day of crop emergence (or following a pyrethroid application), it 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 through 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[466]. These are being updated and tested as part of a current AHDB project[P101]. Models for other pests have been developed in Europe, such as for CSFB[284], but these require validating or altering for UK maritime climates.

DSS models have been developed for other pests but are little used in arable crops. These include emergence models for cabbage root fly[301] and saddle gall midge[460]. A recent study developed a decision support tool for WBF control[505]. Prototype guidelines summarised how sowing date and plant population should be adjusted, and insecticide seed treatments targeted, for different WBF risk situations. This is particularly valuable as chemical control of WBF is now reliant on a single seed treatment which is only effective for crops sown from November onwards. Most wheat is sown before this cut-off date and these crops have no current chemical control options. A similar approach could be used for other stem mining pests of cereals e.g., frit fly and gout fly. Further work has investigated the potential of a model based on meteorological variables to predict WBF risk well in advance of sowing[334]. In high-risk years, sowing date and/or seed rate could then be used to combat the pest despite the limited availability of chemical control options.

There are some excellent examples of crop protection DSS across Europe which are well tested and implemented, but the impact of DSS has been constrained by a number of factors[444].

- Regional fragmentation of DSS development and user communities, limiting awareness and access to what is available.
- Lack of quantification of the economic and environmental benefits of using DSS - often limited by access to sufficiently large datasets across a wide range of sites and seasons
- Inadequate testing of DSS for accuracy and predictive value (also data limited)
- Short-term funding curtailing long-term updating and user support
- DSS addressing single pests, whilst farmer decisions need to account for multiple pests
- DSS which are insufficiently risk-averse to meet farmer needs for protection against economic loss

A Horizon 2020 project Stepping-Up Integrated Pest Management Decision Support for Crop Protection 'IPM Decisions' 2019 -2024 (managed by ADAS) is currently underway. This will bring together expertise and resources to address those factors constraining DSS use and will deliver DSS, data, tools and resources through a pan-European online Platform and an IPM Decisions Network.

There is good potential for DSS models to improve management of a number of important arable pests. For example, the ability to predict the emergence and flight of brassica pod midge adults would allow for insecticides to target the midge rather than cabbage seed weevil, which are currently sprayed to prevent them making the entry hole in pods that allow the midge to lay larvae.

5.4.3. Defoliation (including mowing and grazing)

Defoliation is a method that has been used to combat CSFB larvae in oilseed rape[553]. There is strong evidence that defoliating the crop in the winter reduces larval numbers, with reductions of up to 75% being recorded, but the impact on yield in trials has been mixed. There have been yield losses of up to 1t/ha, but some farmers are likely to persist with this technique as it reduces the carryover of the pest into the next season (White, pers comm). Crops can be defoliated using a flail or by grazing with sheep. This approach is best suited to early drilled crops which will have the highest larval numbers but also be best able to recover from the defoliation. Do not defoliate after stem elongation. Crop recovery is strongly affected by spring weather, which cannot be predicted in the winter. Sheep have also been used to graze cereals in the UK[228] and this would remove cereal aphids.

5.4.4. In-field non-cropped areas

Diversifying the range of plants grown in-field can increase the populations and activity of beneficial insects. Natural enemies of insect pests play an important role in IPM programmes for many important pests e.g., ladybirds, lacewings, hoverflies and parasitoids contribute to aphid control in cereals, oilseed rape and potatoes. These natural enemies will become more important as reliance on the use of insecticides declines.

Beetle banks consist of stands of wildflowers and grasses introduced into arable fields. They are used by some growers in the UK and are designed to act as reservoirs of beneficial insects such as ground beetles and parasitoids, which help to provide natural biological control of aphids[124] and other insect pests[495]. However, they may not be as effective as naturally diverse crop margins[215].

Selected mixed vegetation in crop margins or strips within crops can perform various ecological functions such as conservation of native flora and fauna including pollinators and pest natural enemies[517]. This is currently a popular subject for research, but although much data has been generated on increased incidence of natural enemies and greater biodiversity in the margins, there is much less on associated reductions in numbers of pests or crop damage. Although increased plant diversity can enhance the survival and reproduction of predators and parasitoids, it does not necessarily result in reduced pest numbers and some of the plant species used to benefit natural enemies could even provide additional benefits to pests[540]. Current research is being done on the selection of plant species to include in field vegetable[215] and arable crop margins (EcoStack, a current, EU-funded project), which give both biodiversity and pest control benefits.

5.4.5. Organic amendments

The addition of organic amendments (e.g. slurry, poultry muck, digestate, biosolids) to the crop around establishment have been anecdotally reported to reduce adult CSFB damage [553]. This has been attributed to the smell of the organic amendment either deterring CSFB or interfering with the ability of the beetle to find the crop, or by improving crop growth through the provision of nutrients. However, trial data to support the benefit of organic amendments is sparse and is currently being investigated in AHDB Project 21120185.

5.4.6. Precision application

Work has been attempted to use the patchy distribution of slugs to help improve the precision of molluscicide pellet application and reduce the quantity of material applied[205]. Soil characteristics such as organic matter, pH, bulk density and soil texture were found to be possible indicators of slug patches. The movement of individual slugs was also studied to improve the understanding of patch formation. The combination of results from this work suggested there is strong potential for targeting molluscicides to areas of higher slug densities, although further work is required. There is potential to use precision application methods in other pests, for example, brassica pod midge is a weak flyer, meaning that often only crop headlands are affected[259]. Therefore, insecticides applied to headlands may be equally as effective as applying to the whole field.

5.4.7. Rolling soil post-planting

Rolling soil post-planting can improve the seedbed quality, resulting in more rapid germination of crops, reducing access of soil-borne pests, such as slugs, to seeds[158] and improving tolerance to foliar damage, e.g., CSFB[553]. Rolling may also kill some pests or reduce their mobility.

6. Lodging

6.1. Current status

Lodging is the permanent displacement of plant stems from their vertical position and can occur in all cereal species and oilseed rape. Lodging is a complicated phenomenon that is influenced by many factors including wind, rain, topography, soil type, previous crop, crop husbandry and disease. It is frequently associated with conditions that promote plant growth such as an abundant supply of nutrients. Lodging may occur by two mechanisms: stem lodging (failure of the lower stem) and root lodging (failure of the root/soil anchorage system). Another form of lodging is 'brackling' which results from buckling of the upper part of the stem and becomes more likely close to the time of harvest. The risk of stem lodging is influenced most by changes in crop height and stem strength, whilst the risk of root lodging is affected most by changes to crop height and the strength of the anchorage system.

Widespread lodging occurs on average every three to five years. Lodging surveys have shown that in a widespread lodging year about 16% of the winter wheat crop lodges resulting in costs of £120 million[73], and 27-35% of oilseed rape lodges resulting in costs of £47 to £120 million[300]. Costs of lodging result from loss of yield, quality, extra drying and time to harvest.

Whilst there is no curative solution, the risk of lodging can be significantly reduced by changes in crop and soil management that affect plant growth habit and soil strength. The most common approaches by which farmers minimise the risk of lodging is by choosing varieties with a high resistance to lodging score and the use of chemical plant growth regulators (PGRs). The primary mechanism by which PGRs reduce the risk of lodging is by reducing crop height and thereby, the leverage exerted on the supporting stem and anchorage system.

In 2018, PGRs were applied to 90% of winter wheat, 83% of winter barley, 71% of winter oats, 42% of spring barley and 14% of winter oilseed rape[213]. It should be recognised that for oilseed rape, two fungicide active substances (tebuconazole and metconazole) have growth regulatory activity and are often used to regulate growth in addition to controlling disease. In 2019, there were 855,000 spray ha containing tebuconazole and metconazole out of a total oilseed rape area of 583,000 ha of oilseed rape (the vast majority being winter oilseed rape)[213]. Therefore, it is probable that the majority of oilseed rape receives a chemical product with growth regulating activity. Typically, PGR treated cereal crops receive 1 or 2 PGR applications. Winter wheat and winter barley crops receive two or three PGR products, whereas spring barley and winter oats receive one or two PGR products. The most commonly used active substance on cereals is chlormequat which accounts for 30 to 50% of PGR applied[213]. The active substance trinexapac ethyl is the second most commonly applied product accounting for 25-30% of PGR applied.

6.2. Crop planning

6.2.1. Field history, rotation and break crops

Root lodging occurs when the soil surface is heavily saturated as this leads to a reduction in soil strength[144]. Saturation is more likely to occur after heavy rainfall events in silty and clay soil, which are less porous[67], or lighter soils where drainage is impeded.

High levels of soil N (SNS index 3 or above) promote thick, dense crop canopies that are more susceptible to stem lodging, and to a lesser extent root lodging, with early sown crops being the most affected[66]. Frequent use of manures or high residue crops such as field vegetables can both lead to high soil N residues.

Not all fields or parts of fields are under the same risk of lodging, as localised wind conditions play a significant role on seasonal lodging risk. Factors such as surface roughness, thermal stability and topography affect wind speed and direction and hence, the force applied to the crop by the wind have been described[211]. Figure 6.1 shows the effect of topography, with highest wind speeds on hill crests and downward forces on the leeward side increasing lodging risk. These factors have been incorporated into the lodging model later described[75].

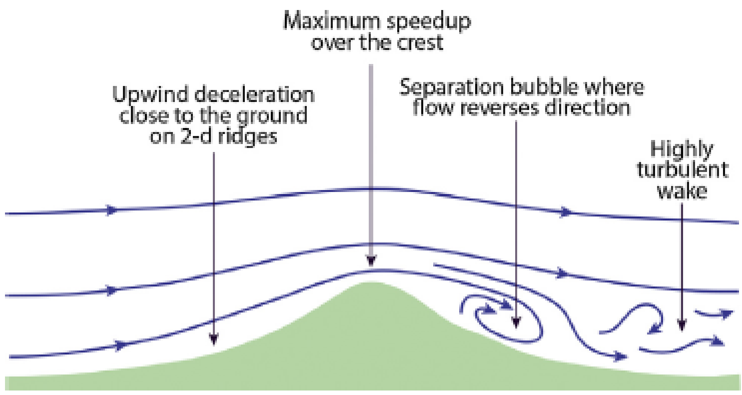

Figure 6.1 Flow over a two-dimensional ridge[276]. Illustration by Kana Kamimura

6.3. Pre-cropping

6.3.1. Pre-cropping nutrition

The effects of phosphorus on lodging resistance have been reviewed in wheat and oats and found that there was little evidence of any consistent effect of phosphorus on lodging resistance[L44]. Whilst phosphorus additions had increased the breaking strength of stems of stems and roots in some experiments, others suggested increased lodging risk through the enhancement of nitrogen uptake. Whilst it is commonly agreed that phosphorus addition to deficient soils promote root growth, the major effect is on the smaller fibrous roots in maize and oilseed rape and not those involved in plant anchorage[345].

The role of potassium has been investigated and indicated that it can reduce lodging in wheat when repairing a deficiency and additional amounts have no effect[429]. This may be due to the important role that this element plays in regulating the turgor of plant tissues. Potassium has been found to increase the stem strength in wheat in a high nitrogen situation (300kg/ha N) but had no effect where nitrogen supply was moderate (180kg/ha N)[310]. They concluded that high NH_4 in the plant can inhibit uptake of K, leading to reduced stem strength. There is no evidence that Potassium applied above normal plant requirement has any effect on lodging.

6.3.2. Variety choice

The most reliable score for a variety's risk of lodging is given on a 1–9 score and is included in AHDB Recommended Lists. Varieties with a score without PGR of 7 or less can be considered "at risk" under normal UK conditions. This 'at risk' category currently accounts for 86% of Winter wheat varieties, 60% of Winter barley and 100% of spring barley. For oilseed rape, there is little variation in lodging scores within the recommended lists, with all but one having a lodging resistance rating of 8.

Whilst there is currently a limited choice of lodging resistant varieties, especially as factors such as resistance to disease or pests may be higher on a farmers priority list, recent advances in plant genetics offer opportunities to provide wider variety choices for lodging resistance

The genetic regulation of height has contributed significantly to improvement of crop productivity, especially in wheat and barley, by reducing stem elongation to improve lodging resistance and enhance partitioning of resources to the inflorescence[250]. In wheat, these benefits have largely been provided by the semi-dwarfing genes[415]; however, due to their effects on seedling emergence, spikelet number, grain weight, and quality (for example), research has continued to investigate novel sources of genetic variation for height. Wheat varieties have been shown to vary substantially for stem strength and anchorage strength[68]. Useful genetic loci have been associated with variation in stem strength and anchorage strength traits in wheat[72]. Ideotype design has indicated that there is scope to breed for high yielding wheat which is very resistant to lodging by optimising height with strong stems and strong anchorage[74]. However, there is little evidence of breeding for the stem or root traits which can confer lodging resistance.

In oilseed rape, current strategies aimed at minimising lodging risk involve the incorporation of dwarfing genes. The loci identified for stem mechanical strength and plant height have been found to be independent which may provide breeders with the opportunity to select phenotypes in combinations that better suit breeding aims[377]. Whilst it is not in the remit of this review, new approaches to identify specific lodging resistance traits can be a major contributor to non-chemical control of lodging[427,428].

6.3.3. Variety mixtures

The practice of mixing cultivars is a strategy to simultaneously grow several cultivars that have dissimilar trait expression (yield potential, drought tolerance, disease and insect resistance) but share enough resemblance (maturity, height, quality, or grain type) to be amenable to large-scale agronomy and marketability[556].

Cultivar blends are mixtures of two or more cultivars which can be used as an alternative to sole crop cultivars to provide advantages such as disease protection and acceptable yield production under variable environmental conditions and stresses (including lodging pressure). In order to be commercially acceptable. Components of blends must have uniform maturity and be compatible for end-use processing. The performance of two winter wheat cultivars in different ratios over three years has been compared[279]. When lodging occurred, blends had intermediate levels of lodging compared to sole crops. The 2:1 blend (low:high lodging) had significantly less lodging than sole high lodging cultivar. As proportions of the high lodging crop increased, the score approached that of sole crop. There was no yield disadvantage to using blends compared to the sole crop of each cultivar. Similar responses were seen in rice but using cultivars of differing maturity dates[409].

6.3.4. Primary cultivations

The use of minimal cultivations or direct drilling to prepare seed beds has been shown to reduce lodging in cereals compared with more traditional methods which usually involve ploughing to about 20 cm depth[188]. It seems likely that observations for direct drilling or minimal cultivations to reduce lodging are mainly caused directly by increased soil strength resulting from greater bulk density[201,475]. The common observations for high bulk density to impede root extension and increase root thickness[357,554], appear to be restricted to sections of the cereal root system that play little part in anchorage, namely, the seminal roots or the distal sections of the crown roots. Another experiment which showed an increase in lodging under intensive and reduced cultivations compared to direct drilling was attributed to eyespot, which highlights one of the difficulties in interpreting this type of large scale experimentation[434].

There is little information on the effect of cultivations on lodging in oilseed rape but a comparison of three cultivations, farm standard, intensive and reduced tillage regimes on winter oilseed rape and found that the reduced cultivation treatment had a higher root lodging resistance than highly intensive tillage[317].

6.3.5. Seed rate

Establishing 200 plants/m^2 compared with 400 plants/m^2 reduced lodging risk by increasing the strength of the anchorage system by more than 50% and the strength of the stem base by 15%[66]. The increase in anchorage strength more than compensated for the increased shoot number on these plants. The greater anchorage strength has been attributed to several morphological changes, including more roots per plant[184], stronger and thicker roots[183], and a wider and deeper root cone[66]. Increased stem diameter, wall thickness and lignification in plants sown at lower densities in the range of 75-375 plants/m^2 has previously been shown[572] .

In oilseed rape, lodging resistance increased with plant populations up to 30 plants per m^2 but decreased with further increases in density[304].

There is substantial scope to reduce the plant population of wheat and oilseed rape crops below what is normally targeted without reducing yield potential[456,497].

6.3.6. Seedbed quality

Whilst there is no direct evidence of seedbed quality affecting lodging, a poor seedbed will affect the number of plants established (section 6.3.5) and may limit sowing depth.

Field experiments comprising three wheat varieties sown at different depths revealed that the relatively deeply sown seeds up to 6–7 cm had better soil anchorage with reduced lodging, this was confirmed in spring wheat[32,442]. Sowing shallowly at 30 mm or less has been shown to result in more shallow anchorage than sowing more deeply at 55 mm[70]. Plant height was also affected by deep planting and reduced after deeper sowing of wheat seeds up to the optimum level, which indicated less risk of lodging[485].

6.3.7. Sowing date

Late sowing of winter wheat can substantially reduce the threat of lodging in wheat, particularly by shortening the internode lengths, plant height, and culm length at the centre of gravity, and via increasing culm wall thickness, diameter, and grain filling duration[151].

For example, delayed sowing by only two weeks could decrease the risk of wheat lodging by up to 30%[498]. Wheat cultivated during the first weeks of September and December has been reported to show heights of 94 cm and 66 cm with 6.2 and 4.8 extended internodes, respectively[308]. Sowing winter wheat 6 weeks earlier has been shown to increase both root and stem lodging risk by increasing the base bending moment of the shoot by about 30% and by reducing the strength of the stem base and the strength of the anchorage system by about 50%[66]. Early sowing results in a greater number of extended internodes, and this probably caused the longer stems which gave rise to the greater base bending moment[501]. It should be recognised that sowing late (after mid-October) usually reduces yield[498].

The root systems of oilseed rape from later planting dates generally had few or no lateral roots that can resist a certain breaking force, because the diameter of laterals are generally less than 0.7 mm[558]. The smaller lateral roots had lower bending strengths and did not contribute greatly to plant anchorage. Conversely, the early planting date had larger taproot systems which were always accompanied by several large lateral roots, known as secondary branch roots, which emerged from the base of the stem and pointed radially outwards and tapered downwards). The lateral roots with large radii and larger angular spread away from the vertical near the onset of the stem base and further branched, resulting in many tertiary roots. Therefore, the simple tap root structure without large lateral roots attached that resulted from the late planting date was not well anchored. Conversely, the early drilled crop was well anchored by multiple strong lateral roots with great angular spread away from the vertical resulted in greater anchorage. No differences were found in stem strength.

6.4. In-crop techniques

6.4.1. Bioprotection and low-risk plant protection products (PPPs)

There is evidence of mechanical benefits from silica applications: Silica (Si) can accumulate in cell walls forming phytoliths and strengthen stems, resulting in reduced lodging[335,346]. Phytoliths are formed in cell walls when silica (SiO_2) is deposited into polymerised SiO_2[473]. Similar effects have been seen in soybean when silicon was applied as a foliar spray during the seedling stage[267].

6.4.2. Biostimulants

Biostimulants are products based on micro-organisms, plant extracts and other natural compounds. The properties and modes of action of commercially available biostimulants have been extensively reviewed[506]. Whilst there is no data available that directly links to lodging resistance, many products demonstrate improved root growth and stem modifications that could contribute (either positively or negatively). Many of the studies reported have been carried out in controlled environment conditions so, although they demonstrate that effects are occurring these may not translate to field conditions[411].

6.4.3. Decision support (including thresholds)

Modelling has a huge potential to predict lodging risk to avoid unnecessary use of PGRs and better target IPM solutions. Currently, there no commercially available models to predict lodging risk, so farmers have to rely on personal on-farm observations in previously lodged crops to identify 'at risk' areas. There is increased research interest in mapping the occurrence and location of lodging events using Multi spectral and Hyperspectral as well as LiDar/RADAR, from satellites, aircraft and drones, but this is not commonly available on a farm scale. Furthermore, as it is only applicable after lodging has occurred, it has limited predictive value to guide management decisions. This area of research has been comprehensively reviewed[508].

A Crop Failure Assessment Due to Lodging Losses (CROPFALL) framework to calculate lodging risk using information about topography, land cover, soil type and meteorological data, combined with a mechanistic model of lodging, and crop parameters at a regional, farm, field and sub-field scales has been outlined[75] (Figure 6.2). This has the potential to be developed into a commercial service for predicting lodging risk and targeting preventative measures.

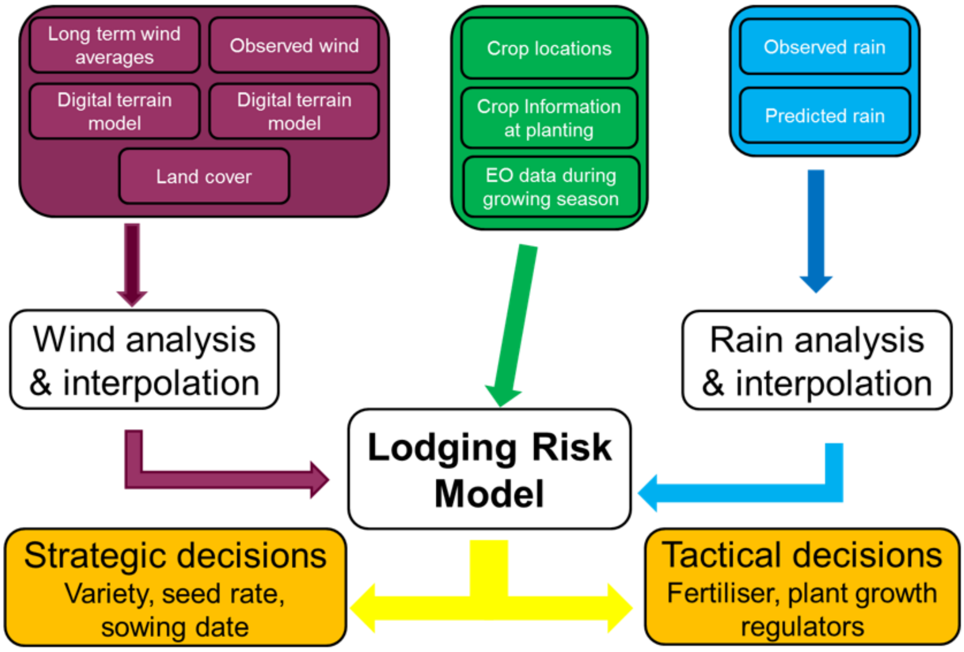

Figure 6.2 Outline of the CROPFALL decision support system for predicting lodging risk

Green area Index has been used as an in-season indicator of lodging risk in cereals and oilseed rape. For oilseed rape, a GAI over 1.0 at green bud, or 2 at yellow bud is deemed sufficient for lodging prevention measures[13]. Similarly for wheat values of a GAI above 1.0 at GS30 indicates an above average risk of lodging[71].

6.4.4. Nutrient management

Increasing the nitrogen supply to winter wheat, through either greater amounts of soil residual nitrogen at sowing or through larger applications of fertilizer in the spring[66] has been shown to reduce the strength of the stem base and, to a lesser extent, reduce the strength of the anchorage system[145]. Increases in crop height were generally small. Reductions in stem strength could be as much as 50% when high levels of residual nitrogen were combined with applications of fertilizer early in the spring[66]. Greater nitrogen supply almost always decreases the dry weight per unit length of the basal internodes of wheat[66,144] and barley[552]. In relation to this, stem diameter and stem wall width are also frequently reduced. High levels of residual nitrogen have been shown to reduce the strength of the stem wall material[66]. Reductions in anchorage strength in response to more nitrogen can be linked with fewer roots, which are thinner with smaller bending and tensile strengths[145. 183].

In oilseed rape, work has shown that as the rate of N applied increases, initially stems are strengthened and lodging resistance increases; however, these effects reverse at N rates higher than the optimum for yield which increase lodging risk[558]. The converse trend between seed yield and anchorage strength to N application, implied that lodging could be a major constraint for yield performance under high–yielding conditions. Use of organic manures with high or variable N content (especially digestate) can lead to over application because of difficulties in accurately assessing nitrogen content, which in turn increases the risk of over application. Indeed, Defra’s Farm Practices Survey indicates that around half of farms in England do not estimate or measure the nutrient concentrations in the manures they apply.

Lodging risk is affected not only by nitrogen rates but also by application timings. In wheat, the greatest increase in lodging is usually observed in response to early applications of nitrogen fertilizer before the onset of stem elongation, with applications after anthesis having no effect[67,376,429]. Research has been completed on a single plot trial study which indicated that a split dressing practice (N50+150) increased the lodging resistance when compared with a single application N200 treatment[558].

6.4.5. Rolling

Rolling to consolidate soil is another management practice that has been shown to reduce lodging[68,311]. This can be done immediately after the primary cultivations or can be done in autumn and/or in spring to reconsolidate the topsoil after it has been loosened by cycles of freezing and thawing.

Rolling a sandy loam in the spring has been shown to increase shear strength in the top 5 cm by 25% and this effect persisted until harvest[68]. No effects were observed on the biomechanical properties of the wheat roots. This study also showed that rolling before growth stage (GS) 30 reduced lodging but rolling after GS31 had no effect on lodging. It was hypothesized that this treatment damaged the extending stems, which encouraged extra tillering, and these extra shoots countered the effects of the stronger soil. This theory was supported by rolling experiments to break cereal stems[416]. However, some researchers have claimed that the mechanical wounding expected from rolling can reduce the length and increase both the diameter and wall diameter of basal nodes (and hence lodging resistance) by increasing lignin accumulation[482]. Others support this theory but stress the complexity of mechano-responses and their dependence on frequency, intervals and duration of the treatments[219].

6.4.6. Disease

Wheat crops with a greater incidence of eyespot (*Tapesia yallundae*), and of sharp eyespot (Rhizoctonia) brought about through inoculation had more lodging [479]. It has been shown that severe levels of either disease can reduce the failure moment of the lower internodes by between 30 and 40%, thus increasing the likelihood of stem lodging[69]. Interestingly, slight or medium levels of disease did not appear to weaken the stems. There is no evidence that take-all root disease increases the risk of lodging. Disease control is discussed elsewhere in this document but it useful to appreciate the interaction between disease and lodging.

7. 'Trade-offs' between strategies

The implementation of non-chemical control measures can sometimes have negative effects that counterbalance the benefits they bring. The tables below detail the main strategies for which significant trade-offs exist and detail the positive and negative effects of each. For clarity we have specified a directional approach for each strategy (for example, early sowing); however, the effect can be reversed. For example, early sowing is detailed below as increasing the risk of BYDV but reducing the risk of yellow rust. Conversely, late sowing can be used in cereals to reduce BYDV risk but doing so, would increase the risk of yellow rust.

Table 7.1 Non-chemical control strategies for cereals (wheat and barley), where significant trade-offs exist.

Strategy	Approach	Positive effect	Negative effect
Sowing date	Earlier sowing	Certainty of cropping Seed borne diseases Certainty of establishment Spread of workload Yellow rust Mildew WBF Slugs Frit fly Saddle gall midge	Grass weeds Lodging (wheat) BYDV Gout fly Septoria Eyespot Take-all (2nd wheat) Brown rust Lodging
Varietal choice	Selecting resistant varieties	Septoria Yellow rust Lodging BYDV OWBM	Reduced options for quality premiums
	Growing varietal Mixtures	Yellow rust Septoria Yield	Marketability Reduced access to quality premiums Timing of crop protection inputs
	Growing more competitive varieties	Weed competition	Reduced options for quality premiums
Primary and secondary cultivations	Non-inversion tillage	Reduced establishment costs Soil stability	Compaction Grassweed control (e.g. Bromes)

		Root lodging Eyespot (2nd wheat) Slugs Wireworms Frit fly Leatherjackets OWBM	Increased herbicide use Natural enemies
Nutrient management	Delay fertiliser	Lodging Mildew Septoria Yellow rust Eyespot	Take-all Risk of yield loss (due to insufficient canopy size)
Seed rate	High seed rates	Grass weeds Reduced risk of sub optimal plant population WBF Slugs	Lodging Take-all Eyespot Mildew Septoria tritici
Undersowing/companion cropping	Companion crop	Aphids Natural enemies CSFB RWSW	
In-field non-cropped areas	In-field strips or margins containing wildflowers	Natural enemies Most pests	Weeds
Rolling soil post-planting	Rolling soil post-planting	Slugs Weeds	

Table 7.2 Non-chemical control strategies for Oilseeds, where significant trade-offs exist.

Strategy	Approach	Positive effect	Negative effect
Sowing date	Earlier sowing	Certainty of establishment Spread of workload Phoma Slugs Adult CSFB Pollen beetle	Light leaf spot (if high risk) Clubroot Larval CSFB Cabbage root fly Turnip sawfly TuYV Weeds
Varietal choice	Selecting resistant varieties (includes herbicide tolerance)	Lodging Clubroot Verticillium Light leaf spot Phoma TuYV Weeds	Selection of herbicide resistant weeds
Primary and secondary cultivations	Ploughing	Compaction Sclerotia buried Grassweed control Slugs CSFB Weeds	Previous sclerotia brought to surface Reduced emergence due to loss of moisture Natural enemies
Nutrient management	Delay fertiliser	Lodging	Risk of yield loss (due to insufficient canopy size)
Seed rate	High seed rates	Reduced risk of sub-optimal plant population Slugs Weeds	Lodging
Stubble management	Leaving long stubble	CSFB	Reduced straw yield (where it is baled)
Trap crops	Leave volunteer OSR in nearby fields	CSFB	Possible delays in cultivations, and increased Phoma risk
Defoliation	Grazing or topping in the winter	CSFB larvae	Risk of yield loss
In-field non-cropped areas	In-field strips or margins containing wildflowers	Natural enemies Most pests	Weeds
Rolling soil post-planting	Rolling soil post-planting	Slugs, CSFB, weeds	Potential for impeding establishment. where capping occurs.

Table 7.3 Non-chemical control strategies for Potatoes, where significant trade-offs exist.

Strategy	Approach	Positive effect	Negative effect
Sowing date	Earlier planting	Miss the late blight epidemic	Slower to emerge Increased risk from stem canker
Harvest date	Early Harvest	Slugs Wireworms Black dot Silver scurf Alternaria (tuber) Black scurf Blackleg (tuber)	Potential reduction in yield
Flooding		Wireworms PCN Weed control	Only suitable for specific fields
Varietal choice	Selecting resistant varieties	List diseases with disease ratings (or known differences here) PVA, PVY, PLRV PCN Spraing Black and silver scurf Late and early blight Dry rot Common and powdery scab	Characteristics required may not be in the same variety.
Primary and secondary cultivations	Ploughing	Bury crop residues Slugs, wireworms Grass weeds	Natural enemies
Nutrient management	Increase fertiliser	Late blight risk increase	
Seed rate	Increase spacing		Weeds
Irrigation	More frequent irrigation	Less powdery scab More common scab Cutworm	More powdery scab Less common scab
In-field non-cropped areas	In-field strips or margins containing wildflowers	Natural enemies Most pests	Weeds

8. Opportunities to develop non-chemical control strategies

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 20 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 20 factors. For tables showing all calculated priority scores, see appendix sections 11.12 – 11.17.

Where there is currently public research ongoing into a particular factor, this has been identified with an asterisk (*) in the final column. Where knowledge exchange resources are currently available, these are referenced in the appendix.

8.1. Research priority areas

8.1.1. Cereals (wheat and barley) (full table in appendix).

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)	Research Ongoing
Disease	Septoria	Decision support (including thresholds)	4	3	4	5	3	4	2	4	2	12.3	1	*
Disease	Septoria	Varietal mixtures	4	3	4	5	3	3	1	3	2	12.0	2	
Pest	BYDV Vectors	Decision support (including thresholds)	4	2	4	4	4	4	1	4	3	11.8	3=	*
Disease	Yellow Rust	Decision support (including thresholds)	4	3	4	4	4	4	1	4	3	11.8	3=	
Weeds	Annual Grasses	Precision application	4	2	2	5	2	4	1	4	3	11.8	3=	*
Pest	BYDV Vectors	Varietal Choice	4	3	3	4	4	4	1	4	3	11.5	6=	*
Weeds	Annual Grasses	Undersowing and companion crops	4	2	2	5	2	4	2	4	2	11.5	6=	*
Disease	Septoria	Bioprotectants and low-risk PPPs	3	2	3	5	4	4	1	3	2	11.3	8=	
Disease	Yellow Rust	Varietal mixtures	4	3	4	4	3	4	1	3	2	11.3	8=	
Weeds	Annual Grasses	Mechanical weeding	4	3	2	5	2	3	2	3	1	11.0	10	*
Weeds	Annual Grasses	Varietal choice	3	3	3	5	3	4	3	4	1	10.8	11=	*
Weeds	BLW - Tap Root	Varietal choice	3	3	3	5	3	4	3	4	1	10.8	11=	
Lodging	Stem Lodging	Decision support (including thresholds)	4	3	4	3	4	5	3	5	2	10.8	11=	
Lodging	Stem Lodging	Nutrient management	4	3	4	3	4	5	3	5	2	10.8	11=	
Lodging	Root Lodging	Decision support (including thresholds)	4	3	4	3	4	5	3	5	2	10.8	11=	
Lodging	Root Lodging	Nutrient management	4	3	4	3	4	5	3	5	2	10.8	11=	
Pest	Slugs	Precision application	4	3	4	3	3	4	1	4	3	10.5	17=	*
Pest	Wheat Bulb Fly	Decision support (including thresholds)	4	3	4	3	4	3	1	4	3	10.5	17=	*
Disease	Take-All	Varietal choice	4	3	4	3	4	4	2	4	2	10.5	17=	
Weeds	Annual Grasses	Use of cover crops	3	2	2	5	2	4	2	4	2	10.5	17=	*
Pest	Slugs	Decision support (including thresholds)	4	3	4	3	4	4	3	4	1	10.3	17=	
Weeds	Annual Grasses	Decision support (including thresholds)	3	2	4	5	2	2	2	3	1	10.3	17=	
Weeds	BLW - Tap Root	Primary cultivations (crop residue burial)	4	3	3	3	4	5	3	4	1	10.3	17=	*

8.1.2. **Oilseeds** (full table in appendix).

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)	Research Ongoing
Pest	Cabbage Stem Flea Beetle	Decision support (incl. thresholds)	4	3	4	5	4	4	1	4	3	12.8	1	*
Pest	Cabbage Stem Flea Beetle	Trap crops	4	3	3	5	3	4	1	4	3	12.3	2	*
Pest	Cabbage Stem Flea Beetle	Sowing date	4	3	3	5	3	4	3	4	1	11.8	3=	*
Pest	Cabbage Stem Flea Beetle	In field non-cropped areas	4	2	3	5	3	2	1	4	3	11.8	3=	
Pest	TuYV Vectors	Decision support (incl. thresholds)	4	2	4	4	4	4	1	4	3	11.8	3=	
Weeds	Annual Grasses	Precision application	4	2	2	5	2	4	1	4	3	11.8	3=	
Pest	Cabbage Stem Flea Beetle	Seed rate	3	3	3	5	5	4	1	3	2	11.5	7	*
Pest	Cabbage Stem Flea Beetle	Varietal choice	3	1	3	5	4	4	2	4	2	11.3	8=	*
Pest	Cabbage Stem Flea Beetle	Bioprotection and low-risk PPPs	3	1	2	5	4	4	1	4	3	11.3	8=	
Weeds	Annual Grasses	Undersowing companion crops	4	2	2	5	2	4	2	3	1	11.3	8=	*
Pest	Cabbage Stem Flea Beetle	Stubble Management	3	2	3	5	3	4	1	3	2	11.0	11=	*
Pest	Cabbage Stem Flea Beetle	Defoliation (incl. mowing and grazing)	3	3	3	5	3	4	1	3	2	11.0	11=	
Pest	Cabbage Stem Flea Beetle	Seedbed quality	3	3	3	5	3	4	3	4	1	10.8	13=	
Pest	Cabbage Stem Flea Beetle	Organic amendments	3	1	3	5	2	4	1	3	2	10.8	13=	*
Weeds	BLW - Tap Root	Precision application	4	3	2	4	2	4	1	4	3	10.8	13=	
Pest	Slugs	Precision application	4	3	4	3	3	4	1	4	3	10.5	16=	*
Disease	Light Leaf Spot	Spatial separation	3	3	5	4	3	5	3	4	1	10.5	16=	
Pest	Cabbage Stem Flea Beetle	Undersowing and Companion cropping	3	2	2	5	2	4	2	3	1	10.3	18=	*
Pest	Cabbage Stem Flea Beetle	Rolling soil post-planting	2	2	4	5	4	4	3	4	1	10.3	18=	
Pest	Slugs	Decision support (incl. thresholds)	4	3	4	3	4	4	3	4	1	10.3	18=	
Weeds	Annual Grasses	Decision support (incl. thresholds)	3	2	4	5	2	2	2	3	1	10.3	18=	

8.1.3. **Potatoes** (full table in appendix)

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)	Research Ongoing
Disease	Storage Diseases	Field history, Rotation & break crops	4	2	2	5	3	4	2	4	2	11.8	1	
Disease	Late Blight	Decision support (including thresholds)	4	3	2	5	3	4	2	3	1	11.5	2	
Pest	Potato Cyst Nematode	Decision support (including thresholds)	4	3	4	4	3	4	3	5	2	11.3	3=	
Disease	Storage Diseases	Hygiene	4	3	2	5	3	3	3	4	1	11.3	3=	
Disease	Late Blight	Seed testing	3	1	3	5	3	4	2	4	2	11.0	5=	
Weeds	All Weeds Pre-Emergence	Thermal control	4	3	1	5	2	4	1	2	1	11.0	5=	
Pest	Viruses (Aphid Borne)	Decision support (including thresholds)	4	3	3	4	3	4	3	4	1	10.8	7=	
Disease	Blackleg	Decision support (including thresholds)	4	1	2	4	3	3	2	5	3	10.8	7=	
Disease	Dry Rot	Varietal choice	3	2	4	5	3	3	1	2	1	10.8	7=	
Disease	Viruses (Soil Borne)	Field history, rotation and break crops	4	3	3	4	3	4	3	4	1	10.8	7=	
Weeds	Annual Grasses	Precision application	4	2	2	4	2	4	1	4	3	10.8	7=	
Weeds	BLW - Fibrous Root	Precision application	4	2	2	4	2	4	1	4	3	10.8	7=	
Disease	Gangrene	Seed testing	3	1	3	5	3	3	3	4	1	10.5	13=	
Disease	Storage Diseases	Varietal choice	3	3	3	5	3	3	3	4	1	10.5	13=	
Disease	Viruses (Soil Borne)	Seed testing	4	1	3	4	2	3	2	4	2	10.5	13=	
Pest	Viruses (Aphid Borne)	Bioprotectants and low-risk PPPs	3	2	3	4	4	3	1	4	3	10.3	16=	
Disease	Black Dot	Seed testing	4	2	4	3	4	4	3	4	1	10.3	16=	
Disease	Blackleg	Seed testing	4	2	1	4	3	3	2	4	2	10.3	16=	
Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	4	2	4	2	3	1	10.3	16=	
Pest	FLN and Spraing	Decision support (including thresholds)	4	3	4	3	3	4	3	4	1	10.0	20=	
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	4	4	2	1	3	2	10.0	20=	

8.2. **Knowledge transfer priority areas**

8.2.1. Cereals (wheat and barley) (full table in appendix)

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)
Weeds	Annual Grasses	Hygiene	4	4	4	5	5	5	4	5	1	12.8	1
Disease	Septoria	Varietal choice	4	5	4	5	4	4	4	5	1	12.3	2=
Disease	Yellow Rust	Varietal choice	5	5	4	4	4	4	4	5	1	12.3	2=
Weeds	Annual Grasses	Primary cultivations (crop residue burial)	4	4	3	5	4	5	4	5	1	12.3	2=
Weeds	Annual Grasses	Secondary cultivations (drilling method)	4	4	3	5	4	3	4	5	1	11.8	5
Disease	Septoria	Sowing date	3	4	4	5	2	4	2	4	2	11.0	6
Weeds	All Weeds Pre-Emergence	Hygiene	4	4	4	3	5	5	4	5	1	10.8	7=
Weeds	All Weeds Pre-Emergence	Secondary cultivations (drilling method)	4	4	3	4	4	3	4	5	1	10.8	7=
Lodging	Stem Lodging	Variety choice	4	4	4	3	5	5	4	5	1	10.8	7=
Lodging	Root Lodging	Variety choice	4	4	4	3	5	5	4	5	1	10.8	7=
Lodging	Root Lodging	Seed rate	4	5	3	3	5	5	2	4	2	10.8	7=
Pest	BYDV Vectors	Sowing date	3	5	3	4	3	4	1	4	3	10.3	12=
Disease	Brown Rust	Varietal choice	4	4	4	3	4	4	4	5	1	10.3	12=
Disease	Septoria	Nutrient management	2	4	3	5	3	4	1	3	2	10.0	14
Lodging	Stem Lodging	Seed rate	3	5	3	3	5	5	2	4	2	9.8	15
Disease	Yellow Rust	Sowing date	3	4	4	4	2	3	1	2	1	9.5	16
Disease	Ear Blight	Varietal choice	3	4	4	3	4	4	3	4	1	9.3	17
Lodging	Root Lodging	Sowing date	3	4	3	3	3	5	2	3	1	9.0	18
Disease	Yellow Rust	Nutrient management	2	4	2	4	4	3	1	2	1	8.5	19
Weeds	BLW - Fibrous Root	Primary cultivations (crop residue burial)	2	4	3	3	4	5	3	4	1	8.3	20

8.2.2. **Oilseeds** (full table in appendix)

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)
Weeds	Annual Grasses	Secondary Cultivations (drilling method)	4	4	3	5	4	4	4	5	1	12.0	1
Disease	Light Leaf Spot	Varietal Choice	4	5	4	4	4	5	4	5	1	11.5	2=
Disease	Phoma Stem Canker	Varietal Choice	4	5	4	4	4	5	4	5	1	11.5	2=
Disease	Phoma Stem Canker	Decision support (including thresholds)	4	5	3	4	3	5	2	5	3	11.5	2=
Pest	TuYV Vectors	Varietal choice	4	4	3	4	4	4	2	4	2	11.3	5=
Weeds	Annual Grasses	Hygiene	3	4	4	5	5	3	4	5	1	11.3	5=
Disease	Clubroot	Decision support (including thresholds)	5	5	3	3	3	5	3	5	2	11.3	5=
Disease	Light Leaf Spot	Sowing date	4	4	4	4	3	5	3	4	1	11.3	5=
Disease	Phoma Stem Canker	Sowing date	4	4	4	4	3	5	3	4	1	11.3	5=
Weeds	BLW - Tap Root	Select low-risk locations	4	4	3	4	4	4	3	4	1	11.0	10=
Disease	Clubroot	Hygiene and prevention	5	5	3	3	3	5	4	5	1	11.0	10=
Disease	Light Leaf Spot	Field history, Rotation & break crops	3	4	5	4	4	5	3	5	2	11.0	10=
Disease	Light Leaf Spot	Primary cultivations / Crop residue burial	4	5	3	4	3	5	3	4	1	11.0	10=
Disease	Phoma Stem Canker	Primary cultivations / Crop residue burial	4	5	3	4	3	5	3	4	1	11.0	10=
Disease	Clubroot	Good drainage	5	5	2	3	3	5	3	4	1	10.8	15=
Disease	Light Leaf Spot	Stubble Management	4	4	2	4	3	5	3	4	1	10.8	15=
Disease	Phoma Stem Canker	Field history, Rotation & break crops	3	5	5	4	4	5	4	5	1	10.8	15=
Disease	Phoma Stem Canker	Stubble Management	4	4	2	4	3	5	3	4	1	10.8	15=
Disease	Verticillium Wilt	Field history, Rotation & break crops	4	5	5	3	4	5	4	5	1	10.8	15=
Disease	Verticillium Wilt	Varietal Choice	4	4	4	3	4	5	3	5	2	10.8	15=

8.2.3. **Potatoes** (full table in appendix)

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)
Disease	Late Blight	Varietal choice	5	4	3	5	2	4	2	4	2	12.8	1
Disease	Late Blight	Control volunteers & weeds	4	4	2	5	4	4	3	5	2	12.0	2=
Disease	Late Blight	Early harvest	4	4	4	5	3	4	4	5	1	12.0	2=
Disease	Late Blight	Hygiene	4	4	4	5	3	4	4	5	1	12.0	2=
Disease	Late Blight	Field history, Rotation & break crops	4	4	3	5	3	4	4	5	1	11.8	5=
Disease	Blackleg	Hygiene	5	4	2	4	3	4	3	5	2	11.8	5=
Disease	Late Blight	Spatial separation	4	4	3	5	2	4	3	4	1	11.5	7=
Disease	Late Blight	Sowing date	4	4	3	5	3	3	2	3	1	11.5	7=
Disease	Blackleg	Early harvest	4	4	4	4	3	4	3	5	2	11.3	9
Disease	Late Blight	Select low-risk locations	4	4	3	5	2	2	2	3	1	11.0	10=
Disease	Blackleg	Control volunteers & weeds	4	4	3	4	3	4	2	4	2	11.0	10=
Pest	Potato Cyst Nematode	Varietal Choice	4	5	3	4	3	4	2	3	1	10.8	12=
Disease	Stem Canker and Black Scurf	Early harvest	4	4	3	4	3	4	3	4	1	10.8	12=
Pest	Viruses (Aphid Borne)	Seed testing	4	4	3	4	3	3	3	4	1	10.5	14=
Disease	Late Blight	Seedbed quality	3	4	3	5	3	3	2	3	1	10.5	14=
Pest	Potato Cyst Nematode	Trap crops	3	4	4	4	2	4	1	4	3	10.3	16=
Pest	Viruses (Aphid Borne)	Select low-risk locations	4	4	3	4	2	3	3	4	1	10.3	16=
Pest	Viruses (Aphid Borne)	Control volunteers & weeds	4	4	2	4	3	3	3	4	1	10.3	16=
Pest	Viruses (Aphid Borne)	Hygiene	4	4	2	4	2	4	3	4	1	10.3	16=
Disease	Black Dot	Field history, Rotation & break crops	4	4	3	3	4	4	2	3	1	10.0	20=
Disease	Black Dot	Varietal choice	4	4	4	3	3	4	3	4	1	10.0	20=
Disease	Blackleg	Field history, Rotation & break crops	3	4	3	4	3	4	2	4	2	10.0	20=

9. Summary and recommendations

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.

Considering each of these challenges in turn:

9.1. Identifying where to focus research and knowledge exchange effort

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. To address this, post-project, we intend to survey IPM specialists across the UK and north-western Europe to obtain their consensus estimates of efficacy.

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 to AHDB 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).

9.1.1. Research priorities

Cereals

Greater use of decision support and use of resistant varieties (or mixtures) accounts for over half of the strategies highlighted as priorities for research.

For the control of *Septoria tritici* and yellow rust, the development and validation of decision support systems (ranked 1st and 3rd= in research priorities section 8.1.1), and possibly also the use of varietal mixtures (ranked 2nd) could do much to reduce the requirement for chemical control. Bioprotectants and use of low-risk PPP's (8th=) is also noted as an approach where strength of evidence is low, but potential economic impact and ease of implementation are high. With take-all, the impact of variety choice on its management (17th=) is not well understood, but it is highlighted here as an area where potential is much higher than current use and results would be inexpensive and easy to implement for growers. Research to address this could improve yield in second and subsequent wheat crops.

For the control of BYDV vectors, further development of decision support systems (ranked 3rd=) could reduce the use of autumn insecticides and improve the implementation of non-chemical control methods, such as sowing date and varietal choice. Choosing resistant varieties (6th=) could also bring benefits in terms of risk management and reduced inputs; however, there are currently few of these varieties, and their characteristics and agronomic profiles are unlikely to suit all situations. Understanding these 'trade-offs' may be key to determining the situations where such varieties bring value to growers. Control of slugs through decision support and precision applications (both 17th=), are also highlighted as potential areas where research could bring benefits in terms of reducing dependence on chemical control strategies. Decision support for wheat bulb fly is also highlighted (17th=) as a potential area where uptake could be improved though strengthening the evidence that the models are accurate.

The control of annual grasses in cereals is of high economic importance. Further research to determine the role of precision application (ranked 3rd=), undersowing and companion cropping (6th=), mechanical weeding (10th), varietal choice (11th=), use of cover crops (17th=) and decision support systems (17th=) could usefully improve confidence and uptake of these strategies. The control of tap rooted BLW's through primary cultivations and varietal choice are also areas identified as warranting further research.

The control of stem and root lodging through improved use of decision support (11th=) and nutrient management (11th=), could significantly reduce the widespread use of PGR's in cereals; however, robust evidence is required here that growers can trust due to the potential risk of significant yield loss due to lodging.

Oilseed rape

The league table of research priorities for oilseed rape is dominated by invertebrate pests which account for 16 of 21 entrants. Not surprisingly CSFB is the most important pest accounting for 13 of the 16 pest entrants. High populations of CSFB are common, pyrethroids are the only available chemical control option and there is widespread resistance to these products. IPM is the only practical solution and so there is considerable interest in how a wide range of non-chemical control options might be used to combat the pest. Decision support including the use of thresholds is top of the prioritisation table (8.1.2) as understanding both the relationship between risk and the ultimate impact on yield and knowing when to implement non-chemical control methods will become increasingly important. Ultimately, resistant/tolerant varieties may help to combat CSFB, but this is a strategy for the long term. In the meantime, a better understanding of the non-chemical control options that offer a more short-term return on investment would be valuable to growers. Individual non-chemical control strategies are unlikely to be as effective as a single dose of an insecticide. As a result, it will be important to combine non-chemical control options to try and achieve levels of pest control that are comparable with chemicals.

Decision support systems for TuYV ranks equal third among oilseed rape research priorities. This is understandable as the optimum control strategy is still unclear. Fundamental to this is a greater understanding of the impact of the virus on yield and what factors influence the risk of infection on an annual basis. Resistant varieties are becoming more widely available but alternative control strategies also need to be developed. Chemical control options allow only a single spray so when should this be applied? Also, control at present takes no account of the proportion of the aphid vectors that are carrying the virus. This is similar to the situation with BYDV in cereals and it is possible that strategies for control of aphid borne viruses in cereals and oilseed rape may be complementary.

Slugs remain an important pest of oilseed rape as indicated by the ranking of precision application of molluscicide pellets and decision support as 16th and 18th in the table of oilseed rape research priorities. From 1 April 2022, it will then be illegal to sell and use metaldehyde products, so ferric phosphate will be the only approved molluscicide pellet. Precision application could help reduce the total quantity of pellets applied, but decision support and thresholds will help to indicate when control is unnecessary.

In general, oilseed rape diseases rank lower on the research priority table, with only light leaf spot included. This partly reflects the current situation where some diseases have decreased in economic importance, e.g., sclerotinia, which has occurred at generally low incidence in recent years. Other diseases such as phoma are common every year but judged to have more limited scope for research into integrated control strategies. For light leaf spot, spatial separation was identified as a research priority, and it should be noted that the results of research on this strategy should be applicable to management of the other oilseed diseases which have airborne spore phases.

Potatoes

Pests make up only three of the research priorities in potatoes. PCN remains the major pest of potatoes in the UK. Decision support including thresholds ranks as equal third among research priorities in potatoes. The number of chemical control options for PCN is declining and the future for remaining products is uncertain. It is relatively straightforward to assess PCN levels in soil, but it could be argued that soil analysis is currently used to justify nematicide use. Nematicides are regularly used to combat low numbers of PCN eggs/g soil, and it is possible that more could be made of egg counts to determine the need for chemical control.

For the control of aphid borne viruses, decision support and biopesticides and low risk PPPs rank equal 7th and equal 16th among potato research priorities. These are of much greater importance in seed than ware crops with routine spray programmes advised to prevent virus infection. Improved understanding of the potential risk of infection could help reduce reliance on insecticides as would the availability of effective biopesticides and low risk PPPs which would in turn help to combat the development of resistance.

Decision support for treating FLN ranks equal 20th of the potato research priorities. Control measures, if required, must be implemented at planting to combat the nematode vectors of tobacco rattle virus. The risk of infection is a function of the numbers of nematode vectors and the proportion that are carrying the virus. Nematode numbers can be easily assessed but there is less confidence in the methods available to detect that they have the virus. This is crucial to reducing the reliance on chemical control. The products for free-living nematode control are similar, if not the same, as those for control of PCN, so choice is likely to continue to decline.

Storage diseases were top of the research priorities list as, in the literature, there was often evidence on the impact of field history, rotation and break crops for the management of diseases from planting to harvest, but limited evidence that links those factors from planting to development of disease in store. With the loss of chemistry through withdrawal of approvals and decreased efficacy of fungicides against key diseases, a whole crop approach may be required to mitigate storage losses; however, this would require further research.

Decision support was high on the priority list for two diseases: blackleg and late blight. There is some evidence for late blight on the effectiveness of decision support systems, particularly from other countries. Decision support systems can have varying levels of inputs and outputs and, with increasing pressure on industry to reduce pesticide use as well as the development of resistance to active ingredients, more sophisticated systems incorporating information on genotypes, weather, variety resistance and spray opportunities may be required for management. For blackleg, a current BBSRC project ‘A Decision Support Tool for Potato Black Leg Disease’ led by Durham University (2020 to 2023) is likely to move forward the understanding and development of decision support for this disease.

Potato seed testing is currently done through assessments for seed classification and on seed stocks by suppliers and buyers. However, latent disease, particularly late blight, is difficult to detect on tubers. The development of DNA-based diagnostics or novel technology, such as hyperspectral or scanning techniques on seed stocks, or even in crop, has potential to improve the likelihood of detecting latent infection and preventing outbreaks. This has potential to be useful for a range of other rot and blemish diseases and their management.

9.1.2. Knowledge exchange priorities

Cereals

Varietal choice and sowing date account for half of the strategies identified where good evidence exists but uptake could be improved though greater knowledge exchange. Varietal susceptibility, as detailed in the AHDB RL, to the foliar and ear diseases of cereals (ranked 2nd,3rd,12th=, and 17th in the priority tables) - are already widely used by many to guide varietal choice; however, there is the potential for greater use of varietal resistance, though communicating the benefits in risk management and reduced requirements for chemical control. Selection of resistant varieties restricts choice and may lead to 'trade-offs' that require careful consideration. For Septoria and yellow rust, sowing date (6^{th} and 16^{th}) and nutrient management (14^{th} and 17^{th}) are strategies known to affect disease development. Again, significant 'trade-offs' exist here, especially for nutrient management, as reducing N applications significantly reduced both yield and disease. Sowing date is also known to directly affect BYDV vectors (12^{th}=); however, the significant risks associated with later sowing in terms of crop establishment and yield mean use of this approach is currently limited, perhaps in part to the availability of effective chemical control strategies.

The use of hygiene and cultivations for the control of annual grasses (1^{st}, 2^{nd}=, and 5^{th}), BLW's (20^{th}) and all weeds pre-emergence (7^{th}=), are also widely practised, though it is considered more sharing of existing information could improve the use of these strategies still further.

Much is also known about the impact of varietal choice, sowing date and seed rate on both root and stem lodging (7^{th}= and 16^{th}); however, a greater awareness of their impact could help more growers adopt an integrated approach to lodging control.

Oilseed rape

TuYV, or more particularly its aphid vectors, are the only pests that feature in the knowledge transfer priorities for oilseed rape. Use of varietal choice ranks equal 5^{th} in the prioritisation table. More varieties are now available to the virus and provide a simple solution to the risk of infection. The choice of variety will of course also be affected by how well these resistant varieties compare with non-resistant varieties in terms of their other agronomic characteristics.

Oilseed rape diseases feature commonly in knowledge exchange priorities, with 16 out of 20 listings assigned to the main diseases of light leaf spot, phoma, clubroot and verticillium. This is in contrast to the research priority rankings where only light leaf spot was included. The knowledge exchange priorities for disease management strategies indicate scope for further promotion of the most effective strategies as listed in the table. Selection of disease-resistant oilseed rape varieties is an effective strategy listed for three diseases. Decision support occurs twice, but relatively high in the rankings, for phoma and clubroot, with particular potential for further promotion to help manage phoma stem canker. Taking account of field history, extending rotations and using break crops are also high priorities for light leaf spot, phoma and verticillium wilt control, in knowledge exchange.

Potatoes

PCN and the vectors of aphid borne viruses are the only pests that feature in the league table of knowledge transfer priorities for potatoes. PCN features twice ranking equal 12^{th} for varietal choice and equal 16^{th} for trap crops. More varieties are available that are resistant to the yellow PCN than for the white PCN, although the latter is by far the most common species present in the UK. Choice of variety will also be influenced by whether the growers contract details a specific variety and the agronomic characteristics of non-resistant varieties. Nevertheless, widespread dissemination of varietal options could help reduce reliance on nematicides. Trap crops are a potential alternative to nematicides and have been very effective in some studies. Fitting these into an existing potato rotation has been problematic as has establishing sufficient plants to reduce PCN populations. However, trap crops are likely to become more important in future and so, greater awareness of their potential should be encouraged.

Non-chemical control of aphid borne viruses primarily concentrates on avoiding the potential for virus infection. Seed testing ranks equal 14th in the league table with selecting a low-risk location, control of volunteers and weeds and hygiene all ranking equal 16th. Various laboratories offer seed testing, and this is a simple means of ensuring that ware seed is free of virus. Selecting a low-risk location is applicable mainly to seed crops. General hygiene in relation to potato dumps and controlling volunteers and weeds are important factors when attempting to reduce the potential risk of virus infection. If managed correctly, they can reduce the availability of sources of virus to the aphid vectors.

Late blight control is high on the knowledge transfer list, as the use of resistant varieties as part of the disease management strategy has been proven to be highly effective and the evidence exists to support it. This information was included in a comprehensive late blight management guide published by AHDB in 2013. Effective fungicides are available, so industry preferences on varieties, as well as the need to control other pests and diseases using variety resistance, often take precedence when selecting varieties. The GB *Phytophthora infestans* population has changed over the last 15 years, with the dominance of aggressive strains and appearance of strains with decreased sensitivity to fungicides. There is a move towards breeding and selling late blight resistant varieties with desirable market characteristics, and the information should be available to support this.

Blackleg with regards to hygiene, was also ranked high on the knowledge transfer table. An AHDB blackleg management guide is available; however, there is new information on strategies for monitoring, handling, packing and transport to reduce contamination as well as methods for tracing seed stock contamination that may be useful to include.

9.2. **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’s 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 septoria would appear at relevant time points, with links to information guiding variety choice, sowing date and treatment decisions.

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.

9.3. Aligning AHDB IPM information with ELMS IPM Land Management Planning

The 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 is ongoing to investigate how IPM Land Management Plans might be incentivised and supported by advice and guidance. Two of the recommendations from the interim 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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11. Appendix

11.1. **Weeds in cereals (score tables)**

Non- chemical control strategies in arable crops – Weeds in cereals		All weeds pre-emergence									Perennial grasses								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Current chemical control for comparison	**Sensitive weeds**	4									4								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow	3	2	2	4	5	1	1	2		4	4	3	2	4	4	3	3	565
	Field history, rotation & break crops	4	3	3	4	5	5	5	5	374	4	4	3	2	4	4	5	5	368,148
	Select low-risk locations	3	4	3	4	2	5	3	3		4	4	3	2	4	4	3	3	
Pre-cropping	Drainage																		
	Early harvest	3	3	4	4	3	4	2	2										
	Flooding																		
	Hygiene	4	4	4	3	5	5	4	5										
	Primary cultivations (crop residue burial)	4	4	3	4	4	5	5	5		3	5	3	2	4	4	5	5	388
	Secondary cultivations (drilling method)	4	4	3	4	4	3	4	5	401									
	Seed rate																		
	Seedbed quality	3	3	2	4	2	3	3	3										
	Sowing date	4	4	3	4	2	4	4	4										
	Stubble management	3	3	3	4	3	4	3	4		3	4	3	2	3	4	3	4	
	Use of cover crops	3	3	1	4	1	4	2	4	5,369,410	4	2	4	2	2	3	2	4	410,147
	Varietal choice																		
	Varietal mixtures																		
In-crop techniques	Bioprotection & low risk PPP's	2	2	2	4	4	4	1	2	490,178									
	Decision support (including thresholds)																		
	Defoliation (incl. mowing and grazing)																		
	In-field, non-cropped area																		
	Intercropping	3	2	1	4	1	3	1	3	255									
	Hand weeding/roguing																		
	Mechanical weeding																		
	Precision application										4	2	5	2	4	4	1	4	344,217
	Thermal control	4	2	1	4	1	3	1	2	528									
	Undersowing & companion crops	3	2	1	4	1	4	2	4	255									

Non- chemical control strategies in arable crops – Weeds in cereals		Annual grasses									BLW - tap root								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Current chemical control for comparison	**Sensitive weeds**	4									4								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow	4	3	4	5	4	4	4	4		1	4	4	3	4	4	3	3	127
	Field history, rotation & break crops	4	3	3	5	5	4	4	4	148,391,247,567	4	5	3	3	5	4	3	3	374
	Select low-risk locations	3	4	3	5	4	4	3	3		4	4	3	3	4	4	3	3	
Pre-cropping	Drainage	2	2	4	5	2	3	3	4	59, 423									
	Early harvest	4	3	4	5	3	4	4	4	297,425,557									
	Flooding	3	2	3	5	2	4	1	1	536	3	2	3	3	2	4	1	1	536
	Hygiene	4	4	4	5	5	5	4	5	79,347,275,545	2	4	4	3	5	5	3	3	294
	Primary cultivations (crop residue burial)	4	4	3	5	4	5	4	5	343,388,453,568	4	3	3	3	4	5	3	4	
	Secondary cultivations (drilling method)	4	4	3	5	4	3	4	5	343	3	4	3	3	4	3	4	4	401
	Seed rate	4	4	2	5	5	3	4	4	343	3	3	2	3	5	3	3	3	
	Seedbed quality	3	3	3	5	2	3	3	3		3	3	3	3	2	3	3	3	
	Sowing date	4	4	2	5	2	4	4	4	343,390,83,371	4	4	2	3	2	4	4	4	83
	Stubble management	4	3	3	5	4	3	4	4	391, 393	4	3	3	3	4	3	3	4	13,237
	Use of cover crops	3	2	2	5	2	4	2	4	314,410, 147	4	2	2	3	2	4	2	4	314
	Varietal choice	3	3	3	5	3	4	3	4	343,76,133,131	3	3	3	5	3	4	3	4	
	Varietal mixtures																		
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	5	2	2	1	2	490,178	2	2	2	3	2	2	1	2	490,178
	Decision support (including thresholds)	3	2	4	5	2	2	2	3	354	4	3	4	3	2	2	2	2	354
	Defoliation (incl. mowing and grazing)	4	3	2	5	3	4	3	3	34	2	2	2	3	3	4	2	3	34
	In-field, non-cropped area	3	3	4	5	4	2	4	4	370,468	3	3	4	3	4	2	2	4	370,468
	Intercropping	3	2	2	5	2	3	2	3	255	3	2	2	3	2	3	2	3	255
	Hand weeding/roguing	4	4	1	5	4	4	4	4										
	Mechanical weeding	4	3	2	5	2	3	2	3	156,83	3	3	2	3	2	3	2	3	156,83
	Precision application	4	2	2	5	2	4	1	4	217,344,375	4	3	2	3	2	4	1	4	217,344
	Thermal control	4	2	1	4	1	3	1	2	114,41,43	2	2	1	3	1	3	1	2	
	Undersowing & companion crops	4	2	2	5	2	4	2	4	216,246	4	2	2	3	2	4	2	4	216,246

Non- chemical control strategies in arable crops – Weeds in cereals		BLW - fibrous root									Volunteer potatoes								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Current chemical control for comparison	**Sensitive weeds**	4									4								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow	1	4	4	3	4	4	3	3	127	4	3	1	3	4	3	2	2	
	Field history, rotation & break crops	4	5	3	3	5	4	3	3	179,330,507	4	5	4	3	5	4	4	4	149
	Select low-risk locations	4	4	3	3	4	4	3	3		4	5	4	3	5	4	3	3	
Pre-cropping	Drainage									59, 423									
	Early harvest																		
	Flooding	3	2	3	3	2	4	1	1	536									
	Hygiene	2	4	4	3	5	5	3	3		3	3	4	3	4	4	3	3	
	Primary cultivations (crop residue burial)	2	4	3	3	4	5	3	4		3	5	3	3	4	4	4	4	
	Secondary cultivations (drilling method)	4	4	3	3	4	3	4	4	401	3	3	3	3	4	3	4	4	
	Seed rate	3	3	2	3	5	3	3	3										
	Seedbed quality	3	3	3	3	2	3	3	3										
	Sowing date	4	4	2	3	2	4	4	4	83									
	Stubble management	4	3	3	3	4	3	3	4	W9,237	4	5	4	3	5	4	3	3	47
	Use of cover crops	4	2	2	3	2	4	2	4	314	3	1	2	3	2	3	1	3	374
	Varietal choice	3	2	3	3	4	4	2	3		2	1	3	3	3	3	1	1	
	Varietal mixtures																		
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	3	2	2	1	2	490,178									
	Decision support (including thresholds)	4	3	4	3	2	2	2	2	354									
	Defoliation (incl. mowing and grazing)	2	2	2	3	3	4	2	3	34									
	In-field, non-cropped area	3	3	4	3	4	2	2	4	370,468									
	Intercropping	3	2	2	3	2	3	2	3	255	3	1	2	3	3	3	2	3	
	Hand weeding/roguing										4	4	2	3	4	4	4	4	
	Mechanical weeding	4	3	2	3	2	3	2	3	156,83									
	Precision application	4	3	2	3	2	4	1	4	217,344	4	3	2	3	2	4	1	4	217,344
	Thermal control	4	2	1	3	1	3	1	2	114,41,43									
	Undersowing & companion crops	4	2	2	3	2	4	2	4	216,246	3	1	2	3	3	3	2	3	

11.2. **Weeds in oilseeds (score tables)**

Non- chemical control strategies in arable crops – Weeds in oilseeds		All weeds pre-emergence									Perennial grasses								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Current chemical control for comparison	**Sensitive weeds**	4									4								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow										4	4	3	1	4	4	3	3	565
	Field history, rotation & break crops	3	3	3	1	5	3	3	3	374	4	4	3	1	4	3	3	3	368,148
	Select low-risk locations	3	3	3	1	5	5	1	4		4	4	3	1	4	4	3	4	
Pre-cropping	Drainage																		
	Flooding																		
	Hygiene	4	4	3	1	5	3	4	5										
	Primary cultivations (crop residue burial)	4	4	3	1	4	4	3	3		3	4	3	1	4	4	4	5	388
	Secondary cultivations (drilling method)	4	4	3	1	4	4	4	5	401									
	Seed rate																		
	Seedbed quality	3	3	3	1	2	3	3	3										
	Sowing date																		
	Stubble management										3	4	3	1	3	4	3	5	
	Use of cover crops	3	3	1	1	1	4	2	4	5,369,410	3	2	3	1	2	3	2	4	410,147
	Varietal choice																		
	Varietal mixtures																		
In-crop techniques	Bioprotectants & low risk PPP's	3	4	1	1	1	4	1	1	490,178									
	Decision support (incl. thresholds)																		
	Defoliation (incl. mowing and grazing)																		
	In-field, non-cropped area																		
	Hand weeding/roguing																		
	Intercropping	3	2	1	1	1	3	1	2										
	Mechanical weeding																		
	Precision application										4	2	2	1	4	4	1	4	344,217
	Thermal control	4	4	1	1	1	4	1	3	528									
	Undersowing companion crops	3	2	1	1	1	4	2	3										

Non- chemical control strategies in arable crops – Weeds in oilseeds		Annual grasses									BLW - tap root								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Current chemical control for comparison	**Sensitive weeds**	4									4								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow	4	3	4	5	4	4	3	3	127	1	4	4	3	4	4	3	3	127
	Field history, rotation & break crops	4	4	3	5	4	3	3	3	148,391,567,247	3	3	3	4	5	3	3	3	374
	Select low-risk locations	3	4	3	5	4	4	3	3		4	4	3	4	4	4	3	4	
Pre-cropping	Drainage	3	2	4	5	2	3	3	3	59,131									
	Flooding	3	2	3	5	2	4	1	1	536	3	2	3	4	2	4	1	1	536
	Hygiene	3	4	4	5	5	3	4	5	79,347,275,545	2	4	4	4	5	3	3	4	294
	Primary cultivations (crop residue burial)	4	4	3	5	4	4	3	3	343,388,453,568	2	4	3	4	4	4	3	3	
	Secondary cultivations (drilling method)	4	4	3	5	4	4	4	5	343	2	4	3	4	4	4	4	5	401
	Seed rate	2	3	3	5	3	3	2	2	342,483	3	3	2	4	5	3	2	2	
	Seedbed quality	3	3	3	5	2	3	3	3		3	3	3	4	2	3	3	3	
	Sowing date																		
	Stubble management	2	3	3	5	3	3	2	5	391, 393	4	3	3	4	4	3	3	3	13,237
	Use of cover crops	3	2	2	5	1	4	2	3	314,410,147	4	2	2	4	2	4	2	2	314
	Varietal choice	4	4	3	5	4	4	4	4		4	4	4	4	4	4	4	4	62
	Varietal mixtures																		
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	5	2	2	1	2	490,178	2	2	2	4	2	2	1	2	490,178
	Decision support (incl. thresholds)	3	2	4	5	2	2	2	3	354	4	3	4	4	2	2	2	2	354
	Defoliation (incl. mowing and grazing)	2	2	2	5	2	2	1	2		2	2	2	4	2	2	1	2	
	In-field, non-cropped area	3	3	4	5	4	2	3	3	370,468	3	3	4	4	4	2	2	3	370,468
	Hand weeding/roguing	2	2	1	5	1	2	1	1										
	Intercropping	3	2	2	5	2	3	2	2	255,104	3	2	2	4	2	3	2	2	255,104
	Mechanical weeding	3	3	2	5	2	3	2	3	156,83	4	4	2	4	2	3	3	3	156,83
	Precision application	4	2	2	5	2	4	1	4	344,217,366	4	3	2	4	2	4	1	4	344,217,366
	Thermal control	3	3	2	5	2	3	1	2	114,41,43	4	3	2	4	2	3	2	2	114,41,43
	Undersowing companion crops	4	2	2	5	2	4	2	3	181	3	2	2	4	2	4	2	3	181

Non- chemical control strategies in arable crops – Weeds in oilseeds		BLW - fibrous root								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Current chemical control for comparison	**Sensitive weeds**	4								
	Herbicide resistant grasses	1								
	Herbicide resistant BLW	4								
Crop planning	Fallow	1	4	4	3	4	4	3	3	127
	Field history, rotation & break crops	3	3	3	3	5	3	3	3	374
	Select low-risk locations	4	4	3	3	4	4	3	3	
Pre-cropping	Drainage									59,131
	Flooding	3	2	3	3	2	4	1	1	536
	Hygiene	2	4	4	3	5	3	2	4	
	Primary cultivations (crop residue burial)	2	4	3	3	4	4	3	3	
	Secondary cultivations (drilling method)	2	4	3	3	4	4	4	5	401
	Seed rate	3	3	2	3	5	3	2	2	
	Seedbed quality	3	3	3	3	2	3	3	3	
	Sowing date									343 127,83
	Stubble management	4	3	3	3	4	3	3	3	13,237
	Use of cover crops	4	2	2	3	2	4	2	3	314
	Varietal choice	4	4	4	3	4	4	4	4	62
	Varietal mixtures									
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	3	2	2	1	2	490,178
	Decision support (incl. thresholds)	4	3	4	3	2	2	2	2	354
	Defoliation (incl. mowing and grazing)	2	2	2	3	2	2	1	2	
	In-field, non-cropped area	3	3	4	3	4	2	2	3	370,468
	Hand weeding/roguing									
	Intercropping	3	2	2	3	2	3	2	2	255,104
	Mechanical weeding	4	4	2	3	2	3	3	3	156,83
	Precision application	4	3	2	3	2	4	1	4	344,217,366
	Thermal control	4	3	2	3	2	3	2	2	114,41,43
	Undersowing companion crops	4	2	2	3	2	4	2	3	181

11.3. **Weeds in potatoes (score tables)**

Non- chemical control strategies in arable crops – Weeds in potatoes		All weeds pre-emergence									Perennial grasses								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Efficacy of chemical control for comparison	**Sensitive weeds**	4									2								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow										4	4	3	1	4	4	5	5	565
	Field history, rotation and break crops	4	3	3	5	5	5	5	5	374	4	4	3	1	4	4	5	5	368,148
	Select low-risk locations	3	3	3	5	4	4	1	1		4	4	3	1	4	4	5	5	
Pre-cropping	Drainage																		
	Flooding																		
	Hygiene																		
	Primary cultivations (crop residue burial)										5	5	3	1	4	4	5	5	388
	Stubble management										3	4	3	1	3	4	3	3	
	Use of cover crops										4	2	4	1	2	3	2	3	105
	Varietal choice																		
In-crop techniques	Bioprotectants & low risk PPP's																		
	Decision support (including thresholds)																		
	Precision application										4	2	3	1	4	4	1	4	344,217
	In-field, non-cropped area																		
	Hand weeding/roguing																		
	Mechanical weeding	4	4	3	5	4	4	4	4	306									
	Thermal control	4	3	1	5	2	4	1	2	528									
	Undersowing & companion crops	3	2	1	5	1	4	1	1										

Non- chemical control strategies in arable crops – Weeds in potatoes		Annual grasses									BLW - tap root								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Efficacy of chemical control for comparison	**Sensitive weeds**	4									4								
	Herbicide resistant grasses	1									1								
	Herbicide resistant BLW	4									4								
Crop planning	Fallow	4	3	4	4	4	4	5	5		1	4	4	3	4	4	3	3	127
	Field history, rotation and break crops	4	3	3	4	5	4	4	4	148,391,567,247	4	5	3	3	5	4	3	3	374
	Select low-risk locations	3	3	3	3	4	4	4	5		4	4	3	3	4	4	3	3	
Pre-cropping	Drainage	3	2	4	4	2	3	3	3	59, 423									
	Flooding	3	2	3	4	2	4	1	1	536	3	2	3	3	2	4	1	1	536
	Hygiene	4	4	4	4	5	5	4	4	79,347,275,545	2	4	4	3	5	2	3	4	294
	Primary cultivations (crop residue burial)	4	4	4	4	5	5	4	4	343,388,453,568	2	4	4	3	5	5	3	3	
	Stubble management	3	3	3	4	4	3	4	4	13,237	4	3	3	3	4	3	3	3	391,393
	Use of cover crops	3	2	2	4	2	4	2	3	105	4	2	2	3	2	4	2	3	105
	Varietal choice	2	3	4	4	4	4	1	1	125,111	2	4	4	3	4	4	1	1	125,111
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	4	2	2	1	2	490,178	2	2	2	3	2	2	1	2	490,178
	Decision support (including thresholds)	3	2	4	4	2	2	2	2		4	3	4	3	2	2	2	2	NO REF
	Precision application	4	2	2	4	2	4	1	4	344,217	4	3	2	3	2	4	1	4	344,217
	In-field, non-cropped area	2	3	4	4	4	2	1	3	370,468	3	3	4	3	4	2	1	3	370,468
	Hand weeding/roguing	5	2	1	4	2	4	1	1	NO REF									
	Mechanical weeding	3	3	2	4	2	3	3	4	306	4	4	2	3	2	3	2	3	306
	Thermal control	3	3	2	4	2	3	1	2	114,41,43	4	3	2	3	2	3	2	2	114,41,43
	Undersowing & companion crops	4	2	2	4	2	4	1	1	441	4	2	2	3	2	4	1	1	441

Non- chemical control strategies in arable crops – Weeds in potatoes		BLW - fibrous root								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References
Efficacy of chemical control for comparison	**Sensitive weeds**	4								
	Herbicide resistant grasses	1								
	Herbicide resistant BLW	4								
Crop planning	Fallow	1	4	4	4	4	4	3	3	127
	Field history, rotation and break crops	4	5	3	4	5	4	3	3	374
	Select low-risk locations	4	4	3	4	4	4	3	3	NO REF
Pre-cropping	Drainage									
	Flooding	3	2	3	4	2	4	1	1	536
	Hygiene	2	4	4	4	5	2	3	4	NO REF
	Primary cultivations (crop residue burial)	2	4	4	4	5	5	3	3	NO REF
	Stubble management	4	3	3	4	4	3	3	3	391,393
	Use of cover crops	4	2	2	4	2	4	2	3	105
	Varietal choice	2	4	4	4	4	4	1	1	125,111
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	4	2	2	1	2	490,178
	Decision support (including thresholds)	4	3	4	4	2	2	2	2	NO REF
	Precision application	4	2	2	4	2	4	1	4	344,217,95
	In-field, non-cropped area	3	3	4	4	4	2	1	3	370,468
	Hand weeding/roguing									
	Mechanical weeding	4	4	2	4	2	3	2	3	306
	Thermal control	4	3	2	4	2	3	2	2	114,41,43
	Undersowing & companion crops	4	2	2	4	2	4	1	1	411

11.4. **Diseases in cereals (score tables)**

Non- chemical control strategies in arable crops – Diseases in Cereals		Brown rust (*P. hordei, P recondita*)									Ear blight (*Fusarium* spp)									Eyespot (*Tapesia yallundae*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	5									3									2								
Crop Planning	Field history, rotation & break crops	2	2	3	3	3	3	1	1	16	2	2	3	3	1	3	2	3		3	4	2	2	2	2	2	3	
	Select low-risk locations																			2	3	3	2	2	2	3	3	16
	Spatial separation																											
Pre-cropping	Alternative seed treatments																											
	Control volunteers & weeds	1	3	3	3	3	5	3	3	14	1	2	3	3	1	3	1	1		1	2	2	2	2	4	1	1	
	Hygiene																											
	Lime																											
	Pre-cropping Nutrition																											
	Primary cultivations (crop residue burial)										3	3	3	3	2	3	1	2	55.503	2	4	3	2	3	3	2	2	56,282
	Secondary cultivations (drilling method)																											
	Seed rate																			2	2	2	2	1	4	2	2	
	Seed testing										1	2	3	3	3	3	1	2										
	Sowing date	2	2	4	3	3	4	1	2	14	2	3	3	3	3	3	1	2	229, 290	3	4	2	2	4	4	3	3	14,123
	Seedbed quality																											
	Varietal choice	4	4	4	3	4	4	4	5	29	3	4	4	3	4	4	3	4	29	3	4	4	2	4	4	2	3	29
	Varietal mixtures	3	2	4	3	3	4	1	1	143										1	2	4	2	3	4	1	1	396, 471, 395
In-Crop Techniques	Bioprotectants and low risk PPP's	3	2	4	3	4	4	1	3	292																		
	Decision support (including thresholds)	3	3	4	3	4	5	2	4	186	3	3	4	3	4	4	2	4	459	3	4	3	2	3	4	2	3	8,25
	Good drainage																											
	Nutrient management	2	2	3	3	2	4	2	3	452										2	2	2	2	3	4	1	2	

Non- chemical control strategies in arable crops – Diseases in Cereals		Leaf & glume blotch (*Phaeosphaeria nodorum*)									Mildew (*Blumeria graminis*)									Ramularia (*Ramularia collo-cygni*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	4									5									4								
Crop Planning	Field history, rotation & break crops	2	4	2	1	2	3	1	1	16	1	2	3	2	3	3	2	2	14	3	2	3	2	4	2	2	3	
	Select low-risk locations										2	2	3	2	3	3	2	2										
	Spatial separation																											
Pre-cropping	Alternative seed treatments																											
	Control volunteers & weeds										1	3	3	2	2	4	1	1	14									
	Hygiene																			3	2	2	2	2	3	1	3	97
	Lime																											
	Pre-cropping Nutrition																											
	Primary cultivations (crop residue burial)	2	2	3	1	3	3	1	1																			
	Secondary cultivations (drilling method)																											
	Seed rate																											
	Seed testing																											
	Sowing date	2	2	3	1	3	3	1	1		3	2	3	2	3	3	2	3		3	3	3	2	3	3	1	3	97
	Seedbed quality																											
	Varietal choice	3	2	4	1	4	4	1	1		5	5	4	2	4	4	3	4	29	2	2	4	2	2	4	1	3	160
	Varietal mixtures										4	2	3	2	3	3	1	3	520									
In-Crop Techniques	Bioprotectants and low risk PPP's										3	2	2	2	3	4	1	3	292									
	Decision support (including thresholds)	3	2	3	1	3	3	1	1		3	3	4	2	4	4	1	3										
	Good drainage																											
	Nutrient management										3	4	2	2	3	4	2	3	126									

Non- chemical control strategies in arable crops – Diseases in cereals		Seed borne diseases (bunt, smut, leaf stripe)									Septoria leaf blotch (*Septoria tritici*)								
		Effectiveness	**Strength of the evidence**	**Inexpensive to Implement**	**Economic importance**	**Ease of implementation**	**Speed of impact**	**Current use**	**Potential use**	**References**	**Effectiveness**	**Strength of the evidence**	**Inexpensive to Implement**	**Economic importance**	**Ease of implementation**	**Speed of impact**	**Current use**	**Potential use**	**References**
	Efficacy of Chemical control (for comparison)	5									5								
Crop Planning	Field history, rotation & break crops	1	2	3	2	3	2	1	1	14,16	1	4	3	5	3	2	1	1	
	Select low-risk locations																		
	Spatial separation	2	2	3	2	3	2	1	2	14									
Pre-cropping	Alternative seed treatments	4	3	3	2	3	3	1	3	356									
	Control volunteers & weeds	2	3	3	2	3	3	1	2	14									
	Hygiene	2	3	2	2	2	3	1	2	14									
	Lime																		
	Pre-cropping Nutrition																		
	Primary cultivations (crop residue burial)	1	2	2	2	3	3	2	2		1	2	3	5	3	3	1	1	
	Secondary cultivations (drilling method)																		
	Seed rate										1	3	2	5	2	2	1	1	387
	Seed testing	5	4	3	2	3	3	2	4	14									
	Sowing date	2	3	3	2	3	3	1	2	430, 336, 14	3	4	4	5	2	4	2	4	387, 14
	Seedbed quality																		
	Varietal choice										4	5	4	5	4	4	4	5	29
	Varietal mixtures										4	3	4	5	3	3	1	3	29, 313
In-Crop Techniques	Bioprotectants and low risk PPP's	3	3	4	2	3	4	1	3	163,292,515	3	2	3	5	4	4	1	3	305,203, 418, 350, 493, 194
	Decision support (including thresholds)										4	3	4	5	3	4	2	4	289
	Good drainage																		
	Nutrient management										2	4	3	5	3	4	1	3	484

Non- chemical control strategies in arable crops – Diseases in cereals		Take-all (*Gaeumannomyces graminis*)									Yellow rust (*Puccinia striiformis*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	3									5								
Crop Planning	Field history, rotation & break crops	5	5	3	3	4	2	4	4	29, 499	1	4	3	4	2	2	1	1	16
	Select low-risk locations										1	4	3	4	2	2	1	1	14
	Spatial separation										2	2	3	4	2	2	1	1	7
Pre-cropping	Alternative seed treatments																		
	Control volunteers & weeds	2	4	3	3	3	2	3	4	281	2	3	3	4	3	3	2	3	14
	Hygiene																		
	Lime	2	4	4	3	3	3	2	3	395									
	Pre-cropping Nutrition	2	4	2	3	3	3	3	4										
	Primary cultivations (crop residue burial)																		
	Secondary cultivations (drilling method)	1	2	3	3	4	3	2	2	262									
	Seed rate	1	2	2	3	2	3	1	1	226									
	Seed testing																		
	Sowing date	3	4	2	3	2	3	2	2	239	3	4	4	4	2	3	1	2	220,199
	Seedbed quality	3	4	4	3	3	3	3	3	253									
	Varietal choice	4	3	4	3	4	4	2	4	29,65	5	5	4	4	4	4	4	5	29
	Varietal mixtures										4	3	4	4	3	4	1	3	266
In-Crop Techniques	Bioprotectants and low risk PPP's										2	2	3	4	3	4	1	3	163
	Decision support (including thresholds)										4	3	4	4	4	4	1	4	
	Good drainage	2	2	2	3	1	2	3	3										
	Nutrient management	2	4	3	3	4	3	2	4	91,253	2	4	2	4	4	3	1	2	

11.5. **Diseases in oilseeds (score tables)**

Non- chemical control strategies in arable crops – Diseases in Oilseeds		Clubroot (*Plasmodiophora brassicae*)									Light leaf spot (*Pyrenopeziza brassicae*)									Phoma stem canker (*Leptosphaeria maculans*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	0									4									4								
Crop Planning	Field history, Rotation & break crops	4	5	5	3	3	4	4	4	412, 544	3	4	5	4	4	5	3	5	27	3	5	5	4	4	5	4	5	20
	Select low-risk locations	4	5	4	3	3	5	3	3	359																		
	Spatial separation	4	4	4	3	3	5	3	3	544	3	3	5	4	3	5	3	4	19	3	4	5	4	3	5	3	4	353,49
Pre-cropping	Control volunteers & weeds	3	3	3	3	3	5	3	5	566																		
	Drainage	5	5	2	3	3	5	3	4	252, 177																		
	Hygiene and prevention	5	5	3	3	3	5	4	5	268																		
	Lime	3	5	2	3	3	4	2	4	359, 405																		
	Pre cropping Nutrition	3	3	2	3	3	4	2	2	231																		
	Primary cultivations (Crop residue burial)										4	5	3	4	3	5	3	4	19	4	5	3	4	3	5	3	4	20
	Sowing date	3	3	4	3	4	5	3	4	412	4	4	4	4	3	5	3	4	509	4	4	4	4	3	5	3	4	50
	Stubble Management										4	4	2	4	3	5	3	4	509	4	4	2	4	3	5	3	4	49
	Varietal Choice	4	5	3	3	4	5	3	5	102	4	5	4	4	4	5	4	5	171, 424, 550	4	5	4	4	4	5	4	5	382, 99
In-Crop Techniques	Bioprotectants and low risk PPP's																											
	Decision support (incl. thresholds)	5	5	3	3	3	5	3	5	252	3	4	3	4	3	5	2	5	26	4	5	3	4	3	5	2	5	28
	Nutrient management	3	3	2	3	4	4	4	4	359																		

Non- chemical control strategies in arable crops – Diseases in Oilseeds		Sclerotinia stem rot (*Sclerotinia sclerotiorum*)									Verticiilium wilt (*Verticillium longisporum*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	4									0								
Crop Planning	Field history, Rotation & break crops	4	5	5	3	3	4	4	5	167, 174	4	5	5	3	4	5	4	5	166
	Select low-risk locations	3	5	5	3	3	5	3	4	525	4	5	5	3	3	5	2	2	166
	Spatial separation	3	2	5	3	3	3	2	3	549	4	4	5	3	3	5	2	2	166
Pre-cropping	Control volunteers & weeds																		
	Drainage																		
	Hygiene and prevention										4	5	3	3	2	5	4	5	166
	Lime																		
	Pre cropping Nutrition																		
	Primary cultivations (Crop residue burial)	4	3	3	3	3	4	2	3	525									
	Sowing date																		
	Stubble Management																		
	Varietal Choice	1	4	1	3	1	5	1	5	174, 361	4	4	4	3	4	5	3	5	196,197, 516, 569
In-Crop Techniques	Bioprotectants and low risk PPP's										2	4	2	3	2	4	1	3	200, 472, 491
	Decision support (incl. thresholds)	4	4	3	3	2	5	3	4	117, 309, 564, 21									
	Nutrient management																		

11.6. **Diseases in potatoes (score tables)**

Non- chemical control strategies in arable crops – Diseases in Potatoes		Black dot (*Colletotricum coccodes*)									Common scab (*Streptomyces scabies*)									Dry rot (*Fusarium* spp.)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	4									1									3								
Crop Planning	Field history, Rotation & break crops	4	4	3	3	4	4	2	3	327,285	3	4	3	4	3	3	3	4										
	Select low-risk locations																											
	Spatial separation																											
Pre-Cropping	Control volunteers & weeds	3	4	3	3	3	3	3	4	440	2	4	3	4	3	2	2	3		2	1	4	5	3	3	3	3	87
	Early harvest	5	4	3	3	3	4	3	3	12,94																		
	Drainage																											
	Hygiene																											
	Primary cultivations (crop residue burial)	3	4	3	3	3	3	3	3	327,172,12	3	4	2	4	2	2	3	3		2	1	4	5	3	3	2	3	
	Seed testing	4	2	4	3	4	4	3	4																			
	Seedbed quality	3	4	3	3	2	2	2	3		3	4	2	4	3	3	3	3										
	Sowing date																											
	Varietal choice	4	4	4	3	3	4	3	4	541	3	4	4	4	3	3	3	4		3	2	4	5	3	3	1	2	87
In-Crop Techniques	Decision support (incl. thresholds)	4	3	2	3	4	1	3	4	327, 355																		
	Nutrient management																											

Non- chemical control strategies in arable crops – Diseases in Potatoes		Early blight (*Alternaria solani*)									Gangrene (*Boeremia foveata*)									Late blight (*Phytophthora infestans*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential Use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	4									1									5								
Crop Planning	Field history, Rotation & break crops	2	1	2	3	3	2	2	3	2,39										4	4	3	5	3	4	4	5	135,
	Select low-risk locations																			4	4	3	5	2	2	2	3	18
	Spatial separation	3	1	3	3	3	3	2	3											4	4	3	5	2	4	3	4	18,573
Pre-Cropping	Control volunteers & weeds										2	4	3	5	3	3	2	3		4	4	2	5	4	4	3	5	204
	Early harvest										3	4	3	5	4	4	4	4	337	4	4	4	5	3	4	4	5	397,398, 394
	Drainage																			2	4	3	5	3	3	2	3	448
	Hygiene																			4	4	4	5	3	4	4	5	53
	Primary cultivations (crop residue burial)	3	1	3	3	3	3	2	3																			
	Seed testing	3	1	3	3	3	3	2	4		3	1	3	5	3	3	3	4		3	1	3	5	3	4	2	4	53
	Seedbed quality																			3	4	3	5	3	3	2	3	53
	Sowing date																			4	4	3	5	3	3	2	3	
	Varietal choice	4	3	3	3	2	3	1	3	113,321,559										5	4	3	5	2	4	2	4	118,53,54
In-Crop Techniques	Decision support (incl. thresholds)																			4	3	2	5	3	4	2	3	402,488
	Nutrient management																			2	3	3	5	3	3	2	2	107,457

Non- chemical control strategies in arable crops – Diseases in Potatoes		Blackleg *(Pectobacterium atrosepticum)*									Powdery scab (*Spongospora subterranea*)									Silver scurf (*Helminthosporium solani*)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	1									3									3								
Crop Planning	Field history, Rotation & break crops	3	4	3	4	3	4	2	4		3	4	3	3	2	3	3	3	332,326,337	4	4	3	3	2	2	4	5	88
	Select low-risk locations										3	4	3	3	2	3	3	3										
	Spatial separation																											
Pre-Cropping	Control volunteers & weeds	4	4	3	4	3	4	2	4	9	4	4	3	3	2	2	3	3	53	4	4	3	3	2	2	3	4	245
	Early harvest	4	4	4	4	3	4	3	5	470										3	4	3	3	2	2	3	4	202
	Drainage	3	4	3	4	4	3	2	2	419	3	4	2	3	2	2	1	4	198									
	Hygiene	5	4	2	4	3	4	3	5	9	3	4	4	3	2	3	3	3	93									
	Primary cultivations (crop residue burial)	3	2	2	4	3	2	3	4	9										3	4	3	3	2	2	2	3	
	Seed testing	4	2	1	4	3	3	2	4	9	3	4	4	3	2	3	3	3	93,198	4	2	2	3	3	4	2	4	88, 355
	Seedbed quality	3	3	3	4	3	3	3	3		3	1	3	3	4	3	4	4										
	Sowing date																											
	Varietal choice	2	2	3	4	4	3	2	2	9	4	3	3	3	4	3	3	3	542									
In-Crop Techniques	Decision support (incl. thresholds)	4	1	2	4	3	3	2	5	168	4	1	2	3	3	2	1	3	93,92,103									
	Nutrient management																											

Non- chemical control strategies in arable crops – Diseases in Potatoes		Stem canker and black scurf (*Rhizoctonia solani*)									Storage diseases									Viruses (soil borne eg PMTV)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of Chemical control (for comparison)	4									4									3								
Crop Planning	Field history, Rotation & break crops	4	4	2	3	3	3	3	4	522	4	2	2	5	3	4	2	4		4	3	3	4	3	4	3	4	155
	Select low-risk locations																											
	Spatial separation																											
Pre-Cropping	Control volunteers & weeds	3	4	2	3	3	4	3	3											4	1	3	4	2	2	3	3	136
	Early harvest	4	4	3	3	3	4	3	4	551																		
	Drainage																											
	Hygiene										4	3	2	5	3	3	3	4	53	4	3	4	4	4	3	3	3	
	Primary cultivations (crop residue burial)	4	4	2	3	3	3	3	4																			
	Seed testing	4	2	3	3	3	3	2	4											4	1	3	4	2	3	2	4	
	Seedbed quality	3	4	3	3	4	3	4	4																			
	Sowing date	3	4	3	3	3	3	3	3																			
	Varietal choice	4	2	3	3	2	3	2	4	113,321	3	3	3	5	3	3	3	4		4	3	3	4	3	4	3	3	108
In-Crop Techniques	Decision support (incl. thresholds)	4	2	2	3	2	2	2	4	328																		
	Nutrient management																											

11.7. **Pests in cereals (score tables)**

Non- chemical control strategies in arable crops – Pests in Cereals		Barley yellow dwarf virus vectors									Frit fly									Gout fly								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	3									1									1								
Crop planning	Field history, Rotation & break crops										2	3	3	1	3	3	1	2										
	Select low-risk locations	2	3	3	4	3	3	1	2	206																		
	Spatial separation																											
Pre-cropping	Control volunteers & weeds	2	2	3	4	4	4	2	3	562																		
	Primary cultivations (Crop residue burial)	2	3	3	4	3	4	2	3		2	3	3	1	3	3	1	3										
	Secondary cultivations (drilling method)	2	3	3	4	3	4	2	3		2	3	3	1	3	3	1	3										
	Seed rate																											
	Seedbed quality																											
	Sowing date	3	5	3	4	3	4	1	4	360	3	3	3	1	4	4	1	3	316	2	3	3	1	3	3	1	2	
	Undersowing & companion cropping	3	3	2	4	2	3	1	3																			
	Use of cover crops																											
	Varietal Choice	4	3	3	4	4	4	1	4	458, 96																		
In-crop techniques	Decision support (incl. thresholds)	4	2	4	4	4	4	1	4	24, 466	1	1	4	1	3	4	1	2		1	1	4	1	3	4	1	2	
	In field non-cropped areas	3	2	3	4	3	3	1	3	124																		
	Precision application																											
	Rolling soil post-planting										2	2	2	1	3	3	1	2										

Non- chemical control strategies in arable crops – Pests in Cereals		Leatherjackets									Saddle gall midge									Slugs								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	1									2									4								
Crop planning	Field history, Rotation & break crops	2	3	3	1	3	3	1	3	295,78	2	2	3	1	3	3	1	3	454,489	2	4	3	3	3	3	2	3	
	Select low-risk locations																											
	Spatial separation										2	2	3	1	3	3	1	2										
Pre-cropping	Control volunteers & weeds																											
	Primary cultivations (Crop residue burial)	2	3	3	1	3	3	1	3	77										2	2	3	3	3	3	1	3	223,438,325
	Secondary cultivations (drilling method)	2	3	3	1	3	3	1	3	431,570										2	2	3	3	3	3	1	3	224,225,431
	Seed rate																											
	Seedbed quality	2	2	3	1	4	4	1	3											2	3	3	3	3	3	2	4	*324,389*
	Sowing date										2	2	3	1	3	3	1	2	227,489									
	Undersowing & companion cropping																											
	Use of cover crops																											
	Varietal Choice																											
In-crop techniques	Decision support (incl. thresholds)										3	3	3	1	3	4	1	3	460	4	3	4	3	4	4	3	4	
	In field non-cropped areas																											
	Precision application																			4	3	4	3	3	4	1	4	205
	Rolling soil post-planting																			2	3	3	3	3	3	1	3	158

Non- chemical control strategies in arable crops – Pests in Cereals		Summer aphids									Wheat blossom midge (orange)									Wheat blossom midge (yellow)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	4									3									3								
Crop planning	Field history, Rotation & break crops										2	3	3	1	2	3	1	2	*454*	2	3	3	1	2	3	1	3	
	Select low-risk locations																											
	Spatial separation										2	3	3	1	3	3	1	2		2	3	3	1	3	3	1	2	
Pre-cropping	Control volunteers & weeds																											
	Primary cultivations (Crop residue burial)																											
	Secondary cultivations (drilling method)																											
	Seed rate																											
	Seedbed quality																											
	Sowing date																											
	Undersowing & companion cropping																											
	Use of cover crops																											
	Varietal Choice										5	4	3	1	4	4	3	5	458, 96									
In-crop techniques	Decision support (incl. thresholds)										2	3	3	1	3	3	1	2	98									
	In field non-cropped areas	2	2	3	2	3	2	1	3	124	2	2	4	1	3	2	1	2	495	2	2	4	1	3	2	1	2	495
	Precision application																											
	Rolling soil post-planting																											

Non- chemical control strategies in arable crops – Pests in Cereals		Wheat bulb fly									Wireworms								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	2									1								
Crop planning	Field history, Rotation & break crops	2	3	2	3	2	2	1	3		2	4	2	1	3	3	3	4	
	Select low-risk locations																		
	Spatial separation	2	3	3	3	3	3	1	2										
Pre-cropping	Control volunteers & weeds																		
	Primary cultivations (Crop residue burial)										2	4	3	1	3	4	1	3	
	Secondary cultivations (drilling method)										2	4	3	1	3	4	1	3	431, 570
	Seed rate	2	4	2	3	4	3	1	3	334,505	2	2	2	1	4	3	1	2	61,446
	Seedbed quality										2	2	3	1	3	3	1	3	*225*
	Sowing date	3	3	3	3	4	3	1	3	334,505									
	Undersowing & companion cropping																		
	Use of cover crops	2	2	2	3	2	2	1	2										
	Varietal Choice	2	2	3	3	3	2	1	2	190, 189									
In-crop techniques	Decision support (incl. thresholds)	4	3	4	3	4	3	1	4	334,505									
	In field non-cropped areas																		
	Precision application																		
	Rolling soil post-planting										2	2	3	1	3	3	1	3	

11.8. **Pests in oilseeds (score tables)**

Non- chemical control strategies in arable crops – Pests in oilseeds		Brassica pod midge									Cabbage root fly									Cabbage seed weevil								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	1									3									3								
Crop planning	Field history, rotation & break crops																											
	Spatial separation	2	3	3	2	3	3	1	2																			
Pre-cropping	Primary cultivations (Crop residue burial)																											
	Secondary cultivations (drilling method)																											
	Seed rate																											
	Seedbed quality																											
	Sowing date										4	3	3	1	4	4	1	2	33									
	Stubble Management																											
	Trap crops																											
	Undersowing & Companion cropping																											
	Varietal choice																											
In-crop techniques	Bioprotectants and low risk PPP's																											
	Decision support (incl. thresholds)	2	1	2	2	3	3	1	2		3	4	3	1	4	4	1	2	301	3	2	3	2	3	3	4	5	
	Defoliation (incl. mowing and grazing)																											
	In field non-cropped areas																			2	2	3	2	3	2	1	2	
	Organic amendments																											
	Rolling soil post-planting																											
	Precision application	2	1	4	2	4	4	1	3	259																		

Non- chemical control strategies in arable crops – Pests in oilseeds		Cabbage stem flea beetle									Cabbage stem weevil									Mealy cabbage aphid								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	1									4									4								
Crop planning	Field history, rotation & break crops																											
	Spatial separation																											
Pre-cropping	Primary cultivations (Crop residue burial)																											
	Secondary cultivations (drilling method)																											
	Seed rate	3	3	3	5	5	4	1	3	521,553																		
	Seedbed quality	3	3	3	5	3	4	3	4	*553*																		
	Sowing date	4	3	3	5	3	4	3	4	61, 553	2	2	3	1	3	3	1	2										
	Stubble Management	3	2	3	5	3	4	1	3																			
	Trap crops	4	3	3	5	3	4	1	4	*553, 60*																		
	Undersowing & Companion cropping	3	2	2	5	2	4	2	3	*407,104,89*																		
	Varietal choice	3	1	3	5	4	4	2	4	553																		
In-crop techniques	Bioprotectants and low risk PPP's	3	1	2	5	4	4	1	4	256																		
	Decision support (incl. thresholds)	4	3	4	5	4	4	1	4	284										3	3	3	1	3	4	2	3	
	Defoliation (incl. mowing and grazing)	3	3	3	5	3	4	1	3	553,																		
	In field non-cropped areas	4	2	3	5	3	2	1	4	495	2	1	3	1	3	2	1	3		2	2	3	1	2	2	1	2	124
	Organic amendments	3	1	3	5	2	4	1	3	553																		
	Rolling soil post-planting	2	2	4	5	4	4	3	4	553																		
	Precision application																											

Non- chemical control strategies in arable crops – Pests in oilseeds		**Pollen beetle**									**Rape winter stem weevil**									**Slugs**								
		Effectiveness	**Strength of the evidence**	**Inexpensive to Implement**	**Economic Importance**	**Ease of implementation**	**Speed of impact**	**Current use**	**Potential use**	**References**	**Effectiveness**	**Strength of the evidence**	**Inexpensive to Implement**	**Economic Importance**	**Ease of implementation**	**Speed of impact**	**Current use**	**Potential use**	**References**	**Effectiveness**	**Strength of the evidence**	**Inexpensive to Implement**	**Economic Importance**	**Ease of implementation**	**Speed of impact**	**Current use**	**Potential use**	**References**
	Efficacy of chemical control for comparison	3									2									4								
Crop planning	Field history, rotation & break crops																			3	4	3	3	3	4	3	3	
	Spatial separation																											
Pre-cropping	Primary cultivations (Crop residue burial)																			3	4	3	3	4	4	3	3	223, 438
	Secondary cultivations (drilling method)																			3	4	3	3	4	4	3	3	431,406,570
	Seed rate																			2	2	2	3	4	4	1	2	299
	Seedbed quality																			2	3	3	3	4	4	3	3	*324,225*
	Sowing date	2	2	3	3	3	3	1	2	480																		
	Stubble Management																											
	Trap crops	2	3	4	3	3	3	1	2	130,128,129																		
	Undersowing & Companion cropping										2	1	2	2	2	4	1	2										
	Varietal choice																											
In-crop techniques	Bioprotectants and low risk PPP's																			3	2	2	3	2	2	1	3	225,248
	Decision support (incl. thresholds)	4	4	4	3	4	4	2	4	192,128,170										4	3	4	3	4	4	3	4	248, 225,
	Defoliation (incl. mowing and grazing)																											
	In field non-cropped areas	2	2	3	3	3	2	1	2	517	2	2	3	2	2	2	1	2	495									
	Organic amendments																											
	Rolling soil post-planting																			2	3	3	3	4	4	2	3	158
	Precision application																			4	3	4	3	3	4	1	4	205

Non- chemical control strategies in arable crops – Pests in oilseeds		Turnip sawfly									TuYV vectors								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	4									3								
Crop planning	Field history, rotation & break crops																		
	Spatial separation	2	2	3	1	4	3	1	2										
Pre-cropping	Primary cultivations (Crop residue burial)																		
	Secondary cultivations (drilling method)																		
	Seed rate																		
	Seedbed quality	3	3	4	1	3	4	1	2	*234*									
	Sowing date	2	2	4	1	3	4	1	2	170									
	Stubble Management																		
	Trap crops																		
	Undersowing & Companion cropping																		
	Varietal choice										4	4	3	4	4	4	2	4	29
In-crop techniques	Bioprotectants and low risk PPP's																		
	Decision support (incl. thresholds)	2	2	3	1	3	3	1	2		4	2	4	4	4	4	1	4	
	Defoliation (incl. mowing and grazing)																		
	In field non-cropped areas	2	2	3	1	3	2	1	2	517	2	2	3	4	3	2	1	3	124
	Organic amendments																		
	Rolling soil post-planting																		
	Precision application																		

11.9. **Pests in potatoes (score tables)**

Non- chemical control strategies in arable crops – Pests in potatoes		Cutworms									FLN & spraing									Potato cyst nematode								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	4									4									4								
Crop planning	Field history, Rotation & break crops										3	3	3	3	4	3	2	3		3	4	3	4	3	4	3	4	454
	Select low-risk locations										3	4	3	3	4	3	3	3		3	4	3	4	3	4	3	3	
	Spatial separation																											
Pre-cropping	Biofumigation										2	2	2	3	2	3	1	2		2	2	2	4	2	3	1	2	529
	Control volunteers & weeds	3	3	3	2	3	4	3	4											4	4	3	4	3	4	4	4	53
	Early harvest	3	4	3	2	3	3	2	3																			
	Flooding																			2	3	1	4	1	3	1	2	496
	Hygiene																			4	4	3	4	3	4	4	4	
	Primary culitvations (Crop residue burial)																											
	Secondary cultivations (drilling method)																											
	Seed testing																											
	Seedbed quality																											
	Trap crops																			3	4	4	4	2	4	1	4	191,476,477
	Varietal Choice										3	4	3	3	3	4	2	3	23	4	5	3	4	3	4	2	3	23
In-crop techniques	Bioprotectants and low risk PPP's	3	4	2	2	2	4	3	4	86,351	2	2	4	3	2	2	1	2		2	2	4	4	4	2	1	2	
	Decision support (incl. thresholds)	4	4	3	2	3	4	3	4	86	4	3	4	3	3	4	3	4		4	3	4	4	3	4	3	5	195
	In-field non-cropped areas																											
	Precision application																											

Non- chemical control strategies in arable crops – Pests in potatoes		Slugs									Wireworms									Viruses (aphid borne eg POTY)								
		Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control for comparison	4									3									3								
Crop planning	Field history, Rotation & break crops	3	4	3	2	3	4	3	3		2	4	3	3	4	4	2	4										
	Select low-risk locations										2	4	3	3	4	4	2	4		4	4	3	4	2	3	3	4	
	Spatial separation																			3	3	3	4	2	4	3	4	40
Pre-cropping	Biofumigation										3	2	2	3	2	3	1	3										
	Control volunteers & weeds																			4	4	2	4	3	3	3	4	53
	Early harvest	2	3	3	2	3	4	2	2		2	3	3	3	4	4	2	2	474									
	Flooding																											
	Hygiene																			4	4	2	4	2	4	3	4	40
	Primary culitvations (Crop residue burial)	4	3	3	2	3	3	3	3	325,223,438																		
	Secondary cultivations (drilling method)	3	4	3	2	4	4	3	3	431																		
	Seed testing																			4	4	3	4	3	3	3	4	
	Seedbed quality																											
	Trap crops																											
	Varietal Choice																			3	3	3	4	3	3	3	4	23
In-crop techniques	Bioprotectants and low risk PPP's	3	2	1	2	2	2	1	3	248, 225	3	2	4	3	4	3	1	2		3	2	3	4	4	3	1	4	481
	Decision support (incl. thresholds)	2	3	3	2	4	4	3	3		3	3	3	3	3	3	1	3		4	3	3	4	3	4	3	4	
	In-field non-cropped areas																			2	2	2	4	2	2	1	3	124,215
	Precision application	3	3	3	2	3	4	1	3	205																		

11.10. **Lodging in cereals (score table)**

Non- chemical control strategies in arable crops – Lodging in Cereals		Stem lodging									Root lodging								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control	4									4								
Crop planning	Field history, Rotation & break crops	3	3	4	3	3	3	4	5	144,67,66,211,75	3	3	4	3	3	3	4	5	144,67,66,211,75
Pre-cropping	Early harvest	1	2	4	3	4	5	2	3		1	2	4	3	4	5	2	3	
	Decision support (including thresholds)	4	3	4	3	4	5	3	5	71,75,508	4	3	4	3	4	5	3	5	71,75,508
	Variety choice	4	4	4	3	5	5	4	5	250,415,68	4	4	4	3	5	5	4	5	68,74
	Variety Mixtures	2	3	3	3	2	5	1	2	279,409,556	1	3	3	3	2	5	1	2	279,409,556
	Drilling method	1	2	3	3	2	5	2	3	188,201,434	2	2	3	3	2	5	2	3	188,201,357,554
	Seed rate	3	5	3	3	5	5	2	4	304,572	4	5	3	3	5	5	2	4	66,183,184,304
	Sowing date	2	4	3	3	3	5	2	3	151,308,498	3	4	3	3	3	5	2	3	66
	Nutrient management	4	3	4	3	4	5	3	5	66,144,145,183,552	4	3	4	3	4	5	3	5	66,144,145,183,552
	Pre-cropping Nutrition	2	1	3	3	4	2	4	5	429,345,310	2	2	3	3	4	2	4	5	429,345,310
	Biostimulants	1	1	2	3	5	5	2	4	335,346,473	1	1	2	3	5	5	2	4	335,346,473
In-crop techniques	Bioprotectants & low risk PPP's	2	2	2	3	4	5	1	4	267,335	1	2	2	3	4	5	1	4	267,335
	Rolling soil post-planting	1	3	2	3	2	5	2	3	68,311,416	2	3	2	3	2	5	2	3	68,311

11.11. **Lodging in oilseeds (score table)**

Non- chemical control strategies in arable crops		Stem lodging									Root lodging								
		Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References	Effectiveness	Strength of the evidence	Inexpensive to implement	Economic importance	Ease of implementation	Speed of impact	Current use	Potential use	References
	Efficacy of chemical control	3									3								
Crop planning	Field history, Rotation & break crops	3	3	4	3	4	3	4	5	144,67,66,211,75	3	3	4	3	4	3	4	5	144,67,66,211,75
Pre-cropping	Early harvest	1	1	4	3	3	5	2	3		1	1	4	3	3	5	2	3	
	Decision support (including thresholds)	3	2	4	3	4	5	3	5	75,508	3	2	4	3	4	5	3	5	75,508
	Variety choice	3	4	4	3	5	5	4	5	68,377,428	3	4	4	3	5	5	4	5	68,377,428
	Variety Mixtures	1	1	3	3	2	5	1	2	556	1	1	3	3	2	5	1	2	556
	Drilling method	1	1	3	3	2	5	3	4	317,475	2	2	3	3	2	5	3	4	317,475
	Seed rate	4	5	3	3	5	5	2	3	304,456,497	4	5	3	3	5	5	2	3	304,456,497
	Sowing date	2	2	3	3	3	5	2	3	558	3	3	3	3	3	5	2	3	558
	Nutrient management	3	2	4	3	4	5	4	5	558	3	2	4	3	4	5	4	5	558
	Pre-cropping Nutrition	1	1	3	3	4	5	1	3	345,429	2	1	3	3	4	5	1	3	345
	Biostimulants	1	1	2	3	5	5	1	4	411,506	1	1	2	3	5	5	1	4	411,506
In-crop techniques	Bioprotectants & low risk PPP's	1	1	2	3	4	5	1	4	267,335	1	1	2	3	4	5	1	4	267,335
	Rolling soil post-planting	1	1	2	3	3	5	1	2	68	1	1	2	3	3	5	1	2	68

11.12. **Cereals knowledge exchange (all-priorities table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)
Weeds	Annual Grasses	Hygiene	4	4	4	5	5	5	4	5	1	12.8	1
Disease	Septoria	Varietal choice	4	5	4	5	4	4	4	5	1	12.3	2=
Disease	Yellow Rust	Varietal choice	5	5	4	4	4	4	4	5	1	12.3	2=
Weeds	Annual Grasses	Primary cultivations (crop residue burial)	4	4	3	5	4	5	4	5	1	12.3	2=
Weeds	Annual Grasses	Secondary cultivations (drilling method)	4	4	3	5	4	3	4	5	1	11.8	5
Disease	Septoria	Sowing date	3	4	4	5	2	4	2	4	2	11.0	6
Weeds	All Weeds Pre-Emergence	Hygiene	4	4	4	3	5	5	4	5	1	10.8	7=
Weeds	All Weeds Pre-Emergence	Secondary cultivations (drilling method)	4	4	3	4	4	3	4	5	1	10.8	7=
Lodging	Stem Lodging	Variety choice	4	4	4	3	5	5	4	5	1	10.8	7=
Lodging	Root Lodging	Variety choice	4	4	4	3	5	5	4	5	1	10.8	7=
Lodging	Root Lodging	Seed rate	4	5	3	3	5	5	2	4	2	10.8	7=
Pest	BYDV Vectors	Sowing date	3	5	3	4	3	4	1	4	3	10.3	12=
Disease	Brown Rust	Varietal choice	4	4	4	3	4	4	4	5	1	10.3	12=
Disease	Septoria	Nutrient management	2	4	3	5	3	4	1	3	2	10.0	14
Loding	Stem Lodging	Seed rate	3	5	3	3	5	5	2	4	2	9.8	15
Disease	Yellow Rust	Sowing date	3	4	4	4	2	3	1	2	1	9.5	16
Disease	Ear Blight	Varietal choice	3	4	4	3	4	4	3	4	1	9.3	17
Loding	Root Lodging	Sowing date	3	4	3	3	3	5	2	3	1	9.0	18
Disease	Yellow Rust	Nutrient management	2	4	2	4	4	3	1	2	1	8.5	19
Weeds	BLW - Fibrous Root	Primary cultivations (crop residue burial)	2	4	3	3	4	5	3	4	1	8.3	20
Disease	Take-All	Nutrient management	2	4	3	3	4	3	2	4	2	8.0	
Lodging	Stem Lodging	Sowing date	2	4	3	3	3	5	2	3	1	8.0	
Pest	Wheat Bulb Fly	Seed rate	2	4	2	3	4	3	1	3	2	7.8	
Disease	Take-All	Lime	2	4	4	3	3	3	2	3	1	7.8	
Pest	Slugs	Field history, Rotation & break crops	2	4	3	3	3	3	2	3	1	7.5	
Disease	Take-All	Control volunteers & weeds	2	4	3	3	3	2	3	4	1	7.3	
Disease	Take-All	Pre-cropping Nutrition	2	4	2	3	3	3	3	4	1	7.3	

11.13. Oilseeds knowledge exchange (all-priorities table)

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking
Weeds	Annual Grasses	Secondary Cultivations (drilling method)	4	4	3	5	4	4	4	5	1	12.0	1
Disease	Light Leaf Spot	Varietal Choice	4	5	4	4	4	5	4	5	1	11.5	2=
Disease	Phoma Stem Canker	Varietal Choice	4	5	4	4	4	5	4	5	1	11.5	2=
Disease	Phoma Stem Canker	Decision support (including thresholds)	4	5	3	4	3	5	2	5	3	11.5	2=
Pest	TuYV Vectors	Varietal choice	4	4	3	4	4	4	2	4	2	11.3	5=
Weeds	Annual Grasses	Hygiene	3	4	4	5	5	3	4	5	1	11.3	5=
Disease	Clubroot	Decision support (including thresholds)	5	5	3	3	3	5	3	5	2	11.3	5=
Disease	Light Leaf Spot	Sowing date	4	4	4	4	3	5	3	4	1	11.3	5=
Disease	Phoma Stem Canker	Sowing date	4	4	4	4	3	5	3	4	1	11.3	5=
Weeds	BLW - Tap Root	Select low-risk locations	4	4	3	4	4	4	3	4	1	11.0	10=
Disease	Clubroot	Hygiene and prevention	5	5	3	3	3	5	4	5	1	11.0	10=
Disease	Light Leaf Spot	Field history, Rotation & break crops	3	4	5	4	4	5	3	5	2	11.0	10=
Disease	Light Leaf Spot	Primary cultivations / Crop residue burial	4	5	3	4	3	5	3	4	1	11.0	10=
Disease	Phoma Stem Canker	Primary cultivations / Crop residue burial	4	5	3	4	3	5	3	4	1	11.0	10=
Disease	Clubroot	Good drainage	5	5	2	3	3	5	3	4	1	10.8	15=
Disease	Light Leaf Spot	Stubble Management	4	4	2	4	3	5	3	4	1	10.8	15=
Disease	Phoma Stem Canker	Field history, Rotation & break crops	3	5	5	4	4	5	4	5	1	10.8	15=
Disease	Phoma Stem Canker	Stubble Management	4	4	2	4	3	5	3	4	1	10.8	15=
Disease	Verticillium Wilt	Field history, Rotation & break crops	4	5	5	3	4	5	4	5	1	10.8	15=
Disease	Verticillium Wilt	Varietal Choice	4	4	4	3	4	5	3	5	2	10.8	15=
Pest	Pollen Beetle	Decision support (incl. thresholds)	4	4	4	3	4	4	2	4	2	10.5	
Disease	Clubroot	Varietal Choice	4	5	3	3	4	5	3	5	2	10.5	
Disease	Light Leaf Spot	Decision support (including thresholds)	3	4	3	4	3	5	2	5	3	10.5	
Disease	Phoma Stem Canker	Spatial separation	3	4	5	4	3	5	3	4	1	10.5	
Lodging	Stem Lodging	Seed rate	4	5	3	3	5	5	2	3	1	10.5	
Lodging	Root Lodging	Seed rate	4	5	3	3	5	5	2	3	1	10.5	
Disease	Sclerotinia Stem Rot	Field history, Rotation & break crops	4	5	5	3	3	4	4	5	1	10.3	
Disease	Sclerotinia Stem Rot	Decision support (including thresholds)	4	4	3	3	2	5	3	4	1	9.8	
Disease	Verticillium Wilt	Hygiene and prevention	4	5	3	3	2	5	4	5	1	9.8	
Lodging	Stem Lodging	Variety choice	3	4	4	3	5	5	4	5	1	9.8	
Lodging	Root Lodging	Variety choice	3	4	4	3	5	5	4	5	1	9.8	
Disease	Sclerotinia Stem Rot	Select low-risk locations	3	5	5	3	3	5	3	4	1	9.5	
Weeds	BLW - Tap Root	Hygiene	2	4	4	4	5	3	3	4	1	9.3	
Weeds	BLW - Tap Root	Secondary cultivations (drilling method)	2	4	3	4	4	4	4	5	1	9.0	
Disease	Clubroot	Lime	3	5	2	3	3	4	2	4	2	8.8	
Weeds	BLW - Fibrous Root	Hygiene	2	4	4	3	5	3	2	4	2	8.5	
Weeds	BLW - Fibrous Root	Secondary cultivations (drilling method)	2	4	3	3	4	4	4	5	1	8.0	
Disease	Verticillium Wilt	Bioprotectants & low risk PPP's	2	4	2	3	2	4	1	3	2	7.5	
Disease	Sclerotinia Stem Rot	Varietal Choice	1	4	1	3	1	5	1	5	4	6.8	

11.14. **Potatoes knowledge exchange (all-priorities table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking (top 20)
Disease	Late Blight	Varietal choice	5	4	3	5	2	4	2	4	2	12.8	1
Disease	Late Blight	Control volunteers & weeds	4	4	2	5	4	4	3	5	2	12.0	2=
Disease	Late Blight	Early harvest	4	4	4	5	3	4	4	5	1	12.0	2=
Disease	Late Blight	Hygiene	4	4	4	5	3	4	4	5	1	12.0	2=
Disease	Late Blight	Field history, Rotation & break crops	4	4	3	5	3	4	4	5	1	11.8	5=
Disease	Blackleg	Hygiene	5	4	2	4	3	4	3	5	2	11.8	5=
Disease	Late Blight	Spatial separation	4	4	3	5	2	4	3	4	1	11.5	7=
Disease	Late Blight	Sowing date	4	4	3	5	3	3	2	3	1	11.5	7=
Disease	Blackleg	Early harvest	4	4	4	4	3	4	3	5	2	11.3	9
Disease	Late Blight	Select low-risk locations	4	4	3	5	2	2	2	3	1	11.0	10=
Disease	Blackleg	Control volunteers & weeds	4	4	3	4	3	4	2	4	2	11.0	10=
Pest	Potato Cyst Nematode	Varietal Choice	4	5	3	4	3	4	2	3	1	10.8	12=
Disease	Stem Canker and Black Scurf	Early harvest	4	4	3	4	3	4	3	4	1	10.8	12=
Pest	Viruses (Aphid Borne)	Seed testing	4	4	3	4	3	3	3	4	1	10.5	14=
Disease	Late Blight	Seedbed quality	3	4	3	5	3	3	2	3	1	10.5	14=
Pest	Potato Cyst Nematode	Trap crops	3	4	4	4	2	4	1	4	3	10.3	16=
Pest	Viruses (Aphid Borne)	Select low-risk locations	4	4	3	4	2	3	3	4	1	10.3	16=
Pest	Viruses (Aphid Borne)	Control volunteers & weeds	4	4	2	4	3	3	3	4	1	10.3	16=
Pest	Viruses (Aphid Borne)	Hygiene	4	4	2	4	2	4	3	4	1	10.3	16=
Disease	Black Dot	Field history, Rotation & break crops	4	4	3	3	4	4	2	3	1	10.0	20=
Disease	Black Dot	Varietal choice	4	4	4	3	3	4	3	4	1	10.0	20=
Disease	Blackleg	Field history, Rotation & break crops	3	4	3	4	3	4	2	4	2	10.0	20=
Pest	Potato Cyst Nematode	Field history, Rotation & break crops	3	4	3	4	3	4	3	4	1	9.8	
Disease	Common Scab	Varietal choice	3	4	4	4	3	3	3	4	1	9.8	
Disease	Common Scab	Field history, Rotation & break crops	3	4	3	4	3	3	3	4	1	9.5	
Disease	Gangrene	Control volunteers & weeds	2	4	3	5	3	3	2	3	1	9.5	
Disease	Late Blight	Good drainage	2	4	3	5	3	3	2	3	1	9.5	
Disease	Stem Canker and Black Scurf	Field history, Rotation & break crops	4	4	2	3	3	3	3	4	1	9.3	
Disease	Stem Canker and Black Scurf	Primary cultivations (crop residue burial)	4	4	2	3	3	3	3	4	1	9.3	
Disease	Silver Scurf	Field history, Rotation & break crops	4	4	3	3	2	2	4	5	1	9.0	
Disease	Silver Scurf	Control volunteers & weeds	4	4	3	3	2	2	3	4	1	9.0	
Weeds	BLW - Fibrous Root	Hygiene	2	4	4	4	5	2	3	4	1	9.0	
Pest	FLN and Spraing	Varietal Choice	3	4	3	3	3	4	2	3	1	8.8	
Disease	Black Dot	Control volunteers & weeds	3	4	3	3	3	3	3	4	1	8.5	
Pest	Wireworm	Field history, Rotation & break crops	2	4	3	3	4	4	2	4	2	8.3	
Pest	Wireworm	Select low-risk locations	2	4	3	3	4	4	2	4	2	8.3	
Disease	Common Scab	Control volunteers & weeds	2	4	3	4	3	2	2	3	1	8.3	
Disease	Powdery Scab	Good drainage	3	4	2	3	2	2	1	4	3	8.3	
Disease	Black Dot	Seedbed quality	3	4	3	3	2	2	2	3	1	8.0	
Disease	Silver Scurf	Early harvest	3	4	3	3	2	2	3	4	1	8.0	
Disease	Silver Scurf	Primary cultivations (crop residue burial)	3	4	3	3	2	2	2	3	1	8.0	
Weeds	BLW - Tap Root	Hygiene	2	4	4	3	5	2	3	4	1	8.0	

11.15. **Cereals research (all-priorities table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking
Diseases	Septoria	Decision support (including thresholds)	4	3	4	5	3	4	2	4	2	12.3	1
Diseases	Septoria	Varietal mixtures	4	3	4	5	3	3	1	3	2	12.0	2
Pest	BYDV Vectors	Decision support (including thresholds)	4	2	4	4	4	4	1	4	3	11.8	3=
Diseases	Yellow Rust	Decision support (including thresholds)	4	3	4	4	4	4	1	4	3	11.8	3=
Weeds	Annual Grasses	Precision application	4	2	2	5	2	4	1	4	3	11.8	3=
Pest	BYDV Vectors	Varietal Choice	4	3	3	4	4	4	1	4	3	11.5	6=
Weeds	Annual Grasses	Undersowing & companion crops	4	2	2	5	2	4	2	4	2	11.5	6=
Diseases	Septoria	Bioprotection & low risk PPP's	3	2	3	5	4	4	1	3	2	11.3	8=
Diseases	Yellow Rust	Varietal mixtures	4	3	4	4	3	4	1	3	2	11.3	8=
Weeds	Annual Grasses	Mechanical weeding	4	3	2	5	2	3	2	3	1	11.0	10
Weeds	Annual Grasses	Varietal choice	3	3	3	5	3	4	3	4	1	10.8	11=
Weeds	BLW - Tap Root	Varietal choice	3	3	3	5	3	4	3	4	1	10.8	11=
Lodging	Stem Lodging	Decision support (including thresholds)	4	3	4	3	4	5	3	5	2	10.8	11=
Lodging	Stem Lodging	Nutrient management	4	3	4	3	4	5	3	5	2	10.8	11=
Lodging	Root Lodging	Decision support (including thresholds)	4	3	4	3	4	5	3	5	2	10.8	11=
Lodging	Root Lodging	Nutrient management	4	3	4	3	4	5	3	5	2	10.8	11=
Pest	Slugs	Precision application	4	3	4	3	3	4	1	4	3	10.5	17=
Pest	Wheat Bulb Fly	Decision support (including thresholds)	4	3	4	3	4	3	1	4	3	10.5	17=
Diseases	Take-All	Varietal choice	4	3	4	3	4	4	2	4	2	10.5	17=
Weeds	Annual Grasses	Use of cover crops	3	2	2	5	2	4	2	4	2	10.5	17=
Pest	Slugs	Decision support (including thresholds)	4	3	4	3	4	4	3	4	1	10.3	17=
Weeds	Annual Grasses	Decision support (incl. thresholds)	3	2	4	5	2	2	2	3	1	10.3	17=
Weeds	BLW - Tap Root	Primary cultivations (crop residue burial)	4	3	3	3	4	5	3	4	1	10.3	17=
Weeds	Annual Grasses	Intercropping	3	2	2	5	2	3	2	3	1	10.0	
Pest	BYDV Vectors	In field non-cropped areas	3	2	3	4	3	3	1	3	2	9.8	
Diseases	Brown Rust	Decision support (including thresholds)	3	3	4	3	4	5	2	4	2	9.8	
Weeds	All Weeds Pre-Emergence	Stubble management	3	3	3	4	3	4	3	4	1	9.8	
Weeds	BLW - Tap Root	Stubble management	4	3	3	3	4	3	3	4	1	9.8	
Weeds	BLW - Tap Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	
Weeds	BLW - Fibrous Root	Stubble management	4	3	3	3	4	3	3	4	1	9.8	
Weeds	BLW - Fibrous Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	
Weeds	Volunteer Potatoes	Precision application	4	3	2	3	2	4	1	4	3	9.8	
Diseases	Brown Rust	Bioprotection & low risk PPP's	3	2	4	3	4	4	1	3	2	9.5	
Diseases	Ear Blight	Decision support (including thresholds)	3	3	4	3	4	4	2	4	2	9.5	
Weeds	All Weeds Pre-Emergence	Thermal control	4	2	1	4	1	3	1	2	1	9.5	
Weeds	Annual Grasses	Drainage	2	2	4	5	2	3	3	4	1	9.5	
Weeds	Annual Grasses	Thermal control	4	2	1	4	1	3	1	2	1	9.5	
Weeds	BLW - Tap Root	Use of cover crops	4	2	2	3	2	4	2	4	2	9.5	
Weeds	BLW - Tap Root	Undersowing & companion crops	4	2	2	3	2	4	2	4	2	9.5	
Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	3	2	4	2	4	2	9.5	
Weeds	BLW - Fibrous Root	Undersowing & companion crops	4	2	2	3	2	4	2	4	2	9.5	
Pest	BYDV Vectors	Undersowing / companion cropping	3	3	2	4	2	3	1	3	2	9.3	
Weeds	All Weeds Pre-Emergence	Fallow	3	2	2	4	5	1	1	2	1	9.3	
Pest	BYDV Vectors	Control volunteers & weeds	2	2	3	4	4	4	2	3	1	9.0	
Pest	Wheat Bulb Fly	Sowing date	3	3	3	3	4	3	1	3	2	9.0	
Diseases	Yellow Rust	Bioprotection & low risk PPP's	2	2	3	4	3	4	1	3	2	9.0	
Weeds	All Weeds Pre-Emergence	Use of cover crops	3	3	1	4	1	4	2	4	2	9.0	
Weeds	All Weeds Pre-Emergence	Undersowing & companion crops	3	2	1	4	1	4	2	4	2	9.0	
Weeds	BLW - Tap Root	In-field, non-cropped area	3	3	4	3	4	2	2	4	2	9.0	
Weeds	BLW - Fibrous Root	Varietal choice	3	2	3	3	4	4	2	3	1	9.0	
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	3	4	2	2	4	2	9.0	
Weeds	BLW - Fibrous Root	Mechanical weeding	4	3	2	3	2	3	2	3	1	9.0	
Pest	BYDV Vectors	Primary culitvations / Crop residue burial	2	3	3	4	3	4	2	3	1	8.8	
Pest	BYDV Vectors	Secondary cultivations / drilling method	2	3	3	4	3	4	2	3	1	8.8	

Weeds	All Weeds Pre-Emergence	Bioprotectants & low risk PPP's	2	2	2	4	4	4	1	2	1	8.8	
Weeds	All Weeds Pre-Emergence	Intercropping	3	2	1	4	1	3	1	3	2	8.8	
Weeds	Annual Grasses	Bioprotectants & low risk PPP's	2	2	2	5	2	2	1	2	1	8.8	
Lodging	Stem Lodging	Field history, Rotation & break crops	3	3	4	3	3	3	4	5	1	8.8	
Lodging	Root Lodging	Field history, Rotation & break crops	3	3	4	3	3	3	4	5	1	8.8	
Pest	BYDV Vectors	Select low-risk locations	2	3	3	4	3	3	1	2	1	8.5	
Diseases	Yellow Rust	Control volunteers & weeds	2	3	3	4	3	3	2	3	1	8.5	
Weeds	BLW - Fibrous Root	Thermal control	4	2	1	3	1	3	1	2	1	8.5	
Lodging	Stem Lodging	Biopesticides & low risk PPP's	2	2	2	3	4	5	1	4	3	8.5	
Diseases	Ear Blight	Primary cultivations (crop residue burial)	3	3	3	3	2	3	1	2	1	8.3	
Weeds	Volunteer Potatoes	Use of cover crops	3	1	2	3	2	3	1	3	2	8.3	
Weeds	Volunteer Potatoes	Intercropping	3	1	2	3	3	3	2	3	1	8.3	
Weeds	Volunteer Potatoes	Undersowing & companion crops	3	1	2	3	3	3	2	3	1	8.3	
Diseases	Brown Rust	Sowing date	2	2	4	3	3	4	1	2	1	8.0	
Weeds	BLW - Tap Root	Intercropping	3	2	2	3	2	3	2	3	1	8.0	
Weeds	BLW - Tap Root	Mechanical weeding	3	3	2	3	2	3	2	3	1	8.0	
Weeds	BLW - Fibrous Root	Intercropping	3	2	2	3	2	3	2	3	1	8.0	
Pest	Slugs	Primary culitvations / Crop residue burial	2	2	3	3	3	3	1	3	2	7.8	
Pest	Slugs	Secondary cultivations / drilling method	2	2	3	3	3	3	1	3	2	7.8	
Pest	Slugs	Seedbed quality	2	3	3	3	3	3	2	4	2	7.8	
Pest	Slugs	Rolling soil post-planting	2	3	3	3	3	3	1	3	2	7.8	
Lodging	Stem Lodging	Variety Mixtures	2	3	3	3	2	5	1	2	1	7.8	
Lodging	Root Lodging	Drilling method	2	2	3	3	2	5	2	3	1	7.8	
Pest	Wheat Bulb Fly	Spatial separation	2	3	3	3	3	3	1	2	1	7.5	
Diseases	Brown Rust	Nutrient management	2	2	3	3	2	4	2	3	1	7.5	
Diseases	Ear Blight	Sowing date	2	3	3	3	3	3	1	2	1	7.5	
Weeds	BLW - Tap Root	Defoliation (incl. mowing and grazing)	2	2	2	3	3	4	2	3	1	7.5	
Weeds	BLW - Fibrous Root	Defoliation (incl. mowing and grazing)	2	2	2	3	3	4	2	3	1	7.5	
Lodging	Stem Lodging	Early harvest	1	2	4	3	4	5	2	3	1	7.5	
Lodging	Stem Lodging	Pre-cropping Nutrition	2	1	3	3	4	2	4	5	1	7.5	
Lodging	Stem Lodging	Biostimulants	1	1	2	3	5	5	2	4	2	7.5	
Lodging	Root Lodging	Early harvest	1	2	4	3	4	5	2	3	1	7.5	
Lodging	Root Lodging	Pre-cropping Nutrition	2	2	3	3	4	2	4	5	1	7.5	
Lodging	Root Lodging	Biostimulants	1	1	2	3	5	5	2	4	2	7.5	
Lodging	Root Lodging	Biopesticides & low risk PPP's	1	2	2	3	4	5	1	4	3	7.5	
Lodging	Root Lodging	Rolling soil post-planting	2	3	2	3	2	5	2	3	1	7.5	
Pest	Wheat Bulb Fly	Varietal Choice	2	2	3	3	3	2	1	2	1	7.3	
Pest	Wheat Bulb Fly	Field history, Rotation & break crops	2	3	2	3	2	2	1	3	2	7.0	
Diseases	Ear Blight	Field history, rotation & break crops	2	2	3	3	1	3	2	3	1	7.0	
Pest	Wheat Bulb Fly	Use of cover crops	2	2	2	3	2	2	1	2	1	6.8	
Weeds	BLW - Tap Root	Bioprotectants & low risk PPP's	2	2	2	3	2	2	1	2	1	6.8	
Weeds	BLW - Fibrous Root	Bioprotectants & low risk PPP's	2	2	2	3	2	2	1	2	1	6.8	
Lodging	Stem Lodging	Drilling method	1	2	3	3	2	5	2	3	1	6.8	
Lodging	Root Lodging	Variety Mixtures	1	3	3	3	2	5	1	2	1	6.8	
Diseases	Ear Blight	Seed testing	1	2	3	3	3	3	1	2	1	6.5	
W	BLW - Tap Root	Thermal control	2	2	1	3	1	3	1	2	1	6.5	
Lodging	Stem Lodging	Rolling soil post-planting	1	3	2	3	2	5	2	3	1	6.5	

11.16. **Oilseeds research (all-priorities table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking
Pest	Cabbage Stem Flea Beetle	Decision support (incl. thresholds)	4	3	4	5	4	4	1	4	3	12.8	1
Pest	Cabbage Stem Flea Beetle	Trap crops	4	3	3	5	3	4	1	4	3	12.3	2
Pest	Cabbage Stem Flea Beetle	Sowing date	4	3	3	5	3	4	3	4	1	11.8	3=
Pest	Cabbage Stem Flea Beetle	In field non-cropped areas	4	2	3	5	3	2	1	4	3	11.8	3=
Pest	TuYV Vectors	Decision support (incl. thresholds)	4	2	4	4	4	4	1	4	3	11.8	3=
Weeds	Annual Grasses	Precision application	4	2	2	5	2	4	1	4	3	11.8	3=
Pest	Cabbage Stem Flea Beetle	Seed rate	3	3	3	5	5	4	1	3	2	11.5	7
Pest	Cabbage Stem Flea Beetle	Varietal choice	3	1	3	5	4	4	2	4	2	11.3	8=
Pest	Cabbage Stem Flea Beetle	Bioprotectants & low risk PPP's	3	1	2	5	4	4	1	4	3	11.3	8=
Weeds	Annual Grasses	Undersowing companion crops	4	2	2	5	2	4	2	3	1	11.3	8=
Pest	Cabbage Stem Flea Beetle	Stubble Management	3	2	3	5	3	4	1	3	2	11.0	11=
Pest	Cabbage Stem Flea Beetle	Defoliation (incl. mowing and grazing)	3	3	3	5	3	4	1	3	2	11.0	11=
Pest	Cabbage Stem Flea Beetle	Seedbed quality	3	3	3	5	3	4	3	4	1	10.8	13=
Pest	Cabbage Stem Flea Beetle	Organic amendments	3	1	3	5	2	4	1	3	2	10.8	13=
Weeds	BLW - Tap Root	Precision application	4	3	2	4	2	4	1	4	3	10.8	13=
Pest	Slugs	Precision application	4	3	4	3	3	4	1	4	3	10.5	16=
Disease	Light Leaf Spot	Spatial separation	3	3	5	4	3	5	3	4	1	10.5	16=
Pest	Cabbage Stem Flea Beetle	Undersowing & Companion cropping	3	2	2	5	2	4	2	3	1	10.3	18=
Pest	Cabbage Stem Flea Beetle	Rolling soil post-planting	2	2	4	5	4	4	3	4	1	10.3	18=
Pest	Slugs	Decision support (incl. thresholds)	4	3	4	3	4	4	3	4	1	10.3	18=
Weeds	Annual Grasses	Decision support (incl. thresholds)	3	2	4	5	2	2	2	3	1	10.3	18=
Weeds	Annual Grasses	Stubble management	2	3	3	5	3	3	2	5	3	10.0	
Weeds	Annual Grasses	Use of cover crops	3	2	2	5	1	4	2	3	1	10.0	
Weeds	Annual Grasses	Mechanical weeding	3	3	2	5	2	3	2	3	1	10.0	
Weeds	Annual Grasses	Thermal control	3	3	2	5	2	3	1	2	1	10.0	
Weeds	BLW - Tap Root	In-field, non-cropped area	3	3	4	4	4	2	2	3	1	9.8	
Weeds	BLW - Fibrous Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	
Disease	Sclerotinia Stem Rot	Primary cultivations / Crop residue burial	4	3	3	3	3	4	2	3	1	9.8	
Disease	Stem Lodging	Decision support (including thresholds)	3	2	4	3	4	5	3	5	2	9.8	
Disease	Root Lodging	Decision support (including thresholds)	3	2	4	3	4	5	3	5	2	9.8	
Disease	Clubroot	Sowing date	3	3	4	3	4	5	3	4	1	9.5	
Disease	Stem Lodging	Nutrient management	3	2	4	3	4	5	4	5	1	9.5	
Disease	Root Lodging	Nutrient management	3	2	4	3	4	5	4	5	1	9.5	
Weeds	BLW - Tap Root	Undersowing companion crops	3	2	2	4	2	4	2	3	1	9.3	
Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	3	2	4	2	3	1	9.3	
Weeds	BLW - Fibrous Root	Undersowing companion crops	4	2	2	3	2	4	2	3	1	9.3	
Disease	Clubroot	Control volunteers & weeds	3	3	3	3	3	5	3	5	2	9.3	
Disease	Sclerotinia Stem Rot	Spatial separation	3	2	5	3	3	3	2	3	1	9.0	
Disease	Stem Lodging	Field history, Rotation & break crops	3	3	4	3	4	3	4	5	1	9.0	
Disease	Root Lodging	Field history, Rotation & break crops	3	3	4	3	4	3	4	5	1	9.0	
Disease	Root Lodging	Sowing date	3	3	3	3	3	5	2	3	1	9.0	
Weeds	Annual Grasses	Biopesticides & low risk PPP's	2	2	2	5	2	2	1	2	1	8.8	
Weeds	Annual Grasses	Defoliation (incl. mowing and grazing)	2	2	2	5	2	2	1	2	1	8.8	
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	3	4	2	2	3	1	8.8	
Pest	TuYV Vectors	In field non-cropped areas	2	2	3	4	3	2	1	3	2	8.5	
Disease	Root Lodging	Pre-cropping Nutrition	2	1	3	3	4	5	1	3	2	8.5	
Pest	Slugs	Bioprotectants & low risk PPP's	3	2	2	3	2	2	1	3	2	8.0	
Pest	Slugs	Rolling soil post-planting	2	3	3	3	4	4	2	3	1	8.0	
L	Stem Lodging	Sowing date	2	2	3	3	3	5	2	3	1	8.0	
Pest	Pollen Beetle	Trap crops	2	3	4	3	3	3	1	2	1	7.8	
Pest	Slugs	Seed rate	2	2	2	3	4	4	1	2	1	7.8	
Weeds	BLW - Tap Root	Biopesticides & low risk PPP's	2	2	2	4	2	2	1	2	1	7.8	
Weeds	BLW - Tap Root	Defoliation (incl. mowing and grazing)	2	2	2	4	2	2	1	2	1	7.8	
Disease	Stem Lodging	Biostimulants	1	1	2	3	5	5	1	4	3	7.8	

Disease	Root Lodging	Drilling method	2	2	3	3	2	5	3	4	1	7.8	
Disease	Root Lodging	Biostimulants	1	1	2	3	5	5	1	4	3	7.8	
Pest	Pollen Beetle	Sowing date	2	2	3	3	3	3	1	2	1	7.5	
Disease	Stem Lodging	Pre-cropping Nutrition	1	1	3	3	4	5	1	3	2	7.5	
Disease	Stem Lodging	Biopesticides & low risk PPP's	1	1	2	3	4	5	1	4	3	7.5	
Disease	Root Lodging	Biopesticides & low risk PPP's	1	1	2	3	4	5	1	4	3	7.5	
Pest	Pollen Beetle	In field non-cropped areas	2	2	3	3	3	2	1	2	1	7.3	
Disease	Stem Lodging	Early harvest	1	1	4	3	3	5	2	3	1	7.3	
Disease	Root Lodging	Early harvest	1	1	4	3	3	5	2	3	1	7.3	
Weeds	BLW - Fibrous Root	Biopesticides & low risk PPP's	2	2	2	3	2	2	1	2	1	6.8	
Weeds	BLW - Fibrous Root	Defoliation (incl. mowing and grazing)	2	2	2	3	2	2	1	2	1	6.8	
Disease	Stem Lodging	Variety Mixtures	1	1	3	3	2	5	1	2	1	6.8	
Disease	Stem Lodging	Drilling method	1	1	3	3	2	5	3	4	1	6.8	
Disease	Stem Lodging	Rolling soil post-planting	1	1	2	3	3	5	1	2	1	6.8	
Disease	Root Lodging	Variety Mixtures	1	1	3	3	2	5	1	2	1	6.8	
Disease	Root Lodging	Rolling soil post-planting	1	1	2	3	3	5	1	2	1	6.8	

11.17. Potatoes research (all-priorities table)

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Priority Ranking
Diseases	Storage Diseases	Field history, Rotation & break crops	4	2	2	5	3	4	2	4	2	11.8	1
Diseases	Late Blight	Decision support (including thresholds)	4	3	2	5	3	4	2	3	1	11.5	2
Pest	Potato Cyst Nematode	Decision support (including thresholds)	4	3	4	4	3	4	3	5	2	11.3	3=
Diseases	Storage Diseases	Hygiene	4	3	2	5	3	3	3	4	1	11.3	3=
Diseases	Late Blight	Seed testing	3	1	3	5	3	4	2	4	2	11.0	5=
Weeds	All Weeds Pre-Emergence	Thermal control	4	3	1	5	2	4	1	2	1	11.0	5=
Pest	Viruses (Aphid Borne)	Decision support (including thresholds)	4	3	3	4	3	4	3	4	1	10.8	7=
Diseases	Blackleg	Decision support (including thresholds)	4	1	2	4	3	3	2	5	3	10.8	7=
Diseases	Dry Rot	Varietal choice	3	2	4	5	3	3	1	2	1	10.8	7=
Diseases	Viruses (Soil Borne)	Field history, Rotation & break crops	4	3	3	4	3	4	3	4	1	10.8	7=
Weeds	Annual Grasses	Precision application	4	2	2	4	2	4	1	4	3	10.8	7=
Weeds	BLW - Fibrous Root	Precision application	4	2	2	4	2	4	1	4	3	10.8	7=
Diseases	Gangrene	Seed testing	3	1	3	5	3	3	3	4	1	10.5	13=
Diseases	Storage Diseases	Varietal choice	3	3	3	5	3	3	3	4	1	10.5	13=
Diseases	Viruses (Soil Borne)	Seed testing	4	1	3	4	2	3	2	4	2	10.5	13=
Pest	Viruses (Aphid Borne)	Bioprotection + low risk PPP's	3	2	3	4	4	3	1	4	3	10.3	16=
Diseases	Black Dot	Seed testing	4	2	4	3	4	4	3	4	1	10.3	16=
Diseases	Blackleg	Seed testing	4	2	1	4	3	3	2	4	2	10.3	16=
Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	4	2	4	2	3	1	10.3	16=
Pest	FLN and Spraing	Decision support (including thresholds)	4	3	4	3	3	4	3	4	1	10.0	20=
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	4	4	2	1	3	2	10.0	20=
Diseases	Dry Rot	Primary cultivations (crop residue burial)	2	1	4	5	3	3	2	3	1	9.8	
Diseases	Silver Scurf	Seed testing	4	2	2	3	3	4	2	4	2	9.8	
Diseases	Stem Canker and Black Scurf	Seed testing	4	2	3	3	3	3	2	4	2	9.8	
Weeds	BLW - Tap Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	
Pest	Viruses (Aphid Borne)	Spatial separation	3	3	3	4	2	4	3	4	1	9.5	
Pest	Viruses (Aphid Borne)	Varietal Choice	3	3	3	4	3	3	3	4	1	9.5	
Diseases	Early Blight	Varietal choice	4	3	3	3	2	3	1	3	2	9.5	
Diseases	Stem Canker and Black Scurf	Varietal choice	4	2	3	3	2	3	2	4	2	9.5	
Diseases	Late Blight	Nutrient management	2	3	3	5	3	3	2	2	0	9.3	
Diseases	Powdery Scab	Decision support (including thresholds)	4	1	2	3	3	2	1	3	2	9.3	
Weeds	Annual Grasses	Use of cover crops	3	2	2	4	2	4	2	3	1	9.3	
Weeds	BLW - Tap Root	Use of cover crops	4	2	2	3	2	4	2	3	1	9.3	
Pest	Wireworm	Bioprotection + low risk PPP's	3	2	4	3	4	3	1	2	1	9.0	
Diseases	Black Dot	Decision support (including thresholds)	4	3	2	3	4	1	3	4	1	9.0	
Diseases	Blackleg	Primary cultivations (crop residue burial)	3	2	2	4	3	2	3	4	1	9.0	
Diseases	Stem Canker and Black Scurf	Decision support (including thresholds)	4	2	2	3	2	2	2	4	2	9.0	
Weeds	Annual Grasses	Select low-risk locations	3	3	3	3	4	4	4	5	1	9.0	
Weeds	Annual Grasses	In-field, non-cropped area	2	3	4	4	4	2	1	3	2	9.0	
Weeds	Annual Grasses	Mechanical weeding	3	3	2	4	2	3	3	4	1	9.0	
Weeds	Annual Grasses	Thermal control	3	3	2	4	2	3	1	2	1	9.0	
Weeds	BLW - Tap Root	In-field, non-cropped area	3	3	4	3	4	2	1	3	2	9.0	
Pest	FLN and Spraing	Field history, Rotation & break crops	3	3	3	3	4	3	2	3	1	8.8	
Pest	Potato Cyst Nematode	Bioprotection + low risk PPP's	2	2	4	4	4	2	1	2	1	8.8	
Pest	Wireworm	Decision support (including thresholds)	3	3	3	3	3	3	1	3	2	8.8	
Diseases	Early Blight	Seed testing	3	1	3	3	3	3	2	4	2	8.8	
Diseases	Early Blight	Spatial separation	3	1	3	3	3	3	2	3	1	8.5	
Diseases	Early Blight	Primary cultivations (crop residue burial)	3	1	3	3	3	3	2	3	1	8.5	
Pest	Wireworm	Biofumigation	3	2	2	3	2	3	1	3	2	8.3	
Pest	Potato Cyst Nematode	Biofumigation	2	2	2	4	2	3	1	2	1	8.0	
Pest	Viruses (Aphid Borne)	In-field non-cropped areas	2	2	2	4	2	2	1	3	2	8.0	

11.18. **Cereals combined knowledge exchange and research priorities (table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Scoring	Priority Area
Weeds	Annual Grasses	Hygiene	4	4	4	5	5	5	4	5	1	12.8	Research
Disease	Septoria	Varietal choice	4	5	4	5	4	4	4	5	1	12.3	Research
Disease	Septoria	Decision support (including thresholds)	4	3	4	5	3	4	2	4	2	12.3	Research
Disease	Yellow Rust	Varietal choice	5	5	4	4	4	4	4	5	1	12.3	Research
Weeds	Annual Grasses	Primary cultivations (crop residue burial)	4	4	3	5	4	5	4	5	1	12.3	KTE
Disease	Septoria	Varietal mixtures	4	3	4	5	3	3	1	3	2	12.0	Research
Weeds	Annual Grasses	Fallow	4	3	4	5	4	4	4	4	0	12.0	Research
Weeds	Annual Grasses	Field history, rotation & break crops	4	3	3	5	5	4	4	4	0	12.0	Research
Pest	BYDV Vectors	Decision support (including thresholds)	4	2	4	4	4	4	1	4	3	11.8	Research
Disease	Yellow Rust	Decision support (including thresholds)	4	3	4	4	4	4	1	4	3	11.8	Research
Weeds	Annual Grasses	Early harvest	4	3	4	5	3	4	4	4	0	11.8	Research
Weeds	Annual Grasses	Secondary cultivations (drilling method)	4	4	3	5	4	3	4	5	1	11.8	Research
Weeds	Annual Grasses	Precision application	4	2	2	5	2	4	1	4	3	11.8	Research
Pest	BYDV Vectors	Varietal Choice	4	3	3	4	4	4	1	4	3	11.5	Research
Weeds	Annual Grasses	Seed rate	4	4	2	5	5	3	4	4	0	11.5	Research
Weeds	Annual Grasses	Stubble management	4	3	3	5	4	3	4	4	0	11.5	Research
Weeds	Annual Grasses	Undersowing & companion crops	4	2	2	5	2	4	2	4	2	11.5	Research
Disease	Septoria	Bioprotection & low risk PPP's	3	2	3	5	4	4	1	3	2	11.3	Research
Disease	Yellow Rust	Varietal mixtures	4	3	4	4	3	4	1	3	2	11.3	Research
Weeds	All Weeds Pre-Emergence	Field history, rotation & break crops	4	3	3	4	5	5	5	5	0	11.3	Research
Weeds	Annual Grasses	Defoliation (incl. mowing and grazing)	4	3	2	5	3	4	3	3	0	11.3	Research
Weeds	Annual Grasses	Hand weeding/roguing	4	4	1	5	4	4	4	4	0	11.3	Research
Disease	Septoria	Sowing date	3	4	4	5	2	4	2	4	2	11.0	Research
Weeds	All Weeds Pre-Emergence	Primary cultivations (crop residue burial)	4	4	3	4	4	5	5	5	0	11.0	Research
Weeds	Annual Grasses	Sowing date	4	4	2	5	2	4	4	4	0	11.0	Research
Weeds	Annual Grasses	Mechanical weeding	4	3	2	5	2	3	2	3	1	11.0	KTE
Weeds	All Weeds Pre-Emergence	Hygiene	4	4	4	3	5	5	4	5	1	10.8	Research
Weeds	All Weeds Pre-Emergence	Secondary cultivations (drilling method)	4	4	3	4	4	3	4	5	1	10.8	Research
Weeds	Annual Grasses	Select low-risk locations	3	4	3	5	4	4	3	3	0	10.8	Research
Weeds	Annual Grasses	Varietal choice	3	3	3	5	3	4	3	4	1	10.8	Research
Weeds	BLW - Tap Root	Varietal choice	3	3	3	5	3	4	3	4	1	10.8	Research
Lodging	Stem Lodging	Decision support (including thresholds)	4	3	4	3	4	5	3	5	2	10.8	Research
Lodging	Stem Lodging	Variety choice	4	4	4	3	5	5	4	5	1	10.8	Research
Lodging	Stem Lodging	Nutrient management	4	3	4	3	4	5	3	5	2	10.8	Research
Lodging	Root Lodging	Decision support (including thresholds)	4	3	4	3	4	5	3	5	2	10.8	Research
Lodging	Root Lodging	Variety choice	4	4	4	3	5	5	4	5	1	10.8	KTE
Lodging	Root Lodging	Seed rate	4	5	3	3	5	5	2	4	2	10.8	Research

Lodging	Root Lodging	Nutrient management	4	3	4	3	4	5	3	5	2	10.8	Research
Pest	Slugs	Precision application	4	3	4	3	3	4	1	4	3	10.5	Research
Pest	Wheat Bulb Fly	Decision support (including thresholds)	4	3	4	3	4	3	1	4	3	10.5	Research
Disease	Take-All	Varietal choice	4	3	4	3	4	4	2	4	2	10.5	Research
Weeds	Annual Grasses	Use of cover crops	3	2	2	5	2	4	2	4	2	10.5	Research
Weeds	Annual Grasses	In-field, non-cropped area	3	3	4	5	4	2	4	4	0	10.5	Research
Pest	BYDV Vectors	Sowing date	3	5	3	4	3	4	1	4	3	10.3	KTE
Pest	Slugs	Decision support (including thresholds)	4	3	4	3	4	4	3	4	1	10.3	Research
Disease	Brown Rust	Varietal choice	4	4	4	3	4	4	4	5	1	10.3	Research
Disease	Take-All	Field history, rotation & break crops	5	5	3	3	4	2	4	4	0	10.3	Research
Weeds	All Weeds Pre-Emergence	Sowing date	4	4	3	4	2	4	4	4	0	10.3	KTE
Weeds	Annual Grasses	Flooding	3	2	3	5	2	4	1	1	0	10.3	KTE
Weeds	Annual Grasses	Decision support (incl. thresholds)	3	2	4	5	2	2	2	3	1	10.3	KTE
Weeds	BLW - Tap Root	Primary cultivations (crop residue burial)	4	3	3	3	4	5	3	4	1	10.3	Research
Weeds	Volunteer Potatoes	Field history, rotation & break crops	4	5	4	3	5	4	4	4	0	10.3	Research
Weeds	Volunteer Potatoes	Select low-risk locations	4	5	4	3	5	4	3	3	0	10.3	Research
Weeds	Volunteer Potatoes	Stubble management	4	5	4	3	5	4	3	3	0	10.3	Research
Disease	Septoria	Nutrient management	2	4	3	5	3	4	1	3	2	10.0	Research
Weeds	Annual Grasses	Seedbed quality	3	3	3	5	2	3	3	3	0	10.0	KTE
Weeds	Annual Grasses	Intercropping	3	2	2	5	2	3	2	3	1	10.0	Research
Weeds	BLW - Tap Root	Field history, rotation & break crops	4	5	3	3	5	4	3	3	0	10.0	Research
Weeds	BLW - Fibrous Root	Field history, rotation & break crops	4	5	3	3	5	4	3	3	0	10.0	Research
Pest	BYDV Vectors	In field non-cropped areas	3	2	3	4	3	3	1	3	2	9.8	Research
Disease	Brown Rust	Decision support (including thresholds)	3	3	4	3	4	5	2	4	2	9.8	Research
Weeds	All Weeds Pre-Emergence	Early harvest	3	3	4	4	3	4	2	2	0	9.8	Research
Weeds	All Weeds Pre-Emergence	Stubble management	3	3	3	4	3	4	3	4	1	9.8	Research
Weeds	BLW - Tap Root	Select low-risk locations	4	4	3	3	4	4	3	3	0	9.8	Research
Weeds	BLW - Tap Root	Stubble management	4	3	3	3	4	3	3	4	1	9.8	KTE
Weeds	BLW - Tap Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	Research
Weeds	BLW - Fibrous Root	Select low-risk locations	4	4	3	3	4	4	3	3	0	9.8	KTE
Weeds	BLW - Fibrous Root	Stubble management	4	3	3	3	4	3	3	4	1	9.8	Research
Weeds	BLW - Fibrous Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	Research
Weeds	Volunteer Potatoes	Precision application	4	3	2	3	2	4	1	4	3	9.8	KTE
Lodging	Stem Lodging	Seed rate	3	5	3	3	5	5	2	4	2	9.8	Research
Disease	Brown Rust	Bioprotection & low risk PPP's	3	2	4	3	4	4	1	3	2	9.5	KTE
Disease	Ear Blight	Decision support (including thresholds)	3	3	4	3	4	4	2	4	2	9.5	KTE
Disease	Yellow Rust	Sowing date	3	4	4	4	2	3	1	2	1	9.5	Research
Weeds	All Weeds Pre-Emergence	Select low-risk locations	3	4	3	4	2	5	3	3	0	9.5	KTE
Weeds	All Weeds Pre-Emergence	Thermal control	4	2	1	4	1	3	1	2	1	9.5	Research
Weeds	Annual Grasses	Drainage	2	2	4	5	2	3	3	4	1	9.5	KTE
Weeds	Annual Grasses	Thermal control	4	2	1	4	1	3	1	2	1	9.5	Research
Weeds	BLW - Tap Root	Use of cover crops	4	2	2	3	2	4	2	4	2	9.5	Research
Weeds	BLW - Tap Root	Undersowing & companion crops	4	2	2	3	2	4	2	4	2	9.5	Research
Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	3	2	4	2	4	2	9.5	Research
Weeds	BLW - Fibrous Root	Secondary cultivations (drilling method)	4	4	3	3	4	3	4	4	0	9.5	Research

Weeds	BLW - Fibrous Root	Undersowing & companion crops	4	2	2	3	2	4	2	4	2	9.5	Research
Weeds	Volunteer Potatoes	Hand weeding/roguing	4	4	2	3	4	4	4	4	0	9.5	Research
Pest	BYDV Vectors	Undersowing / companion cropping	3	3	2	4	2	3	1	3	2	9.3	Research
Disease	Ear Blight	Varietal choice	3	4	4	3	4	4	3	4	1	9.3	Research
Weeds	All Weeds Pre-Emergence	Fallow	3	2	2	4	5	1	1	2	1	9.3	Research
Pest	BYDV Vectors	Control volunteers & weeds	2	2	3	4	4	4	2	3	1	9.0	Research
Pest	Wheat Bulb Fly	Sowing date	3	3	3	3	4	3	1	3	2	9.0	KTE
Disease	Yellow Rust	Bioprotection & low risk PPP's	2	2	3	4	3	4	1	3	2	9.0	Research
Weeds	All Weeds Pre-Emergence	Use of cover crops	3	3	1	4	1	4	2	4	2	9.0	Research
Weeds	All Weeds Pre-Emergence	Undersowing & companion crops	3	2	1	4	1	4	2	4	2	9.0	Research
Weeds	BLW - Tap Root	Sowing date	4	4	2	3	2	4	4	4	0	9.0	Research
Weeds	BLW - Tap Root	Decision support (incl. thresholds)	4	3	4	3	2	2	2	2	0	9.0	Research
Weeds	BLW - Tap Root	In-field, non-cropped area	3	3	4	3	4	2	2	4	2	9.0	Research
Weeds	BLW - Fibrous Root	Sowing date	4	4	2	3	2	4	4	4	0	9.0	Research
Weeds	BLW - Fibrous Root	Varietal choice	3	2	3	3	4	4	2	3	1	9.0	Research
Weeds	BLW - Fibrous Root	Decision support (incl. thresholds)	4	3	4	3	2	2	2	2	0	9.0	Research
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	3	4	2	2	4	2	9.0	Research
Weeds	BLW - Fibrous Root	Mechanical weeding	4	3	2	3	2	3	2	3	1	9.0	KTE
Weeds	Volunteer Potatoes	Fallow	4	3	1	3	4	3	2	2	0	9.0	Research
Weeds	Volunteer Potatoes	Hygiene	3	3	4	3	4	4	3	3	0	9.0	Research
Lodging	Root Lodging	Sowing date	3	4	3	3	3	5	2	3	1	9.0	KTE
Pest	BYDV Vectors	Primary culitvations / Crop residue burial	2	3	3	4	3	4	2	3	1	8.8	Research
Pest	BYDV Vectors	Secondary cultivations / drilling method	2	3	3	4	3	4	2	3	1	8.8	Research
Disease	Brown Rust	Varietal mixtures	3	2	4	3	3	4	1	1	0	8.8	KTE
Weeds	All Weeds Pre-Emergence	Seedbed quality	3	3	2	4	2	3	3	3	0	8.8	Research
Weeds	All Weeds Pre-Emergence	Bioprotectants & low risk PPP's	2	2	2	4	4	4	1	2	1	8.8	Research
Weeds	All Weeds Pre-Emergence	Intercropping	3	2	1	4	1	3	1	3	2	8.8	KTE
Weeds	Annual Grasses	Bioprotectants & low risk PPP's	2	2	2	5	2	2	1	2	1	8.8	Research
Weeds	Volunteer Potatoes	Primary cultivations (crop residue burial)	3	5	3	3	4	4	4	4	0	8.8	Research
Lodging	Stem Lodging	Field history, Rotation & break crops	3	3	4	3	3	3	4	5	1	8.8	KTE
Lodging	Root Lodging	Field history, Rotation & break crops	3	3	4	3	3	3	4	5	1	8.8	KTE
Pest	BYDV Vectors	Select low-risk locations	2	3	3	4	3	3	1	2	1	8.5	Research
Disease	Take-All	Seedbed quality	3	4	4	3	3	3	3	3	0	8.5	KTE
Disease	Yellow Rust	Control volunteers & weeds	2	3	3	4	3	3	2	3	1	8.5	KTE
Disease	Yellow Rust	Nutrient management	2	4	2	4	4	3	1	2	1	8.5	KTE
Weeds	BLW - Tap Root	Hygiene	2	4	4	3	5	5	3	3	0	8.5	Research
Weeds	BLW - Tap Root	Secondary cultivations (drilling method)	3	4	3	3	4	3	4	4	0	8.5	Research
Weeds	BLW - Tap Root	Seed rate	3	3	2	3	5	3	3	3	0	8.5	KTE
Weeds	BLW - Fibrous Root	Hygiene	2	4	4	3	5	5	3	3	0	8.5	KTE
Weeds	BLW - Fibrous Root	Seed rate	3	3	2	3	5	3	3	3	0	8.5	Research
Weeds	BLW - Fibrous Root	Thermal control	4	2	1	3	1	3	1	2	1	8.5	Research
Weeds	Volunteer Potatoes	Secondary cultivations (drilling method)	3	3	3	3	4	3	4	4	0	8.5	Research
Lodging	Stem Lodging	Biopesticides & low risk PPP's	2	2	2	3	4	5	1	4	3	8.5	KTE
Disease	Ear Blight	Primary cultivations (crop residue burial)	3	3	3	3	2	3	1	2	1	8.3	Research
Disease	Septoria	Primary cultivations (crop residue burial)	1	2	3	5	3	3	1	1	0	8.3	Research

Weeds	BLW - Tap Root	Flooding	3	2	3	3	2	4	1	1	0	8.3	Research
Weeds	BLW - Fibrous Root	Flooding	3	2	3	3	2	4	1	1	0	8.3	KTE
Weeds	BLW - Fibrous Root	Primary cultivations (crop residue burial)	2	4	3	3	4	5	3	4	1	8.3	KTE
Weeds	Volunteer Potatoes	Use of cover crops	3	1	2	3	2	3	1	3	2	8.3	KTE
Weeds	Volunteer Potatoes	Intercropping	3	1	2	3	3	3	2	3	1	8.3	Research
Weeds	Volunteer Potatoes	Undersowing & companion crops	3	1	2	3	3	3	2	3	1	8.3	KTE
Disease	Brown Rust	Sowing date	2	2	4	3	3	4	1	2	1	8.0	Research
Disease	Septoria	Field history, rotation & break crops	1	4	3	5	3	2	1	1	0	8.0	Research
Disease	Take-All	Nutrient management	2	4	3	3	4	3	2	4	2	8.0	Research
Weeds	BLW - Tap Root	Seedbed quality	3	3	3	3	2	3	3	3	0	8.0	Research
Weeds	BLW - Tap Root	Intercropping	3	2	2	3	2	3	2	3	1	8.0	Research
Weeds	BLW - Tap Root	Mechanical weeding	3	3	2	3	2	3	2	3	1	8.0	KTE
Weeds	BLW - Fibrous Root	Seedbed quality	3	3	3	3	2	3	3	3	0	8.0	KTE
Weeds	BLW - Fibrous Root	Intercropping	3	2	2	3	2	3	2	3	1	8.0	KTE
Lodging	Stem Lodging	Sowing date	2	4	3	3	3	5	2	3	1	8.0	Research
Pest	Slugs	Primary culitvations / Crop residue burial	2	2	3	3	3	3	1	3	2	7.8	KTE
Pest	Slugs	Secondary cultivations / drilling method	2	2	3	3	3	3	1	3	2	7.8	KTE
Pest	Slugs	Seedbed quality	2	3	3	3	3	3	2	4	2	7.8	Research
Pest	Slugs	Rolling soil post-planting	2	3	3	3	3	3	1	3	2	7.8	Research
Pest	Wheat Bulb Fly	Seed rate	2	4	2	3	4	3	1	3	2	7.8	Research
Disease	Take-All	Lime	2	4	4	3	3	3	2	3	1	7.8	Research
Disease	Take-All	Sowing date	3	4	2	3	2	3	2	2	0	7.8	Research
Disease	Yellow Rust	Spatial separation	2	2	3	4	2	2	1	1	0	7.8	KTE
Lodging	Stem Lodging	Variety Mixtures	2	3	3	3	2	5	1	2	1	7.8	KTE
Lodging	Root Lodging	Drilling method	2	2	3	3	2	5	2	3	1	7.8	Research
Pest	Slugs	Field history, Rotation & break crops	2	4	3	3	3	3	2	3	1	7.5	KTE
Pest	Wheat Bulb Fly	Spatial separation	2	3	3	3	3	3	1	2	1	7.5	Research
Disease	Brown Rust	Nutrient management	2	2	3	3	2	4	2	3	1	7.5	Research
Disease	Ear Blight	Sowing date	2	3	3	3	3	3	1	2	1	7.5	Research
Disease	Septoria	Seed rate	1	3	2	5	2	2	1	1	0	7.5	KTE
Weeds	BLW - Tap Root	Defoliation (incl. mowing and grazing)	2	2	2	3	3	4	2	3	1	7.5	Research
Weeds	BLW - Fibrous Root	Defoliation (incl. mowing and grazing)	2	2	2	3	3	4	2	3	1	7.5	Research
Lodging	Stem Lodging	Early harvest	1	2	4	3	4	5	2	3	1	7.5	Research
Lodging	Stem Lodging	Pre-cropping Nutrition	2	1	3	3	4	2	4	5	1	7.5	Research
Lodging	Stem Lodging	Biostimulants	1	1	2	3	5	5	2	4	2	7.5	KTE
Lodging	Root Lodging	Early harvest	1	2	4	3	4	5	2	3	1	7.5	KTE
Lodging	Root Lodging	Pre-cropping Nutrition	2	2	3	3	4	2	4	5	1	7.5	KTE
Lodging	Root Lodging	Biostimulants	1	1	2	3	5	5	2	4	2	7.5	Research
Lodging	Root Lodging	Biopesticides & low risk PPP's	1	2	2	3	4	5	1	4	3	7.5	Research
Lodging	Root Lodging	Rolling soil post-planting	2	3	2	3	2	5	2	3	1	7.5	KTE
Pest	Wheat Bulb Fly	Varietal Choice	2	2	3	3	3	2	1	2	1	7.3	KTE
Disease	Brown Rust	Field history, rotation & break crops	2	2	3	3	3	3	1	1	0	7.3	Research
Disease	Take-All	Control volunteers & weeds	2	4	3	3	3	2	3	4	1	7.3	KTE
Disease	Take-All	Pre-cropping Nutrition	2	4	2	3	3	3	3	4	1	7.3	Research
Weeds	Volunteer Potatoes	Varietal choice	2	1	3	3	3	3	1	1	0	7.3	Research

Pest	Wheat Bulb Fly	Field history, Rotation & break crops	2	3	2	3	2	2	1	3	2	7.0	Research
Disease	Ear Blight	Field history, rotation & break crops	2	2	3	3	1	3	2	3	1	7.0	Research
Weeds	BLW - Tap Root	Fallow	1	4	4	3	4	4	3	3	0	7.0	Research
Weeds	BLW - Fibrous Root	Fallow	1	4	4	3	4	4	3	3	0	7.0	Research
Pest	Wheat Bulb Fly	Use of cover crops	2	2	2	3	2	2	1	2	1	6.8	Research
Disease	Brown Rust	Control volunteers & weeds	1	3	3	3	3	5	3	3	0	6.8	Research
Disease	Yellow Rust	Field history, rotation & break crops	1	4	3	4	2	2	1	1	0	6.8	KTE
Disease	Yellow Rust	Select low-risk locations	1	4	3	4	2	2	1	1	0	6.8	KTE
Weeds	BLW - Tap Root	Bioprotectants & low risk PPP's	2	2	2	3	2	2	1	2	1	6.8	Research
Weeds	BLW - Fibrous Root	Bioprotectants & low risk PPP's	2	2	2	3	2	2	1	2	1	6.8	Research
Lodging	Stem Lodging	Drilling method	1	2	3	3	2	5	2	3	1	6.8	KTE
Lodging	Root Lodging	Variety Mixtures	1	3	3	3	2	5	1	2	1	6.8	KTE
Disease	Ear Blight	Seed testing	1	2	3	3	3	3	1	2	1	6.5	Research
Disease	Take-All	Secondary cultivations / drilling method	1	2	3	3	4	3	2	2	0	6.5	Research
Weeds	BLW - Tap Root	Thermal control	2	2	1	3	1	3	1	2	1	6.5	Research
Lodging	Stem Lodging	Rolling soil post-planting	1	3	2	3	2	5	2	3	1	6.5	Research
Disease	Take-All	Good drainage	2	2	2	3	1	2	3	3	0	6.3	Research
Disease	Ear Blight	Control volunteers & weeds	1	2	3	3	1	3	1	1	0	5.8	KTE
Disease	Take-All	Seed rate	1	2	2	3	2	3	1	1	0	5.8	Research

11.19. **Oilseeds combined knowledge exchange and research priorities (table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Area of Focus
Pests	Cabbage Stem Flea Beetle	Decision support (incl. thresholds)	4	3	4	5	4	4	1	4	3	12.8	Research
Pests	Cabbage Stem Flea Beetle	Trap crops	4	3	3	5	3	4	1	4	3	12.3	Research
Weeds	Annual Grasses	Secondary Cultivations (drilling method)	4	4	3	5	4	4	4	5	1	12.0	KTE
Pests	Cabbage Stem Flea Beetle	Sowing date	4	3	3	5	3	4	3	4	1	11.8	Research
Pests	Cabbage Stem Flea Beetle	In field non-cropped areas	4	2	3	5	3	2	1	4	3	11.8	Research
Pests	TuYV Vectors	Decision support (incl. thresholds)	4	2	4	4	4	4	1	4	3	11.8	Research
Weeds	Annual Grasses	Precision application	4	2	2	5	2	4	1	4	3	11.8	Research
Diseases	Light Leaf Spot	Varietal Choice	4	5	4	4	4	5	4	5	1	11.5	KTE
Diseases	Phoma Stem Canker	Varietal Choice	4	5	4	4	4	5	4	5	1	11.5	KTE
Diseases	Phoma Stem Canker	Decision support (including thresholds)	4	5	3	4	3	5	2	5	3	11.5	KTE
Pests	Cabbage Stem Flea Beetle	Seed rate	3	3	3	5	5	4	1	3	2	11.5	Research
Pests	TuYV Vectors	Varietal choice	4	4	3	4	4	4	2	4	2	11.3	KTE
Weeds	Annual Grasses	Hygiene	3	4	4	5	5	3	4	5	1	11.3	KTE
Diseases	Clubroot	Decision support (including thresholds)	5	5	3	3	3	5	3	5	2	11.3	KTE
Diseases	Light Leaf Spot	Sowing date	4	4	4	4	3	5	3	4	1	11.3	KTE
Diseases	Phoma Stem Canker	Sowing date	4	4	4	4	3	5	3	4	1	11.3	KTE
Pests	Cabbage Stem Flea Beetle	Varietal choice	3	1	3	5	4	4	2	4	2	11.3	Research
Pests	Cabbage Stem Flea Beetle	Bioprotectants & low risk PPP's	3	1	2	5	4	4	1	4	3	11.3	Research
Weeds	Annual Grasses	Undersowing companion crops	4	2	2	5	2	4	2	3	1	11.3	Research
Weeds	BLW - Tap Root	Select low-risk locations	4	4	3	4	4	4	3	4	1	11.0	KTE
Diseases	Clubroot	Hygiene and prevention	5	5	3	3	3	5	4	5	1	11.0	KTE
Diseases	Light Leaf Spot	Field history, Rotation & break crops	3	4	5	4	4	5	3	5	2	11.0	KTE
Diseases	Light Leaf Spot	Primary cultivations / Crop residue burial	4	5	3	4	3	5	3	4	1	11.0	KTE
Diseases	Phoma Stem Canker	Primary cultivations / Crop residue burial	4	5	3	4	3	5	3	4	1	11.0	KTE
Pests	Cabbage Stem Flea Beetle	Stubble Management	3	2	3	5	3	4	1	3	2	11.0	Research
Pests	Cabbage Stem Flea Beetle	Defoliation (incl. mowing and grazing)	3	3	3	5	3	4	1	3	2	11.0	Research
Diseases	Clubroot	Good drainage	5	5	2	3	3	5	3	4	1	10.8	KTE
Diseases	Light Leaf Spot	Stubble Management	4	4	2	4	3	5	3	4	1	10.8	KTE
Diseases	Phoma Stem Canker	Field history, Rotation & break crops	3	5	5	4	4	5	4	5	1	10.8	KTE
Diseases	Phoma Stem Canker	Stubble Management	4	4	2	4	3	5	3	4	1	10.8	KTE
Diseases	Verticillium Wilt	Field history, Rotation & break crops	4	5	5	3	4	5	4	5	1	10.8	KTE
Diseases	Verticillium Wilt	Varietal Choice	4	4	4	3	4	5	3	5	2	10.8	KTE
Pests	Cabbage Stem Flea Beetle	Seedbed quality	3	3	3	5	3	4	3	4	1	10.8	Research
Pests	Cabbage Stem Flea Beetle	Organic amendments	3	1	3	5	2	4	1	3	2	10.8	Research
Weeds	BLW - Tap Root	Precision application	4	3	2	4	2	4	1	4	3	10.8	Research
Pests	Pollen Beetle	Decision support (incl. thresholds)	4	4	4	3	4	4	2	4	2	10.5	KTE
Diseases	Clubroot	Varietal Choice	4	5	3	3	4	5	3	5	2	10.5	KTE

Diseases	Light Leaf Spot	Decision support (including thresholds)	3	4	3	4	3	5	2	5	3	10.5	KTE
Diseases	Phoma Stem Canker	Spatial separation	3	4	5	4	3	5	3	4	1	10.5	KTE
Lodging	Stem Lodging	Seed rate	4	5	3	3	5	5	2	3	1	10.5	KTE
Lodging	Root Lodging	Seed rate	4	5	3	3	5	5	2	3	1	10.5	KTE
Pests	Slugs	Precision application	4	3	4	3	3	4	1	4	3	10.5	Research
Diseases	Light Leaf Spot	Spatial separation	3	3	5	4	3	5	3	4	1	10.5	Research
Diseases	Sclerotinia Stem Rot	Field history, Rotation & break crops	4	5	5	3	3	4	4	5	1	10.3	KTE
Pests	Cabbage Stem Flea Beetle	Undersowing & Companion cropping	3	2	2	5	2	4	2	3	1	10.3	Research
Pests	Cabbage Stem Flea Beetle	Rolling soil post-planting	2	2	4	5	4	4	3	4	1	10.3	Research
Pests	Slugs	Decision support (incl. thresholds)	4	3	4	3	4	4	3	4	1	10.3	Research
Weeds	Annual Grasses	Decision support (incl. thresholds)	3	2	4	5	2	2	2	3	1	10.3	Research
Weeds	Annual Grasses	Stubble management	2	3	3	5	3	3	2	5	3	10.0	Research
Weeds	Annual Grasses	Use of cover crops	3	2	2	5	1	4	2	3	1	10.0	Research
Weeds	Annual Grasses	Mechanical weeding	3	3	2	5	2	3	2	3	1	10.0	Research
Weeds	Annual Grasses	Thermal control	3	3	2	5	2	3	1	2	1	10.0	Research
Diseases	Sclerotinia Stem Rot	Decision support (including thresholds)	4	4	3	3	2	5	3	4	1	9.8	KTE
Diseases	Verticillium Wilt	Hygiene and prevention	4	5	3	3	2	5	4	5	1	9.8	KTE
Lodging	Stem Lodging	Variety choice	3	4	4	3	5	5	4	5	1	9.8	KTE
Lodging	Root Lodging	Variety choice	3	4	4	3	5	5	4	5	1	9.8	KTE
Weeds	BLW - Tap Root	In-field, non-cropped area	3	3	4	4	4	2	2	3	1	9.8	Research
Weeds	BLW - Fibrous Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	Research
Diseases	Sclerotinia Stem Rot	Primary cultivations / Crop residue burial	4	3	3	3	3	4	2	3	1	9.8	Research
Lodging	Stem Lodging	Decision support (including thresholds)	3	2	4	3	4	5	3	5	2	9.8	Research
Lodging	Root Lodging	Decision support (including thresholds)	3	2	4	3	4	5	3	5	2	9.8	Research
Diseases	Sclerotinia Stem Rot	Select low-risk locations	3	5	5	3	3	5	3	4	1	9.5	KTE
Diseases	Clubroot	Sowing date	3	3	4	3	4	5	3	4	1	9.5	Research
Lodging	Stem Lodging	Nutrient management	3	2	4	3	4	5	4	5	1	9.5	Research
Lodging	Root Lodging	Nutrient management	3	2	4	3	4	5	4	5	1	9.5	Research
Weeds	BLW - Tap Root	Hygiene	2	4	4	4	5	3	3	4	1	9.3	KTE
Weeds	BLW - Tap Root	Undersowing companion crops	3	2	2	4	2	4	2	3	1	9.3	Research
Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	3	2	4	2	3	1	9.3	Research
Weeds	BLW - Fibrous Root	Undersowing companion crops	4	2	2	3	2	4	2	3	1	9.3	Research
Diseases	Clubroot	Control volunteers & weeds	3	3	3	3	3	5	3	5	2	9.3	Research
Weeds	BLW - Tap Root	Secondary cultivations (drilling method)	2	4	3	4	4	4	4	5	1	9.0	KTE
Diseases	Sclerotinia Stem Rot	Spatial separation	3	2	5	3	3	3	2	3	1	9.0	Research
Lodging	Stem Lodging	Field history, Rotation & break crops	3	3	4	3	4	3	4	5	1	9.0	Research
Lodging	Root Lodging	Field history, Rotation & break crops	3	3	4	3	4	3	4	5	1	9.0	Research
Lodging	Root Lodging	Sowing date	3	3	3	3	3	5	2	3	1	9.0	Research
Diseases	Clubroot	Lime	3	5	2	3	3	4	2	4	2	8.8	KTE
Weeds	Annual Grasses	Biopesticides & low risk PPP's	2	2	2	5	2	2	1	2	1	8.8	Research
Weeds	Annual Grasses	Defoliation (incl. mowing and grazing)	2	2	2	5	2	2	1	2	1	8.8	Research
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	3	4	2	2	3	1	8.8	Research
Weeds	BLW - Fibrous Root	Hygiene	2	4	4	3	5	3	2	4	2	8.5	KTE
Pests	TuYV Vectors	In field non-cropped areas	2	2	3	4	3	2	1	3	2	8.5	Research
Lodging	Root Lodging	Pre-cropping Nutrition	2	1	3	3	4	5	1	3	2	8.5	Research

Weeds	BLW - Fibrous Root	Secondary cultivations (drilling method)	2	4	3	3	4	4	4	5	1	8.0	KTE
Pests	Slugs	Bioprotectants & low risk PPP's	3	2	2	3	2	2	1	3	2	8.0	Research
Pests	Slugs	Rolling soil post-planting	2	3	3	3	4	4	2	3	1	8.0	Research
Lodging	Stem Lodging	Sowing date	2	2	3	3	3	5	2	3	1	8.0	Research
Pests	Pollen Beetle	Trap crops	2	3	4	3	3	3	1	2	1	7.8	Research
Pests	Slugs	Seed rate	2	2	2	3	4	4	1	2	1	7.8	Research
Weeds	BLW - Tap Root	Biopesticides & low risk PPP's	2	2	2	4	2	2	1	2	1	7.8	Research
Weeds	BLW - Tap Root	Defoliation (incl. mowing and grazing)	2	2	2	4	2	2	1	2	1	7.8	Research
Lodging	Stem Lodging	Biostimulants	1	1	2	3	5	5	1	4	3	7.8	Research
Lodging	Root Lodging	Drilling method	2	2	3	3	2	5	3	4	1	7.8	Research
Lodging	Root Lodging	Biostimulants	1	1	2	3	5	5	1	4	3	7.8	Research
Diseases	Verticillium Wilt	Bioprotectants & low risk PPP's	2	4	2	3	2	4	1	3	2	7.5	KTE
Pests	Pollen Beetle	Sowing date	2	2	3	3	3	3	1	2	1	7.5	Research
Lodging	Stem Lodging	Pre-cropping Nutrition	1	1	3	3	4	5	1	3	2	7.5	Research
Lodging	Stem Lodging	Biopesticides & low risk PPP's	1	1	2	3	4	5	1	4	3	7.5	Research
Lodging	Root Lodging	Biopesticides & low risk PPP's	1	1	2	3	4	5	1	4	3	7.5	Research
Pests	Pollen Beetle	In field non-cropped areas	2	2	3	3	3	2	1	2	1	7.3	Research
Lodging	Stem Lodging	Early harvest	1	1	4	3	3	5	2	3	1	7.3	Research
Lodging	Root Lodging	Early harvest	1	1	4	3	3	5	2	3	1	7.3	Research
Diseases	Sclerotinia Stem Rot	Varietal Choice	1	4	1	3	1	5	1	5	4	6.8	KTE
Weeds	BLW - Fibrous Root	Biopesticides & low risk PPP's	2	2	2	3	2	2	1	2	1	6.8	Research
Weeds	BLW - Fibrous Root	Defoliation (incl. mowing and grazing)	2	2	2	3	2	2	1	2	1	6.8	Research
Lodging	Stem Lodging	Variety Mixtures	1	1	3	3	2	5	1	2	1	6.8	Research
Lodging	Stem Lodging	Drilling method	1	1	3	3	2	5	3	4	1	6.8	Research
Lodging	Stem Lodging	Rolling soil post-planting	1	1	2	3	3	5	1	2	1	6.8	Research
Lodging	Root Lodging	Variety Mixtures	1	1	3	3	2	5	1	2	1	6.8	Research
Lodging	Root Lodging	Rolling soil post-planting	1	1	2	3	3	5	1	2	1	6.8	Research

11.20. **Potatoes combined knowledge exchange and research cores (table)**

Category	Factor	Strategy	Effectiveness	Strength of the evidence	Inexpensive to Implement	Economic Importance	Ease of implementation	Speed of impact	Current use	Potential use	p- c USE	Priority Score	Area of Focus
Diseases	Late Blight	Varietal choice	5	4	3	5	2	4	2	4	2	12.8	KTE
Diseases	Late Blight	Control volunteers & weeds	4	4	2	5	4	4	3	5	2	12.0	KTE
Diseases	Late Blight	Early harvest	4	4	4	5	3	4	4	5	1	12.0	KTE
Diseases	Late Blight	Hygiene	4	4	4	5	3	4	4	5	1	12.0	KTE
Diseases	Late Blight	Field history, Rotation & break crops	4	4	3	5	3	4	4	5	1	11.8	KTE
Diseases	Blackleg	Hygiene	5	4	2	4	3	4	3	5	2	11.8	KTE
Diseases	Storage Diseases	Field history, Rotation & break crops	4	2	2	5	3	4	2	4	2	11.8	Research
Diseases	Late Blight	Spatial separation	4	4	3	5	2	4	3	4	1	11.5	KTE
Diseases	Late Blight	Sowing date	4	4	3	5	3	3	2	3	1	11.5	KTE
Diseases	Late Blight	Decision support (including thresholds)	4	3	2	5	3	4	2	3	1	11.5	Research
Diseases	Blackleg	Early harvest	4	4	4	4	3	4	3	5	2	11.3	KTE
Pests	Potato Cyst Nematode	Decision support (including thresholds)	4	3	4	4	3	4	3	5	2	11.3	Research
Diseases	Storage Diseases	Hygiene	4	3	2	5	3	3	3	4	1	11.3	Research
Diseases	Late Blight	Select low-risk locations	4	4	3	5	2	2	2	3	1	11.0	KTE
Diseases	Blackleg	Control volunteers & weeds	4	4	3	4	3	4	2	4	2	11.0	KTE
Diseases	Late Blight	Seed testing	3	1	3	5	3	4	2	4	2	11.0	Research
Weeds	All Weeds Pre-Emergence	Thermal control	4	3	1	5	2	4	1	2	1	11.0	Research
Diseases	Dry Rot	Varietal choice	3	2	4	5	3	3	1	2	1	10.8	Research
Pests	Potato Cyst Nematode	Varietal Choice	4	5	3	4	3	4	2	3	1	10.8	KTE
Diseases	Stem Canker and Black Scurf	Early harvest	4	4	3	4	3	4	3	4	1	10.8	KTE
Pests	Viruses (Aphid Borne)	Decision support (including thresholds)	4	3	3	4	3	4	3	4	1	10.8	Research
Diseases	Blackleg	Decision support (including thresholds)	4	1	2	4	3	3	2	5	3	10.8	Research
Diseases	Viruses (Soil Borne)	Field history, Rotation & break crops	4	3	3	4	3	4	3	4	1	10.8	Research
Weeds	Annual Grasses	Precision application	4	2	2	4	2	4	1	4	3	10.8	Research
Weeds	BLW - Fibrous Root	Precision application	4	2	2	4	2	4	1	4	3	10.8	Research
Pests	Viruses (Aphid Borne)	Seed testing	4	4	3	4	3	3	3	4	1	10.5	KTE
Diseases	Late Blight	Seedbed quality	3	4	3	5	3	3	2	3	1	10.5	KTE
Diseases	Gangrene	Seed testing	3	1	3	5	3	3	3	4	1	10.5	Research
Diseases	Late Blight	Nutrient management	3	3	3	5	3	3	2	3	1	10.5	Research
Diseases	Storage Diseases	Varietal choice	3	3	3	5	3	3	3	4	1	10.5	Research
Diseases	Viruses (Soil Borne)	Seed testing	4	1	3	4	2	3	2	4	2	10.5	Research
Pests	Potato Cyst Nematode	Trap crops	3	4	4	4	2	4	1	4	3	10.3	KTE
Pests	Viruses (Aphid Borne)	Select low-risk locations	4	4	3	4	2	3	3	4	1	10.3	KTE
Pests	Viruses (Aphid Borne)	Control volunteers & weeds	4	4	2	4	3	3	3	4	1	10.3	KTE
Pests	Viruses (Aphid Borne)	Hygiene	4	4	2	4	2	4	3	4	1	10.3	KTE
Pests	Viruses (Aphid Borne)	Bioprotection + low risk PPP's	3	2	3	4	4	3	1	4	3	10.3	Research
Diseases	Black Dot	Seed testing	4	2	4	3	4	4	3	4	1	10.3	Research
Diseases	Blackleg	Seed testing	4	2	1	4	3	3	2	4	2	10.3	Research

Weeds	BLW - Fibrous Root	Use of cover crops	4	2	2	4	2	4	2	3	1	10.3	Research
Diseases	Black Dot	Field history, Rotation & break crops	4	4	3	3	4	4	2	3	1	10.0	KTE
Diseases	Black Dot	Varietal choice	4	4	4	3	3	4	3	4	1	10.0	KTE
Diseases	Blackleg	Field history, Rotation & break crops	3	4	3	4	3	4	2	4	2	10.0	KTE
Pests	FLN and Spraing	Decision support (including thresholds)	4	3	4	3	3	4	3	4	1	10.0	Research
Weeds	BLW - Fibrous Root	In-field, non-cropped area	3	3	4	4	4	2	1	3	2	10.0	Research
Pests	Potato Cyst Nematode	Field history, Rotation & break crops	3	4	3	4	3	4	3	4	1	9.8	KTE
Diseases	Common Scab	Varietal choice	3	4	4	4	3	3	3	4	1	9.8	KTE
Diseases	Dry Rot	Primary cultivations (crop residue burial)	2	1	4	5	3	3	2	3	1	9.8	Research
Diseases	Silver Scurf	Seed testing	4	2	2	3	3	4	2	4	2	9.8	Research
Diseases	Stem Canker and Black Scurf	Seed testing	4	2	3	3	3	3	2	4	2	9.8	Research
Weeds	BLW - Tap Root	Precision application	4	3	2	3	2	4	1	4	3	9.8	Research
Diseases	Common Scab	Field history, Rotation & break crops	3	4	3	4	3	3	3	4	1	9.5	KTE
Diseases	Gangrene	Control volunteers & weeds	2	4	3	5	3	3	2	3	1	9.5	KTE
Diseases	Late Blight	Good drainage	2	4	3	5	3	3	2	3	1	9.5	KTE
Pests	Viruses (Aphid Borne)	Spatial separation	3	3	3	4	2	4	3	4	1	9.5	Research
Pests	Viruses (Aphid Borne)	Varietal Choice	3	3	3	4	3	3	3	4	1	9.5	Research
Diseases	Early Blight	Varietal choice	4	3	3	3	2	3	1	3	2	9.5	Research
Diseases	Stem Canker and Black Scurf	Varietal choice	4	2	3	3	2	3	2	4	2	9.5	Research
Diseases	Stem Canker and Black Scurf	Field history, Rotation & break crops	4	4	2	3	3	3	3	4	1	9.3	KTE
Diseases	Stem Canker and Black Scurf	Primary cultivations (crop residue burial)	4	4	2	3	3	3	3	4	1	9.3	KTE
Diseases	Powdery Scab	Decision support (including thresholds)	4	1	2	3	3	2	1	3	2	9.3	Research
Weeds	Annual Grasses	Use of cover crops	3	2	2	4	2	4	2	3	1	9.3	Research
Weeds	BLW - Tap Root	Use of cover crops	4	2	2	3	2	4	2	3	1	9.3	Research
Diseases	Silver Scurf	Field history, Rotation & break crops	4	4	3	3	2	2	4	5	1	9.0	KTE
Diseases	Silver Scurf	Control volunteers & weeds	4	4	3	3	2	2	3	4	1	9.0	KTE
Weeds	BLW - Fibrous Root	Hygiene	2	4	4	4	5	2	3	4	1	9.0	KTE
Pests	Wireworm	Bioprotection + low risk PPP's	3	2	4	3	4	3	1	2	1	9.0	Research
Diseases	Black Dot	Decision support (including thresholds)	4	3	2	3	4	1	3	4	1	9.0	Research
Diseases	Blackleg	Primary cultivations (crop residue burial)	3	2	2	4	3	2	3	4	1	9.0	Research
Diseases	Stem Canker and Black Scurf	Decision support (including thresholds)	4	2	2	3	2	2	2	4	2	9.0	Research
Weeds	Annual Grasses	Select low-risk locations	3	3	3	3	4	4	4	5	1	9.0	Research
Weeds	Annual Grasses	In-field, non-cropped area	2	3	4	4	4	2	1	3	2	9.0	Research
Weeds	Annual Grasses	Mechanical weeding	3	3	2	4	2	3	3	4	1	9.0	Research
Weeds	Annual Grasses	Thermal control	3	3	2	4	2	3	1	2	1	9.0	Research
Weeds	BLW - Tap Root	In-field, non-cropped area	3	3	4	3	4	2	1	3	2	9.0	Research
Pests	FLN and Spraing	Varietal Choice	3	4	3	3	3	4	2	3	1	8.8	KTE
Pests	FLN and Spraing	Field history, Rotation & break crops	3	3	3	3	4	3	2	3	1	8.8	Research
Pests	Potato Cyst Nematode	Bioprotection + low risk PPP's	2	2	4	4	4	2	1	2	1	8.8	Research
Pests	Wireworm	Decision support (including thresholds)	3	3	3	3	3	3	1	3	2	8.8	Research
Diseases	Early Blight	Seed testing	3	1	3	3	3	3	2	4	2	8.8	Research
Diseases	Black Dot	Control volunteers & weeds	3	4	3	3	3	3	3	4	1	8.5	KTE
Diseases	Early Blight	Spatial separation	3	1	3	3	3	3	2	3	1	8.5	Research
Diseases	Early Blight	Primary cultivations (crop residue burial)	3	1	3	3	3	3	2	3	1	8.5	Research
Pests	Wireworm	Field history, Rotation & break crops	2	4	3	3	4	4	2	4	2	8.3	KTE

Pests	Wireworm	Select low-risk locations	2	4	3	3	4	4	2	4	2	8.3	KTE
Diseases	Common Scab	Control volunteers & weeds	2	4	3	4	3	2	2	3	1	8.3	KTE
Diseases	Powdery Scab	Good drainage	3	4	2	3	2	2	1	4	3	8.3	KTE
Pests	Wireworm	Biofumigation	3	2	2	3	2	3	1	3	2	8.3	Research
Diseases	Black Dot	Seedbed quality	3	4	3	3	2	2	2	3	1	8.0	KTE
Diseases	Silver Scurf	Early harvest	3	4	3	3	2	2	3	4	1	8.0	KTE
Diseases	Silver Scurf	Primary cultivations (crop residue burial)	3	4	3	3	2	2	2	3	1	8.0	KTE
Weeds	BLW - Tap Root	Hygiene	2	4	4	3	5	2	3	4	1	8.0	KTE
Pests	Potato Cyst Nematode	Biofumigation	2	2	2	4	2	3	1	2	1	8.0	Research
Pests	Viruses (Aphid Borne)	In-field non-cropped areas	2	2	2	4	2	2	1	3	2	8.0	Research