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Review of weed control options and future opportunities for UK crops

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1. Abstract

In the UK, growers rely almost entirely on synthetic herbicides to control weeds cost effectively. However, the use of these products is coming under increasing pressure from legislation, climate change and market requirements such as reduced pesticide inputs and maximum residue levels. This, combined with herbicide resistance is having a significant impact on arable and horticultural sectors.

This report is a comprehensive literature review of weed control options on a national and international level that could benefit UK crop production in horticultural crops, cereals and oilseeds, sugar beet, potatoes, grassland, legumes and maize.

The different techniques available for weed control are reviewed in Section 3. The efficacy of these techniques in different crops is then discussed in Section 4 and finally, Section 5 highlights the weaknesses in the biology of key weed species, as this can then be exploited for weed control.

For effective weed control a knowledge of the weed lifecycle is essential. The lifecycle is simply the seasonal pattern of growth and reproduction. For the purpose of this review the lifecycle has been split into five sections. Each weed control technique described in the review will be effective in controlling weeds at one or more sections of the lifecycle and effective weed control generally involves the use of more than one method. This is the heart of integrated weed (pest) management (IWM/IPM).

1. Prevent seed return

Those weeds that are most difficult to control produce high levels of seed and can establish large viable seedbanks in just one season. Seed heads are often above the crop canopy and seed can be removed/spread from/within the field at harvesting. In other cases, for instance short-term horticultural crops, weeds do not even get a chance to complete their lifecycle before the crop is harvested (which can benefit later crops in a rotation).

2. Deplete seedbank

Soil contains many weed seeds from previous years seeding and this is known as the 'seedbank'. The number of seeds in the seedbank increases as weeds set and shed seeds, some buried seed will become dormant and survive for many years. Seed numbers decrease over time as some

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germinate, some decay and some are eaten by wildlife. Understanding the seedbank is at the heart of effective weed management. Cultivations stir up the seedbank burying freshly shed seed and bringing seed, from lower down the profile, to the surface. Weeds emerge each year, generally only from the top 5 cm of the soil.

3. Kill weed seedlings

Weeds emerge at different times during the year and interact with the crop. Most problems occur when weeds and crops emerge at the same time. Knowing when a weed germinates can help determine the most appropriate control methods. Cultivation strategies can be optimised to reduce weed numbers.

As weeds grow they compete with the crop. The damage they cause depends on: the species, density, the competitive ability of the crop, and the growth stage when crop and weeds compete. While some weeds are highly competitive, others pose little threat and may be valuable to wildlife.

4. Stop seed set.

Although by this stage weeds may have competed with the current crop, there is now a great opportunity to reduce weed seed production, which in turn reduces the weed seedbank for future years. This is most applicable to weeds that are difficult to control (e.g. weed beet in sugar beet, weeds resistant to herbicides) and when weed densities are low. It is often overlooked how important this step can be to stop an early stage infestation becoming a larger problem.

5. On-farm hygiene

Preventing weed seeds arriving on farm or being moved from an infested field to a clean field is key in the battle to control weeds. This will include preventing ingress of weed seeds from non-cropped areas. This is particularly important for windblown species into perennial crops.

The review is comprehensive and the specific key findings were:

- Herbicides are the most common weed control method.
- Herbicide use is generally reactive (when weeds are visible).
- Proactive use of herbicides is increasing, (increased use of pre-emergence products), particularly where difficult to control weeds are present. This is predominately in arable crops.

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- Other weed control approaches need to be integrated with an in-depth knowledge of the weed biology to achieve desired outcomes.
- Vast amount of information is available on weed biology and control but this is not always accessible, particularly to growers.

The way forward for weed control has to be Integrated Weed Management (IWM) which is alternatively known as integrated pest management (IPM). IWM is the use of multiple weed control methods to sustainably manage a weed problem. It is a component of integrated pest management (IPM) and can include cultural, genetic, mechanical and biological weed control in conjunction with the use of herbicides. The aim of IWM is to diversify weed management strategies to reduce the reliance on herbicides, and promote the use of site specific weed management and target applications to reduce herbicide impacts where possible.

However, there is a general lack of uptake of IWM to date. IWM is knowledge intensive and one of the main barriers to its uptake have been identified as being little visible evidence of immediate success and little idea of the return in investment of time and money. Further reasons include that fact that herbicides are convenient, less complex, and are generally cheaper and take less time to apply. It appears that any non- chemical practices are only adopted as compensating for reduced herbicide efficiency, which could be when herbicide resistance is present in weed populations on the farm.

The overall recommendations and priorities resulting from the review findings are to:

Increase access to and use of current knowledge

Growers are probably unaware of all the information that is available to them to help with weed management. That knowledge is often kept within the individual sectors (e.g. crops or horticulture).There is much relevant work on weeds that was once funded by MAFF or Defra and it is often hard to find, with only the current researchers knowing of its existence and so it will be lost when they leave the industry. Peer reviewed information is unavailable to many whom it could be beneficial. Consequently making better use of existing knowledge is a very high priority. Enabling greater access to it should be a high priority and eroding barriers between different cropping sectors through putting the weed biology at the centre of the knowledge will enable good progress in all sectors. Decision support tools that incorporate up to date information on weed management could also be developed. A targeted central location for weed control that covers

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all crop sectors should be developed with simple messages that would also harness farmer-to-farmer knowledge learning.

Link practical knowledge better with fundamental research

As in many other science disciplines there is too great a gap between those who undertake fundamental research and those who are looking to apply their findings in practice. There is huge scope to derive more benefits from research. To do so needs more involvement of those with an in-depth and practical understanding of weed management in the setting of project objectives. A good example would be to better focus research on those areas where gaps in the understanding of weed biology are hindering the development of better control options.

Maximise herbicide availability

The availability of herbicides continues to decline. Further actives will be withdrawn and there are unlikely to be many new herbicides to replace them. Good stewardship of current active substances is vital and requires companies, regulators and users to work together to retain them through continued support and prevention of bad practice.

Retaining product efficacy by minimising resistance and ensuring good practice, is something over which agronomists and growers have considerable ‘control’. Much is known about the risks of weeds developing resistance to herbicides. Pro-active identification of the high risk uses/situations which could select for resistance should be a priority. Weed management strategies for these high risk situations should be agreed and communicated widely and monitoring of weed species shifts and emerging cases of herbicide resistance in relation to herbicide use and other integrated weed management strategies is needed.

Agree funding for Integrated Weed Management (IWM)

Both growers and politicians recognise the need to maximise non-chemical control of weeds and develop integrated weed management. However, research in these areas typically does not attract commercial funding. To ensure future development of sustainable weed management solutions will require collective funding from farmers/growers and/or those promoting non-chemical approaches. The availability of suitable funding mechanisms to drive what are often too costly and less effective options is not an industry priority. However, if government and industry can work together it will be possible to make more progress than is currently the case.

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Weed research and approaches to control need to be considered more strategically

Reviewing and compiling information for this review has highlighted how the current approach to weed control is very often based on the use of herbicides against specific weeds and/or in specific crops. It is very clear however, that as with nutrient and soil management there is considerable scope for a more strategic approach that is relevant to the whole cropping system which can then be deployed in specific crops. A key recommendation is that there should be a more strategic approach to weed research and control.

Putting weed biology/weed life cycles at the heart of control strategies will enable more rapid progress across multiple crops. Interventions need to target and exploit the weakest stage of the weed lifecycle, whilst maximising the tolerance of the current and future crops. A cross-sector, multi-annual approach is therefore vital.

Understand selectivity between crops and weeds

All technologies require a differential selectivity between the crop and the weed. Development of appropriate techniques will build on those principles. Selectivity can be achieved by a number of routes:

- **Spatial selectivity** is a major opportunity for chemical and non-chemical approaches and irrespective of the crop we need to be able to identify one from the other. The wider the row spacing the greater the opportunities. This could be optical and ground or satellite based. Additionally alternative ways of highlighting where the crop is ('plant marking') should be considered, such as by seed treatments or genetic. There are now much better systems to detect and locate weeds within fields and that is already very helpful. Agreeing criteria and operating speeds is a key need to enable wider deployment of all technologies.

- **Temporal selectivity** enables treatments to be made when crops are more tolerant or weeds more sensitive. Just as pre-emergence herbicides are widely used, such approaches should be considered for non-chemical approaches.

- **Crop and weed tolerance** is critical for herbicides, but also for non-chemical approaches. Information on what it takes to kill a weed and what it takes not to kill a crop will be vital considerations in enabling current and new non-chemical approaches, but also in prioritising herbicide options. The screening of herbicides for minor crops could be

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advanced, and cost minimised, through a more strategic approach which considers weed and crop tolerance independently and enables a more focussed approach to deliver quicker results. In parallel the regulatory issues of using herbicides on a wider range of crops will need to be addressed and requires a combined grower, regulator and retailer approach.

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2. Introduction

In the UK growers rely almost entirely on synthetic herbicides to control weeds cost effectively. However, the use of these products is coming under increasing pressure from legislation, climate change, the development of resistance in target organisms and market requirements such as reduced pesticide inputs and maximum residue levels.

Pesticide regulation such as the review of Approval for Active Substances, Maximum Residue Limits (MRLs), Definition of Endocrine Disruptors, Sustainable Use Directive (SUD), Water Framework Directive (WFD) and Candidates for Substitution, continue to erode the number of available herbicidal active substances. This, combined with herbicide resistance is having a significant impact on the horticultural sector but is also affecting potatoes, grassland, cereals & oilseeds and sugar beet.

Integrated weed management (IWM) aims to diversify weed management strategies to reduce the reliance on herbicides. This includes the integration of a wide range of cultural control options such as cultivations, drilling date, cropping choice, biocontrol, mechanical and other physical control. However, there is a general lack of uptake of IWM to date (Mortensen *et al*., 2012, Young *et al.,* 2017, Moss 2019), for a wide range of reasons including economic, social and a lack of technology.

Horticulture

With a decreasing number of herbicides available to the horticultural industry, weed control has become more challenging across many horticultural crops. Under current production methods broad-leaved weeds and grass weeds have the potential to reduce crop yield and quality by about £110 million per year (Andersons, 2014). A gap analysis conducted for AHDB Horticulture (AHDB, 2016) identified weed control as a high priority in 38 crop or crop groups.

The loss of herbicides to control weeds will increase the need for hand weeding. As a result of Brexit labour is likely to become increasingly difficult to find and therefore significantly more expensive. If weeds are left unchecked they could cause difficulties at harvest by outcompeting crops and/or contaminating the produce with seeds which could affect marketability. The financial impact to outdoor lettuce production of having no suitable control measures for weeds is estimated at £70 million per year with a 50% loss in marketable yield (AHDB, 2016).

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Cereals & Oilseeds

Loss of key herbicide active ingredients in cereals and oilseeds 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. Although resistance in black-grass (*Alopecurus myosuroides*) dominates thinking, UK populations of wild-oats (*Avena sterilis*), ryegrass (*Lolium* spp.), poppy (*Papaver* spp.) and chickweed (*Stellaria media*) and mayweed (*Tripleurospermum inodorum*) are all locally resistant to a range of herbicides. Resistance issues are also emerging in bromes (*Anisantha* spp. and *Bromus* spp.) although not nationally significant all are increasing in frequency and for individual farmers can present serious problems, with associated business costs. While cultural control is effective for some weeds (e.g. changing drilling date to control black-grass for others (e.g. poppies), long lived seedbanks, extended germination periods or other biological or agronomic features make cultural options very limited.

The cost of weeds to cereal and oilseed production is significant, with an £89-125/ha average herbicide spend in winter wheat (Nix, 2018). The presence of black-grass resistance can increase this spend from £65/ha to £134/ha (Wilmott, 2015).

Potatoes

Yield losses in potatoes in the absence of any weed control can vary from 14% to 80% and losses could equate to up to £228 million a year. The most competitive weeds could cause losses of £55 million each (Twining *et al*., 2009). Weed control options in potatoes have become more limited with the loss of linuron and further losses could occur due to the water framework directive. Therefore cultivation will become more important but is significantly more expensive than herbicide treatment. The seed sector is at particular risk due to the loss of post-emergence actives.

Sugar beet

In 2017, sugar beet was grown on 110,000 ha in the UK by over 3,000 growers. Sugar beet weed control plays an important role in the crop rotation as it is a spring-sown crop. In the future there will be some major changes that will affect weed control in UK sugar beet, these include the potential loss of phenmedipham, desmedipham, trisulfuron-methyl, a range of graminicides and chloridazon. Sugar beet is very susceptible to weed competition in its early stages of growth and, if uncontrolled, weeds can lead to crop failure.

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The loss of these herbicides would not only adversely affect sugar production, but also animal feed and bio-energy from sugar beet. Phenmedipham is also used in other crops such as red beet, fodder beet, spinach, chard and strawberries.

ALS tolerant sugar beet is expected to be introduced in the near future but the system's potential effectiveness in sugar beet without phenmedipham and the longer-term implications for rotational weed control need examining.

<u>Grassland</u>

Current issues in grassland are mainly centred on establishing new grass leys or grassland rejuvenation. Although there are a range of herbicides for controlling weeds during crop establishment they can have impact on clover mixes and on other species such as chicory and plantain. Grassland renewal accounts for 7% of the total UK land use and therefore having relevant weed control measures is an important part in the grassland renewal process.

Other areas of concern include weed control in upland areas such as bracken control where there is currently limited synthetic chemistry available with asulam being one of the only available products specifically for its control.

<u>Legumes</u>

Legumes are a very valuable part of a rotation as they fix nitrogen and make this available to other crops. Since the introduction of greening rules in 2017, farms of 10-30 ha have to grow two or more crops in the rotation and those over 30 ha have to grow three or more crops (Rural Payments Agency, 2018). The area of legumes grown has decreased since the introduction of the greening rules probably due to the difficulty in achieving good weed control in these crops. The number of herbicides approved for use is very limited and alternative methods of weed control are needed.

<u>Maize</u>

The area of maize has steadily increased over recent years due to the introduction of new varieties more suitable for the UK climate, the use of the crop in feeding livestock and its use in anaerobic digestors. It is being incorporated into rotations and many of the herbicides used are in group B (ALS inhibitors) which has implications for the development of herbicide resistant (HR) weeds in the rotation. The crop is very sensitive to weed competition at early growth stages and weed

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control is an important part of achieving high yields.

It is clear that alternative non-chemical options are needed for weed control in the short, medium and long term. This review will help to identify the technologies in development to remedy this situation as well as highlighting gaps in current research that need to be addressed to help crop production.

The review will cover but not be limited to new and existing chemistry, biopesticides, non-chemical/cultural control, application technology and novel technology including robots as well as drawing information from other industries.

2.1. Document structure

This document will initially review the different techniques available for weed control (Section 3). The efficacy of these techniques in different crops will then be discussed (Section 4) and finally, weaknesses in the biology of key weed species will be considered to investigate whether may be exploited for weed control (Section 5). A brief summary of what will be covered in each section is given below.

Section 3. Weed control techniques.

This section reviews weed control options and is subdivided into:

1. **Cultural control** – rotations (including livestock), tillage and cultivations (timing, depth), cultivations for seedbank manipulation, mechanical weeding, cover cropping, crop species and varietal choices (sensitivity, competitiveness, phenology), seed rates, row widths, crop competition (including manipulating N rates and timing), drilling date (including autumn vs spring cropping).
2. **Non-chemical control** – physical weeding, thermal weeding, allelopathy, weed seed control (including methods such as seed destruction, crimped grain and whole crop silage).
3. **Chemical control** – precision application (including nozzle technology, drift reduction and cross contamination), bioherbicides, optimising use of existing chemistry, new chemistry, biopesticides, biological control, alternatives to glyphosate, weed wiping, crop desiccation, comments on future pesticide availability, herbicide resistance modelling, herbicide resistance diagnostics.

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4. **Novel and emerging technologies** - robotics & automation, aerial imagery (satellites, aeroplane technology, drones) within field imagery (boom mounted cameras and sensors such as NDVI (Normalised Vegetation Difference Index) and spectral reflectance); prediction modelling, decision support systems.
5. **Digital tools** -prediction modelling, decision support systems, internet tools.
6. **Genetic tools –** genetic modification and CRISPR technology, herbicide tolerant crops, RNAi technology.
7. **Preventative weed control –** the use of contaminated straw, forage, sown seeds, water. As well as practises such as machine cleaning, managing weeds in none cropped areas, the use of composting and anaerobic digestion, and predation.

Section 4. The applicability of weed control options in different crops.

An evaluation of how the control options identified in Section 3 provide weed control benefits in individual crops. The following crop areas are included:

1. ***Horticulture***
2. ***Cereals and oilseeds***
3. ***Potatoes***
4. ***Sugar beet*** **–** to provide answers to the following:
   i. The decision making process and guidance required in the absence of phenmedipham and desmedipham.
   ii. A review of the implications and robustness of ALS tolerant varieties, especially in the absence of phenmedipham.
   iii. Identification of those weeds will be of particular concern if phenmedipham and desmedipham are not re-registered for use in sugar beet and consideration of alternative strategies for their control.
5. ***Grassland***
6. ***Legumes***
7. ***Maize***

Section 5. Weed species biology

For each weed species the key weaknesses in their lifecycle will be identified, the review will have identified how the weed control method will disrupt the cycle of weed growth e.g. plant destruction,

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seed removal or prevention of seed set. The selected method will also have a degree of selectivity, be that chemical, spatial or temporal (time related).

Section 6. Recommendations and priorities

An outline of suggested future strategies for weed management across the industry.

3. Weed control techniques

For effective weed control a knowledge of the weed lifecycle is essential. The lifecycle is simply the seasonal pattern of growth and reproduction (Figure 1). For the purpose of this review the lifecycle has been split into four sections (below). Additionally, on-farm hygiene has been included, as this is an important way of preventing ingress and spread of weeds. Each weed control technique described in the review will be effective in controlling weeds at one or more sections of the lifecycle and effective weed control generally involves the use of more than one method. This is the heart of integrated weed (pest) management (IWM/IPM).

1. **Prevent seed return**

   Those weeds that are most difficult to control produce high levels of seed and can establish large viable seedbanks in just one season. Seed heads are often above the crop canopy and seed can be removed/spread from/within the field at harvesting. In other cases, for instance short-term horticultural crops, weeds do not even get a chance to complete their lifecycle before the crop is harvested (which can benefit later crops in a rotation).

2. **Deplete seedbank**

   Soil contains many weed seeds from previous years seeding and this is known as the ‘seedbank’. The number of seeds in the seedbank increases as weeds set and shed seeds, some buried seed will become dormant and survive for many years. Seed numbers decrease over time as some germinate, some decay and some are eaten by wildlife. Understanding the seedbank is at the heart of effective weed management. Cultivations stir up the seedbank burying freshly shed seed and bringing seed, from lower down the profile, to the surface. Weeds emerge each year, generally only from the top 5 cm of the soil.

3. **Kill weed seedlings**

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Weeds emerge at different times during the year and interact with the crop. Most problems occur when weeds and crops emerge at the same time. Knowing when a weed germinates can help determine the most appropriate control methods. Cultivation strategies can be optimised to reduce weed numbers.

As weeds grow they compete with the crop. The damage they cause depends on: the species, density, the competitive ability of the crop, and the growth stage when crop and weeds compete. While some weeds are highly competitive, others pose little threat and may be valuable to wildlife.

4. Stop seed set.

Although by this stage weeds may have competed with the current crop, there is now a great opportunity to reduce weed seed production, which in turn reduces the weed seedbank for future years. This is most applicable to weeds that are difficult to control (e.g. weed beet in sugar beet, weeds resistant to herbicides) and when weed densities are low. It is often overlooked how important this step can be to stop an early stage infestation becoming a larger problem.

5. On-farm hygiene

Preventing weed seeds arriving on farm or being moved from an infested field to a clean field is key in the battle to control weeds. This will include preventing ingress of weed seeds from non-cropped areas. This is particularly important for windblown species into perennial crops.

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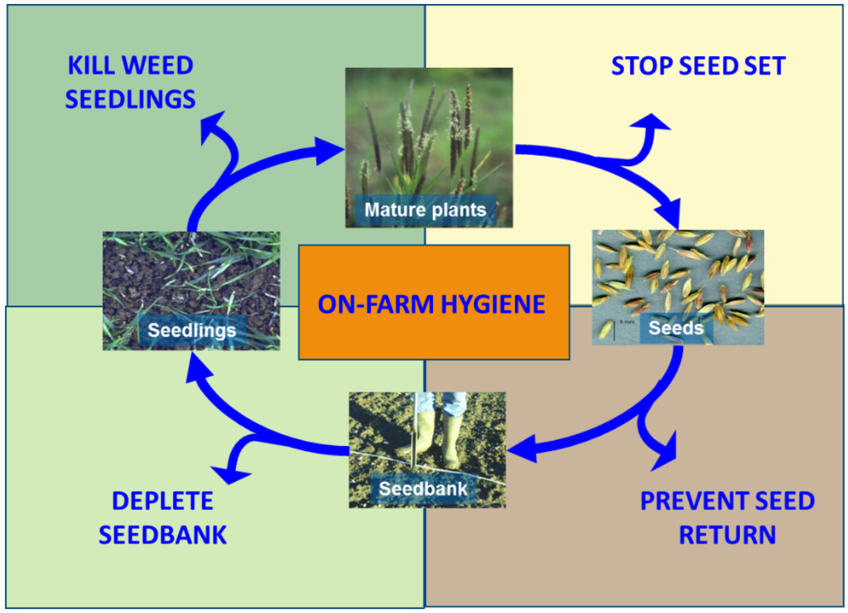

Figure 1 The five opportunities to control weeds within the annual weed lifecycle.

This figure appears again in Sections 3.1 to 3.7 below where it is used to indicate at which stage of the weed lifecycle the weed control technique under discussion is effective.

3.1. Integrated weed management

Integrated weed management (IWM) is the use of multiple weed control methods to sustainably manage a weed problem. It is a component of integrated pest management (IPM) and can include cultural, genetic, mechanical and biological weed control in conjunction with the use of herbicides (Lewis *et al*., 1997; Mortensen *et al*., 2000). The aim of IWM is to diversify weed management strategies to reduce the reliance on herbicides, and promote the use of site specific weed management and target applications to reduce herbicide impacts where possible.

However, there is a general lack of uptake of IWM to date (Mortensen *et al*., 2012, Young *et al.,* 2017, Moss 2019). Mortensen *et al*., (2012) identified that the limitation to adoption of traditional IWM is its basis in knowledge-intensive practices, not on saleable products. Therefore, much higher levels of integration of tactics and application specificity are needed to achieve success in IWM. A recent paper by Moss (2019) discusses this issue in detail and lists 16 barriers to IWM, one of the main ones being that there is little visible evidence of immediate success and little idea of the return on their investment of time and money. Further reasons include the fact that herbicides are convenient, less complex, and are generally cheaper and take less time to apply. It appears that any non-chemical practices are only adopted as compensating for reduced

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herbicide efficiency, which could be when herbicide resistance is present in weed populations on the farm. Moss also highlights the recent '5 for 5' for black-grass campaign (AHDB, 2017d), which is a form of IWM combining a range of well-proven control techniques (delayed drilling, cultivations choices, spring cropping, varietal choices etc.) for black-grass, demonstrating it is not a short-term fix and requires commitment and a proactive and disciplined approach to successfully managing black-grass (Figure 2).

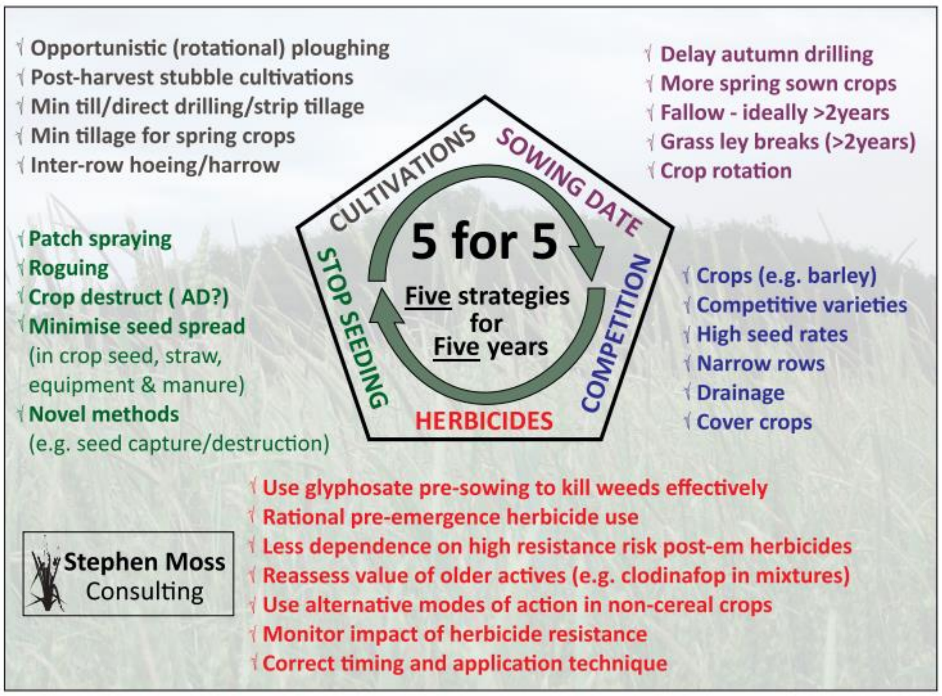

Figure 2 The 5 for 5 strategy for black-grass management could be considered as an IWM approach.

IWMPRAISE is a current Horizon 2020 project (IWMpraise, 2019) that will support and promote the implementation of IWM in Europe. The five-year project (2017-2022) is coordinated by Aarhus University, Denmark and will develop, test and assess management strategies delivered across whole cropping systems for four contrasting management scenarios representing typical crops in Europe.

The four scenarios that the project will focus on are:

- Annually drilled crops in narrow rows (e.g. small grain cereals, oilseed rape)
- Annually drilled crops in wide rows (e.g. maize, sunflowers, field vegetables)
- Perennial herbaceous crops (e.g. grasslands, alfalfa, red clover)
- Perennial woody crops (e.g. pome fruits, citrus fruits, olives)

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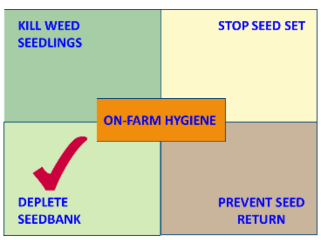
The effectiveness and value of IWM as a total approach to weed control is hoped to become more widespread with increasing application specificity and true integration, which is advancing all the time with technology, information systems and decision support (Young *et al*., 2017). There are social and economic barriers that will always be challenging, but to make IWM more appealing it must be promoted by the industry as a whole and its value demonstrated and understood by fellow growers to ensure its long-term success. IWM should be part of the 'normal' mind set for sustainable weed management in any UK crop and not something considered as an additional factor.

3.2. Cultural Control

Cultural control refers to any technique that involves maintaining field conditions such that weeds are less likely to become established and/or increase in number.

3.2.1. Rotations



Crop choice and rotation are the essential building blocks of a weed management strategy. Prior to introduction of chemical weed control, rotations were the basis of good husbandry minimising pest and diseases and adding to the improvement of soil fertility. Liebman & Dyck (1993) in a review reported that weed densities in test crops were lower in 21 cases, higher in one case and the same in five cases, compared to monoculture systems. The ideal rotation should include different crops designed to avoid the dominance of any one single weed species (McErlich & Boydston, 2013). Murphy *et al., (*2006) showed that weed species diversity increased with more varied rotations. Alternating winter and spring crops, both broad-leaved species and cereals creates an effective break in the cycle of weeds and a greater diversification in the use of different herbicide groups (Zeller, 2018). In the UK the move to a simplified rotation of continuous autumn sown wheat established by minimal tillage has led to the predominance of black-grass (Moss, 1980a, b). Zeller, (2018) showed that black-grass populations could be reduced by including spring crops in the rotation. The Star project (Morris, 2016) showed that spring crops were valuable for controlling grass weeds but it was important to achieve well established competitive crops as weed control was compromised by poorly established crops.

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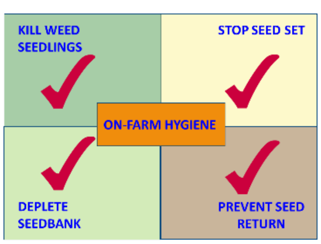
The selection of a crop affects:

- Weed species
- Type and timing of cultivations
- Time of drilling
- The extent and range of approved herbicides

The value of rotations in the EU has been recognised primarily for improving soil quality and since 2017 UK farmers have been subject to greening rules which aim to increase the sustainability of agriculture in the European Union. Within the scheme, if the farm size is 10-30 ha, two or more crops have to be grown, and if it is 30 ha three or more crops have to be grown (Rural Payments Agency, 2018). The improvement of rotations should also contribute to improved weed control.

The weed seedbank may contain similar numbers and species of weeds but the frequency of their occurrence as growing plants varies with respect to the crop (Brenchley & Warrington, 1933). In any crop the predominant weed will be a species with a lifecycle similar to that of the crop, for example in spring sown crops there will be spring germinating weeds and in autumn sown crops, autumn germinating weeds (Squire *et al*., 2000). Herbicide usage also influences the composition of weed species. Ball (1992) noted that cropping sequence was the most dominant factor influencing species composition in the seedbank and attributed this in part to herbicide use in each cropping sequence producing a shift in the weed seedbank in favour of species less susceptible to applied herbicides. For example, in grass leys herbicide use may lead to a reduction in the population of black-grass and wild-oats (*Avena sterilis*) but a build-up in the population of couch grasses (*Elymus* sp.) (Cussans, 1973). Overall rotations tend to increase the diversity of weed species present (Doucet *et al*., 1999; Légère & Samson, 1999; Légère *et al*., 2005 and Sosnoskie *et al*., 2006). Crop volunteers are an additional weed problem that can be directly attributed to rotations (Cussans, 1976).

3.2.2. Rotational livestock grazing and weed management



There are many benefits of having a wide cropping rotation including a grazed grass or herbal ley for a two to three year period, which is standard practice for mixed or organic farmers. This benefits not only the soil health, but can also improve the control of problematic weed species by breaking the weed seed cycle, due to minimising seed return,

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and natural seed bank decline. This is particularly beneficial when resistant black-grass or other grass weeds are present. Arable farmers struggling with these resistant grass weeds are therefore showing an increasing interest in returning to these older mixed farming methods and re-introducing livestock into an arable rotation for a longer-term sustainable weed management system.

The grass or herbal ley can be grazed by sheep or cattle. If the farm is not a mixed farm, sharing livestock with neighbouring farmers as a cooperative scheme could be an option. The AHDB Guide 'Livestock and the arable rotation' (AHDB, 2018a), provides a comprehensive range of opportunities, including choice of leys and specific case studies of farmers who share their knowledge from their practical experiences.

There is a current project funded by AHDB Beef & Sheep sector 'Sustainable beef systems on arable units' (April 2016-March 2020) led by ADAS. The project is investigating the practical, economic, environmental and agronomic implications of integrating beef enterprises into arable system at two farms (in Cambridgeshire & Somerset). Both sites are being grazed with store cattle for around six months with the aim to achieve >1 kg daily live weight gain (DLWG) at a value of £1/day to the beef operator. The high costs and increasing competition for land means that starting or expanding beef enterprises can be challenging. Integrating beef enterprises into arable rotations provides new opportunities for both beef producers and arable farmers. For beef producers, this represents an opportunity for new entrants to the beef industry or for enterprise expansion. For arable farmers, beef cattle may be able to achieve the same or higher net margin per hectare as traditional arable rotations, with the additional benefits of better weed control and improved soil condition resulting from the establishment of grass leys. There is a specific objective in the project to assess the effectiveness of the grass/herbal ley within an arable rotation to reduce black-grass numbers.

Sheep in the arable rotation may be a preferred option for some farmers as they can be moved around more easily and have a different grazing habit. The National Sheep Association (NSA) Guide 'The benefits of sheep in arable rotations' (NSA, 2018), includes case studies of farmers who are currently successfully practicing this method, including those specifically looking to manage black-grass.

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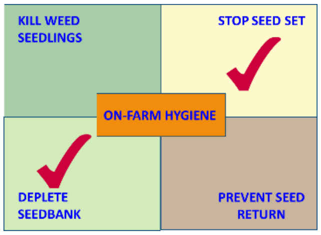
3.2.3. Crop species



Crops species vary widely in their ability to compete with weeds and within each species cultivars will have different competitive abilities. The traits that make a species competitive are not always clear but it is often a combination of traits that lead to effective weed suppression. The most consistent factor from many studies is that the most competitive species have vigorous growth which reduces both the quality and quantity of light that penetrates the crop canopy (Buhler, 2002).

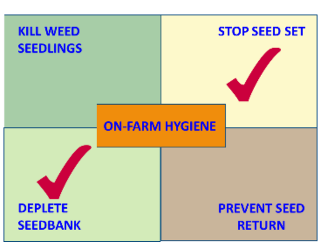
Table 1 ranks crops as to their competiveness (AHDB, 2017a), this ranking may change slightly in different years, locations, soil types, and growing conditions. The competitiveness of oilseed rape depends on the level of establishment achieved and the autumn and winter growing conditions. In late winter, pigeons can strip the plants allowing light to reach the soil surface and stimulate further emergence of weeds in the spring. At the end of the season, when the leaves fall, further weeds can germinate. The choice of crop additionally changes many agronomic factors including the time of drilling, type and timing of cultivations and the range of herbicides available for weed control.

Table 1: Competitive ability of autumn and spring drilled crops (* depends on establishment) (AHDB, 2017a)

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

Ranging from ++++ high to + low

3.2.4. Crop cultivars



Competitive crop cultivars have been identified in cereal crops but breeding for competitive varieties has not been a priority. Lutman *et al.*, (2013) reviewed the data in eight experiments and calculated that the use of competitive wheat cultivars can decrease head number/m^2 in black-grass by 20% when compared to the mean of all cultivars tested.

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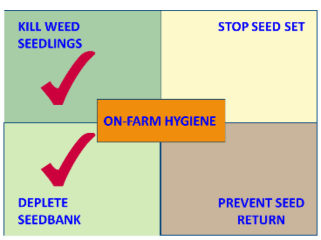
In a more recent review of the potential for competitive cereal cultivars, Andrew *et al*., (2015) identified three aspects to competitiveness of a cultivar:

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 is discussed separately in section 3.3.5.

Using a suppressive cultivar will reduce weed seed production and can be used a part of a long-term strategy for weed control. Using a tolerant cultivar will allow weeds to reproduce, increasing the population possibly to levels where they can no longer be tolerated. Andrew *et al*., (2015) contended that tolerance and suppression should be considered as separate entities but can combine together to achieve weed suppression.

3.2.5. Tillage and cultivations



Cultivations are used to prepare the soil for sowing the crop. They stir up the seedbank, burying freshly shed seed and bringing seed from deeper in the profile to the surface. Many weed seedlings growing are either buried or severed, this is the basis of mechanical weeding and is discussed in section 3.3.

The number of weed seeds in the soil seedbank varies, for example in an English cereal field the number can vary from 5,000-67,000 seeds/m² (Roberts & Chancellor, 1986). Cultivations can be used to move seeds either to where they can germinate or put them at depths where they cannot.

The seed in a seedbank declines at an exponential rate (Roberts & Feast, 1972; Roberts & Feast, 1973), but individual species have different rates of decline (Table 2), the data that contributed to this summary table is dated between 1933 and 2006.

Table 2: Rate of annual decline (%) of seeds with and without annual cultivation (Cook *et al*., 2013)

Common name	Species	Under cultivation	No of data sets	No cultivation	No of data sets
Sterile brome	*Anisantha sterilis*	100	2	100	2
Meadow brome	*Bromus commutatus*	No information			

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Italian ryegrass	*Lolium multiflorum*	96-99 (plough)	1	95	-
Black-grass	*Alopecurus myosuroides*	67.9	15	54.3	7
Wild-oats	*Avena fatua*	66.8	9	19-70	3
Annual meadow grass	*Poa annua*	44.8	9	34.5	6
Scentless mayweed	*Tripleurospermum inodorum*	43.0	11	19.9	10
Chickweed	*Stellaria media*	47.6	16	34.3	8
Green field-speedwell	*Veronica hederifolia*	62.0	5	19.0	2
Common field-speedwell	*Veronica persica*	51.4	10	37.3	4
Field Pansy	*Viola arvensis*	41.1	9	28.0	5
Cleavers	*Galium aparine*	74.7	11	18-100	2
Fat hen	*Chenapodium album*	32.0	17	13.3	12
Poppy	*Papaver rhoeas*	30.8	10	21.7	5

The rate of decline is influenced by the dormancy characteristics of the seed, depth of incorporation and intensity of cultivation. Buried seed can also die either due to decay or predation, seed predation is discussed in Section 3.8.8.

Traditionally weed control has been the primary reason for tillage (Morris *et al*., 2010). The timing, depth, method and frequency of cultivations influence the composition, density and persistence of the weed population (Mohler & Galford, 1997). With the introduction of herbicides it became possible to reduce the intensity and number of cultivations, and since the introduction of non-selective herbicides such as paraquat and glyphosate, establishment of crops without cultivations has become possible.

Cultivations for weed control can be divided into those immediately following the harvest of the crop (stubble cultivations) and those done to prepare the soil for the next crop (primary and secondary cultivations). Primary and secondary cultivations can be further sub-divided.

Stubble cultivations

Stubble cultivations immediately after harvest can stimulate weed seed germination by improving seed-soil contact for seeds on the soil surface, by moving freshly shed seeds into moisture and buried seed into a suitable situation for growth. Moisture is necessary for good germination. Newly

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emerged weeds can be controlled through cultivation or non-selective chemical control before planting the crop.

Primary cultivations

Primary cultivation is the first cultivation that is done to prepare the soil for the next crop and can be classified into four groups; plough, deep and shallow till, no-till and others. Changing the primary cultivation is an effective way of changing weed populations. Figure 3 shows the effect of primary cultivation method on freshly shed seeds and those in the weed seed bank.

Cultivation	After harvest	Plough	Deep till	Shallow till	No-till
Soil movement		Inversion	Deep	Little	No mixing
Cultivations depth		Over 5cm, inverted	Over 5cm	Under 5cm	None
Example		Plough	Discs over 5cm	Discs under 5cm	No-till drill
		Many old seeds brought to surface, most new seeds buried.	Fewer old seeds brought to surface, some new seeds buried.	Very few old seeds brought to surface. Few seeds added to the seedbank.	A few seeds may change layers.

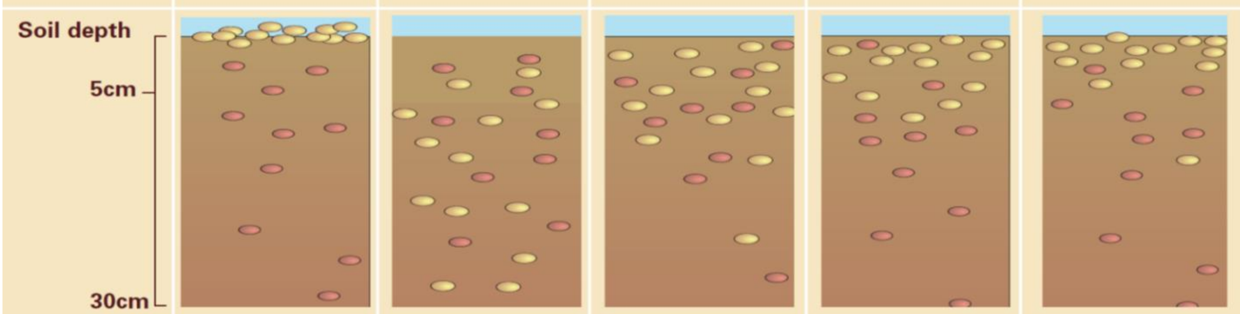

Figure 3: Cultivation options and the effects on seeds in the weed seedbank (AHDB, 2017a).

Ploughing

Ploughing inverts the soil, burying 86% of freshly shed seed to below 6 cm but brings up 20% of old seed buried by previous cultivations (Mohler *et al*., 2006; Figure 4). Subsequent shallow cultivations to establish the crop generally do not to disturb the buried seed if they are at a shallower depth. Most of the seed that germinates is seed shed in previous seasons. Generally, ploughing reduces weed populations, particularly grass weeds. 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 (Lutman *et al*., 2013). Annual meadow grass (*Poa annua*) seeds were 70% lower after nine years of ploughing compared to shallow rotary tillage (Roberts & Stokes, 1965). In the STAR project (Morris, 2016) there were no grass

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weeds in the continuous plough treatment compared to increasing populations in the non-inversion treatments. Perennial weeds can also be kept at manageable levels for annual crops by ploughing.

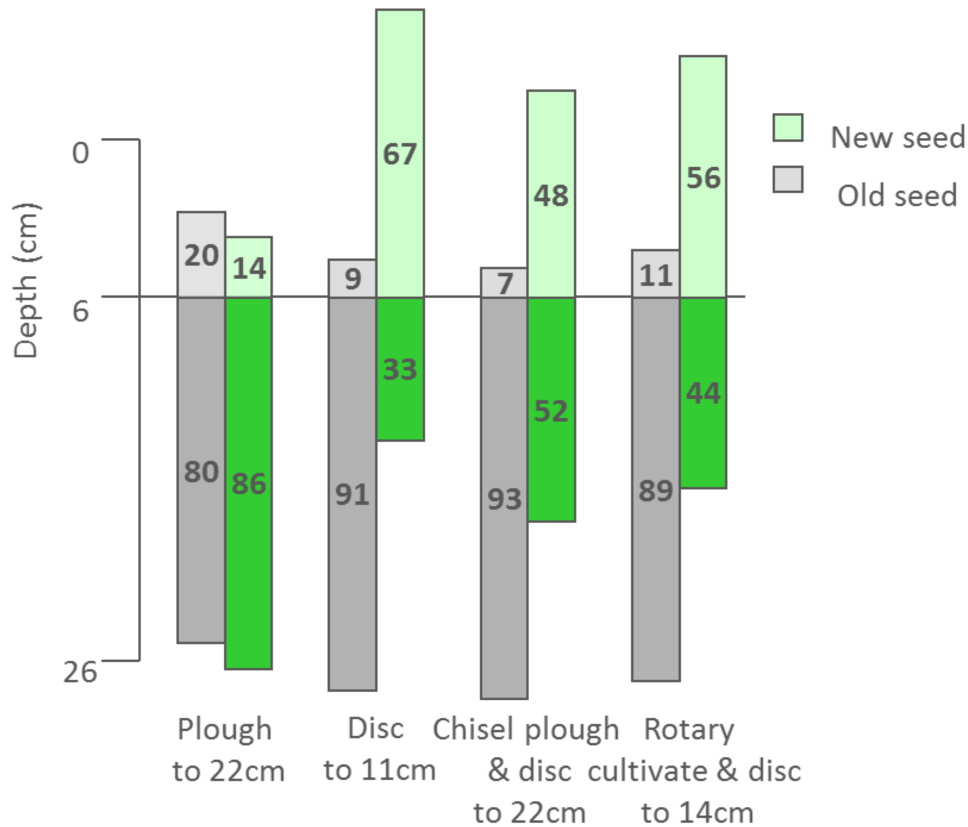

Figure 4: Percentage distribution of old (seed below 6 cm) and new seed (on the soil surface) after primary cultivation (Mohler *et al*., 2006)

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 seed from previous seasons (Figure 3). Approximately a third of newly shed seed is buried below germination depth (6 cm) and 9% of old seed returns to the surface (Mohler *et al*., 2006; Figure 4). Generally shallow burial of seed promotes germination due to availability of light, alternating temperatures and decreasing soil moisture (El Titi, 2003). The deeper seeds are buried the less likely they are to emerge.

The depth of burial of weed seeds affects the length of time taken to emerge (Table 3). Most seed when present on the soil surface germinates between five and seven days. The depth at which

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50% of the seed did not emerge is 5.7 cm for black-grass, 3.5 cm for chickweed (*Stellaria media*), 7.0 cm for cleavers (*Galium aparine*) and 6.0 cm for cut-leaved cranesbill (*Geranium dissectum*), larger seed will emerge from greater depths (Benvenuti *et al*., 2001). Mixing of soil by cultivating will place seed at varying depths and cause emergence to be staggered.

Table 3: Weeds, percent emergence and number of days to emergence at different sowing depths

	Black-grass (*Alopecurus myosuroides*)		Chickweed (*Stellaria media*)		Cleavers (*Galium aparine*)		Cut leaf cranesbill (*Geranium dissectum*)	
Seed depth (cm)	Percent emergence	Days to emerge	Percent emergence	Days to emerge	Percent emergence	Days to emerge	Percent emergence	Days to emerge
0	90	5.5	79	5.7	88	6.8	75	7.3
2	89	6.8	67	7.1	87	7.7	70	8.5
4	85	8.8	38	9.2	80	10.1	68	11.0
6	57	11.3	5	12.0	50	13.2	30	13.6
8	8	17.1	0	0	38	19.1	20	20.2
10	0	0	0	0	15	22.6	2	23.1
12	0	0	0	0	0	0	0	0

The cultivation equipment available for non-inversion tillage is very variable ranging from light tines to heavy discs that work at a range of depths. The use of non-inversion tillage has led to lower levels of broad-leaved weeds (Froud Williams *et al*., 1983) and an increase in the level of grass weeds, particularly bromes (*Bromus* and *Anisantha* spp.), ryegrass (*Lolium* spp.) and black-grass (Hakansson, 2003). After three years in the STAR project (Morris, 2016), a factorial treatment structure comparing four cultivation methods and four rotations, meadow brome, sterile brome, black-grass and wild-oats were increasingly present in the continuous wheat, non-inversion treatments. In this project, grass weeds developed within the first five years and required intensified herbicide programmes for their control. The long term trends for grass weed management showed that manageable grass weed populations were achieved in all rotation and cultivation combinations except where continuous shallow tillage was used.

Minimum tillage (non-inversion, 15-20 cm depth) was also shown to favour perennial species, biennials and some annuals predominantly grass weeds (Cioni, 2010; Table 4) particularly if maintained for several years.

Table 4 Spreading of weed species related to the time duration of minimum tillage (Cioni, 2010).

Species	Years on minimum tillage (15-20 cm)

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	1	2	3
Agropyron repens	0	0	++
Cirsium arvense	+	0	+++
Picris echioides	+	0	+++
Taraxacum officinale	0	0	++
Alopecurus myosuroides	++	++	+++
Daucus carota	0	0	+
Lolium multiflorum	0	0	++
Poa annua	+	++	++
Senecio vulgaris	+	0	++
Sonchus spp	+	+	++++
Veronica persica	+	+	++

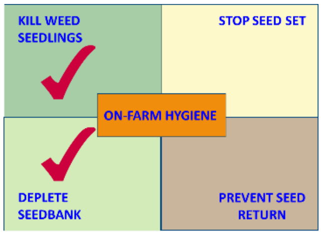
0 = not present, + only presence, ++ low spread, +++medium spread, ++++ high spread

No-till / direct drilling

With this technique soil is only moved by the drill and the freshly shed seed remains on the soil surface, some weed seed falls down cracks in the soil (Figure 3). The use of no-till /direct drilling has also led to an increase in grass weeds in rotations, particularly sterile brome (Froud-Williams, 1983) and relies on herbicides to control perennial weeds. Direct drilling in winter wheat increased black-grass populations by 16% when compared to non-inversion tillage (Lutman *et al*., 2013). Direct drilling has been shown to decrease weed seedbank density, but increase weed diversity particularly perennial and biennial species (Murphy *et al*., 2006).

In oilseed rape, subcasting is often used to establish crops with minimum soil disturbance, a subsoiler leg is fitted with a seedbox, some seed falls down the crack made by the subsoiler leg and sometimes weeds germinate from depth if the crack is not closed.

Strip tilling



A narrow band of soil is cultivated sufficient in which to establish the crop and the majority of the field is left uncultivated. The conservation technology information centre (CITC, 2002) defines strip tillage as a modification to direct drilling with disturbance if 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 (Morris *et al*., 2010).

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Secondary cultivations

These cultivations are done after the primary cultivation and aim to create a fine tilth for a seedbed, Working depth is shallower than the primary cultivation and is usually up to 10 cm. Varying the number and timing of these cultivations can be used as a technique for weed control.

Cultivations in the dark

Exposure to light can break weed seed dormancy and stimulate germination. Blair & Berry (1997) reviewed the effects of light (visible radiation and near infra-red (inc. 730 nm) wavelengths) on the germination of weed seeds (Table 5). In summary, there was a lack of information on the light responses of weeds, generally the responses by species are related to the ratio of Red:Far Red light and cannot be considered in isolation from dormancy, after-ripening of seed, environmental conditions of the parent plant and the subsequent effects on the progeny. Blair & Jones (1997) conducted a range of incubator studies on common UK species and the results are presented in Table 5.

Bond *et al*., (2007a) noted that cultivation in the dark can reduce weed emergence by up to 70% but the effect is inconsistent, still leaving enough weeds to reduce crop yield. The inconsistency can be attributed to a range of factors: not all weed species have light sensitive seeds, some can lose their light requirement with age, and some are small seeded and only emerge from shallow layers of soil receiving sufficient light to germinate.

In the UK, trials were done using a tine cultivator, with and without shrouds during the day and night but no differences were seen between the treatments (Blair & Jones, 1997).

Reimans *et al*., (2007) used a covered rotary harrow during the day prior to drilling lettuce, this was effective in reducing weed levels by 17% in two out of three years in a stale seedbed and by 60% during plant bed preparation, with the differences in control between years attributed to different dormancy states.

Table 5: Effects of light on the germination of a range of species (D – Dark, L – light)

Weed species (common name)	Weed species	Blair & Berry review (1997)	Blair & Jones, (1997)
Wild-oats	*Avena fatua*	D> L	D>L
Black-grass	*Alopecurus myosuroides*	L>D	L
Chickweed	*Stellaria media*	L=D, L>D, Partial None	L=D

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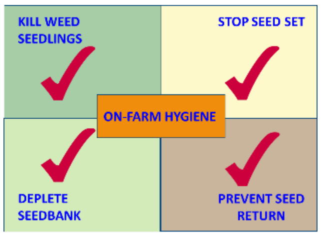
Scentless mayweed	*Tripleurospermum inodorum*	-	L
Sterile brome	*Anisantha sterilis*	D>L	D>L
Meadow brome	*Bromus commutatus*	-	D>L
Cleavers	*Galium aparine*	L=D, L>D, Partial	L=D
Ivy-leaved speedwell	*Veronica hederifolia*	None, Partial	D>L

3.2.6. Fallow



A fallow is a period without a crop. Fallowing with multiple cultivations was designed to reduce infestations of perennial weeds such as common couch (*Elymus repens)* and docks (*Rumex spp.)* before the use of herbicides was widespread*.* Here continuous chopping of rhizomes and roots exhausts the plants reserves and reduces the population (Zaller, 2004; Bond *et al*., 2007a, b).

A comprehensive review of fallowing covering 14 major arable weeds: Black-grass, sterile brome, wild-oat (*Avena fatua*), meadow brome (*Bromus commutatus*), fat hen (*Chenapodium album*), cleavers, Italian ryegrass (*Lolium multiflorum*), annual meadow grass, chickweed, scentless mayweed (*Tripleurospermum inodorum*), ivy-leaved speedwell (*Veronica hederifolia*), and common field speedwell (*Veronica persica*) was done in 2013 by Cook *et al*. The review highlighted how little is known about the detailed biology of the majority of weeds in the UK, and that most work has been done on periodicity, seed decline emergence, germination and dormancy by Roberts and his students between 1958 and 1986 but weeds that are the most prevalent today, cleavers and black-grass, were not covered*.*

The opportunities for reducing the seedbank of the key weed species in a single year fallow, or less, is very limited (Table 6). In an autumn sown crop there is a moderate chance of controlling sterile brome, meadow brome, and Italian ryegrass. Introducing a spring sown crop into the rotation will generally deplete the seedbanks of these grass weeds due to their short persistence and predominantly autumn emergence. With the 10 broad-leaved weed species there is virtually no opportunity for depleting the seedbank prior to drilling a crop in early or late autumn.

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Table 6: A summary of the level of confidence in the management strategy depleting the weed seedbank and the lifecycle parameters of weed species (Cook *et al*., 2013)

Strategy	*Anisantha sterilis*	*Bromus commutatus*	*Lolium multiflorum*	*Alopecurus myosuroides*	*Avena fatua*	*Poa annua*	*Tripleurospermum inodorum*	*Stellaria media*	*Veronica hederifolia*	*Veronica persica*	*Viola arvensis*	*Galium aparine*	*Chenapodium album*	*Papaver rhoeas*
Cover fallow year	High	High	High	High	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Low	Low
Cultivated fallow year	High	High	High	High	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Low	Low
Spring sown after cover	High	High	High	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Low	Low	Low
Spring sown after fallow	High	High	High	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Mod	Low	Low	Low
Late-sown autumn crop	Mod	Mod	Mod	Low-mod	Low	Low	Low	Low	Low	Low	Low	Low	Low	V. Low
Autumn sown crop	Mod	Mod	Low	V. Low	Low	Low	Low	Low	Low	Low	Low	V. Low	Low	V. Low

Level of confidence in depleting the weed seedbank

High	Mod = moderate	Low

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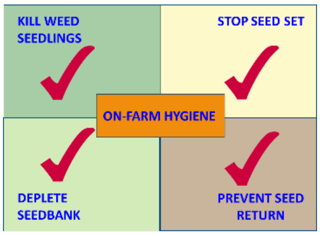
3.2.7. Cover cropping



Cover crops are grown between the harvest and establishment of main (cash) crops. They are crops which are grown primarily for the purpose of 'protecting or improving' (Anon, 2015) the soil and water, nutrient scavenging and cycling and other ecosystem services (White *et al*., 2016). Examples of cover crop species grown widely in the UK include: brassicas such as mustard and oilseed radish, legumes such as vetches, berseem clover, and white clover, cereals such as rye or oats, and others such as phacelia or buckwheat. Cover crops are usually grown as mixes of two or more species.

Cover crops have the potential to suppress weed growth by direct competition for light, water and nutrients (Creamer *et al*., 1996), and/or releasing allelopathic substances (see section 3.3.7), or providing a break in the rotation. This break may be in the form of a longer term ley, or simply the over winter period of a cover crop, which allows other weed control measures to be used between the main crops in the rotation.

The impact of early light interception on weed suppression is dependent on the relative height increase of the target weed species compared to the cover crop species (Kruidhof, 2008). Small weed species, such as annual meadow grass or common chickweed may be affected throughout the period of growth of a taller, denser cover crop, but tall weed species, such as fat hen may only be affected in the early stages of establishment before out-growing the height of a cover crop (Kruidhof, 2008). Surface mulches physically suppress weeds by altering the light quality, quantity and temperature at the soil surface. They can also act as a barrier to reduce successful seedling emergence. Variation in cover crop competitive ability differs between species and cultivars within a species. Increased competitive ability has been attributed to early emergence, seedling vigour, rapid growth (i.e. accumulation of biomass, density of tillering, increases in height) and canopy closure (White *et al*., 2016). For example, rye cover crops are able to produce a dense canopy which can compete effectively with weeds for light, moisture, and nutrients, resulting in a suppression of their growth (Weston, 1996). A study in a tilled vegetable system in California found that of three cover crops tested mustard was found to be the best for weed control due its early season growth and weed suppressive abilities (Brennan & Smith 2005). Mirsky (2008) tested five cover and cash crop systems in Maine and Pennsylvania and found that less suppressive cover crop systems which allowed weed seed production always resulted in net seedbank increases. Additionally, systems which included oats or a slow growing legume were less suppressive compared to the high disturbance systems (yellow mustard, followed by buckwheat, followed by winter canola (oilseed) and summer fallow). Cover crop residues left on the soil surface can also have a physical weed suppressing effect. For example, cover crop residue on the soil surface could deter growth of weeds

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species dependent on light to germinate (Teasdale, 1996). However, uniform distribution of cover crop residues is needed to consistently suppress weed emergence (Creamer *et al*., 1996).

The release of allelopathic substances (discussed in section 3.3.7) from living or decomposing cover crops tissue may also have a negative effect on weed growth.

Cover crops, also provide a means of weed control by providing a break in the rotation, either through annual leys or shorter periods of growth. One example of this is the rotational switch to spring cropping, in order to target the control of black-grass, offering the opportunity to grow cover crops. It should be noted that, in a rotational context, the direct effects of cover crops on grass weeds is small (Cussans & Storkey, 2018). Almost all of the effects on black-grass populations can be explained by the underlying cultural control approach (Cussans & Storkey, 2018). Cussans & Storkey, 2018, concluded from the combined approaches of pot experiments, field trials and that 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. The yellow mustard, followed by buckwheat, followed by winter canola (oilseed) system consistently depleted the weed seedbank through weed germination and control of the emerged plants (Mirsky, 2008). 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 may provide a thick cover crop residue, which prevents germination. Glyphosate is widely used for cover crop destruction and as a weed management tool. There is a need for more research on the impacts of cover crop destruction methods and spring crop cultivations on many factors in the rotation, including weed control.

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 (Moonen & Bárberi, 2004). 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 (Melander, 2005).

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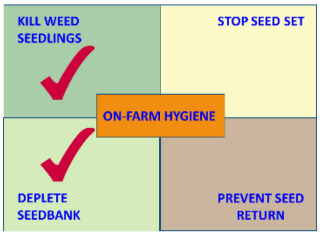
3.2.8. Intercropping or companion cropping



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' (Howard, 2016). 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 (Howard, 2016). The two terms can be used interchangeably and can encompass many different combinations of crops, including but not limited to temporary intercropping (where a plant species is only there for part of the main crop life cycle, or is not taken to harvest, but planted at the same time as the main crop), full season (synchronised) intercropping, living mulches, undersowing, and agro-forestry.

In the Nuffield review of the potential for companion cropping and intercropping in the UK (Howard, 2016) outlines the advantages for weed control as follows: Intercrops compete for water and nutrients more efficiently than sole crops and therefore compete more efficiently with weeds. This extends to the intercropping of legumes and cereals/brassicas, which will compete with the weeds for the legume fixed nitrogen, resulting in a reduction of the weed biomass compared to a single legume crop. Some weed species only germinate when soil nitrate levels are around 50 ppm, so a cereal and legume mix can reduce soil nitrate levels and therefore weed seed germination (further discussed in section 3.2.12). Some intercrop species combinations can reduce the amount of light reaching the soil surface, reducing the amount of light available for weeds. Weed diversity decreases with intercrops, due to competition. It is noted that the weed advantages of intercropping will be more pronounced where herbicides are not used, such as in organic systems (Howard, 2016). In a Swiss trial, winter wheat intercropped with white clover (*Trifolium repens* L.), subterranean clover (*Trifolium subterraneum* L.), and birdsfoot trefoil (*Lotus corniculatus* L had significantly fewer broad-leaved and grass weeds than unmulched plots (Hiltbrunner *et al.,* 2007). Field trials in Germany (2009 and 2010) found that mixed cropping of lentil and a companion crop reduced weed biomass by 24 to 41% depending on the mixing ratio (Wang *et al*., 2012). Companion cropping in OSR, which is becoming more widespread in the UK, has been reported to give the same weed control as a pre-emergence herbicide, less herbicide use and reduced the biomass of cranesbill (Howard, 2016). For weed suppression Howard (2016) recommends 1800 g of green matter going into the winter, roughly divided as 1000 to 1200 g of OSR and 600 to 700 g of companion crop.

A potential disadvantage of companion cropping is that it could limit herbicide choice. For example, some herbicides which can be used in a single crop, may not be suitable for an intercrop as they could damage or kill one of the crops in the mix. Also weeds germinating during the season will be able to produce seed and replenish the seedbank. The success of weed control will be dependent on the establishment of both crop and cover and the availability of specific herbicides.

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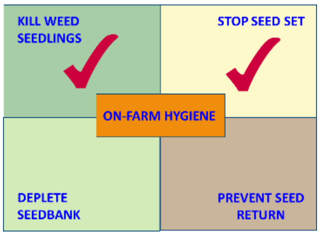
3.2.9. Seed rates



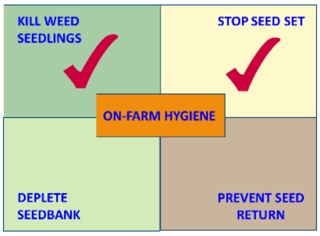
A crop that rapidly establishes a vigorous canopy, intercepts maximum light and shades the ground, will provide optimum levels of competition against weeds. Lower seed rates lead to sparser crops leaving more space for weeds to emerge and grow.

The optimum plant density for each crop will differ with growing conditions, time of sowing and economic viability. In unfavourable conditions (e.g. delayed sowing or poor soil conditions) growth of individual plants becomes limited, so higher plant densities may improve competitive ability and yield. It is also not possible to increase seedrates in crops where size and quality of the harvestable produce is important such as in potatoes and many horticultural crops.

In arable crops organic growers tend to use high seed rates, above 300 seeds/m² to combat weed competition. Welsh *et al* (1999) in their study of weed competition in organic winter wheat, used 500 seeds/m². Lutman *et al*., (2013) looked at six experiments comparing the competitive effects of winter wheat sown at two or three densities (range 64 to 508 wheat plants m²), crop density above 100 plants m² had no effect on weed plant numbers, but reduced the number of heads per m² by 15% for every additional increase in 100 crop plants, up to the highest density tested (350 wheat plants m²).

Increasing seedrates can also be used in conjunction with other weed control methods such as mechanical weeding (section 3.3.2) that can reduce crop populations.

3.2.10. Row widths



Crops are grown on a range of different row widths, which is often determined by the cultural requirements of the crop or their requirement for space to achieve maximum yield e.g. potatoes and, sugar beet. In general decreasing row widths increases the density of the crop reducing the amount of light that can penetrate to the base of the crop and hence reducing weed biomass. Crops grown on wider rows take longer to achieve a complete canopy and this results in a longer period for weeds to establish.

Crop row width can also determine whether it is possible to use mechanical in-crop weed control. For example, cereal crops are usually grown at 10-15 cm row widths, but where use of interrow hoeing (see 3.3.2) is planned it is recommended to use row widths of 20-24 cm to avoid crop damage (Melander *et al*., 2005). The effect of increasing row width on yield can be variable. Increasing row width in crops with low weed pressure can reduce yield, but in crops with high weed pressure and

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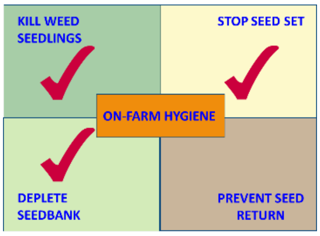
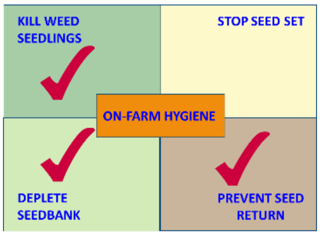
when used in combination with mechanical in-crop weed control increased row width can increase yield (Rasmussen, 2004; Melander *et al*., 2005).

3.2.11. Drilling dates



The interval between harvesting a crop and the drilling of the next one can be used to control weeds. Delaying drilling increases the time available for weed control but can also reduce the competitiveness of the following crop. Sowing date has a major effect on early crop vigour, canopy development, dry matter production and final yield, and all these factors have a direct impact on the competitive ability of a crop. The efficacy of delaying drilling for weed control depends on the emergence period of the weeds. Seedling emergence is affected by seed dormancy, depth of burial, soil temperature and soil water potential in addition to cultural practices, in particular tillage. Delayed drilling is a technique used widely for control of black-grass. In an average of 19 experiments, delaying drilling of winter wheat from September to October decreased black-grass populations on average by 50% (Lutman *et al*., 2013).

Stale seedbeds



A stale seedbed is defined as a seedbed prepared days, weeks or months before establishing a crop. This technique is used to encourage a flush of weeds that are then killed by cultivation or non-selective chemical control (e.g. glyphosate), depleting the upper layers of the seed bank and reducing subsequent weed emergence within the crop (Bond *et al*., 2003). Using cultivations, especially when wet, can lead to movement of established weeds rather than death. Cultivating deeper than 1-2 cm can result in a further flush of weeds and further delay before drilling.

3.2.12. Timing of nitrogen

The timing of nitrogen (N) fertiliser application can influence the germination, emergence, and competitiveness of weeds. Spring N fertiliser applications increase weed growth, but the influence of N on weed emergence is dependent on the weed species, seed source, and environmental conditions (Sweeney *et al*., 2008).

Field application of nitrate was shown to reduce dormancy in seeds of fat hen, germination in the laboratory was increased from 3-34% (Fawcett & Slife, 1978). Field application of nitrate in spring as ammonium nitrate has been used in North America to stimulate depletion of weed seeds including wild-oat (Sexsmith & Pittman, 1963).

Blackshaw *et al*., (2003) looked at the response of 23 weed species to added nitrogen. Seven out of 23 species took up similar or greater amounts of nitrogen than did wheat. He postulated that the high

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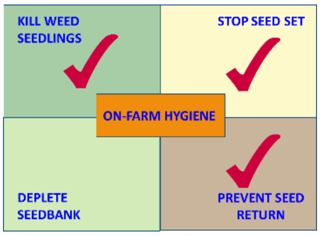
responsiveness of many weed species to N may be a weakness to be exploited through development of fertiliser management methods that enhance crop competitiveness with weeds. In a further experiment (Blackshaw & Brandt, 2008), the competitive ability of the low N-responsive species, Persian darnel (*Lolium persicum*) and Russian thistle (*Salsola kali*), was not influenced by N rate but the competitiveness of the high N-responsive species redroot pigweed (*Amaranthus retroflexus*) increased with increasing N rate. Wild-oat competitiveness was unaffected by N fertiliser rate. Arvalis (2018) encouraged farmers to control weeds in winter wheat prior to fertiliser application in the spring.

Nitrogen levels also influenced the susceptibility of weeds to herbicides, control of green foxtail (*Setaria viridis*) grown under low N required approximately six times the dose of nicosulfuron compared with plants grown under high N, but N did not influence the efficacy of mesotrione, glufosinate, or atrazine when applied to velvetleaf (*Abutilon grandifolium*) (Cathcart *et al*., 2004). The authors postulated that differences in herbicide efficacy resulting from soil N levels may alter weed community structure and may explain weed control failures on farm fields.

3.3. Non-Chemical Control

Non chemical weed control includes techniques that are specifically undertaken to control weeds in crops that do not involve the use of chemicals.

3.3.1. Manual removal of weeds



The manual removal of weeds can be separated into three categories; hand weeding, pulling (roguing) and hoeing.

Hand weeding

Hand weeding is a slow, time consuming method of weed control, generally used for small areas and predominately on organic farms. 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 (McErlich and Boydston, 2013). Often hand weeders will follow a pass of a mechanical weeder to clear-up missed weeds.

Pulling/roguing

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

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appear above the crop canopy such as 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 hand held 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.

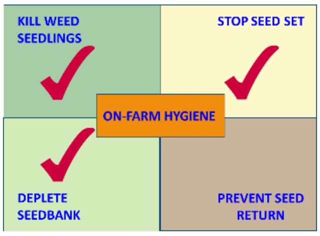
Hoeing

There are a range of hoe designs, they are used to cut weeds and move soil which then dislodges or buries weed seedlings.

- Draw hoes – cut when pulled
- Push hoes – cut when pushed
- Oscillating or stirrup hoes – cut on pulling and pushing

They can be used with long or short handles depending on personal preference (Davies *et al*., 2008).

3.3.2. Mechanical weeding



Mechanical weeding is the most common physical method used for weed control in a range of crops, it kills weeds by burying, cutting or uprooting. It can deal with all weeds including those that are herbicide resistant. The success of mechanical weeding is dependant, in part, on the weather, if done in wet conditions weeds can be uprooted and transplanted. The best time to control weeds is at the white thread stage, when the root emerges from the seed, but 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.

Reviews of non-chemical weed management particularly in reference to the organic sector can be found in Welsh *et al*., (2002), Bond *et al*., (2003), Melander *et al*., (2005), Melander (2006), Chicouene (2007), Van der Weide *et al*., (2008), Harker & O'donovan (2013), Melander *et al*., (2013) and Pannacci *et al*., (2017). Illustrations of the majority of implements mentioned can be seen in Bowman (1997). A review of robotic weed control systems can be seen in Slaughter *et al*., (2008a). Two handbooks are available; 'Weed management for organic farmers, growers and smallholders' (Davies *et al*., 2008) and 'Practical weed control in arable farming and outdoor vegetable cultivation without chemicals' (van der Schans *et al*., 2006).

Jones *et al*. (1995 & 1996), determined the type of physical damage needed to kill a seedling weed, finding that burial to 1 cm depth was the most effective treatment, closely followed by cutting at the

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soil surface. Total burial is required for control of weeds but plant size, angle and growth habit influence the depth of covering required (Baerveldt & Ascard, 1999).

Plant spacing is critical to the success of mechanical weeding. Crops need to be sown in rows or 'on the square'. Its effectiveness is also 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.

Harrows and tine weeders

Harrows and tine weeders uproot seedling weeds and cover them with a thin layer of soil. These can be used in all soil types and work best where the soil surface has a medium to fine tilth. They disturb the soil at a depth of 2-5 cm and are effective on weeds at the early growth stages (up to 2.5 cm in height). Weeds are generally controlled by burial, but there is some uprooting where working depth and speed of travel are increased (van der Schans *et al*., 2006).

Traditional harrows tend to be ridged but tines tend to be flexible and vibrate through the soil and glide around objects. Tines can be adjusted to increase the intensity of attack.

Harrows and tine weeders can be used 'pre-emergence' of the crop at a shallower depth than drilling. For later passes crops need to be well established and rooted to prevent uprooting.

Kvik-up harrow

The Kvik-up harrow (KVIKagro, 2018; Figure 5) can be linkage mounted or semi-mounted and its working width is variable from 160 to 640 cm depending on the model. This method removes roots and uses gravity to separate plant material from soil. The Kvik-up harrow comprises large tines with goosefeet ends which are responsible for loosening the soil to a depth of 10 to 15 cm and strong rotating spring-tines working at a depth of 5 to 7 cm that grab soil and plant material and throw 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*).

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Figure 5: Kvik-up harrow, from www.kvikagro.com

Inter-row weeders

Mounted or trailed hoes

These target weeds between the rows, they can be front or rear mounted, powered or ground driven. They can be steered from the tractor, have a second operator, vision guidance, GPS, or GIS. Weeds are cut off at 1-2 cm below the soil surface. The blades are usually A or L shaped and selected to target a specific weed.

A good seedbed and precise drilling of the crop are needed to avoid excessive crop damage. Row width needs to be 15 cm or greater. Mounted or trailed hoes can be used in crops from when the rows are visible up until the crops overspill the row or cover the soil entirely. Weed kill can be increased by a higher forward speed to increase soil cover. Discs, plates or protective hoods can be fitted to protect the crop from damage.

Rotary cultivators

These are driven by the forward speed of the tractor and include basket or cage weeders. They uproot the weed in the top 2.5 cm of the soil or strip the leaves from the weed. They are often used in conjunction with an inter-row hoe that breaks the soil surface before rotary cultivation.

Cageweede*r*

The K.U.L.T Cageweeder (K.U.L.T, 2019; Figure 6) is comprised of two weeding cages which work within the crop rows at an adjustable soil depth of 1-4cm. The first cage is responsible for loosening the soil and loosening the weeds and the second cage removes the weeds from the soil. To use this

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equipment crop rows should be more than 20 cm apart and the working width coverage is 150-600 cm. The K.U.L.T cageweeder speed varies within 3-12 km/h. This equipment can be used in vegetables, other field crops and tree nurseries.

Figure 6: K.U.L.T Cageweeder

Brush weeder

Strong rotating nylon brushes uproot weeds on the soil surface. This type of weeder is used mainly between the rows of vegetable crops and in field production of herbaceous perennial nursery stock. It is generally used where surfaces are level.

Finger weeder

This is used in well-established crops to prevent them being uprooted when there is a size difference between weed and crop. Weeds are taken out within the row (intra-row). Two rubber discs with finger like protrusions are angled down and into the row. This technique relies on a loose surface tilth and is not suitable where soil is consolidated.

Torsion weeder

Spring tines are angled backwards and downwards either side of the crop row and flex around the crop plants uprooting small weeds within the row. This technique relies on a loose surface tilth and is not suitable where soil is consolidated.

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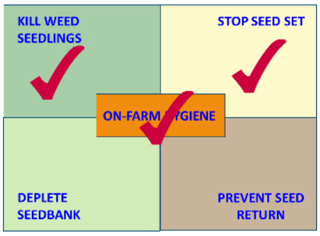
3.3.3. Mowing and cutting



Mowing is often used to control weeds to prevent flowering and seed set. In black-grass the effectiveness of different mowing scenarios can be seen in Table 7 (Colbach *et al*., 2010). When mowing patches, it will take three cuts to minimise seed return. Although in set-aside (single year fallow) Clarke *et al*., (1995) reported seven cuts were needed to prevent black-grass from seeding. The rule of thumb is to start early and finish late but a good plant cover is essential for competition. Increased mowing will be needed on heavy soils and in moist conditions (Clarke *et al*., 1995). Delaying mowing means plants will already have set viable seed.

Table 7: Ranking of mowing scenarios for controlling black-grass – simulation from the model ALOMYSYS (Colbach *et al*., 2010)

Scenario (mowing dates)	Black-grass seed bank (seeds/m^2)
Triple mowing (mid-May, early July, mid-August)	1266
Triple mowing (mid-May, mid-June, mid-July)	1274
Double mowing (mid-May and mid-July)	1819
Double mowing (mid-May and mid-June)	1946
Triple mowing (late May, late June, late July)	4292
Double mowing (mid-May and early June)	7391
Single mowing (mid-June)	25,042
Double mowing (mid-May and mid-August)	66,327
Single mowing (mid-May)	66,509
Single mowing (mid-July)	108,737
Control (no mowing)	176,453
Single mowing (mid-August)	178,004

It has been traditional to mow around field edges but sterile brome recovers from mowing and grows back shorter after each cut making subsequent control more difficult (Figure 7; from Shield & Godwin, 1992). Establishment of a perennial cover will provide competition for the weeds and prevent their regrowth.

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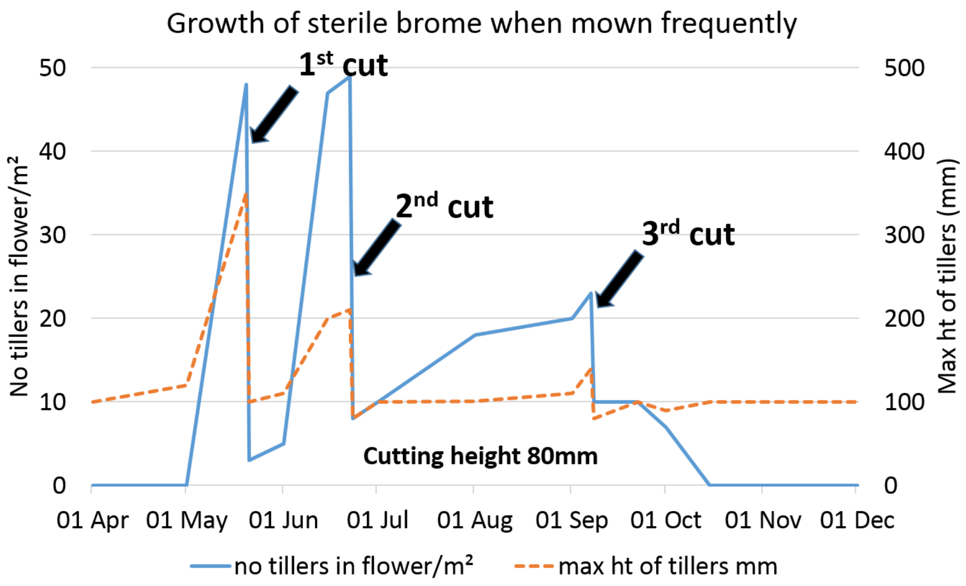

Figure 7: The growth of brome when mown frequently (Shield & Godwin, 1992)

CombCut weed cutter

The CombCut (Just Common Sense, 2018) consists of immobile blades and brushes and has the ability to 'comb' the crop and cut large weeds without causing damage to the thinner crop plants when they pass through the blades (Figure 8). It can control various weed species and it is used in different cropping systems. The machine selectively cuts the weeds and not the crop, for this to happen there must be a physical difference between the weed and the grass. If the weed has a thicker stem, a stiffer stem or more branches than the crop, then selective cutting is possible. The minimum speed is 8-10 km/h, the brushes can be moved forward and the angle of the blades and their operational height are adjustable depending on the crop characteristics and growth stage. Repeated cuts might be required one to four weeks after the first operation. The CombCut weed cutter has been used successfully with creeping thistles (*Cirsium arvense*), nettles (*Urtica* spp.), charlock (*Sinapis arvensis*), docks and black grass.

Figure 8: CombCut weed cutter

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In Norway (Beachell, 2018) the CombCut was trialled in a grass sward, it left several dock plants uncut after treatments and there was no clear reduction in numbers of flowering or vegetative plants. Two passes of the CombCut reduced weed biomass significantly compared with one-pass treatments. Grass yield was unaffected by the CombCut treatments.

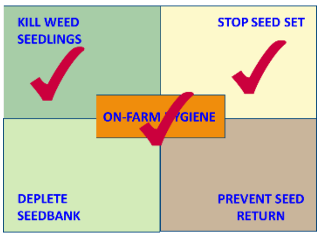
Weed surfer

The principle of this equipment is based on cutting off weed seed heads. It is rear or front tractor-mounted and it comprises of 10 or 14 four-blade rotors (Figure 9). The operation height is adjustable enabling the weed surfer to provide effective control for volunteers, annual and perennial weeds including docks and creeping thistles. If the weed surfer is used before viable seed is set, it can reduce the weed population by preventing seed return to the soil seedbank. The weed surfer can also be upgraded with hydraulic wheels to keep it at a specific height above the soil surface.

Figure 9: Weed surfers

Weeds are cut after they are visible above the crop and they have already significantly compromised crop yield. Cut parts are left in the field and can contain viable seed depending on the timing of cutting and the season. Developed for use in sugar beet for the control of weed beet it has now been used for controlling charlock, wild-oats and black-grass in wheat and barley, thistles in beans and peas, general weed growth in red beet and carrots and docks in pasture land (CTM, 2018).

3.3.4. Thermal weeding



Thermal weed control includes various techniques and currently is mostly used in organic farming. The basic principle is the generation of heat to kill weeds. Thermal weeding provides wide-spectrum weed control and it can be part of an herbicide resistance management programme. However, as with all weed control methods, it has some drawbacks including potentially higher cost and energy consumption, slow application speeds and applicator safety concerns. The high value of horticultural crops can justify the use of thermal weeders and other high cost machinery

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(Bond *et al*., 2003). Thermal weed control techniques include flaming, infrared weeding, hot water, steaming and dry heating, radiation with microwaves, ultraviolet and lasers, control with electric shock and control by freezing and are outlined below.

Electrical weeding

Controlling weeds by electrocution is not a new concept and has been in development since the 1970's (Diprose & Benson, 1984, Bond *et al*., 2003). However in the UK, concerns regarding Health and Safety and the popularity and widespread use of glyphosate resulted in growers not considering alternative weed control options. With modern technology new methods of electrical weeding are in development.

The key advantages of electrical weeding is 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 and they aim to launch a mechanical solution for vegetables in 2019. There is also a current trial running in bush and cane fruit, with a small tractor mounted system (European Agricultural Fund for Rural Development (EAFRD) project 104559 'Electrical weeding in bush and cane fruit'). A probe or lance, attached to a tractor-mounted system or hand-held device containing electrodes has to make direct contact with a weed to conduct an electrical current (generating a shock of 12-20kV) which kills the living plant tissues. 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. A study by ADAS in 2014 showed that the energy consumed by a static electric 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) (ADAS, 2014b). However, it is suggested that the energy consumption of the electric weeder should be compared with another non-chemical mechanical method. Various studies have been conducted by ADAS investigating the weed control efficacy of an electric weeder in the amenity sector, field vegetables and blackcurrants. The results showed that the handheld device controlled common nettle, broad-leaved dock and creeping thistle. A creeping thistle at 1.3 m tall, touched by the probe in the middle of the stem, took 25 seconds to be killed. For a broad-leaved dock at 1.5 m tall, the comparable time to kill the weed was 34 seconds (ADAS, 2014b).

The key benefits of electrical weeding compared to other non-chemical techniques such as mechanical weeding, hand pulling, flame weeding, or hot foam treatments include:

- Non-toxic to micro-organisms in the surrounding soil
- No naked flames or need for propane gas such as with a flame weeder

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- 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

Flame weeding

Flame weeding had a reputation as a dangerous method of weed control, but opinions have changed and it is now one of the standard methods used in organic farming (Ascard, 1995; Bond *et al*., 2003; Cisneros & Zandstra, 2008). The theory of the flame weeder is to disrupt and destroy the cells of the upper-surface-of plant tissues. This method can be applied pre-emergence of the crop to the whole field (most favoured) and post emergence either to the full field or between the rows depending on the heat-tolerance of each individual crop. For instance, in crops which show heat-tolerance at specific growth stages, the burners are placed at an angle facing the base of the crop (Ascard, 1998). In contrast for heat-sensitive crops, flame weeding is applied within the rows either by using shields or by moderating the flame dosage. Perennial weeds species should be treated before the two-leaf growth stage to be effectively controlled. Studies have shown that, in order to control 95% of various weed species from the cotyledon to four true-leaf stage, 10-40 kg/ha of propane is required, in contrast to 40-150 kg/ha of propane needed for weeds at 4-12 true-leaf growth stage (Ascard, 1995; Morelle, 1993), therefore for propane at £2/kg the cost would be £20-300/ha. Other factors which affect the efficacy of flame weeders include the fuel pressure and the application speed (Ascard, 1997). Also, it is recommended that soil should be levelled, without clods which can shield the weeds resulting in poor control. The machinery is expensive, but the cost of it can be justified for use in some horticulture crop systems (Bond *et al.,* 2003). There are many studies which evaluated the damage caused by flame weeding in a range of crops including; lettuce and white cabbage (Balsari *et al*., 1994; Netland *et al*., 1994) and orchards (Rifai *et al.,* 2002; Ferrero *et al.,* 1993). Current research investigating the benefits of flame weeding in vegetable systems is being investigated in a European H2020 funded project IWMPraise (2016).

A thermal flame spot weeder has been developed and trialled in Denmark (Poulson, 2018), on board cameras identify weeds and small burners are activated to control weeds identified by the cameras.

Hot water and hot foam

Hot water is another thermal weed control method. Results from trials done in apple orchards showed that effective weed control without tree damage can be achieved when water at 85-95^{o}C is applied at a speed of 6 km/h (Kurfess & Kleisinger, 2000). The hot water technique can successfully

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control recently emerged annual and perennial weeds whereas it struggles to kill well established perennials.

Recently in the UK, a hot foam system has been developed and patented with a system using renewable plant oils and sugars including oilseed rape, potato, wheat and maize, by Weedingtech™ (2018) called Foamstream. The principle of this method is based on the use of foam which insulates the heat to increase the effectiveness of weed control. A hand held system allows the foam to be applied to roads, paths and many other areas. The weeds are killed by heat.

Trials on the weed control efficacy of the hot foam technology from Foamstream were done by ADAS as part of the EMT/HDC/HTA Weeds Fellowship project in 2013/2014. This particular hot foam method uses renewable plant oils and sugars including oilseed rape, potato, wheat and maize. It was tested in three different horticultural situations including hardy ornamental nursery stock (Figure 10a), strawberries (Figure 10b) 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 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 (ADAS, 2013b).

Figure 10: The use of hot foam a) hardy nursery stock b) strawberries

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Steaming

Steaming is well known as the principal method used for soil sterilisation, and weed and disease control prior to crop establishment in glasshouses. Studies have shown that this technique is capable of effectively reducing the viability of weed seeds in soil up to 10 cm deep when applied between three and eight minutes at 70-100˚C (Bond *et al.,* 2003). However, as with all the other thermal weeding techniques, steaming is not energy and time efficient taking 40-100 hours/ha and it is a potential hazard for the operator. Band-steaming is a method in which steam is applied only within the crop-rows and it is targeted at field vegetables. In contrast to traditional steaming, band-steaming is more energy efficient and less time consuming with working hours being reduced to 8 hours/ha (Melander *et al.,* 2002; Melander *et al.,* 2005). The results of studies (Ascard *et al*., 2007) comparing band-steaming with flame weeding have shown that steam is more effective at delaying weed emergence. The importance of steam temperature was highlighted by Melander and Jorgensen (2005) showing that more than 90% of weed control can be achieved when soil temperature is between 60-80ºC. However, the soil type and soil moisture affects the weed control efficacy (Melander & Kristensen, 2011).

The use of steam weeding has been effective in many horticultural crops such as strawberries, leeks, apple orchards (Samtani *et al*., 2011; Sirvydas, 2004; Melander & Jorgensen, 2005; Rifai *et al*., 2002; Lacko-Bartosova & Rifai, 2008). In Germany where chemical soil sterilants are not available, steam sterilisation is the only way of controlling of soil-borne diseases and weeds prior to planting nursery beds. However it is time consuming taking on average about an hour to treat 150 metres of bed and expensive, costing approximately €8,000/ha. A steam injector has been developed by Mobildampf in Stuttgart with a trailing heat resistant skirt which enables the heat to be retained in the bed for longer. Products are available for amenity, vineyards, orchards and horticultural row crops from WeedTechnics, in 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.

Freezing

Freezing techniques have been investigated for their potential to control weeds. Two types of freezing have been tested; liquid nitrogen and dry ice (CO_2). The act of flash freezing weed shoot tissues ruptures cell membranes and induces plant injury. The freezing media remains close to the soil surface and destroys the plant base (Rask & Kristoffersen, 2007), plants with raised meristems or leaves protecting the base may survive the treatment.

Results from previous studies have been variable Fergedal (1993) compared freezing against flame weeding and found that flame weeding was more effective. Generally, liquid nitrogen is more

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effective than carbon dioxide for flash freezing weeds (Cutulle *et al*., 2013) However, flash freezing alone does not always damage enough tissue to result in plant death (Rask & Kristoffersen, 2007) Gradual freezing and subsequent slow thawing of plant tissue is more damaging to the plant than flash freezing alone. Cutelle *et al*., (2013) evaluated freezing combined with crushing using a ballasted roller. This was found to be more effective than freezing alone.

Microwaves

Microwaves superheat weed plants, creating micro-steam explosions in plant structures to kill weeds. The use of microwaves for pre- and post-emergence weed control has been assessed since the late 1990s. Early studies had determined that microwaves were ineffective at controlling weeds when applied pre-emergence due to the high level of energy required and lack of soil penetration (Nelson, 1996). However, the results were better when this method was applied post-emergence, with the energy level requirements being substantially reduced (Menges & Wayland, 1974; Wayland *et al.*, 1975). More recent trials showed the weed control potential of microwaves but also highlighted the high energy use (Sartorato *et al*., 2006). In Australia, recent work (Brodie, 2016; Khan & Brodie, 2018), demonstrated that microwave heating, using a suitable device to project the microwave energy onto plants and the soil, can kill weed plants and their seeds. Microwave treatment is not affected by weather such as wind or rain.

Lasers

A promising weed control method, which is not yet commercially available, is based on the use of CO_2 lasers. Recent studies have shown the importance of applying this method exactly at the weed plant meristems where 90% control can be achieved. However, if the laser is applied above the meristem, then the weeds will re-grow (Heisel *et al*., 2001). The energy consumption of this method is dependent on the size of the weed stem (Heisel *et al*., 2002). More recent studies have shown the positive potential of using lasers as a non-chemical method for weed control but further research is considered essential (Mathiassen *et al*., 2006; Woltjen *et al.,* 2008). A BBSRC-funded iCASE studentship at Harper Adams University is investigating the use of low energy lasers to manage weeds, both alone and in conjunction with low doses of herbicide (Harper Adams, 2018).

Soil solarisation

Soil solarisation is a technique in which plastic sheets are placed on the top of the soil with the purpose of increasing soil temperature so that it is high enough to kill weeds, pests and diseases (Horowitz *et al.,* 1983). The existence of prolonged sunshine and high temperatures are essential factors for soil solarisation to be successful at controlling the weeds (Standifer *et al.,* 1984). For that reason this method is unlikely to be as effective in the UK as it is in warmer countries. In fact, studies

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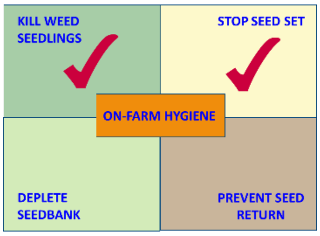
have shown that covering the soil with plastic sheets, in the UK, will enhance germination rather than suppress weeds (Bond & Burch, 1989). In warm countries, soil solarisation is successfully used as a weed control method in protected vegetables (Boz, 2011; Mauromicale *et al.,* 2005), cabbage (El-Keblawy & Al-Hamadi, 2009), tomatoes (Candido *et al.,* 2008), carrots (Ricci *et al.,* 2006; Ricci *et al.,* 1999), strawberries (Benlioglu, 2005), soybean (Singh, 2006; Singh *et al.,* 2004; Vizantinopoulos & Katranis, 1993) and fava bean (Mauromicale *et al.,* 2001).

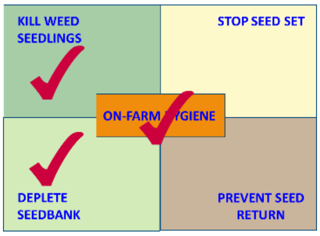
3.3.5. Abrasive weeding



Known as abrasive weeding, or "weed blasting" this technique involves blasting weed seedlings with tiny fragments of organic grit, using an air compressor. Wortmann (2015) looked at a number of grit sources such as walnut shells, granulated maize cob, greensand, and soybean meal. If applied at the right plant growth stage, the force of the abrasive grit severely damages stems and leaves of weed seedlings. Blasted grit does not discriminate between weed and crop seedlings, so it is important to use this method in transplanted crops that are substantially larger than weed seedlings at the time of grit application.

The method is now being tested in different horticultural crops, including broccoli and kale, with and without additional weed control methods. Early results suggest that the presence of polyethylene mulch or biodegradable plastic mulch strongly enhances the success of weed blasting, as compared with straw mulch and bare soil (Wortmann, 2015; Wortmann *et al*., 2017)).

3.3.6. Mulching (excluding living plant ground cover)



Mulches include the use of black plastic film or biodegradable material, such as straw, that are laid on the soil surface to physically suppress weeds. They reduce germination of light-responsive weed seeds and cause the death of any other germinated weed seedlings by blocking light. Mulches physically block and shade out the emergence of most weeds, but are not generally effective against perennial weeds, and can enhance crop growth by conserving soil moisture (Bond and Grundy, 2001).

Although, plastic mulches can be effective for weed control, they have a number of drawbacks. Generally the cost of mulches is high and only economical in high value crops such as vegetables or perennial crops (Bond and Grundy, 2001). Mulches are manufactured from petroleum which is a non-renewable resource and can create high volumes of plastic waste. They do not provide a good habitat for soil fauna such as beetles and earthworms and crops require drip irrigation when they are

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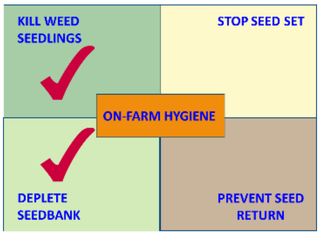
used as rainfall cannot percolate through the plastic mulch (Birkenshaw *et al*., 2008; Cirujeda *et al*., 2012).

One alternative to plastic mulches is woven black polypropylene mulch which also provides a physical barrier to weed growth. It is expensive to purchase, but can last between eight and 12 years, spreading the cost over time it produces less waste than plastic film (Birkenshaw *et al*., 2008).

Biodegradable mulches are also available, some of which do not contain petroleum-derived ingredients and can completely biodegrade and therefore do not require disposal. However, it takes several months for these mulches to biodegrade following soil incorporation and they can therefore still pose a threat to wildlife and can move beyond the field boundary if blown by the wind or are washed into rivers by the rain (Kasirajan & Ngouajio, 2012).

Natural materials, such as straw and cut cover crops, can also be used as a mulch to reduce weed growth. In general natural mulches have a much lower environmental impact than synthetic mulches, and can provide a habitat for seed predators (Bond and Grundy, 2001). However natural materials have been found to be less effective than plastic mulches, and as much as 20t/ha of straw is needed in order to be effective at controlling weeds (Kosterna, 2014). Decomposition of natural mulches can also affect the establishment of the crop as a result of a short term reduction in soil mineral nitrogen and the release of phytotoxins (Bond and Grundy, 2001). Additionally, the source of natural mulches can have an effect on long-term weed control in a field. For example, seeds of black-grass, brome species, and ryegrass species, can be transported in straw and the AHDB advice is to avoid sourcing straw from areas where herbicide resistant weeds are known to occur (AHDB, 2018b).

3.3.7. Allelopathy



Allelopathy is the production of chemicals by a plant that can influence the growth and development of another plant. Effects can include impaired germination, root and shoot growth. Allelopathy is different from the effects of competition for light and nutrients. Allelochemicals can enter the environment through plant degradation, volatilisation, leaching, and root exudation. These allelopathic crops and plants can be used in multiple ways to reduce weed pressure for example, as a cover crop (3.2.7), within crop rotation (2), mixed/intercropping (3.2.8), or as aqueous residue or mulch (Saxena, 2016; Saha, 2018).

Allelopathic compounds are often very complex and short-lived and are therefore difficult to identify and isolate (Worthington & Reberg-Horton, 2013). However, many plant species with allelopathic compounds and modes of actions have been identified and reviewed (Wu *et al*., 1999; Cheng & Cheng, 2015; Jabran, 2015; Bhadoia, 2010; Sangeetha & Baskar, 2015; Albuquerque *et al*. 2010; Haung *et al*., 2013).

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One commercial application, is that the allelopathic characteristics of wild plant types can be transferred into commercial crops by plant breeding to boost their allelopathic traits for weed suppression, which may be useful for the control of herbicide resistant weed varieties (Weston, 1996). Bertholdsson (2012) claimed that there is potential to choose wheat cultivars with high allelopathic activity, which is likely to be important in integrated weed management of both herbicide sensitive and herbicide resistant black-grass.

Some parasitic weeds produce seeds which germinate in response to chemical compounds released from their hosts. For instance, striga (*Striga* spp.) is a parasitic plant of cereals that germinates in response to p-benzoquinone released from its natural host sorghum. Ethylene released from cotton, cucumbers and some legumes, is also stimulates stirga to germinate. Thus, allelochemicals can be applied to make stirga germinate in the absence of a host. This “suicidal germination” of weed seeds reduces the number of dormant seeds in soil (New scientist, 1986; Zwanenburg *et al.* 2016; Chai *et al*. 2015; Khan *et al.* 2002).

There has been discussion of what proportion of weed control is due to allelopathy as opposed to smothering. A study by (Sturm *et al.*, 2018) showed the proportions of competitive and allelopathic effects on weed suppression and indicated an important role of the allelopathic effects in glass house trials. Specialised methods have been developed to help distinguish alleopathic effects from crop competition (He *et al*., 2018). However, Del Moral (1997) stated there was convincing evidence that allelopathy evolved as a result of resource competition and other ecological factors, and separation of resource competition and allelopathy might not be of much ecological relevance under natural systems and that this should be further explored.

Huang *et al*., (2013) produced a comprehensive review of autotoxicity and noted that allelopathy may be an indirect effect, due to changes in microbe community and build-up of detrimental microbes. Zeng (2014), claimed there is a lack of convincing evidence to show the natural existence of allelopathy, and suggested that isolated pure compounds that show phytotoxicity are immediately diluted, absorbed by soil particles, or rapidly degraded. As a result, these naturally released compounds may not reach sufficient concentration or persist long enough in soils to display direct inhibitory effects on their neighbours. The direct inhibitory effects of plant allelochemicals, on which most studies concentrate, may not be so important, raising the likely possibility that the indirect mediator effects of allelochemicals on plant interactions are more important than direct effects as inhibitors (Zeng, 2013).

Despite the progress made within allelopathy, further research is required to evaluate the impact of allelochemicals upon soil macro- and micro-biota, soil properties, ecological patterning, and succession (Inderjit *et al*., 2005). Until now, much remains unknown about the fate or persistence of allelochemicals in the soil or their effects on soil chemistry or microflora (Belz, 2007). However, the

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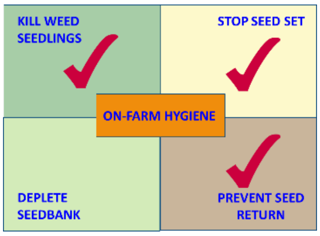
combination of more than one weed control method including allelopathy has been proved to be effective in reducing the probability of the development of herbicide resistance in weeds (Cheng, 2015). Therefore, further research is required, to help design practical weed management plans that incorporate effective use of allelopathy.

3.3.8. Biological control



A recently published review paper (Shaw *et al*., 2017) provides an update on weed biological control in the European Union with reference to those agents applicable to the UK.

Despite the widespread use of biological control in glasshouses and release of least 176 species of exotic arthropods against agricultural pests across Europe, the biological control of weeds is currently a rare occurrence.

There have been several unintentional introductions of biological control agents for weeds in to Europe, one such agent is the weevil, *Stenopelmus rufinasus,* which probably came to Europe on plants of water fern *(Azolla filiculoides*) the weed which it is used to control. In the UK control can be less consistent than in warmer parts of the world due to fewer generations of the insect per year and increased mortality.

Strategic weed biological control began in the 1980's to target the control of bracken (*Pteridium aquilinum*). Although several biological control agents were identified they were never released due to a requirement for further strict testing.

A psyllid (*Aphalara itadori)* was identified as an effective control agent for Japanese knotweed (*Fallopia japonica*) in a research project that began in 2000. Unfortunately this did not perform well during a five year restricted release programme (2010-2015) and the failure has been attributed to i) the founder population being reared under continual Japanese summer conditions in a growth room for almost 90 generations, ii) abnormal and unseasonal weather experienced in the UK in each of the project years and iii) only a single release of insects in each season on small isolated patches of knotweed. More psyllids have since been collected from Japan and these are undergoing further field assessment in the UK.

A rust fungus, *Puccinia komarovii* var. *glanduliferae* was identified for the control of Himalayan balsam (*Impatiens glandulifera*) in a project started in 2006. Two strains of rust have been tested and were released in early 2017 at 34 sites in the UK, infection was good at many sites but further research is needed to investigate why good leaf infection does not always lead to field establishment and why the two strains released are not effective for all Himalayan balsam populations in the UK (CABI, 2019).

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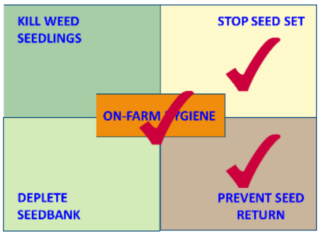
3.3.9. Harvest weed seed control



Harvest weed seed control (HWSC) methods have been developed over the past 20 years in Australia in response to widespread development of herbicide resistance in ryegrass, wild radish (*Raphanus raphanistrum* L.), bromes (*Bromus* and *Anisantha* spp.) and wild-oats and are now being used by many farmers (Walsh and Powles, 2014). The technology is currently being trialled in the UK by Frontier, and as part of the H2020 IWMPraise project.

The technology exploits weeds where the seeds are retained on the plant at harvest. It prevents seeds being added to the weed seedbank because the majority that pass through the combine harvester are contained in the chaff. 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 carts

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 (Walsh & Powles, 2013). 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 (Walsh *et al*., 2018).

Weed seed destruction - Harrington seed destructor

This is a grinding machine that is attached to the combine. Chaff is directed into it and is ground and pulverised by a cage mill. Initially the seed destructor was on an additional trailer behind the combine harvester collecting the chaff, but recently combines with inbuilt seed destructors have been developed. It has been shown to destroy over 95% of a wide range of weed seeds (Walsh *et al*., 2013), 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. It has been shown that 85% of weed seed (ryegrass; *Lolium* spp.) is present in the chaff fraction (Broster, *et al*., 2018). 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. Chaff lining

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places the chaff in a row directly behind the harvester, chaff tramlining locates the chaff in the permanent tramlines in a Controlled Traffic Farming (CTF) system.

In Australia the technique has been used in wheat, barley, oilseed rape and lupins (Figure 11) reducing weed emergence from 65% to under 10% at the highest chaff rate. The amount of chaff is calculated using the formula; Chaff amount = 0.3 x grain yield (t/ha) x (harvester width (m)/tramline width (m)). For example, using a wheat yield of 3.5 t/ha, a 12 m harvester width and a 30 cm chaff line width, the amount of chaff concentrated into a chaff line would be 42 t/ha. For UK situations the amount of chaff will be greater because of higher yields.

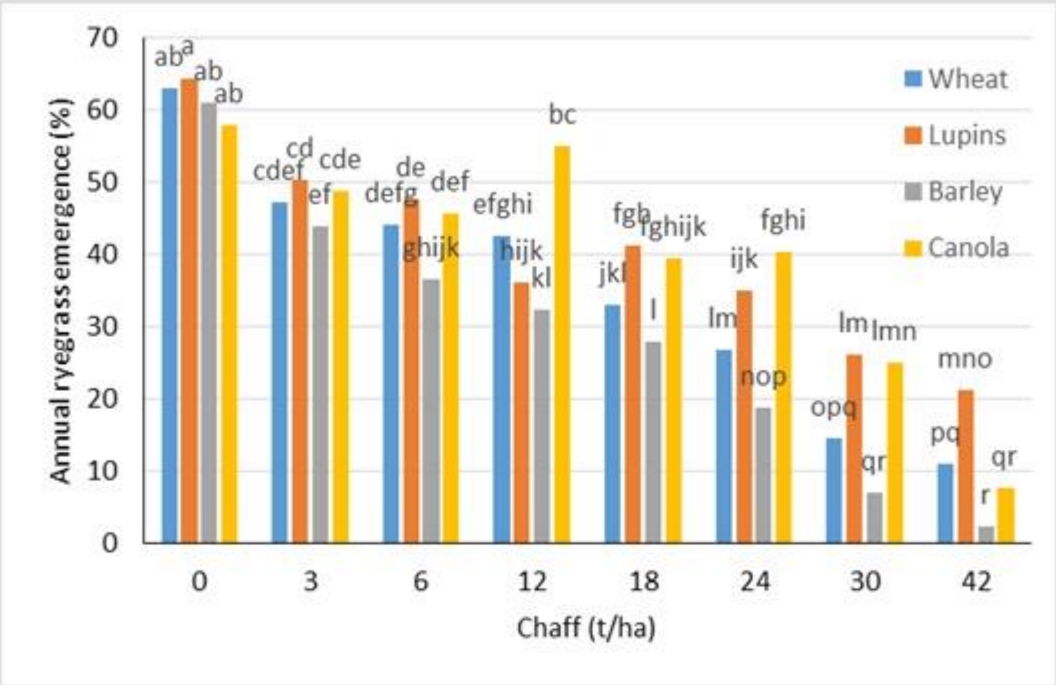
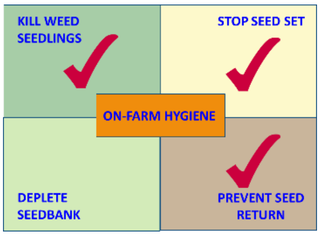


Figure 11: Emergence of annual ryegrass through wheat, lupin, barley and oilseed rape chaff (left to right column bars, respectively) at eight different rates (t/ha) in a pot trial conducted at Wagga Wagga, NSW (Means with same letter are not significantly different). Walsh *et al*., (2017)

3.4. Chemical Control



Chemical weed control refers to any technique that involves the application of a chemical (herbicide or bioherbicide) to weeds or soil to control the germination or growth of the weed species. Herbicides are a very effective way of reducing weed infestations and are used widely in the UK (Table 8).

Herbicide inputs to arable crops were moderate in 2016 with between 3.9 and 6.7 active substances being applied (Table 8, Garthwaite *et al*., 2017a). Only sugar beet was treated with more herbicides and received 16.1 active substances. Herbicide inputs to grassland are generally low, with only 7% of grassland under five years old being treated. Herbicide inputs to permanent pasture and rough

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grazing are even lower with only 4.9 and 1.2% of the total area treated respectively (Barker *et al*., 2018). Maize is included with fodder crops (Barker *et al*., 2018) with more inputs than grassland but less than arable crops.

Herbicides accounted for 38% of the total pesticide treated area of outdoor vegetables in 2014-2015 (Garthwaite *et al*., 2016). Since the previous survey in 2013, the use of pendimethalin, glyphosate, linuron, clomazone, ioxynil, imazamox and dimethenamid-P all increased. Some of these changes, particularly for pendimethalin, clomazone and dimethenamid-P were mainly due to changes in the approval status of metazachlor, where the maximum rate that can be applied was reduced and a limit on the total amount that can be applied to fields over a three year period. Another contributory factor was the reduced availability of other active substances.

Table 8 Herbicide usage in crops in the United Kingdom

Crop	Percentage of area treated with herbicides	Number of spray rounds applied to crops	Number of products applied	Number of active substances applied
Arable crops[3]				
Wheat[1]	98.2	3.1	4.5	6.7
Winter barley	98.2	2.7	3.9	5.4
Spring barley	97.2	2.5	3.5	5.0
Oats[1]	91.2	2.1	2.7	3.9
Rye	89.4	2.3	3.3	4.5
Triticale[1]	98.9	3.1	4.0	5.5
Oilseed rape[1]	98.2	3.7	4.4	5.6
Linseed[1]	92.3	3.8	4.4	4.6
Potatoes	99.2	3.3	5.7	5.8
Seed potatoes	95.3	2.8	4.8	5.1
Peas	97.2	3.5	4.8	5.5
Beans[1]	96.1	2.5	3.4	4.2
Sugar beet	100.0	5.1	10.5	16.1
Fodder crops[6]				
Maize	95.8	2.1	3.1	3.8
Grassland[6]				
New ley direct sown	30.2	1.1	-	-
New ley undersown	29.4	1.0	1.0	1.3
Grassland 2-5 years old	7.0	1.1	-	-
Permanent pasture	4.9	1.1	1.3	2.2
Rough grazing	1.2	1.2	1.3	2.0
Horticultural crops				
Orchard crops[5]	75.8	2.1	3.3	5.0
All soft fruit[4]	68.7	2.4	3.6	3.8
All Edible protected crops[7]	9.1	1.3	-	-
All Outdoor vegetables[2]	91.7	2.7	4.6	5.0

[1] includes winter and spring crops
Taken from [2]Garthwaite *et al*., 2016, Garthwaite *et al*., 2017a[3], b[4], c[5], [6]Barker *et al*., 2018, [7]Mace *et al*., 2018

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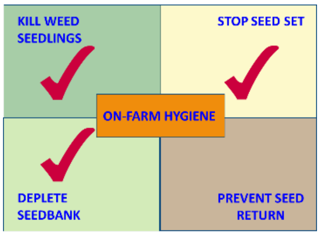
3.4.1. Existing chemistries



There are 96 active substances used as herbicides listed on the HSE website as of 30th November 2018 (Table 9). New products currently coming onto the market are combinations of previously approved actives, for example halauxifen-methyl (Arylex) is now available in mixtures for use in oilseed rape (Belkar). Mesosulfuron-methyl + iodosulfuron-methyl-sodium came off patent in 2017 and similar formulations are now being marketed by Life Scientific.

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Table 9: List of authorised active substances with herbicide activity, their HRAC group and chemical family.

Taken from Pesticides Register of UK Authorised Products https://secure.pesticides.gov.uk/pestreg/ on 30th November 2018.

Active substance	Candidate for substitution or withdrawal date	HRAC group	Substance group		Active substance	Candidate for substitution or withdrawal date	HRAC group	Substance group
Clodinafop-propargyl		A	Aryloxyphenoxy-propionate 'FOPs'		Flurtamone	withdrawn	F1	Other (PDS)
Fenoxaprop-P-ethyl		A	Aryloxyphenoxy-propionate 'FOPs'		Diflufenican	y	F1	Pyridinecarboxamide
Fluazifop-P-butyl		A	Aryloxyphenoxy-propionate 'FOPs'		Picolinafen		F1	Pyridinecarboxamide
Propaquizafop		A	Aryloxyphenoxy-propionate 'FOPs'		Isoxaflutole		F2	Isoxazole
Quizalofop-P-ethyl	y	A	Aryloxyphenoxy-propionate 'FOPs'		Mesotrione		F2	Triketone
Quizalofop-P-tefuryl	y	A	Aryloxyphenoxy-propionate 'FOPs'		Clomazone		F4	Isoxazolidinone
Clethodim		A	Cyclohexanedione 'DIMs'		Glyphosate		G	Glycine
Cycloxydim		A	Cyclohexanedione 'DIMs'		Glufosinate-ammonium	31/01/2020	H	Phosphinic acid
Pinoxaden		A	Phenylpyrazoline 'DEN'		Propyzamide		K1	Benzamide
mazamox	y	B	Imidazolinone		Pendimethalin	y	K1	Dinitroaniline
Propoxycarbazone-sodium	y	B	Sulfonylaminocarbonyl-triazolinone		Carbetamide		K2	Carbamate
Aamidosulfuron		B	Sulfonylurea		Chlorpropham		K2	Carbamate
Flazasulfuron		B	Sulfonylurea		Napropamide		K3	Acetamide
Flupyrsulfuron-methyl		B	Sulfonylurea		Dimethachlor		K3	Chloroacetamide (V2)
Foramsulfuron		B	Sulfonylurea		Dimethenamid-P		K3	Chloroacetamide (V2)
Imazosulfuron	y	B	Sulfonylurea		Metazachlor		K3	Chloroacetamide (V2)
Iodosulfuron-methyl-sodium		B	Sulfonylurea		Pethoxamid		K3	Chloroacetamide (V2)
Mesosulfuron-methyl		B	Sulfonylurea		S-metolachlor		K3	Chloroacetamide (V2)
Metsulfuron-methyl	y	B	Sulfonylurea		Flufenacet	y	K3	Oxyacetamide
Nicosulfuron	y	B	Sulfonylurea		Isoxaben		L	Benzamide
Prosulfuron	y	B	Sulfonylurea		Quinmerac		L	Quinoline carboxylic acid
Rimsulfuron		B	Sulfonylurea		Ethofumesate		N	Benzofuran

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Table 9 (Continued): List of authorised active substances with herbicide activity, their HRAC group and chemical family.

Taken from Pesticides Register of UK Authorised Products https://secure.pesticides.gov.uk/pestreg/ on 30th November 2018.

Active substance	Candidate for substitution or withdrawal date	HRAC group	Substance group		Active substance	Candidate for substitution or withdrawal date	HRAC group	Substance group
Sulfosulfuron		B	Sulfonylurea		Prosulfocarb		N	Thiocarbamate
Thifensulfuron-methyl		B	Sulfonylurea		Tri-allate	y	N	Thiocarbamate
Tribenuron-methyl		B	Sulfonylurea		Fattyacids		None	plant and animal derived
Triflusulfuron-methyl		B	Sulfonylurea		Citronella oil		None	Plant derived
Florasulam		B	Triazolopyrimidine		Pelargonic acid		None	Plant derived
Metosulam		B	Triazolopyrimidine		Maleic hydrazide		None	Pyridazine
Pyroxsulam		B	Triazolopyrimidine		Acetic acid		None	Unclassified
Desmedipham		C1	Phenyl-carbamate		Meptylester		None	Unclassified
Phenmedipham		C1	Phenyl-carbamate		Quinoclamine		None	Unclassified
Chloridazon		C1	Pyridazinone		Tembotrione		Not known	Triketone
Terbuthylazine		C1	Triazine		Halauxifen-methyl		O	Arylpicolinate
Metamitron		C1	Triazinone		Dicamba		O	Benzoic acid (synthetic auxins)
Metribuzin	y	C1	Triazinone		2,4-D		O	Phenoxy-carboxylic-acid
Lenacil	y	C1	Uracil		2,4-DB		O	Phenoxy-carboxylic-acid
Chlorotoluron	y	C2	Urea		Dichlorprop-P		O	Phenoxy-carboxylic-acid
Metobromuron		C2	Urea		MCPA		O	Phenoxy-carboxylic-acid
Bentazone		C3	Benzothiadiazinone		MCPB		O	Phenoxy-carboxylic-acid
Bromoxynil		C3	Nitrile		Mecoprop-P	y	O	Phenoxy-carboxylic-acid
Pyridate		C3	Phenyl-pyridazine		Aminopyralid		O	Pyridine carboxylic acid
Diquat	04/02/2020	D	Bipyridylium		Clopyralid		O	Pyridine carboxylic acid
Bifenox		E	Diphenylether (PPO)		Fluroxypyr		O	Pyridine carboxylic acid
Flumioxazin	y	E	N-phenylphthalimide		Picloram		O	Pyridine carboxylic acid
Pyraflufen-ethyl		E	Phenylpyrazole		Triclopyr		O	Pyridine carboxylic acid
Carfentrazone-ethyl		E	Triazolinone (PPO)		Iron sulphate			inorganic compound

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EAMU approvals can be secured for minor crops. The major UK crops are; grassland, barley, forage maize, oats, wheat, dry harvested field beans, oilseed rape, sugar beet and potatoes (other than seed). Major crops are generally not eligible for Extensions of Authorisation for Minor Use (EAMU) authorisations (in accordance with Article 51 of Regulation (EC) 1107/2009).

The process to secure EAMU approvals on new products is complex and includes collection of residues data, provision of a supporting case, and the completion and submission of applications to the Chemicals Regulation Directorate (CRD).The SCEPTRE plus project model (AHDB, 2018e) is being used to generate new products for the horticultural market through the AHDB Horticulture-funded EAMU programme, so that individual growers do not have to submit products themselves.

There were two emergency authorisations for 2018 (Table 10) for linuron and asulam. It is likely that there will be another Emergency Authorisation for Asulam next year.

Table 10. Emergency authorisations for 2018

Active	Product	Crops	Detail of EAMU
Linuron	Afalon	Carrot and parsnip	120 day Emergency Authorisation for the use of 'Afalon' (M14187) on outdoor carrot and parsnip for control of volunteer potato (*Solanum tuberosum*) The 120 day Emergency Authorisation will expire on 01 October 2018 and will not be renewed.
Asulam	Asulox	Rough Grazing, Moorland, Amenity Grassland Forest	Bracken control

There are also a range of new products in the pipeline (these products are currently being evaluated in efficacy trials either in the UK or Europe and are due to be available to the UK market within five years.

Recently approvals for glufosinate-ammonium, diquat and flurtamone have been withdrawn. Glufosinate-ammonium cannot be sold after 31st Jan 2019 with a final use up of 31st Jan 2020. The European Commission has proposed that diquat is withdrawn from the market by 4th May 2019, with a use-up period for growers up to 4th February 2020. Flurtamone withdrawal dates have yet to be announced.

There are several herbicides on the EU list of candidates for substitution (Table 9, European commission, 2015). Aclonifen is on the list but it is not registered for use in the UK yet but has shown to be useful in horticultural crops.

Choridazon is not being defended by BASF so the revocation is likely to occur sometime during 2019. No new product is being manufactured and existing stocks are being used up.

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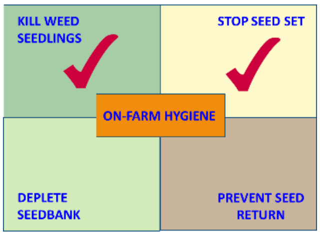
3.4.2. Current uses of glyphosate



Glyphosate is a non-selective, systemic herbicide and is widely used in the UK for weed removal on stale seedbeds, crop desiccation, and weed control in perennial crops. There are currently no confirmed cases of glyphosate resistance in the UK, but this has been reported in 43 weed species in 29 countries worldwide (Heap, 2018). Also UK populations of sterile brome (*Anisantha sterilis*) have been identified that are in the process of evolving resistance to glyphosate (Davies *et al*., 2018). The development of resistance could therefore make the use of glyphosate ineffective for weed control.

There is a current AHDB and company funded research project ‘Managing the resistance risk to retain long-term effectiveness of glyphosate for grass-weed control in UK crop rotations’, led by ADAS (RD-2140006131, 2015-2020). The main aim of the project is to provide practical management guidelines for farmers and agronomists which reduce the risk of development of glyphosate resistance in grass-weeds in arable cropping in the UK.

3.4.3. Alternatives to glyphosate

Glyphosate has low mammalian toxicity, and does not cause adverse effects on developmental, reproductive, or endocrine systems (Williams *et al*., 2000). A peer-review by the European Food Standards Agency (EFSA) concluded that “glyphosate is unlikely to pose a carcinogenic hazard to humans and the evidence does not support classification with regard to its carcinogenic potential” (EFSA, 2015), and the European Chemicals Agency, does not classify glyphosate as a carcinogen (ECHA, 2018). The World Health Organisation (WHO), also found that “glyphosate is unlikely to pose a carcinogenic risk to humans from exposure through the diet” (JMPR, 2016), and the Food and Agriculture Organisation of the United Nations (FAO) stated that “there is no evidence of carcinogenic effects in humans” (FAO, 2016). Panels of independent experts have also concluded that glyphosate is unlikely to pose a carcinogenic risk to humans (Williams *et al*., 2016). However, the International Agency for Research on Cancer (IARC) (part of WHO) classified glyphosate as probably carcinogenic to humans (IARC, 2015). This conclusion by IARC and other social factors, such as opposition to genetically modified crops, has put much public and regulatory pressure on glyphosate, with its use in the European Union recently only approved for five, rather than 15 years (European Commission, 2018). As a result of regulatory and public pressure, and the risk of resistance, alternatives to glyphosate may be needed.

The recently updated (July 2018) Pesticide Action Network Europe report on alternatives to glyphosate in weed management provides an overview of some of the available options focusing on mechanical, thermal, cultural, biological, and bioherbicide weed control (PAN Europe, 2018), which are also covered in this review. However, there are drawbacks to these methods. For example substituting the use of glyphosate with mechanical weeding, such as ploughing, would not provide

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control of couch grass and other perennial weeds, and would greatly increase the risk of soil erosion and remove the benefits of soil conservation tillage (Kehlenbeck *et al*., 2016).

Some other non-selective herbicides could be used as a replacement for glyphosate such as Carfentrazone-ethyl, glufosinate ammonium, diquat, pelargonic acid and pyraflufen-ethyl However, these herbicides are not as effective as glyphosate or systemic and their environmental impact is potentially higher.

Bioherbicides (3.4.7) are often suggested for use as a glyphosate alternative, however, they provide poor weed control compared to glyphosate. Acetic acid (vinegar) is one alternative that has been recently trialled in the UK by Bristol City Council (2017) and Edinburgh Council (The City of Edinburgh Council, 2017). However, in Bristol the number of public complaints about weeds increased and it was found that acetic acid may have caused damage to some hard surfaces and that the costs were prohibitively high (Bristol City Council, 2017). In 2013, the SCEPTRE project found that pelargonic acid, acetic acid, citronella oil, and clove and cinnamon oil gave poor weed control compared to glyphosate. Glyphosate treatments gave 100% weed control, compared with 40-90% for pelargonic acid, 20-40% for acetic acid, citronella oil, and clove and cinnamon oil (Figure 12) (HDC project CP 77 SCEPTRE, 2013). Bioherbicides have also been shown to give poor to moderate control of weeds in field conditions in the short-term, when compared to glyphosate, and six weeks after treatment there were no differences from untreated control plots (Barker and Prostak, 2014). Additionally, Kehlenbeck *et al*., (2016) found that the only alternatives to glyphosate that provided comparable weed control in German arable crops were mechanical methods, with no effective chemical alternatives identified.

Organic and synthetic mulches could be used as effective glyphosate alternatives for use in perennial (e.g. soft and tree fruits) and wide row crops (e.g. onions). Mulches of bark and/or woodchips have been shown to give similar or better levels of annual and perennial weed control as glyphosate in field conditions (Barker and Prostak, 2014). In some perennial crops, plastic mulches can provide 94-100% weed control, and organic mulches can provide 85-98% control, and have been shown to give higher fruit yields than plots treated with glyphosate and cultivated for weed control (Abouziena *et al*., 2008). Plastic mulches have also been suggested for use on stale seedbeds, as they can stimulate weed seeds to germinate by helping retain soil moisture and increase soil temperature, but prevent seedling survival by blocking out light (Bond and Grundy, 2001). However, as discussed in 3.3.5, mulching can have environmental impacts, such as the problems of disposing of large amounts of plastic waste.

Glyphosate is also often used to terminate cover crops (3.2.7) and alternative methods are currently the subject of an innovative farmers group (Soil Association, 2018). The methods used have included mowing, use of a crimper roller, rolling, shallow cultivation and direct drilling.

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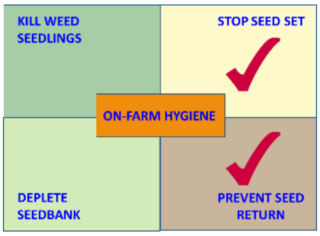
Even with possible alternatives, it is likely that the loss of glyphosate would result in decreased crop yields and increased costs. It has been estimated that the loss of glyphosate in UK combinable cropping could result in a 20% decrease in winter wheat, winter barley and oilseed rape yields and an increase in greenhouse gas emissions of 100 kg/ha (Wynn *et al*., 2014). It was estimated by the Bristol Waste Company that the cost of weed control across the Bristol City area was £60,000 for each glyphosate application, £216,000 for each acetic acid application, and £392,000 for each hot foam application (Bristol City Council, 2017). Young (2004) found that the costs of applications of essential oils, acetic acid, and pine oils as a glyphosate replacement for roadside weed control ranged from $9,240/ha o $10,660/ha, compared with a cost of $210/ha for two glyphosate applications. Based on treatment costs and potential yield loss, Kehlenbeck *et al*., (2016) calculated that under low weed pressure conditions the use of mechanical weed control in arable crops could replace glyphosate with little to no economic impact, but under high weed pressure there would be an economic loss of €55-100/ha. Barker and Prostak (2014) estimated that the costs of materials for mulch application in field conditions could be up to 200 times that of glyphosate, although the mulch materials lasted more than one growing season.

3.4.4. Crop desiccation



Pre-harvest crop desiccation refers to the application of herbicide prior to harvest and is usually done to prepare the crop for harvest but sometimes for weed control. The presence of weeds in crops prior to harvest can reduce combine efficacy, increase grain moisture and delay harvesting. It can also reduce in-field variability due to uneven ripening and secondary tillering. Pre-harvest desiccation occurs at an optimal timing for the control of perennial weeds such as common couch *(Elytrigia repens*) and creeping thistle because they are actively growing and at the most susceptible growth stage (Orson & Davies, 2007). Pre harvest crop desiccation it is not considered suitable for control of many annual weeds which will have already naturally ripened and set seed prior to application of the desiccant.

Glyphosate, diquat, carfentrazone-ethyl, glufosinate-ammonium and pyraflufen are authorised for use as a desiccant in a wide range of arable and horticultural crops. The use of glyphosate is not allowed on crops for seed production and potatoes as it can be translocated within the plant.

Glyphosate is suitable for the control of both annual and perennial weeds as it is translocated to the growing point. The speed of kill with glyphosate desiccation varies for weed species and crop. Annual grassweeds are quickly killed – within seven days, along with cereal leaves and stems. Annual broad-leaved weeds and wheat volunteers take longer to kill – up to 14 days. Some weeds take a particularly long time to die back, these include, prickly sow-thistle (*Sonchus asper*), smooth sow-thistle (*Sonchus oleraceus*), cut-leaved cranesbill (*Geranium dissectum*), fat-hen (*Chenapodium album*), orache (*Atriplex patula*), fool's Parsley (*Aethusa cynapium*), redshank (*Persicaria maculosa*),

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pale persicaria (*Persicaria lapathfolia*), knotgrass (*Polygonum aviculare*), and black-bindweed (*Fallopia convolvulus*). Small nettle (*Urtica urens*), volunteer potato and rosebay willowherb (*Chamerion angustifolium*) are not susceptible at the harvest management rates (Monsanto, 2019b).

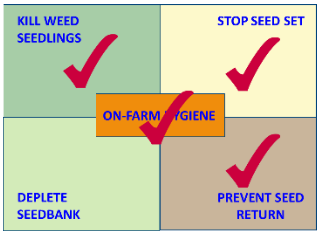
Diquat is being withdrawn during 2019 see section 3.4.1 it is widely used as a desiccant in arable and horticultural crops.

Carfentrazone-ethyl, glufosinate-ammonium and Pyraflufen-ethyl can be used as a desiccant in potatoes see section 4.3.3.

3.4.5. Optimising use of existing chemistry

There have been no new herbicide modes of action introduced for over 20 years, which in combination with the development of herbicide resistance has reduced the options for weed control (Duke, 2012). Additionally, tightening toxicological and environmental restrictions, such as the EU Regulation 1107/2009, have reduced the number of available herbicides (Chauvel *et al*. 2012). It is therefore important to optimise the use of existing chemistry, both by preventing herbicide resistance (as discussed in 3.4.7) and by reducing the environmental impact of herbicides, for example through precision application.

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 (Lutman *et al*., 2002; Gerhards and Christensen, 2003). For example, spot spraying can reduce the use of grass weed herbicides by 90% in winter cereals, 78% in maize, and 36% in sugar beet, and broad-leaved weed herbicides by 60%, 11%, and 41% in the same crops (Timmermann *et al*., 2003).

Spot spraying can either be conducted by field walking and spraying patches using a backpack sprayer, mapping weeds in a field by field walking or using aerial or mounted camera imagery (3.5.1) and using GPS and tractor mounted sprayers to spray patches (Gerhards and Christensen, 2003), or by using robots with weed identification technology (3.5.2). Spot spraying is traditionally used to control low numbers of single weeds, such as docks in grassland or undesirable weeds in SSSIs.

Currently, in the UK spot spraying is usually done using non-selective herbicides to remove patches of weeds that have not been controlled with previous herbicide applications, e.g. with ALS inhibitors due to resistance. However, this is only effective if weeds are treated at the correct growth stage, as non-selective herbicides are only effective when plants are actively growing. Therefore patch

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spraying is most effective when non-selective herbicides are applied either before stem extension (before GS30), or once anthesis is underway (GS64-69) and before full seed ripening (GS77) (Monsanto, 2015; Figure 4).

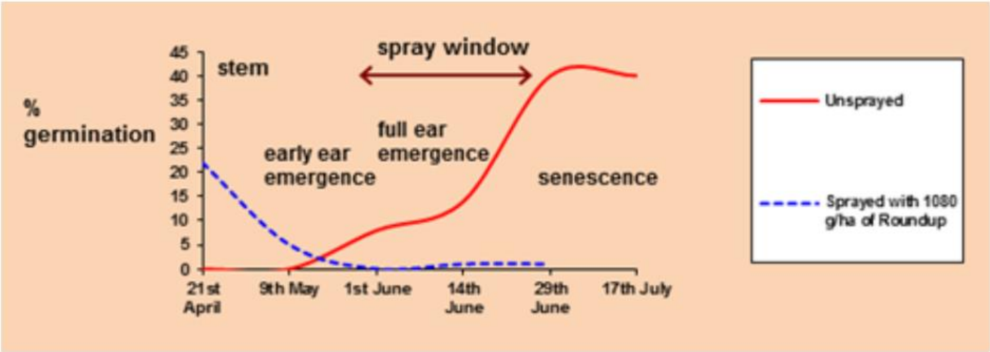
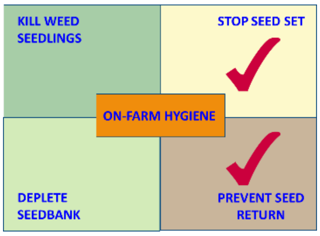


Figure 4: From Monsanto (2015) glyphosate application spray window for effective control of black-grass to reduce seed return at late growth stages

Although spot spraying badly infested areas of the crop with non-selective herbicides destroys the crop as well as the weeds, it can be economically viable in the longer term by preventing large amounts of weed seed return thus reducing weed levels and herbicide applications in following crops (Monsanto, 2018).

This simple principle has been updated for use on a wider scale and utilises existing sprayer booms with associated weed detection systems for example WeedIt. WeedIt is a precision spraying system that can be retrofitted to an existing sprayer. It is a system of linked sensors scans the soil, using infrared technology to detect weeds. The weed is then targeted and sprayed, reducing the quantity of herbicide required (WEEDit, 2018). Syngenta have led the Hyperweeding project, which similarly involves research into weed detection and selective spraying. The benefit of such systems is that in future, if the sprayer is sufficiently precise, non-selective herbicides could be used. Tim Powell from Syngenta (Allen-Stephens, 2018a) claimed that the only reason a boom sprayer is used today is because it suited delivery of pesticides when they were first used. However, if the sprayer were to be re-invented today it would look very different. Similar thinking has led to the development of automated robotic systems which are further discussed in (3.5.2).

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 (Monsanto, 2019). Generally glyphosate is used and several water companies; including Welsh water (2018) and Northern Ireland Water (2018), have purchased weed wipers for free hire by famers to reduce the amount of MCPA reaching water. Weed wiping can be used in any growing crop or in non-cropped areas, providing the herbicide does not touch the crop. For safe application, weeds

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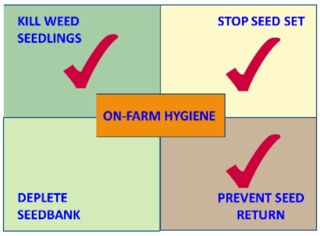
should be a minimum of 10 cm above the height of the crop. Weeds not touched by the herbicide will not be controlled, and two passes in opposite directions may be needed where weeds are dense. Successive applications will be required to control weeds that were below the original wiping level, when they reach the correct height for safe treatment (Monsanto, 2019a). Herbicides need to translocate well in weeds and be transported to the growing point. Timing is important, for example to achieve maximum control of creeping thistle (*Cirsium arvense*) it needs to be treated after flowering. Enough herbicide has to be placed on the plant to ensure control (Harrington & Ghanizadeh, 2017).

Only glyphosate is authorised for use for weed wiping in the UK, but in New Zealand and Canada metsulfuron, clopyralid, triclopyr and picloram have been trialled (Harrington & Ghanizadeh, 2017). These products could offer alternatives to glyphosate if it can no longer be used, either due to resistance development or regulatory pressures.

Harrington & Ghanizadeh (2017) highlighted knowledge gaps about weed wiping, including:

- The most effective growth stage for application
- The uniformity of herbicide application across the length of the wiper
- The efficacy of different wiper applicators
- The effects of potential damage to non-target vegetation

Precision 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 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 (Table 11). 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 (Creech *et al.,* 2015).

Table 11: Summary of Tom Robinson's opinions on optimal spray settings (BASF arable wheat control group 2017 and 2018)

Recommended Settings	Pre emergence
Windspeed (m/s)	1-2
Sprayer speed (km/h)	Up to 12
Water volume (L)/ha	100-200
Nozzle tip height above (cm)	50 (ground)
Nozzle tip pressure (Bar)	2-2.5
Nozzle trajectory	Smooth seed bed: All forwards Cloddy seedbed : alternate forward and rearward

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There are numerous technologies available to improve the precision of herbicide application when sprays are applied, such as three star spray reducing nozzles. AHDB-funded trials have shown that air-induction nozzles are capable of delivering the required efficacy, with a lower propensity to drift. Most drift-reducing nozzles are of the air-induction type, and these currently give the highest levels of drift control (de le Pasture, 2018). An example of positive intervention using these nozzles is the Chlorpyrifos “Say No to Drift Campaign”. When applied through conventional flat fan nozzles, chlorpyrifos no longer passed revised regulatory risk assessment for exposure of aquatic invertebrates from spray drift. The stewardship campaign alerted chlorpyrifos users to the requirement to make all applications through '3 star' low-drift nozzles, with appropriate buffer zones next to watercourses. It also emphasised the importance of doing so in the hope of securing future approvals for chlorpyrifos products (Roberts, 2013), despite this chlorpyrifos was withdrawn in 2016.

As well as new high speed precise sprayers, the formulation of pesticides will also need to be altered to increase efficacy and decrease drift. Tim Powell from Syngenta (Allen-Stephens, 2018a) claimed that a standard formulation the high speed droplets would shatter when they hit the weed leaves, which could bounce off into the crop. Syngenta have produced a formulation that minimises this effect and keeps the spray on the target weed as much as possible. Spray additives that increase spray droplet size have been known to reduce drift. Tests indicate that, in some cases, drift control additives can reduce downwind drift deposits by 50 to 80 percent (NDSU, 2017). Reviews on the effects of formulation on droplet sizes include (Creech *et al.*, 2015; Hilz and Vermeer, 2013).

A study by Soto *et al., (*2018) showed a practical method for how a drop can be fragmented into thousands of smaller droplets by impacting it onto a mesh. As a result pesticide drift of agricultural sprays could be controlled by using initially large drops that are subsequently atomized and conically sprayed by a mesh above the crop.

The “Go Low, Go Slow, get covered” Campaign by Syngenta (Southgate, 2018), has shown that that the single biggest controllable factor to prevent drift and optimise application is maintaining a boom height of 50cm above seed bed (for pre-emergence spraying). The use of auto booms, are useful to maintain the height, especially over an emerged crop or uneven ground.

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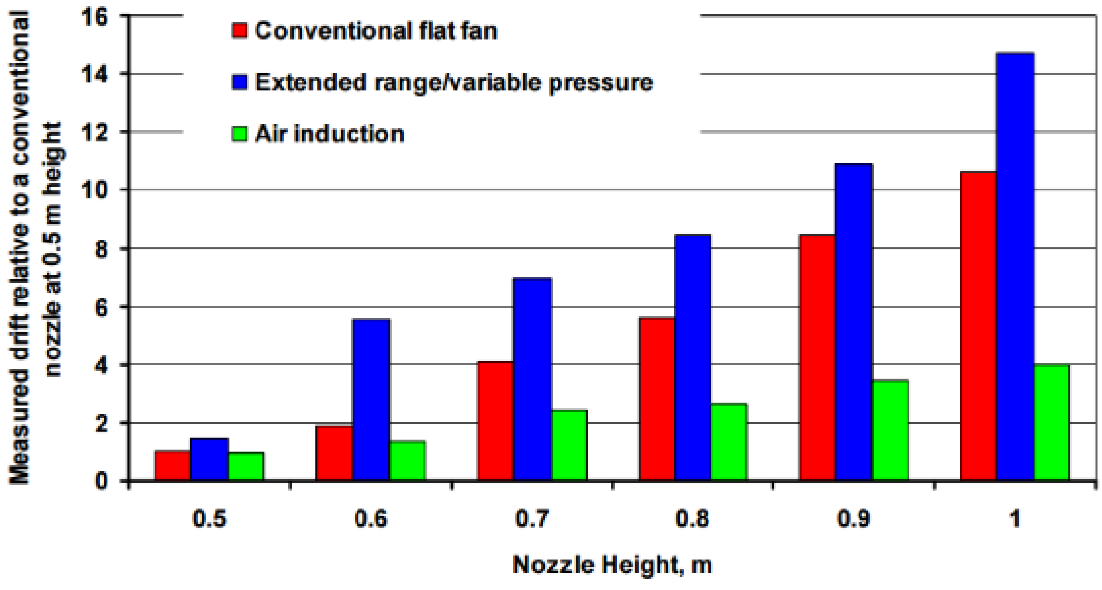
Case study: Go low, go slow, get covered… The Syngenta campaign for applying pre-emergence herbicides.

Difficult weather conditions are common in the autumn and in 2017, between mid-September and the end of October there were only five good spray days at our Cambridgeshire site. With limited time to apply pre-em herbicides, there is pressure to spray in compromised weather conditions.

With any pre-emergence herbicide application it is all about getting the maximum amount of product on the bare ground, with even coverage of the soil surface. In order to maximise efficacy and reduce non-target drift, sprayer operators need to focus on three key areas for pre-emergence application, including: sprayer setup, timing and application technique.

GO LOW…… BOOM HEIGHT IS THE SINGLE BIGGEST CONTROLLABLE FACTOR TO PREVENT DRIFT: Maintaining a boom height of 50 cm above the seedbed is optimum for surface coverage and application rate. Double the boom height = 10x the drift.

A boom height of 50 cm is optimum to minimise drift and achieve best coverage of the target.



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GO SLOW . . FORWARD SPEED NEEDS TO BALANCE WORK RATE AND EFFICACY: Trials over recent seasons have consistently shown the optimum speed for applying pre-emergence herbicides is below 12 kph

GET COVERED… . NOZZLE SELECTION TO HIT THE TARGET & WATER VOLUME SELECTION FOR SPEED AND COVERAGE: Syngenta 3D angled nozzles, alternating forward and backwards along the boom, give all round coverage, including the backs of clods on a typical autumn seedbed. However, these nozzles offer no drift reduction and should only be used in ideal spraying conditions. In compromised spraying conditions, opting for a 90% drift reduction nozzle can help ensure that the spray hits the target. The key is to ensure you get the maximum spray on the target – which will in itself enhance results. It also offers important environmental protection for non-target areas surrounding fields. While trials have shown the best efficacy is achieved with water volumes of 200 l/ha, in some instances operators may still need to spray at 100 L/ha, to achieve necessary work rates where the scale of area to cover or a limited number of available spray days demands. New 90% Drift Reduction Nozzles that are capable of applying 100 L/ha, can help mitigate the risk of drift in these cases.

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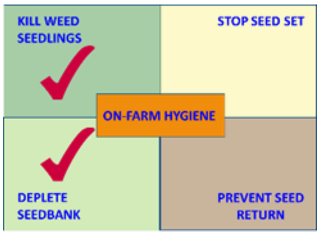
3.4.6. New chemistry



The lack of new chemical herbicide modes of action is due to a number of factors. As a result of EU Regulation 1107/2009, new chemicals are now subjected to more rigorous testing and are assessed for bioaccumulation (both terrestrial and aquatic) and toxicity to water fauna at an earlier stage, reducing the likelihood of new chemistries being taken through to commercialisation (Clark, 2012). The introduction of genetically modified glyphosate resistant crops has also led to the devaluation of other herbicides and, consequently, a disincentive to invest in research and development for new modes of action (Rüegg *et al*. 2007; Duke, 2012). Instead, industry resources have shifted away from discovery of new herbicide modes of action and towards finding genes to use in genetically modified crops to make them resistant to existing herbicides (Clark, 2012; see section 3.7.2). In general the loss of existing actives and the development of herbicide resistance means that new chemistry and herbicide modes of action are still needed (Heap, 2018; Duke, 2018).

The traditional method of discovering new herbicides was to discover herbicidal or phytotoxic compounds and determine their mode of action using physiological and biochemical approaches (Duke, 2018). Natural products, particularly secondary metabolites, provide a large source of new potential pesticide compounds, with almost 70% of new pesticide active ingredients registered in the USA having origins in natural products research. Secondary metabolites are molecules produced by all living organisms, which due to their biological activity could potentially provide a source for new herbicidal chemistry. Over 200,000 secondary metabolites have been identified, but few have been studied for their phytotoxicity (Dayan & Duke, 2014). Dayan & Duke (2014) produced an extensive list of highly effective phytotoxins that could potentially be investigated for herbicidal activity, either as bioherbicides or as a basis for synthetic herbicides. The list includes thiolactomycin a potential inhibitor of fatty acid synthesis produced by *Streptomyces* spp., 5-methyltryptophan an inhibitor of tryptophan synthesis (a pathway not present in the animal kingdom) produced by the fungus *Cantharellus cibarius*, and coronatine a jasmonic acid mimic produced by the bacteria *Pseudomona syringae* that suppresses salicylic acid-dependent plant defence mechanisms including the opening of stomata. However, many phytotoxins also have mammalian toxicity and general cytotoxicity, and are structurally complex, meaning that they would not be safe or economic to develop (Duke, 2018).

'Omics' (genomics paired with proteomics, transcriptomics, metabolomics, and physionomics) are another potential source of new chemistry. For example, a resistance gene genome mining technique was recently used on thousands of fungi to discover a potential new herbicide, aspterric acid, which targets dihydroxy-acid dehydrase in the branched-chain amino acid biosynthetic pathway in plants (Yan, *et al*., 2018). Omics can be used to discern the target of a phytotoxin with an unknown target by comparing its responses to a library of phytotoxins with known molecular target sites, indicating or eliminating known target site activity (Duke *et al*., 2013). Weed genome sequencing

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(3.7.5) could allow for the discovery of new herbicide modes of action by identifying previously unknown target sites allowing for the development of new chemistry aimed at these sites (Ravet *et al*. 2018). Additionally, RNA interference (RNAi) technology could be used with existing herbicide modes of action to reverse target site resistance in weeds increasing the available use of existing modes of action (3.7.4).

An omics approach has already been used to determine the new mode of action of cinmethylin as an inhibitor of fatty acid thioesterases (Campe *et al*., 2018). BASF have submitted a regularity dossier to the EU for the registration of their cinmethylin product, Luximo™, which will have residual activity against a range of grass weeds including black-grass (*Alopecurus myosuroides*). Pending regulatory approval, it is expected that Luximo™ will be available in the UK in 2021 (BASF 2018a; Table 12).

There a several additional new, unregistered actives in the pipeline (Table 12), these actives are currently in trials either in the UK or Europe and are due to be available to the UK market within five years.

Table 12. New actives in the pipeline for possible UK use in the next five years

Product/Active	Crops	Target	Company/Launch/Comments
Aclonifen	Potatoes, beans, peas (+ carrots, parsnips, onions, garlic, parsley & sunflower via EAMU)	Broad-leaved weeds	- Bayer Pre-emergence herbicide for broad-leaved weeds
Cinmethylin (Luximo)	Winter cereals	Pre-emergence, residual control against a broad range of grasses, including difficult-to-control black-grass and ryegrass	- BASF - UK launch anticipated in 2021, pending regulatory approval
Florpyrauxifen-benyl (RinskorTM active)	TBC	Broad spectrum weed control	-Dow AgroSciences - being evaluated and characterized in all major rice crop markets, and in other crops for secondary uses
Foramsulfuron + thiencarbazone-methyl)	ALS-tolerant sugar beet varieties	Broad spectrum weed control	-Bayer with KWS to bring the first commercial tolerant varieties to market

Foramsulfuron + thiencarbazone-methyl (Conviso one®) is destined for the sugar beet market to be used in conjunction with ALS tolerant varieties, further information is available in section 4.4.4.

Aclonifen, a pre-emergence herbicide for broad-leaved weed control, has been evaluated on a wide range of horticultural crops in the SCEPTRE plus project. There has been a submission for registration for use in potatoes with the potential for EAMUs and label extensions for other crops (CPM, 2018).

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Rinskor^{TM} active (Florpyrauxifen-benyl) a new arylpicolinate herbicide from Dow AgroSciences is being evaluated and characterised in all major rice crop markets, and in other crops for secondary uses. The herbicide will provide growers with an alternative for broad spectrum weed control, with safety to the crop and with a very favourable environmental and toxicological profile (Dow AgroSciences, 2018c).

3.4.7. Herbicide resistance

Chemical weed control is only highly effective in the absence of herbicide resistance. Resistance has evolved in multiple weed species, to multiple herbicide modes of action, in numerous countries, with reported cases increasing year on year (Heap, 2018). Herbicide resistance can be caused by many different mechanisms that can be split into two groups, target site resistance (TSR) and non-target site resistance (NTSR). TSR mechanisms are either the consequence of a mutation of the gene that expresses the targeted protein resulting in an amino acid substitution and structural changes at the herbicide-binding site reducing herbicide affinity, or gene amplification and increased expression of the target protein (Powles & Yu, 2010). NTSR mechanisms are any other mechanism of resistance not related to the target site (e.g. reduced translocation, reduced herbicide uptake, enhanced metabolism) and cause a reduction in the amount of herbicide reaching the target site and in some cases can cause cross-resistance to different herbicides (Powles & Yu, 2010).

Evidence indicates that at least in the case of TSR, once it is present in a population it does not disappear, even if the selection pressure is removed (Chauvel *et al*., 2009). Therefore it is important to prevent the development of resistance, both TSR and NTSR, rather than trying to manage resistance once it has appeared in a population. Moreover, recent research found no evidence that using a diversity of different herbicide modes of action in an arable cropping rotation reduced the selection for herbicide resistance evolution in black-grass and that resistance evolution to any new herbicide products would be inevitable without a change in weed control strategies (Hicks *et al*., 2018). For both weed control and herbicide resistance prevention there therefore needs to be a focus on integrated weed management (IWM) with an emphasis on cultural (3.1) and non-chemical control options (3.3), and knowledge transfer to increase uptake and use of these techniques (Moss, 2010). One example of a successful herbicide resistance knowledge transfer campaign is the Australian Herbicide Resistance Initiative (AHRI), from which lessons could be learnt in the UK.

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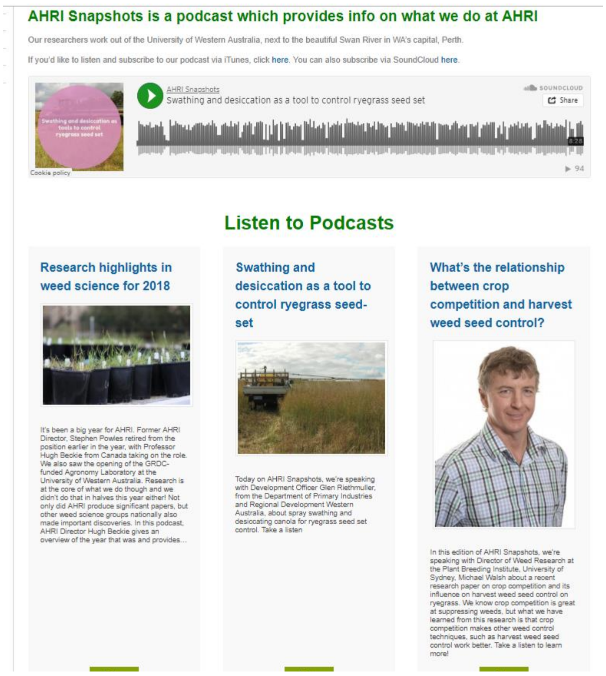
Case study: The Australian Herbicide Resistance Initiative: https://ahri.uwa.edu.au/

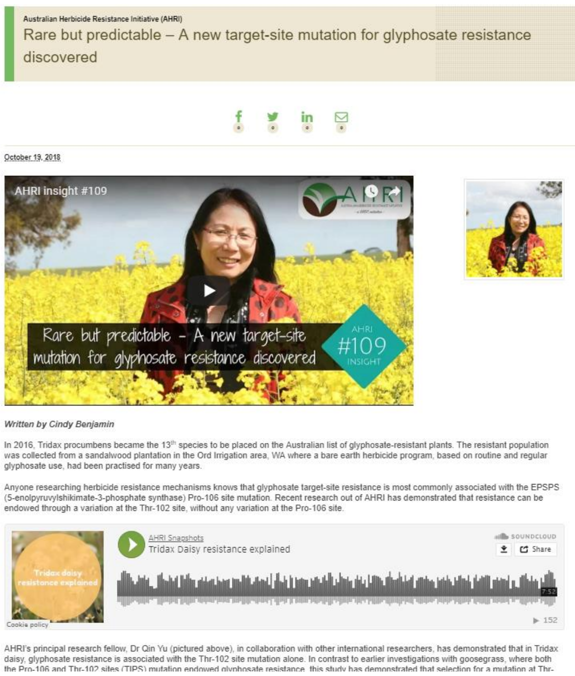
The Australian Herbicide Resistance Initiative (AHRI) is a team of weed researchers and science communicators who focus on weed science and herbicide resistance evolution in the Australian grains industry. They are funded by the Grains Research and Development Corporation and conduct weed research on the biology and population ecology of major crop weed species, cultural and herbicide weed management strategies, and biochemical and molecular herbicide resistance mechanisms.

AHRI researchers conduct annual herbicide resistance surveys, collecting random weed seed samples at harvest and testing them against a range of different herbicides. The surveys provide baseline resistance data and allow AHRI to monitor changes in the frequency of herbicide resistance over time. This annual survey has allowed AHRI to track the decline in the presence and spread of wild radish weeds and increase and evolution of herbicide resistance in brome and wild-oat species. Using this data they have developed tools such as the Brome RIM to enable growers to plan for the best weed control strategies.

As well as research, one of AHRI's main focuses is on knowledge transfer extension activities to encourage sustainable cropping and weed control across Australia. Understanding that growers will not trawl through scientific literature for the latest weed management research, AHRI produce a fortnightly e-newsletter (AHRI insight) to keep growers up to date with the latest research and even host 'Snapshots', a podcast providing information on AHRI and their research.

AHRI produce podcasts and e-newsletters to enable growers to easily access and understand their weed research





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It is important to monitor the effectiveness of resistance prevention strategies, but often monitoring of herbicide resistance is reactive and a result of reports of poor control and the potential for the presence of resistance. A more proactive approach to monitoring for herbicide resistance and an increase in the spread of weed species can enable potential issues to be detected and controlled early using IWM. Again, one such example of this is the monitoring conducted by the AHRI, which could be followed in the UK.

Recently there has been a push towards understanding the eco-evolutionary principles that drive herbicide resistance, in an effort to direct management strategies towards preventing the selection of resistance (Neve *et al*., 2014; Menalled *et al*., 2016). The eco-evolutionary principle aims to understand the drivers behind the evolution of resistance and use this to inform and direct herbicide resistance prevention and weed management strategies to help slow or prevent resistance (Neve, *et al*., 2014). However, the evolution of TSR and NTSR mechanisms can vary. Most TSR mechanisms are dominant or semi-dominant nuclear traits, although there are a few cases of recessive TSR (Powles & Yu, 2010; Délye *et al*. 2013). NTSR is under complex genetic control, with it either being endowed by a single resistance allele, or by the accumulation of multiple minor alleles, resulting in multiple resistance phenotypes (Petit *et al*. 2010; Délye *et al*. 2011; Beckie & Tardiff, 2012). Polygenic enhanced metabolism NTSR mechanisms may be diverse, reflecting the diversity of metabolic pathways and processes involved and inter- and intra-specific variation, meaning that they are hard to identify and can vary between weed populations and species (Délye *et al*. 2013).

One example of the eco-evolutionary approach to herbicide resistance is the investigation of the influence of low herbicide doses on the evolution of NTSR. Low herbicide doses can be applied to weed populations in the field in a number of ways, either through deliberately using below field rate doses to treat weeds within the crop, as shown by Collavo & Sattin (2014), or to reduce costs, as in Australia (Neve *et al*. 2003). Lower herbicide rates can also be applied to weeds through poor spray application where part of the field receives a lower than recommended rate of herbicide due to human error. Alternatively, spray drift can result in a lower rate of herbicide reaching the in areas where the product has not been applied (Baylis, 2000).

Multiple studies have shown that the evolution of NTSR can be selected for using low herbicide doses (doses below recommended field rate). For example glyphosate in rigid ryegrass (*Lolium rigidum*) (Busi *et al*., 2013), tall water-hemp (*Amaranthus tuberculatus*) (Zeleya & Owen, 2005) and black-grass (Davies *et al*., 2017), ACCase inhibitors in rigid ryegrass (Neve & Powles, 2005) and black-grass (Lynch, 2014), and inhibitors of very long chain fatty acids (K3) in rigid ryegrass (Busi *et al*., 2012). However, the effects low dose herbicide selection can be dependent on weed species biology (e.g. mating systems) and standing genetic variation (the presence of different genetic alleles in a population). For example, there is evidence that low dose selection of wild-oats, a hexaploid, selfing species, with ACCase inhibitors can result little or no change in herbicide sensitivity (Moss *et*

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al., 2001). Busi *et al*., (2016) found that a wild-oat populations selected for three years using diclofop-methyl (an ACCase inhibitor) only had a 2.3 fold increase in ED_{50} compared to a 40 fold increase found in rigid ryegrass, with cross-pollination rate, genetic variation and ploidy levels identified as possible causes of these differences between species.

Additionally, the extent of change in herbicide sensitivity even in the same species can be dependent on the herbicide mode of action, for example differences in shifts in herbicide sensitivity with low dose selection of black-grass using ACCase inhibitors (Lynch, 2014), glyphosate (Davies & Neve, 2017), and flufenacet (Defra, 2015a), where respectively large, intermediate, and no shifts in reduced herbicide sensitivity were found. This shows that herbicide mode of action and species biology need to be taken into account when investigating the evolution of herbicide resistance and prevention strategies and that research into this area needs to continue. Recently Moss *et al*., (2019) developed an herbicide resistance risk matrix to try to quantify the inherent risk of herbicide resistance based on weed species and herbicide mode of action. All this information and data can be gathered together and used in conjunction with weed prediction modelling (3.6.1), decision support systems (3.6.2), and integrated weed management strategies to help growers prevent and/or control herbicide resistant weeds, and develop resistance diagnostic techniques (3.4.8).

3.4.8. Herbicide resistance diagnostics

Determining the presence or absence of herbicide resistant weeds in a field can help on-farm decision making regarding which herbicide modes of action will be effective for weed control (Wilson *et al*., 2009), and can help identify evolutionary changes in weed populations giving information on resistance prevention strategies. A number of herbicide resistance diagnostic techniques are available, each with benefits and drawbacks.

Glasshouse herbicide resistance testing

Classic herbicide resistance tests are conducted under glasshouse conditions. Weed seeds are collected from across a field with suspected herbicide resistant weeds and sown into soil filled pots. A known herbicide sensitive population of the weed species being tested is also sown and tested with the suspected resistant population. Known doses of herbicides are then applied to the pots, either before seedling emergence for pre-emergent herbicides, or at the two to-three leaf stage or larger for post-emergent herbicides. Assessments of plant vigour, survival, fresh weight, or dry weight are usually conducted two to six weeks after herbicide application. To show the level of resistance, when testing a species for the first time a range of herbicide doses are usually used in a glasshouse dose-response assay. The dose at which 50% control is achieved (variously known as lethal dose - LD_{50}, effective dose - ED_{50}, or growth rate - GR_{50}) can then be calculated for both the resistant and sensitive population, with the ratio of these estimates enabling the degree of resistance to be described and a discriminating dose to detect resistance to be identified. Once resistance to a

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mode of action has been confirmed in a species using a dose-response assay, screening using one or two discriminating doses can be used to test further populations suspected of herbicide resistance (Seefeldt *et al.* 1995; Moss, 1999a; Burgos *et al*. 2013). Glasshouse resistance testing allows for any herbicide active to be tested on any weed species, under controlled conditions, using doses comparable to those used in the field. They are usually highly accurate and can test for resistance irrespective of the resistance mechanism present in a weed population (Moss, 1999a). However, these glasshouse resistance tests are time consuming, require a lot of man power, and the soil type used in the testing can affect herbicide efficacy.

Rothamsted Rapid Resistance Petri dish test

The Rothamsted Rapid Resistance test (RRRT) is a Petri dish method for testing grass weeds for resistance to ACCase inhibitors and metabolic resistance. Grass weed seeds are germinated in Petri dishes containing either potassium nitrate solution (untreated control) or a discriminating herbicide concentration (treated). Petri dishes are placed in growth chambers or lit incubators for two weeks, after which the number of germinated seedlings is counted. Both known sensitive and resistant weed populations are included in the test, aiding the interpretation of results (Moss, 1999b). RRRTs enable faster testing of weed seed samples for resistance than glasshouse tests, take up less space and resources, and can distinguish between some different resistance mechanisms. However, they can only be used for grass and not broad-leaved weeds, and are not suitable for all herbicide modes of action.

Both glasshouse and Petri dish resistance testing depend on weed seed collection at the end of a growing season when weed control has already failed, affecting that season's crop and enabling any resistant weeds to produce off-spring and return resistant weed seed to the soil seedbank. This allows the herbicide resistance problem to continue into subsequent growing seasons. This has led to the development of in-season resistance testing techniques that can test plant material for the presence of herbicide resistance.

Syngenta Quick test

The Syngenta Quick test was developed in 2001 to enable in-season herbicide resistance testing. Grass-weeds suspected of herbicide resistance are removed from farmer's fields and tested for resistance in the glasshouse by being cut down to size, transplanted into soil to be regenerated and then treated with the recommended herbicide field rate (Boutsalis, 2001). The Quick test can give results in as little as four weeks, and as it is a glasshouse test treating whole plants using already established herbicide rates, it can be used to test for resistance in any grass weed using any herbicide active. However, due to the need to cut and regenerate plant material the Quick test can only be used on grasses and not broad-leaved weeds. Also it is more labour intensive than growing weeds from seeds for resistance testing.

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Syngenta Resistance in Season Quick Test (RISQ)

The Syngenta Resistance In-Season Quick test (RISQ test), was developed to improve in-season assessment of herbicide resistant weeds and involves collecting seedlings from farmer's fields and growing them in agar containing discriminating rates of herbicides with survivors compared to known sensitive and resistant standard populations. The test can be used for both grass and broad-leaved weeds and has been developed to test for resistance to ACCase inhibitors, ALS inhibitors, and glyphosate (Kaudun *et al*. 2011; Kaudun *et al*. 2014). Initially developed to test seedlings at the 2-3 leaf stage, the RISQ test has now been developed further to assess potential resistance in larger, tillered grass weeds, extending its use to later in a growing season when farmers are more likely to suspect resistance (Davies *et al*. 2017). Like the Quick test, the RISQ test can be conducted in-season. It also has advantages over the Quick test and more classic glasshouse resistance testing methods in that: (1) it is fast, with results available within two weeks, (2) it is conducted in agar avoiding potential effects of soil type, and (3) it is conducted in Petri dishes and therefore more space efficient than tests conducted in the glasshouse. However, both the Quick and RISQ tests are less accurate than classic glasshouse dose-response assays and can therefore only be used to infer resistance in populations of species already know to have herbicide resistance and not confirm resistance in new species (Kaudun *et al*., 2011).

Target site resistance testing

Testing for known TSR mutations can be conducted using DNA-based tests, typically the polymerase chain reaction (PCR), and can identify single nucleotide polymorphisms (SNPs) that can cause a change in amino acid sequence and the function of the target protein. PCR can be used to quickly (within one day) to detect TSR to seven herbicide modes of action, including ALS inhibitors, ACCase inhibitors, glyphosate, and PPO inhibitors. Analysis can be scaled up to allow for hundreds of samples to be tested a day in one laboratory. However, false negatives can occur, as only known TSR mutations can be tested for and if an unknown TSR mutation or NTSR is present resistance will not be identified. PCR tests also need to be designed and optimised for each resistance mutation/ species grouping. DNA sequencing can be used to identify known TSR mutations and, with the use of other resistance confirming tests, new TSR mutations. However, DNA sequencing is much more costly than PCR testing (Burgos *et al*., 2013).

Lateral flow device metabolic resistance test

Non-target site metabolic herbicide resistance is where a weed has evolved the ability to detoxify multiple herbicide modes of action. It is controlled by many different genes (polygenic) and is poorly understood on a genetic level, meaning that DNA-based tests cannot easily be used to identify metabolic TSR. However, using protein analysis one glutathione transferase protein, AmGST1, has been found to be enhanced in multiple populations with metabolic resistance (Cummings *et al*. 2013;

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Tétard-Jones *et al*., 2018). A new lateral flow device test (LFD), similar to a pregnancy test, has been developed to detect the presence of AmGST1 in black-grass leaves. Crushed leaves mixed with an extraction buffer solution and dropped onto the LFD. When the AmGSTF1 protein is enhanced and present in large amounts, as in metabolically resistant black-grass, an intense red band appears. When protein expression is not enhanced and is present at 'normal' levels a fainter red line appears (Mologic, 2018; Newcastle University Press Office, 2018). The LFD allows for relatively quick in-season testing, which can be done on the spot by growers, allowing for quick decision making. However, only metabolic resistance not target site resistance can be detected, as one LFD can only test one plant and there are only five tests per kit the tested sample size is extremely small. Also, and as a red band appears for both sensitive and metabolically resistance black-grass the interpretation of results can be variable.

Diversity Array Technology

Diversity Arrays Technology (DArT) can generate a whole-genome fingerprint by typing thousands of gene loci simultaneously in a single assay and scoring the presence or absence of DNA fragments. The technology has already been used to profile the wheat and barley genome, amongst others (Akbari *et al*., 2006). As DArT allows for the genome-wide profiling of complex polygenic traits, like NTSR, it has recently been used to identify genetic markers in rigid ryegrass to discriminate between populations resistant and susceptible to trifluralin (Group D herbicide) (Preston *et al*., 2014). The use of DArT for detection of herbicide resistance is only in the proof of concept stage. Like glasshouse and Petri dish tests, it can only identify differences between resistance and susceptible individuals, rather than distinguishing between TSR and NTSR, and also requires leaf samples to be sent for analysis. However, if DArT is further developed it could potentially be used to identify genetic markers linked to additional modes of action allowing for simultaneous resistance testing to multiple modes of action (Preston *et al*., 2014).

Resistance diagnostics transferable technology

- LAMP (loop-mediated isothermal amplification) is a technique that can be used to detect transgenes in GM crops (Kiddle *et al*., 2012), and could be used to detect herbicide resistance genes in weeds. Methods have already been developed to detect SDHI resistant *Botrytis cinerea* (Fan *et al*., 2018).
- QTL (quantitative trait loci) analysis (Collard *et al*., 2005, 3.7.5) could be used to identify areas of weed genomes that may have genes involved in non-target site resistance.
- Digital PCR can be used to detect DNA and RNA at extremely low concentrations, and is faster than real-time PCR. It has recently been developed for fungicide resistance detection (Zulak *et al*., 2018), and could allow for an increased number of weed samples to be tested to TSR.

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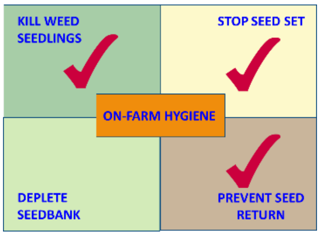
3.4.9. Bioherbicides



Bioherbicides are products derived from a natural origin that can be used for weed control. They can be natural plant products, such as essential oils, from other living organisms, such as fungal pathogens, or the products of natural processes, such as fermentation (Dayan *et al*., 2011; Cai & Gu, 2016; Cordeau *et al*., 2016). The use of bioherbicides differs from classical biological weed control (discussed in section 3.3.8), as it is based on the production of natural products pathogens under controlled conditions that are subsequently spread by growers, rather than the release and natural, uncontrolled spread of biological agents (Cai & Gu, 2016). As natural products bioherbicides have a relatively short persistence and are often viewed as being environmentally benign, although little is known about their environmental fate (Dayan *et al*., 2009).

Compared to other biopesticides the uptake and use of bioherbicides has been low, and they comprise only 7% of approved biopesticides in the USA (Dayan & Duke, 2017) and few are marketed world-wide (Table 13). Their poor commercial success is partly due to inconsistent weed control, high costs, high rates, and threats to human health (e.g. high rates of acetic acid can burn skin) (Cordeau *et al*., 2016; Cai & Gu, 2016). Although many bioherbicidal pathogenic candidates have been identified, few have been commercialised, due to the high costs involved in culturing and the potential damage the pathogens could pose to non-target species (Cai & Gu, 2016).

Essential oils derived from plants, such as pine oil, clove oil, and lemongrass oil, have some contact herbicidal activity and can control some small weeds (Dayan *et al*., 2009) but, results can be poor. For example, testing of a range of essential oil and plant compound based bioherbicides on annual and perennial weeds in the UK showed that they initially scorched annual weeds, but there were signs of recovery within a few days of application (HDC project CP 77 SCEPTRE, 2013) (Figure 12).

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 (Dayan *et al*., 2009). Pelargonic acid was the only bioherbicide tested in the SEPTRE project that provided good control for fat hen, groundsel (*Senecio vulgaris*), and dock after repeat applications, with other weeds not controlled (HDC project CP 77 SCEPTRE, 2013) (Figure 12).

Table 13: Examples of commercially available bioherbicides available world-wide

Example product	Active ingredient	Type	Target	Reference
GreenMatch EX	Lemongrass oil	Essential oil	Non-selective	Dayan *et al*., 2011
Burnout™	Acetic acid and Clove oil	Essential oil	Non-selective	Dayan *et al*., 2011
Organic Inteceptor™	Pine oil	Essential oil	Non-selective	Dayan *et al*., 2011
Organic Weed & Grass Killer™	Citrus oil	Essential oil	Non-selective	Dayan *et al*., 2011

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Matran II	Clove oil	Essential oil	Non-selective	Dayan & Duke, 2010
Weed Zap	Clove and cinnamon oil	Essential oil	Non-selective	Dayan & Duke, 2010
Worry free	Citrus oil	Essential oil	Non-selective	Dayan & Duke, 2010
Organic interceptor	Pine oil	Essential oil	Non-selective	Dayan & Duke, 2010
EcoExempt HC	2-phenethyl propionate/clove oil	Essential oil	Non-selective	Dayan & Duke, 2010
AgraLawn CrabGrass Killer	Cinnamon bark	Crude botanicals	Grasses	Dayan & Duke, 2010
Concern	Corn gluten	Crude botanicals		Dayan & Duke, 2010
Safer	Fatty acid soaps	Fatty acid soaps	Non-selective	Dayan & Duke, 2010
LockDown®	*Colletotrichum gloeosporioides*	Pathogen	*Aeschynomene virginica*	Cordeau *et al*., 2016
Chontrol® Pastes	*Chondrostereum purpureum*	Pathogen	*Prunus, Populus*	Cordeau *et al*., 2016
Smoulder®	*Alternaria destruens*	Pathogen	*Cuscuta*	Cordeau *et al*., 2016
Sarritor®	*Sclerotinia minor*	Pathogen	Dicot weeds in turf	Cordeau *et al*., 2016
Opportune®	Thaxtomin A	Fermentation compound	*Poa*, *Festuca*	Cordeau *et al*., 2016
Kona™	Citric acid + lactic acid	Fermentation compound	*Trifolium, Lotus, Medicago, Oxalis*	Cordeau *et al*., 2016
Beloukha®	Nonanioc acid + pelargonic acid	Plant compounds, organic acids	Non-selective	Cordeau *et al*., 2016
Katoun Gold	Pelargonic acid*	Organic acid	Non-selective	BCPC, 2018
New way weed spray	Acetic acid*	Organic acid	Non-selective	BCPC, 2018
NatureCur®	Black walnut	Plant compounds	*Conyza sp.*	Cai and Gu, 2016
Barrier H	Citronella oil*	Essentail oil	Ragwort	BCPC, 2018

*authorised in the UK

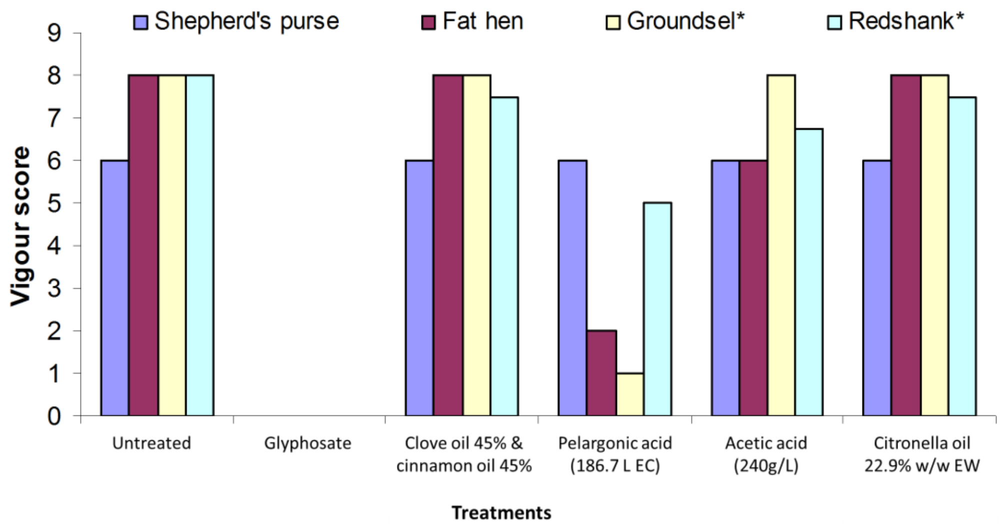

Figure 12: From HDC project CP 77 SCEPTRE (2013). Vigour score (9= healthy, 0=dead) of shepherd's purse, fat hen, groundsel, and redshank 6 weeks after treatment and *3 weeks after treatment with bioherbicides or glyphosate

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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. However, acetic acid concentrations of more than 11% can burn skin and cause severe eye injury, including blindness (Smith-Fiola & Gill, 2017).

Bioherbicides, particularly essential oils and organic acids, often give poor to moderate weed control and require repeated applications at high rates, as they are not systemic and leave the plant meristem intact (Dayan & Duke, 2010). However, due to initial scorching symptoms and 'knock-down' there is potential for bioherbicides to be used as part of an integrated weed management programme (Cordeau *et al*., 2016).

3.4.10. Biopesticides – transferable technology

As mentioned above only 7% of biopesticides approved in the USA are bioherbicides (Dayan & Duke, 2014**).** Transferrable technology could include a plant-incorporated protectant for weed control similar to where crops have been transformed to produce bt toxins. There is the potential to enhance the allelopathy of crops or impart allelochemical production for weed control (Dayan & Duke, 2014).

3.5. Novel and Emerging Technologies

This section covers all new and emerging technologies being evaluated for weed control.

3.5.1. Sensing and predicting the need for control

Information on weed distribution and mapping within a field is necessary to implement spatially variable herbicide application (Perez *et al*., 2000). It can be provided in real-time by identifying weeds in the field and directing a spray nozzle during application, or based upon creating maps of weed infestations ahead of application.

Aerial imagery

There are several methods of creating aerial imagery – satellite, aeroplane and drone that can be used for identifying weedy areas and measuring the response to management tactics. These are especially useful at late weed phenological stages (López-Granados, 2011). In a review by Thorp & Tian (2004), they claimed that remote detection of weeds from ground-, aircraft-, and satellite-based platforms has been used widely but rarely applied to make variable-rate herbicide applications.

Unmanned aerial vehicles (UAV) have been developed to map weed patches and weed densities in fields. Adoption of the technology requires automatic mapping without the need for ground truthing. In a study by Lambert *et al.,* (2017) aerial images of black-grass infestations from 26 fields were collected using an UAV. Images were generated using both RGB (Red Green Blue) and R_{mod} (R_{mod}

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670–750 nm) spectral bands. Weed densities correlated with image intensity and forecast weed densities in other fields, however, results were mixed from field to field.

The MARS project, (Mobile Agricultural Robot Swarms), demonstrated a cloud-based approach to farming (Robohub, 2016). Similarly, the SASA project aims to exploit swarm robotics principles, and a group of small unmanned aerial vehicles (UAVs) will be deployed to monitor fields. Collectively, the robots build a map of the field with semantic tags associated with different areas, so as to convey precise information about the presence and amount of weeds in the different parts of the field. This could facilitate optimal spatiotemporal planning of weeding operations, and autonomous precision weed removal in the future (Echord).

Within field imagery

For site-specific weed control on finer spatial scales, there is interest in monitoring weeds using digital cameras, or spectral or optical sensor systems (non-imaging sensors) from ground-based platforms within the field (López-Granados, 2011). High-resolution on-ground mapping can be used in both map-based and real-time site-selective weed management. This within field technology can be found in tractor based systems, specialised vehicles and robots (Section 3.5.2).

Perez *et al., (*2000) showed weed detection using image processing techniques (colour and shape) has shown potential to estimate weed distribution. However, they stated that to reduce errors in detection that this approach be complemented by other sources of information (species identification, historic yield maps) in order to generate weed maps that are sufficiently comprehensive to use in a patch spraying system. In a traditional machine-vision sensing approach using leaf- or plant shape–based feature recognition, high weed levels are problematic as it is difficult to distinguish between the weed and crop foliage (Franz *et al.* 1991).

There has been some commercial success identifying weeds at early crop growth stages when weed densities are low and crop plants are readily distinguished from weeds by plant size and planting pattern. However, new approaches are needed to identify weeds in moderate to heavy infestations where plant size makes it difficult to identify the weeds (Westwood *et al.*, 2018).

Hyperspectral imaging methods for weed detection are more robust under high weed densities than shape-based methods, because the method measures the reflectance spectra at each point in the image regardless of the visibility of the entire plant or distinct leaf shape (Westwood *et al*., 2018). The species identity is then determined for each point by spectral feature recognition rather than by shape analysis (e.g., Slaughter *et al.* 2004, 2008; Slaughter *et al*., 2008b; Zhang & Slaughter 2011b; Zhang *et al*. 2012b).

Van Der Weide (2008) produced a detailed review of how sensing technologies differ. Vision Robotics’ technology reportedly integrates algorithms with sensor technology to bring automation to

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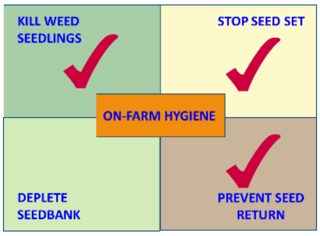
lettuce farming and vineyards. Specifically, computer vision allows robots to generate 3D maps and models of areas of interest and then to complete various tasks within those parameters (Emerj, 2017).

A systems approach is another promising technique that could be implemented commercially in the short term to develop smart machines for automated weed control. Knowledge of the crop-plant locations at planting is mapped and retained for future use in managing crop agronomy such as weed control (Westwood, 2018). One example of utilising this technology is in the FaaS, which described in detail in the robotics section below (3.5.2).

The eyeWeed system explores the use of cameras mounted on ground-based farm machinery (especially sprayers) with the goal of automating the process of creating the geo-referenced maps of black-grass patches without the need for ground truthing (Murdoch *et al*., 2014). The eyeWeed comprises six spray boom-mounted cameras linked to sophisticated computer software that can accurately map black-grass patches within wheat crops in mid-June at much higher resolution than is possible with current aerial imagery (Agrii, 2016).

3.5.2. Tools used to provide control

Robotics and automation



Here robotic weeders are defined as automated, intelligent machines that have the ability to collect and process information for a selected outcome.

The World Economic Forum (2018), claims that deploying information technology, automation, robotics and decision-support technologies in precision agriculture takes the guesswork out of input use, irrigation and livestock management and fishery operations, making farming more efficient, profitable and sustainable. The concept of mechanised and intelligent weeders has long been established (3.3.1). Coupled with the pressure to reduce labour costs, this has led to the development of robotic weeders, which are reportedly gaining popularity in Europe (eeDesignIt, 2018).

There are many robot weeders in development that use pre-existing techniques for weed control such as; laser (3.3.4), heat (steaming) (3.3.4), precision spray (3.4.2), stamping, and soil disturbance (3.3.2). The design and size of robots for weed control depends on the intended use. Some can be used for a range of crops (Ecorobotix) whilst others are designed for a specific crop, for example BAKUS (Vitibot) which was exclusively produced for use in viticulture. Further reviews showing the range of robotic weeders (inter and intra row) have been completed such as; Fennimore (2017),

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Peruzzi *et al., (*2017), Van Der Weide *et al., (*2008), Slaughter *et al., (*2008a), Siemens (2014), Young, (2010), Atkinson, (2018).

Despite the varied designs of automated robotic systems, the key principles and challenges for weed control are similar. Slaughter *et al., (*2008a) in a review on autonomous robotic weed control systems identified four core technologies: (a) guidance, (b) detection and identification, (c) precision in-row weed control, and (d) mapping.

Identification of weeds and automated guidance

The creation of automated weeders has been made possible due to the availability of new supporting technologies, including global positioning systems (GPS), geographic information systems (GIS), sensors, automation of agricultural machinery, and high resolution image sensing (Rhea Project, 2018).

With a rise in the collection and utilisation of "big data", automated robot systems are becoming more efficient at recognising weeds and monitoring growth by improved data collection. Crop tagging, imagining, size and spacing analysis have already proven effective (e.g. IC-Cultivator and Robivator (Siemens, 2008)).

Robohub (2018) claims the technology required by automated weeders is similar to that for autonomous cars. Where it differs is that farming robots often need to manipulate their environment, picking vegetables or fruits, applying pesticides in a localised manner, or planting seeds. All these tasks require sensing, manipulation, and processing of their own. Self-driving technology can turn existing machinery needed to plough, seed, and harvest fields into autonomous robots (EuRobotics, 2018).

Farmers Edge is one of a growing number of big data players in the agriculture sector, offering farmers precision agriculture tools to help them make daily farm management decisions, such as when to apply inputs. They use data sources that include weather stations, satellite imaging and tractor GPS to provide manageable field-level insights to farmers in real time (World Economic Forum, 2018). Although, they are not yet associated with a specific robot or project, the data collected could be used for a number of projects.

Key example existing fully automated farming systems/robots:

1. Using artificial intelligence, large data sets can be analysed to advise on which procedures to follow to maximise yield. For example, "Farming as a service" (FaaS) developed by the Small Robot Company (2017), consists of: A) robots for data collections and digitalising the fields, b) an AI driven operating system that analyses the information gathered about the crop and makes decisions c) Operation robots that are released to manage weeds by micro-spray

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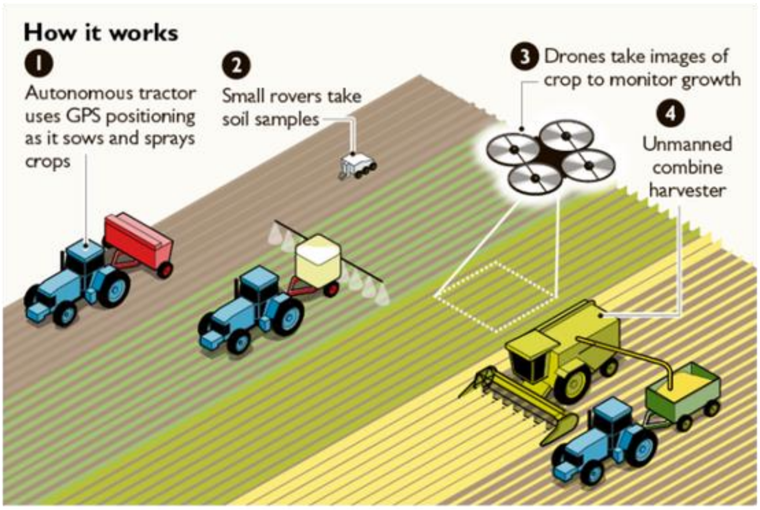
chemical, burning, or crushing as it emerges- utilising the processed data from other robots. These light robots, also reduce soil compaction in comparison to current technology.

2. The BoniRob is a large robotic weeder being developed by Deepfield Robotics. It knows where it is in a field from satellite positioning and lidar measurements and separates weeds from crops using up to 1,000 properties, including shape and light reflectance. To do this, Deepfield has taken thousands of images of fields and then annotated each image's characteristics and the trained software can identify weeds in real-time (Fast Company, 2015)
3. Asterix (2018) claims to be the first fully automated farming robot that uses a Deep Learning Neural Network to map its way around weeds and crops and carefully drop a precise amount of herbicide directly onto the weed, without touching the crop or soil reducing herbicide usage by 95%. Asterix enables intra-row weeding, even in sown crops that are notoriously difficult to weed as the weeds emerge and develop simultaneously with the crop, and expands the available range of herbicides. Novel and environmentally-safe weeding agents such as acetic acid or urea which are not widely used due to the risk to operator health can be used to chemically burn even herbicide-resistant weeds (3.4.7).
4. Automated robotic systems are also commercially available for home growers e.g. FarmBot, which has been considered by NASA for growing and planting in space.
5. Harper Adams Hands free Hectare: Automated machines growing the first arable crop remotely, without operators in the driving seats or agronomists on the ground.



Concerns and further work

Intelligent camera-based systems capable of guiding mechanical and/or thermal weeding devices are effective but still too expensive to be transferred to small farms that still prefer to opt for low-tech and low-cost solutions (Peruzzi *et al.*, 2017). The World Economic Forum (2018) reported that scaling technologies require more than just providing support to individual innovators. Support structures need to be put in place to enable smallholder farmers to adopt the new technologies. Investments in basic agricultural and technological infrastructure (roads and bridges, storage and broadband or connectivity, respectively) as well as last-mile infrastructure are essential.

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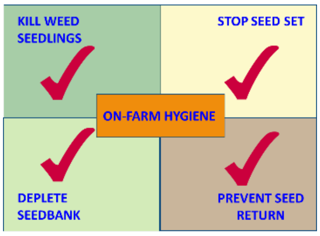
There are also concerns about the practical efficiencies of some of these technologies as they are reliant on rectangular planting (Fennimore *et al.,* 2014, Melander *et al*., 2015) and how these compare with traditional practises. Classifying plants as either crop or weeds is difficult with system accuracies of around only 85%. As a result, further research is considered necessary to quantity how efficient these systems are and how they could be best incorporated in farm management plans.

3.6. Digital tools

This section covers predominantly computer, hand held devices and internet based tools,

3.6.1. Prediction modelling



Prediction modelling for weed control uses mathematical models that quantify changes in weed populations based on weed morphological and life history traits, and their interactions with weed control methods, environmental factors, and cropping systems (Freckleton & Stephens, 2009; Colbach *et al*., 2014; Storkey *et al*., 2014).

The long-term success of weed management techniques can be hard to assess due to a number of reasons: the presence of the weed seed bank, weed life cycle traits (e.g. dormancy, reproduction), time and cost constraints (trials are rarely undertaken over more than two consecutive years), and environmental conditions. Additionally, there is a wide range of methods available for weed control, as shown in this review, and these are rarely used in isolation. Prediction models can overcome some of these difficulties, enabling researchers to assess weed populations dynamics and control success on both temporal (over time) and spatial (over area) scales, and under combinations of multiple different conditions (e.g. variable temperatures, soil types, cropping systems, weed densities, water availability) (Freckleton & Stephens, 2009; Colbach *et al*., 2014; Freckleton *et al*., 2018). This allows researchers and advisors to produce advice for stakeholders and decision makers, from farmers to policy makers (Colbach *et al*., 2014).

Although prediction models can provide information on the likely effects and success of weed control methods over a number of years they have a number of drawbacks. Cropping systems are extremely complex, with a multitude of interactions, making them extremely hard to model. Consequently prediction models might be either too simple or conversely too complex (Colbach *et al*., 2014). Models are 'data hungry', needing validated parameters across spatially and temporally replicated populations, with weed models often influenced by the site-specific factors of the data used (Freckleton *et al*., 2018). Weed morphological and life history traits are also needed for prediction modelling to predict the response of weed communities to changes in weed management. It can be time consuming and costly to obtain the necessary data , but recently a weed trait data base (WTDB)

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has been developed to be used in prediction modelling, with traits of 19 annual weed species and the scope to add more (Storkey *et al*., 2014).

Herbicide resistance modelling

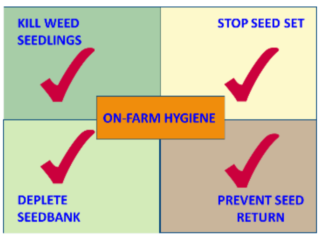
Herbicide resistance models are predictive models that integrate knowledge and hypothesise on the development of herbicide resistance. They can be used to understand and predict the evolutionary processes that may lead to resistance and explore resistance prevention strategies (Renton *et al*, 2014). Herbicide resistance models can address a number of factors relating to the development of resistance and its prevention (Neve *et al*., 2010; Renton *et al*., 2011; Renton *et al*., 2014) such as:

- Predicting the time for resistance to emerge
- Assessing resistance prevention strategies including:
    - Herbicide rotations and mixtures
    - High vs low herbicide dose
    - Cultural control
- Investigating the influence of genetic, ecological, and biological factors
- Examining the spread of resistance through pollen and seed dispersal
- Investigating the influence of polygenic vs monogenic resistance mechanisms
- Assessing the effect of the presence of more than one resistance mechanism
- Highlighting data and knowledge gaps

One benefit of using herbicide resistance models is that they can predict the evolution and spread of underlying resistance mechanisms across millions of individuals over temporal and spatial scales and under different management practices. This is something that is prohibitively costly under experimental conditions (Renton *et al*., 2014). However, like other prediction models, herbicide resistance models are 'data hungry' and require verified data of weed species, cropping systems, and the genetics and inheritance of resistance traits (Neve *et al*., 2010).

A possible use for herbicide resistance prediction modelling in UK cropping systems is to predict the likelihood of development of glyphosate resistance in different cropping systems and weed species, and to evaluate the success of different control methods (Neve, 2008).

3.6.2. Decision support systems



Agricultural decision support systems (DSS) cover a range of tools including pest monitoring, treatment thresholds, forecasting, pest density, and comparison of systems for control. Successful use of weed DSS can reduce the use of herbicides by 20-40% compared to local 'best practice programmes', without reducing efficacy (Rydahl *et al.*, 2017). In Europe

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DSS are often developed to support EU Directive 2009/128/EC and the eight general principles for IPM (Barzman *et al*., 2015; Bückmann *et al*., 2018).

Weed DSS differ from those for invertebrate pest and disease, as weeds are not generally mobile and are present in a field year on year, persisting in the seedbank. This means that more information is often required at an individual field level and management decisions need to take place over consecutive years, rather than in one growing season. One example of this is Weed Manager, a model based DSS that was developed in the UK to support arable farmers in weed control decision making within a single season and over multiple seasons allowing for rotational aspects (Parsons *et al*., 2009).

Some weed DSS can be relatively simple, such as the Corteva (Dow) Kerb postcode checker (http://uk.dowagro.com/oilseed-rape-to-spray-or-not-to-spray/). The only input required by the user is a postcode, with the output using a traffic light system to advise on whether or not conditions are right for Kerb application. However, for most weed DSS much more data input is required from the user for the DSS to be useful on a practical level, such as weed densities, species and growth stage (Rydahl, *et al*., 2017). IPMWise (http://dk.ipmwise.com/) is another DSS that shows users the expected impact of different integrated weed management (IWM) strategies will have on weed control and how to optimise treatment options. Currently, IPMWise is available in Denmark, Norway, Germany, and Spain, and has the potential to move into other countries (Rydahl, *et al*., 2017). However, DSS are developed for certain climatic and crop growth conditions, and therefore need to be validated before they can be used in new countries/climatic zones (Bückmann *et al*., 2018).

Uptake of weed DSS is generally low, as growers are often too busy or reluctant to conduct manual weed inspections to gather data required. Work is being done to help overcome this problem. For example the development of RoboWeedSupport (www.roboweedsupport.com), which is an online tool designed to enable growers to upload and analyse pictures of weeds taken in fields. This type of technology could link DSS use to new technologies and tools such as weed sensing and robotics (discussed in 3.5.1 and 3.5.2). Uptake of weed threshold based DSS is also low as growers tend to apply herbicides at densities lower than the economic threshold. However, increased on-farm demonstrations and long-term research on weed thresholds could remedy this situation (Swanton *et al*., 2008). Some weed threshold DSS are not popular as they only take into account the weed pressure and reduction in herbicide use for one growing season. Even residual weed populations can replenish seedbanks to levels that increase weed pressure and yield loss in subsequent years (Simard *et al*., 2009).

Another reason for low uptake of DSS is that they cannot be easily accessed by farmers, growers, and advisors. To increase DSS access and uptake, the EU will be funding a Horizon 2020 (H2020) project in 2019, Stepping up integrated pest management: Decision support systems (SFS-06-2018-2020), IPM Decisions (led by ADAS). The project aims to bring together existing DSS onto one user-

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friendly, easily accessible platform, making them widely available to users across a broad geographic range (European Commission, 2017).

3.6.3. Internet tools

A range of websites provide free information to farmers on weed control websites where membership/payment is required are not included. The information available to UK farmers is not easy to find and could be made more available.

Distributors and commercial companies

The amount of information available on the sites of agrochemical and distributor companies is variable and sometime behind a paywall, or can be hard to find.

Defra http://randd.defra.gov.uk/

The Defra research and development database contains a wealth of research projects but it can be difficult to search if you don't know the project number or who conducted the research. Sometimes the final reports have not been uploaded.

British Beet Research Organisation (BBRO) https://bbro.co.uk/

The British Beet Research Organisation (BBRO) implements and commissions research specifically for the UK sugar beet industry. The results are shared with growers and advisors at meetings, demonstration farms and events and through our regular publications.

AHDB https://ahdb.org.uk/

The AHDB are a statutory levy board, funded by farmers, growers and others. The website contains a large selection of documents on all aspects of weed control in cereals and oilseeds, grassland, potatoes and horticultural crops.

Processors and growers Research organisation (PGRO) http://www.pgro.org/

PGRO is a non-statutory levy body supported by grower members, the UK trade and also by a substantial amount of outside funding for our research work. UK levy paying growers are automatically members of the PGRO and can access the information and services of the PGRO free of charge. Other organisations and individuals can also access the PGRO research and advisory services by paying to join as associate members. The website contains extensive information on growing vining and combining peas, field beans

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***CROPROTECT* [*https://croprotect.com/*](https://croprotect.com/)**

CROPROTECT is a web-based knowledge exchange system to provide farmers and agronomists with guidance on weed management, especially in situations where effective pesticides are not available and alternative approaches are required. It comprises a grower interface, geographic information system, module gathering information and an information delivery module. The website content is being increased over time, currently there are documents on individual weed species or groups, one on weed competition and one on herbicide resistance. Croprotect is sponsored by the BBSRC NERC Sustainable Agriculture Research & Innovation Club.

***Infloweb* [*http://www.infloweb.fr/*](http://www.infloweb.fr/)**

Infloweb was developed in 2012 by CETIOM, ACTA AgroSup Dijon, ARVALIS-Institut du végétal, FNAMS, INRA, ITAB and ITB, with financial support from the French Ministry of agriculture. The site provides basic knowledge of weeds to support integrated weed control strategies. It includes identification, biology, habitat, factors that favour weeds, harmfulness and non-chemical control methods (Lieven *et al.*, 2013). It covers over 40 major arable weeds.

***Terres Inovia* [*http://www.terresinovia.fr/*](http://www.terresinovia.fr/)**

A website that covers oilseeds, protein crops and hemp which is funded by producers of oilseed and protein crops, Ministry of Agriculture, public research and development contracts (European Commission, French ministries, regions) and research contracts with the industrialists of the sector.

This contains very detailed information on the chemical and cultural control of weeds with specific chemical recommendations and cultural control timings.

***Arvalis* [*https://www.arvalis-infos.fr/*](https://www.arvalis-infos.fr/)**

A website that covers cereals, maize, sorghum, potatoes, fodder crops, flax and tobacco. Run by the Institut du vegetal.

It contains topical articles and more detailed information on subject areas with detailed product information also available.

GRDC (Grains research and development Corporation) https://grdc.com.au/

The GRDC is a statutory corporation, founded in 1990, under the Primary Industries Research and Development Act 1989 (PIRD Act). The GRDC's portfolio department is the Australian Government Department of Agriculture. GRDC's purpose is to invest in RD&E to create enduring profitability for Australian growers. Their website covers many aspects of weed control part of which is the Integrated Weed Management Hub.

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https://grdc.com.au/resources-and-publications/resources/iwmhub

Team Weedsmart https://weedsmart.org.au/

Australia's agricultural sector united to establish *WeedSmart*, an industry-led initiative to enhance on-farm practices and promote the long term sustainability of herbicide use.

AHRI https://ahri.uwa.edu.au/

AHRI is a national research and communication team based at the University of Western Australia. AHRI receives major investment from the Grains Research and Development Corporation (GRDC) and is a GRDC national centre.

3.6.4. Apps

Weed identification apps come as two types, those that take photographs and use recognition software and a database to identify the weed. The second type replies upon the operator to use a key to identify the correct weed species (Table 14). None of the apps are perfect and further development is need to combine the best features of each.

Table 14: Examples of weed identification apps available to download in 2018

Name	Supplier	Comments
ID weeds	University of Missouri's College of Agriculture, Food and Natural Resources' Division of Plant Science.	ID Weeds allows you to search for weeds by their common or latin name, view a list of weeds, or identify weeds based upon a number of different characteristics. Details about each weed are presented, along with photograph(s) of the weed specified.
Weed ID app	BASF	140 species, based on Encyclopaedia of Arable Weeds Based on the acclaimed Encyclopaedia of Arable Weeds and developed in association with ADAS, the BASF Weed ID app aims to provide an easy to use reference guide to the major broad-leaved weeds and grass-weeds in the UK supporting weed identification of 140 species. Full description of each weed species at cotyledon, young plant and mature plant growth stages supported by accompanying pictures aiding identification Detailed grass-weed line drawings to highlight distinguishing features often too difficult to see from a photograph Interactive search of weed library via Weed ID Filter, Common Name List, Scientific Name List, or Free Text Search
Pl@ntNet	Cirad, INRA, Inria, IRD and Tela Botanica network	Upload picture, compares it with a database. App helps identifying plant species from photographs, through a visual recognition software.
Agronomy tool app	Bayer	Weeds can be searched for using their characteristics and high resolution images are provided to help with ID
Bayer Weed spotter	Bayer	This weed identification tool from Bayer CropScience provides an interactive user experience where a farmer can browse photos of almost 100 weeds. Each weed is

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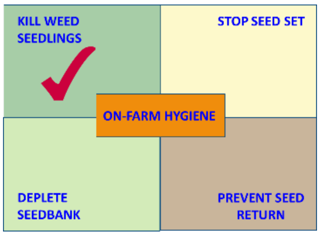
Name	Supplier	Comments
		also described in detail for the user. You can search for a specific weed or browse through them in A to Z format.
BBRO weed identification	BBRO	Weeds are described in detail and pictures provided to help identification of 137 weed species in sugar beet and 35 grass weed species.
Dow Grassland	Dow AgroSciences (Corteva agrisciences)	Helps determine which weed control products are suitable in grasslands and allows growers to calculate the cost of weeds on their farms output.
iSOYLscout	SOYL	iSOYLscout is a field scouting app for iPhones and iPads which enables growers, or anyone else helping to manage the business, to log features and problems on the land while they are in the field. The app makes the recording, monitoring and review of in-field problems and variations much easier for farmers.
iSOYL	SOYL	iSOYL is the pioneering new app which allows you to manage your precision crop production tasks direct from the tractor cab via your iPad. Variable rate application files created in MySOYL are seamlessly transferred to iSOYL ready to be used in the field. After application, data can be sent back directly to your crop management system, eliminating the need for written notes.
ID weeds	The University of Missouri's College of Agriculture, Food and Natural Resources' Division of Plant Science	Another mobile tool for identifying weeds on the go. Photos and detailed descriptions help growers identify the worst weeds in their fields.

3.7. Genetic Tools

Manipulating genes in crop plants and weeds is a new area of technology that may be used to control weeds in the future.

3.7.1. Herbicide tolerant crops



Herbicide tolerant crops have been researched for decades and are crop varieties developed to be tolerant to herbicides to which they are ordinarily sensitive (Lamichane *et al*., 2017). They differ to genetically modified crops (GMCs) (3.7.2) as they are derived from the traditional plant breeding technique of gene mutation rather than the insertion of new DNA (Tran & Bowe, 2012). Mutation of crops without using genetic engineering techniques is done using induced mutagenesis, where random mutations of genes already present in an organism occur as a result of exposure to irradiation or mutagenic chemicals (Forester & Shu, 2012). Most herbicide tolerant crops that are commercially available have been created using induced mutagenesis in a two-step process, with plant seeds, pollen, or microspores exposed to mutagens, and herbicide tolerant off-spring screened against herbicide treatments (Tran & Bowe, 2012).

The use of herbicide tolerant varieties increases the range of available in-crop herbicides, enabling increased weed control, particularly of species closely related to the crop, such as oilseed rape and charlock (*Sinapsis arvensis*) (Lamichane *et al*., 2017). Herbicide tolerant crops can also help

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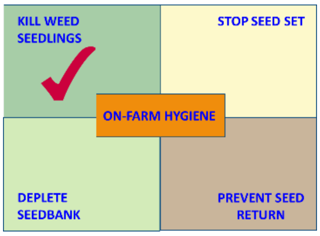
increase weed control by widening rotations (3.2.1) through the development of varieties that are tolerant to residual herbicides used in the previous year's crop, which would otherwise cause injury to non-tolerant varieties (Tan *et al*., 2005). However, there is also the potential for herbicide tolerant varieties to shorten rotations by providing more effective herbicide solutions for hard to control weeds. Additionally the option of using residual herbicides in herbicide tolerant crops could limit cropping options in the following year (Lamichhane *et al*., 2017).

However, like with genetically modified crops there can be issues with the development of herbicide resistant weeds in association with herbicide tolerant crops, and the possibility that the genes conferring herbicide tolerance may transfer from the herbicide tolerant crops to susceptible varieties or even wild relatives (Krato and Petersen, 2012a).

A number of herbicide tolerant crop varieties have been developed, including imidazoline-resistant sunflowers, maize, and wheat, and sulfonylurea-resistant soybeans and sunflowers (Tran & Bowe, 2012). Currently in the UK Clearfield® oilseed rape is available, which is tolerant to imidazoline herbicides (Tan *et al.*, 2005), and it is likely that Conviso® Smart ALS-tolerant sugar beet varieties will be available in the UK in 2020 (Hagues and Stibbe, 2017).

3.7.2. Genetically modified crops



Genetically modified organisms (GMOs) are characterised by the breeding techniques that were used to obtain genetic changes and not the change itself (European Commission, 2001: Directive 2001/18/ED Annex I B). For example, in the EU herbicide tolerant crops produced as a results of mutations are not classified as GMOs, but herbicide tolerant crops where a gene has been inserted into the genome are classified as GMOs (European Commission, 2001).

The insertion of DNA into a plant for genetic modification is often achieved using micro projectile bombardment, where plant cells are bombarded with DNA till it is integrated into the genome. However, this method results in considerable variation in the stability, integration, and expression of the introduced gene. An alternative method is using the bacterium *Agrobacterium tumefaciens.* This contains a circular molecule of DNA or plasmid in which the gene of interest is inserted. When mixed with host plant cells, *A. tumefaciens* has the ability to transfer DNA from the modified plasmid into the plant cells, so that they become genetically modified. Cells modified using either micro projectile bombardment or *A. tumefaciens* are then selected using markers, such as herbicide resistance, and regenerated into whole plants using tissue cell culture methods (Shrawat & Lörz, 2006).

The first genetically modified crops (GMCs) were introduced in 1996, and currently, around the world thirty genetically modified crop species have been approved for use in food or for cultivation, with

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many being modified for herbicide tolerance (ISAAA, 2018). The adoption of herbicide tolerant GMCs has been extremely rapid in some countries, for example since its introduction the area of herbicide tolerant GM maize in the USA has increased from 3% in 1996 to 90% in 2018 (USDA Economic Research Service, 2018) (Figure 13). This rapid adoption can be attributed to the low cost, flexible, and selective weed management strategies associated with herbicide tolerant GMCs and their compatibility with no-till or minimum-tillage systems (Lamichhane *et al*., 2017).

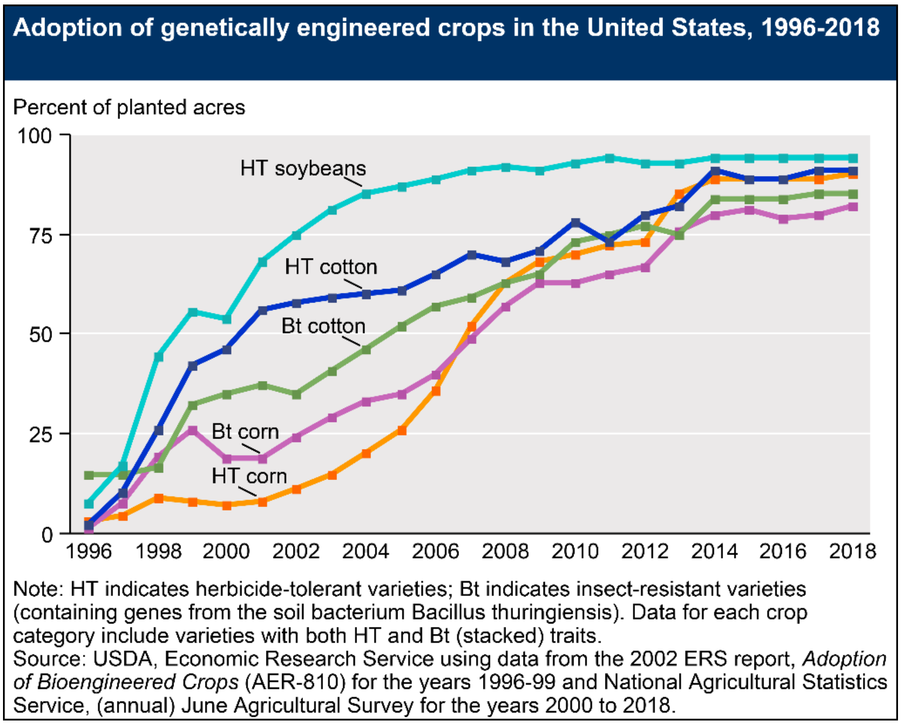

Figure 13: From USDA Economic research service (2018). Percent planted acres in USA of genetically modified crops. (HT Corn is equivalent of HT maize.)

In the EU a technology-based regulatory system, Directive 2001/18/EC, is used for GMOs. All GMOs are subject to an assessment of the risks they pose to humans, animals and the environment. The level of acceptable risk and the decision on whether a GMO can be commercialised is assessed by risk managers, including policy makers and regulators. This means that the regulation of herbicide tolerant GMCs is different to that for other herbicide tolerant crops, even though the overall outcome is the same (Lamichhaine *et al*., 2017). Currently, no herbicide tolerant GMCs are approved to be commercially grown in the European Union (ISAAA, 2018). However, the situation in the UK may change once the country has left the EU. For example, there may be move towards a product-based regulatory system, like that of Canada, where herbicide tolerant GMCs and other herbicide tolerant crops would be assessed on their traits and not how those traits were achieved (Lamichhane *et al*., 2017).

Although there are currently no GMCs grown in the UK, of the thirty approved GMCs five could potentially be grown in the UK with herbicide tolerant traits (Table 15), and the uptake of these could

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potentially lead to improved farming systems. In 2014, a meta-analysis of the impacts of GMCs found that the adoption of herbicide tolerant GMCs resulted in an average increase in yield of 10% and a decrease in pesticide costs of 25%, although pesticide usage was unchanged. Farmer profit was also increased by an average of 65%, although it was not significant compared to non-GMCs due to high variability (Klümper and Qaim, 2014).

Like the use of other herbicide tolerant crops, there are practical issues surrounding the use of herbicide tolerant GMCs. The high use of glyphosate for weed control in glyphosate tolerant GMCs exerts high selection pressure for the development of glyphosate resistance and has led to a rapid increase in the number of glyphosate resistant weeds (Lamichhane *et al*., 2017; Heap, 2018). However, when used within a diverse cropping rotation, with integrated weed management, the evolution of glyphosate resistant weeds in glyphosate tolerant GMCs can be prevented, as has been the case for glyphosate tolerant oilseed rape in western Canada (Harker *et al*., 2012; Heap, 2018). There is also the possibility of gene flow between GMCs and closely related weed species, with the herbicide tolerant trait transferring to conventional varieties or wild populations (Stewart *et al*., 2003), and the escape of GMCs outside of agricultural environments where they have been shown to persist and become weeds themselves (Busi and Powles, 2016). The potential, consequences, and mitigation strategies for both these possibilities would need to be investigated before any introduction of GMCs into the UK. Therefore, herbicide resistance prevention strategies and product stewardship would need to be developed and implemented for any herbicide tolerant GMCs used in the UK.

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Table 15: Adapted from ISAAA (2018). Genetically modified crops approved for use, which could potentially be grown in the United Kingdom for weed control. Countries and year of approval of gene trait in crop listed, for full list of all crops and countries approved for use in food and feed see www.isaaa.org

Crop	Crop trait	Example trade names	Gene Introduced	Gene Source	Function	Approved countries	Year
Oilseed rape (*Brassica napus*)	Glyphosate tolerance	Optimum® Gly canola	Gat4621	*Bacillus licheniformis*	Glyphosate N-acetyltransferase catalyzes and inactivates glyphosate	Australia Canada Japan USA	2016 2012 2015 2013
	Glyphosate tolerance	Roundup Ready™ Canola	cp4 EPSPS (aroA:CP4)	*Agrobacterium tumefaciens*	Glyphosate tolerant form of EPSPS enzyme, decreasing binding affinity of glyphosate	Australia Canada Japan USA	2003 1995 2006 1999
	Glyphosate tolerance	Roundup Ready™ Canola	goxv247	*Ochrobactrum anthropi* strain LBAA	Confers tolerance to glyphosate by degrading it into AMPA and glyoxylate	Australia Canada Japan USA	2003 1995 2006 1999
	Glufosinate tolerance	Liberty Link™ Independence™ Liberty Link™ Innovator™ InVigor™ Canola	bar	*Streptomyces hygroscopicus*	Eliminates glufosinate activity by acetylation	Australia Canada Japan USA	2003 1995 2007 2002
	Glufosinate tolerance	InVigor™ x TruFlex™ Roundup Ready™ Canola InVigor™ Canola	pat (syn)	Synthetic form of pat gene from *Streptomyces viridochromogenes*	Eliminates glufosinate activity by acetylation	Australia Canada Japan USA	2003 1996 2007 1998
	Oxynil tolerance	Navigator™ Canola	bxn	*Klebsiella pneumoniae*	Nitrilase enzyme to eliminate oxynil	Canada Japan	1997 2008
Carnations (*Dianthus caryophyllus*)	ALS inhibitor tolerance	Moonshade™ Moonshadow™ Moondust™ Moonlight™ Moonaqua™ Moonvista™ Moonique™ Moonpearl™ Moonberry™ Moonvelvet™	surB	*Nicotiana tabacum*	ALS inhibitor tolerant form of target gene	Australia Colombia Japan Malaysia Norway	2004 2000 1995 2012 1997
Maize (*Zea mays*)	Glyphosate tolerance	Roundup Ready™ maize Agrisure®	mepsps	Modified form of EPSPS gene	Glyphosate tolerant form of EPSPS enzyme,	Argentina Brazil Canada	2005 2008 1998

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		Agrisure® Duracade™ Agrisure® Viptera™			decreasing binding affinity of glyphosate	Japan Paraguay Philippines South Africa USA Uruguay Vietnam	2005 2015 2009 2010 1997 2011 2015
	Glyphosate tolerance	Roundup Ready™ Maize Roundup Ready™ Liberty Link™ Maize YieldGuard™ MaizeGuard™ Genuity® SmartStax™ Herculex™ RW Roundup Ready™ SmartStax™ Pro x Enlist™ Power Core™	cp4 EPSPS (aroA:CP4)	*Agrobacterium tumefaciens*	Glyphosate tolerant form of EPSPS enzyme, decreasing binding affinity of glyphosate	Argentina Brazil Canada Chile Colombia Cuba Egypt Honduras Japan Pakistan Paraguay Philippines South Africa Uruguay USA	2004 2008 2001 2007 2007 2011 2008 2001 2004 2017 2012 2010 2002 2011 2000
	Glyphosate tolerance	Roundup Ready™ Maize YieldGuard™ MaizeGuard™	goxv247	*Ochrobactrum anthropi* strain LBAA	Confers tolerance to glyphosate by degrading it into AMPA and glyoxylate	Argentina Brazil Canada Chile Colombia Cuba Egypt Honduras Japan Paraguay Philippines South Africa USA Uruguay	1998 2007 1997 2007 2007 2011 2008 2001 2004 2012 2002 1997 1995 2003
	Glufosinate tolerance	Agrisure® Duracade™ Herculex™	pat	*Streptomyces viridochromogenes*	Eliminates glufosinate activity by acetylation	Argentina Brazil Canada Colombia Honduras	2001 2008 1996 2007 2009

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		Herculex™ RW Roundup Ready™ Agrisure® CB/LL Agrisure® GT/CB/LL Agrisure® Viptera™ SmartStax™ Pro x Enlist™ Genuity® SmartStax™ Power Core™				Japan Panama Paraguay Philippines South Africa USA Uruguay Vietnam	2005 2012 2012 2010 2003 2001 2011 2015
	Glufosinate tolerance	NaturGuard Knockout™ Maximizer™	bar	*Streptomyces hygroscopicus*	Eliminates glufosinate activity by acetylation	Argentina Canada Japan USA	1998 1996 2007 1995
	Glyphosate tolerance	Hysyn 101 RR Roundup-Ready™	cp4 EPSPS (aroA:CP4)	*Agrobacterium tumefaciens*	Glyphosate tolerant form of EPSPS enzyme, decreasing binding affinity of glyphosate	Canada	1997
	Glyphosate tolerance	Hysyn 101 RR Roundup-Ready™	goxv247	*Ochrobactrum anthropi* strain LBAA	Confers tolerance to glyphosate by degrading it into AMPA and glyoxylate	Canada	1997
Brassica rapa	Glyphosate tolerance	InVigor™ Sugar beet	cp4 EPSPS (aroA:CP4)	*Agrobacterium tumefaciens*	Glyphosate tolerant form of EPSPS enzyme, decreasing binding affinity of glyphosate	USA	1998
	Glyphosate tolerance	InVigor™ Sugar beet	goxv247	*Ochrobactrum anthropi* strain LBAA	Confers tolerance to glyphosate by degrading it into AMPA and glyoxylate	USA	1998
Sugar beet (*Beta vulgaris*)	Glyphosate tolerance	Roundup Ready™ Sugar beet	cp4 EPSPS (aroA:CP4)	*Agrobacterium tumefaciens*	Glyphosate tolerant form of EPSPS enzyme, decreasing binding affinity of glyphosate	Canada Japan USA	2005 2007 2005
	Glufosinate tolerance	Liberty Link™ Sugar beet	pat	*Streptomyces viridochromogenes*	Eliminates glufosinate activity by acetylation	Canada USA	2001 1998

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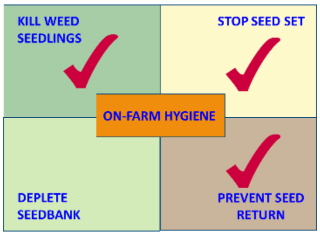
3.7.3. CRISPR technology



CRISPR/Cas (clustered regularly interspaces short palindromic repeats) technology is a precision genome-engineering tool that uses RNA-guided Cas nucleases to cleave/cut targeted sections of double stranded DNA in cells, facilitating genome editing (Cong *et al*., 2013). This technology can be used to 'knock out', edit, or insert targeted sections of DNA resulting in beneficial changes to organisms, such as plants (Neve, 2018).

CRISPR/Cas is different to other genetic modification techniques, which insert DNA, often from different species, into random points of the genome (Kanchiswamy *et al.*, 2015). Current genetic modification techniques only engineer DNA onto one chromosome copy and in diploid organisms, where there two chromosome copies of the DNA are present, only one copy of the DNA is changed, creating heterozygous individuals, with one copy with the 'new' gene and one copy without (Shrawat & Lörz, 2006). CRISPR/Cas can transform both copies of the DNA through the mutagenic chain reaction (MCR), where the initial insertion spreads from the chromosome of origin to the corresponding chromosome creating homozygous individuals with two copies of the DNA, creating a more robust genetically engineered individual. Additionally, reproduction between a genetically engineered homozygous parent and a wild-type individual would usually result in heterozygous off spring, however as a copy of the inserted Cas will be present in the off-spring the MCR will also take place in the off-spring, creating homozygous individuals (Gantz & Bier, 2015). As a result of the MCR, CRISPR/Cas technology could be used in gene drives to spread desirable traits through wild populations by biasing the chances of inheritance to levels above those of 'predictable' Mendelian segregation (Esvel *et al*., 2014).

CRISPR/Cas is cheap, quick and easy to use. It is rapidly developing and is likely to progress much faster than other genetic engineering techniques. CRISPR/Cas therefore offers considerable future potential for use in weed control. CRISPR/Cas technology has the potential to be used to genetically engineer crops for desirable weed control traits, such as creating crops resistant to herbicides to which they are otherwise susceptible, increasing in-crop herbicide availability, or to increase crop competitiveness. Through using gene drives, there could also be the potential to control weed populations through manipulating characters, such as 'weakening' weeds by inserting traits that reduce fitness, or by knocking out target site herbicide resistance (Sun *et al*., 2016; Neve, 2018). However, there are many potential ethical issues related to CRISPR/Cas gene editing, particularly surrounding editing natural populations and the potential to eliminate species through spreading deleterious traits using the MCR (Webber *et al*., 2015). Although in reality it would be more likely that if CRISPR technology were to be used on wild weed populations it would be to knock out herbicide resistance traits (Neve, 2018).

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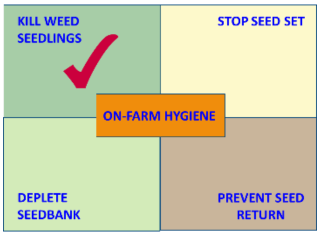
It can be argued that CRISPR/Cas gene editing is similar to the older genetic engineering technique of mutagenesis, as CRISPR/Cas can involve changes to DNA instead of insertion of new DNA, particularly as some CRISPR/Cas changes cannot be detected (Georges & Ray, 2017). However, in August 2018, the Court of Justice for the European Union ruled that CRISPR/Cas gene editing fell under the 2001 GMO directive 2001/18/EC, classifying organisms that have been genetically engineered using CRISPR/Cas as GMOs and subjecting their use to the same restrictions imposed on other GMOs as discussed above (3.7.1). This may reduce the development and use of CRISPR/Cas gene edited crops across the EU (Callaway, 2018). At this moment in time it can only be speculated how this ruling may affect the development and use of CRISPR/Cas agricultural technology in the UK once it has left the European Union. However, the UK government released a statement in response to the ruling, which supports the use of CRISPR/Cas gene editing technology: "Our view remains that gene-edited organisms should not be regulated as GMOs if the changes to their DNA could have occurred naturally or through traditional breeding methods" (Allen-Stevens, 2018b).

3.7.4. RNA interference technology



RNAi technology was first discovered in 1998 and works by delivering double stranded RNA (dsRNA) into cells, which then disrupt the function of targeted genes by targeting the messenger-RNA (mRNA) transcribed from those genes, degrading the mRNA before proteins can be produced, effectively silencing the gene and its function (Montgomery *et al*., 1998). RNAi technology can potentially be used to help combat target site herbicide resistance in weeds. For example, Monsanto (recently acquired by Bayer) are developing BioDirect™, which is a topical application of glyphosate and double stranded RNAi, which will interfere with the glyphosate resistance genes in resistant weeds reversing the resistance (Reddy & Jha, 2016).

3.7.5. Quantitative trait loci

Quantitative traits are traits, such as non-target site herbicide resistance, that are underpinned by variation at a number of different genes. Quantitative trait loci (QTLs) are the areas of the genome that contain genes related to the quantitative trait, and can be used to identify areas of the genome that contain genetic variation in the form of single nucleotide polymorphisms (SNPs) (Collard *et al*., 2005).

QTL mapping is complex, not easily applied to natural populations and requires a large set of genetic markers, and is therefore not practical for most weed species (Délye, 2013). However, QTL mapping can be applied to *Arabidopsis thaliana* populations. As few as 56 *A. thaliana* accessions can be used to detect 98% of SNPs shared between geographic regions, and 67 accessions can be used to detect 98% of all common SNPs (Cao *et al*., 2011). *A. thaliana* QTL mapping could provide insight into areas of interest in the genome of other weed species. Some preliminary work has been done,

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looking into QTLs relating to variation in response to glyphosate in *Arabidopsis thaliana*, highlighting a region on chromosome 2 containing genes associated with translocation amongst others (Davies, 2015).

3.7.6. Weed genome sequencing

Arabidopsis thaliana was the first plant species to have its entire genome sequenced and is used as the basis for molecular, genomic, and genetic approaches for plants that have not had their genome sequenced. This has the drawback that it is assumed that gene functionality has been preserved between species (Arabidopsis Genome Initiative, 2000; Maroli *et al*., 2018). Sequencing the genome of prominent weed species will allow a better understanding of basic weed biology, weed evolution, reproduction, invasiveness, and herbicide resistance (Ravet *et al*., 2018). Genome sequences could be used to better understand the multiple genes involved in NTSR, allowing for improved insight into the evolutionary processes of NTSR and NTSR diagnostics, consequently improving weed management strategy decision making and proactive resistance management (Ravet *et al*., 2018). However, due to the complexity of molecular and environmental interactions genome sequencing needs to be used as part of an integrated systems biology approach in conjunction with other 'omics' approaches (e.g. proteomics, metabolomics), to enable understanding between genotype-phenotype relationships and the improvement of weed management strategies (Maroli *et al*., 2018).

To date only four weed genomes have been sequenced, compared to those of more than 30 plant pests and 275 plant pathogens. In 2017, a questionnaire by the newly established International Weed Genomics Consortium (IWGC) identified rigid/annual ryegrass, hairy fleabane (*Conyza bonariensis*), waterhemp (*Amaranthus tuberculatus*), Johnsongrass (*Sorghum halapense*), black-grass, and hairy crabgrass (*Digitaria sanguinalis*) as the top priority weed species for genome sequencing. Weed genome sequencing is in early development, but the formation of the IWCG, which aims to form a coordinated, international, and multi-disciplinary consortium for weed genomics, shows the increasing interested in this area (Ravet *et al*., 2018).

3.8. Preventative weed control

Preventative weed control refers to any control method that aims to prevent weeds from becoming established on farm. Preventative weed control is a key strategy in IWM systems (Hamill *et al.* 2004).

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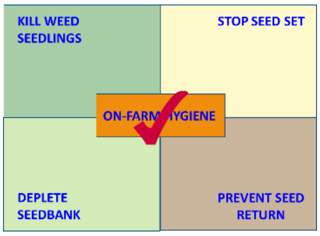
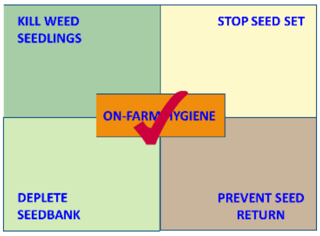
3.8.1. Contaminated straw



Most weed seeds end up on the ground after harvest, but some will be retained on the plant, incorporated into baled straw and removed from the field (AHDB, 2018b). Straw has been highlighted as the primary source of black-grass seed to mixed farms in the west of the UK and Scotland. This is used as bedding and the resulting manure is spread to land. Straw is also used to protect carrots over the winter and in Shropshire this has led to new outbreaks of black-grass.

It has been suggested that straw passports may be the answer. https://www.fwi.co.uk/arable/farmer-focus/farmer-focus-could-straw-passports-help-battle-weeds

3.8.2. Forage, feed and livestock



Livestock can move weed seeds around a farm in a number of ways. They can eat them, they can become attached to their coats and they can be moved in the vehicles used to transport the animals (Hogan & Philips, 2011).

Seeds of great brome (*Bromus diandrus*), *Vulpia* spp., *Wild-oat* (*Avena fatua*) and wild radish (*Raphanus raphanistrum*) were ensiled for a minimum of three months or underwent 48 h *in sacco* digestion in steers or were ensiled prior to digestion, all methods rendered the seeds unviable (Piltz & Staunton, 2017). In the UK, Richard Hull at Rothamsted Research (Pers. Comm.) ensiled black-grass seed and none survived the process.

A proportion of weed seeds have been shown to remain viable after passing through an animal's digestive tract but the majority by-pass the animal and enter or are already present in the bedding. Seed survival of grass species subjected to rumen digestion tended to be less than that of broad-leaf species (Blackshaw & Rode, 1991). Downy brome, foxtail barley, and barnyard grass were non-viable after rumen digestion for 24 h. some green foxtail (17%) and wild-oats (0 to 88%) seeds survived digestion in the rumen.

Weed seeds can also enter livestock systems from palletised feed products. Cash *et al*., (1998) estimated that for palletised products, less than 1% of weed seed survive feed grinding and palletising.

Katovich *et al*., (2004) found that seed survived ensiling, in manures, in digestate and in composted manures and advised avoiding feed containing high levels of weed seed particularly home produced.

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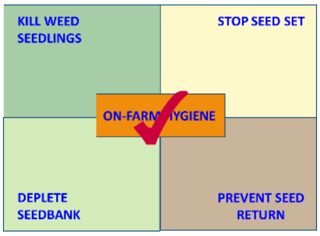
3.8.3. Composting, anaerobic digestion, and sewage sludge

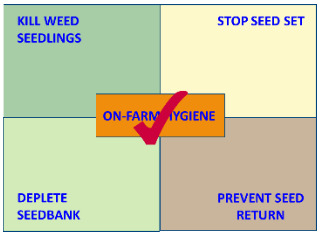


Livestock manures and waste materials can be further processed by composting or anaerobic digestion. Weed species with hardseed coats like field bindweed and velvetleaf (Mallow family) present the greatest risk of surviving composting (Katovich *et al*., 2004). However, if the compost is moist, reaches 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, the manure should be kept in windrows and regularly turned. If the turning and heating process is incomplete then there is likely to be some survival of seeds.

Recent work from WRAP (2013) indicated that there was some survival of black-grass 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).

Sewage sludge can also be applied to crops before planting or to growing crops. Sludge may contain viable weed seeds but any which germinate will usually be controlled by normal farming practices, such as livestock grazing and use of herbicides. However, tomato seeds are particularly hardy and adult plants can be toxic to livestock and sludge should not be applied between March and August of the year the crop is to be planted to reduce the risk of tomatoes germinating (Department of the Environment, 2018).

3.8.4. Weeds in sown seed



Unwanted weed seeds can be harvested within the intended crop seed, especially those which ripen at a similar time. Sieving and separation helps remove weed seeds.

In the UK, Seed Certification Schemes exist to protect farmers and their customers by ensuring that the seed they buy meets certain quality standards. Field are inspected for weeds during production, and all certified collected seed must meet prescribed standards of varietal identity and purity, germination and freedom from weed seeds (NIAB, 2019). Seeds which must be certified before marketing include: beets, cereals, fodder plants, oil and fibre plants, fruits and vegetables. An extensive list can be found at (http://www.legislation.gov.uk/uksi/2011/463/schedule/1/made).

Home saved seed are more likely to contain weed seeds, if not properly cleaned and checked. However, farmers with low weed pressures, may opt to collect their own seed and use professional seed treatment firms which typically costs about £5/kg including the seed royalty, which compares to buying certified seed at about £12/kg (Cooper & de la Pasture, 2016).

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In 2008, an occurrence of black-grass in Angus (Scotland) was identified as a seed contamination in C2 (certified to the second generation) cereal seed (SAC, 2010). The standard for C2 seed is detailed in (Table 16).

Table 16 UK seed standards for certified seed to the second generation (C2), all species except maize

Weed species	Maximum number of seeds
Wild-oat (*Avena fatua)* (*Avena ludoviciana)* (*Avena sterilis)*	0
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

Source: ALPHA, 2016

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 (MacSkimming, 2016). 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. Farmers in Ireland have reported seeing black-grass in rows of wheat and believe it is a result of seed contamination (Farmers Guardian, 2017).

The list below is not extensive, but highlights the variety of weed seeds that can be found within crop seed;

- In cereal seed samples tested in 1961-68 black-bindweed was one of the most frequent contaminants being found in up to 25% of rye, 15% of oats, 23% of barley and 22% of wheat samples tested (Tonkin, 1968).
- Annual meadow-grass seed has been a contaminant in cereal grain and cultivated grass seed and was a frequent impurity in grass seeds of Danish, Irish and Swedish origin (Bond *et al.*, 2007d).
- In clover and grass seed samples tested in Denmark for the period 1966-69, 1955-57, 1939 and 1927-28, soft brome seed was a contaminant in 13.7, 7.5, 8.9 and 14.4% of samples respectively.
- Sterile brome seed was an impurity in sainfoin, barley and wheat seed, particularly in home saved seed.

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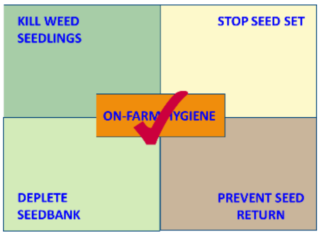
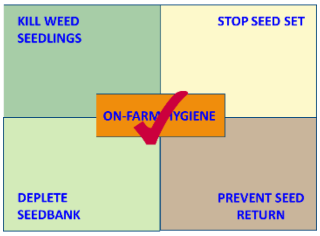
3.8.5. Manage weeds in non-cropped areas



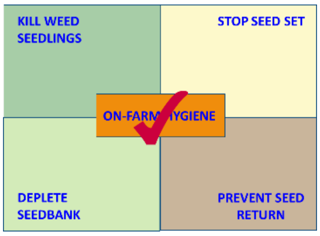
Weed infestations often begin in non-crop areas (e.g. around buildings, along roadsides, along fencelines, in unmanaged areas). Controlling these initial populations will prevent weeds from spreading to other areas. This is particularly important for weeds with wind-blown seed such as sowthistle, ragwort and groundsel which move into areas where bare soil predominates such as oilseed rape post-flowering and potted ornamentals (Atwood, 2013). 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 (Broderick, 1990).

3.8.6. Machinery



Weed seeds are known to attach to all parts of vehicles and farm machinery, often in mud picked up from the ground, fixed directly all parts of the machinery, or carried into the cabin by the driver. In Australia, Moerkerk (2006) inspected 110 vehicles and plant machinery and found 250 contaminant species or taxonomic groups. The majority of seeds were found in the cabin of passenger and four-wheel drive vehicles, with the engine bay being the next most frequent location. Khan *et al* (2018) recorded 397 weed seeds per vehicle on vehicles used to install powerlines in Southeast Queensland, Australia

3.8.7. Water



Flooding is a common source of new weed infestations through the transport of seeds and vegetative propagules such as stolons, rhizomes and tubers. Seed of chickweed has been recovered from irrigation water (Bond *et al*., 2007c). Weed seeds can be spread through water, either through irrigation or by flooding. MacNaeidhe & Curran (1982) demonstrated that rosebay willowherb seed could be transported through flooding.

Irrigation water can also be a source of weed seeds and other propagules, the areas around reservoirs and other water sources should be mown to prevent seeding and water filtered to prevent spread (Holmes & Adlam, 2006, Atwood, 2013).

3.8.8. Predation

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 (Maucheline *et al*., 2005, Gallandt 2004, 2005).

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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 (Menalled, 2008).

4. The Applicability of Weed Control Options by Crop

4.1. Horticulture

4.1.1. Field vegetables

Field vegetables include brassica (e.g. broccoli, cauliflower, cabbage, Brussels sprouts), alliums (including leeks, onions), root crops (such as carrots, parsnips, red beet), salads (including lettuce, celery and babyleaf crops), cucurbits, sweetcorn and perennial vegetables such as asparagus and rhubarb, and herbs. Provisional data (Defra, 2018a) reports 117,067 ha of field vegetables are grown in the UK with a home production value of £1.1 billion. All field vegetables are grown in crop rotations with other arable and horticultural crops and typically in rows. Although some of these crops are processed for use in ready meals, soups and canning or freezing, the main market for these crops is as fresh, unprocessed produce, and therefore crop quality attributes such as appearance are very important.

Weeds present a constant challenge for field vegetable growers. They can compete with the crop for water and nutrients leading to a reduction in yield, be a risk as a product contaminant either as seeds or as a plant in products such as salad bags e.g. groundsel and rocket. Weeds can also reduce production efficiency by slowing down pickers by obscuring the produce and getting in the way, or by deterring them in the case of small nettle as many crops are hand-picked. The most troublesome weeds in annual field vegetables are polygonums, fat hen, black nightshade, nettles (both annual and perennial), compositae such as groundsel and mayweed, and bindweed. Weeds which germinate late spring to early summer are particularly difficult to control as they emerge after the crop has established, and at this point options for control are often limited by plant canopy/ crop growth stage. Many annual field vegetable crops are established in spring with March through to June being the main drilling and planting time.

In perennial vegetables, perennial weed species such as creeping thistle, field bindweed, Marestail, perennial nettle and willowherb are the most difficult to control, with annuals such as black nightshade, mayweed, small nettle and groundsel key issues. Common amaranth is an increasing issue, especially in the drier regions of the south and east where it thrives in the recent dry summers.

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Decision making in horticulture:

Rotations

Rotational cropping is very influential in determining the weed likely to be present as other crops will have an impact on the weed seedbank. Crop volunteers pose a contamination risk to fresh produce and/or pest or disease carryover and typically drive the choice of field in which to grow these crops and presents the major starting point for effective weed control.

Therefore, for all field vegetable crops, the first consideration to aid weed control is crop rotation to minimise weed populations of similar species to the host crops, or build-up of the weeds which then subsequently become difficult to control within the vegetable crop. Growers will rotate species such as brassicas, legumes, root crops and cereals where possible to prevent a build-up of a single weed species. Rotation with autumn-sown cereal crops is advantageous in reducing the build-up of similar weed populations by introducing a different crop establishment timing (autumn), and is often practiced where possible. However, some soil types lend themselves better to a particular type of crop than others, for example root crops are predominantly grown in sand soils, and therefore this has led to regionalisation of growing, with the majority of crops grown in the midlands and East Anglia. Likewise, brassicas are frequently grown on sandy loams, and in particular silts, and have become concentrated in Cornwall and Lincolnshire. Therefore there are some limitations on rotation in these areas and weeds such as redshank, field pennycress and annual nettle can build-up in brassicas if rotations become too short.

To prevent this build-up of selected weed species, and also disease problems such as cavity spot in carrots in these areas, many field vegetable growers rent land so that they can maintain longer rotations between crops. This is shown by a higher proportion of field vegetable growers renting land than the England average. The Defra (2018) reports rented land at 33% for all farm types, while in a survey on land status of field vegetable growers for the PF-Hort project CP107c rented land or shared farm business agreements increase the percentage of 'non-owned' land to over 50%. While this means growers can rent 'new' land, this can also present challenges with volunteers from the previous crop where the rental agreement only starts just before crop planting. A particular issue is volunteer potatoes especially in areas of lighter soils. There is also following crop issues from some of the cereal herbicides where vegetable follow cereals in the rotation. However, vegetables are considered a good way to 'clean up' cereal land from issues such as black-grass (excluding strawed carrots). With the loss of the herbicide linuron for post crop establishment control of volunteers, growers are considering other options for their control, such as obtaining land rental agreements earlier.

Rotational livestock grazing and weed management

There is some livestock rotation on field vegetable holdings, particularly on organic farms where grass/clover leys, cover crops and livestock are necessary within the rotation to build and provide

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nutrients from organic sources such as manures for use on the field vegetable crops. Sheep are used on conventional farms to graze waste brassicas, but this is not particularly for weed control. In root crop rotations, pigs are often included in rotations as they are good at digging out and consuming roots after harvest. Livestock in field vegetable rotation is not widely practiced at present, as a further horticulture or cereal crop gives the best economic return on the soil types used for field vegetables. In addition the retailer protocols require two years from fresh manure applications as part of the human pathogen control measures, so limits this practice being practical for many growers.

Further action: Investigate and evaluate benefits and practicalities of livestock in rotations for weed control, particularly volunteer potatoes.

Crop species

Alliums are the least competitive of all the annual field vegetables as they never reach full cover, with the exception of leeks. Therefore throughout the growing season the crop will receive frequent applications of herbicides (every 10-14 days) to control and suppress weeds, particularly during early growth stages. Conversely, while cucurbits are competitive in terms of speed of growth, they are commonly grown through plastic for weed control because of their sensitivity to many herbicides and therefore lack of chemical control options. Consequently field selection is of particular importance for these crops, and they would most likely follow cereals to help with reducing the weed seedbank within the previous crop prior to drilling or planting.

For perennial vegetable crops such as rhubarb and asparagus, a clean start is of particular importance as there are limited opportunities for weed control and if not controlled in the early years, weed problems can build up very quickly, especially perennial weeds if not eliminated before crop planting. During the dormant phase of these crops, and also during harvest of asparagus these crops are not competitive, and again this gives an opportunity for weeds to compete.

Fallow

This is very rarely practiced unless a field has become so infested with weeds that it is not economical to use it. Unless the land is owned, the grower needs to make a return to cover rental costs, and also the current margins on produce are prohibitively low which means the grower needs to maximise returns from all fields if possible.

Digital tools

Currently prediction modelling and decision support systems are not used in horticulture but could be very useful. Growers do use weed ID apps, and are becoming more and more technologically aware, therefore these tools could be useful to aid targeting of weeds, and perhaps drilling to aid control.

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Further action: Develop Decision Support Systems and prediction modelling for weed control in field vegetable crops.

Genetic tools

These are not currently available for field vegetable crops in the UK, but could provide an option for future investigation to aid weed control for difficult targets. GM sweetcorn is available in the USA, and breeding crops with resistance to selected herbicides could be useful for the most troublesome of weeds for example, field bindweed in asparagus or groundsel in lettuce and salad crops. ALS-tolerant oilseed rape varieties have been developed so that charlock can be controlled (3.7.1), and this could also be very useful to aid control of charlock in vegetable brassicas. This is a particular problem in the south-west of the UK.

Horticultural crop establishment

Tillage and cultivations

Stale seed beds are used where possible, though this can be challenging to implement when inclement weather and demanding drilling programmes to meet retail schedules often dictate when crops are drilled, and plans have to be adjusted to suit. Cultivation is mainly plough based with ploughing largely taking place either in the autumn or spring depending on time of harvest of the previous crop, soil type, and the crop planting or drilling date. However, in salad crops which are drilled throughout the year, cultivation can take place throughout summer as appropriate too. Power harrowing or shallower cultivations of circa 5cm depth are then used to prepare the seedbed. Where a bed system is used, such as in carrots or salads, a bedformer would be used to ‘make’ the beds.

Ploughing is used for weed management as well as soil preparation purposes as it buries many seeds below depth of germination. Minimum tillage is currently not practiced in field vegetables, but a small number of growers are trialling strip-till in crops such as brassicas, for example Southern England Farms in Cornwall are trialling it as an alternative method of establishment and weed suppression, strip tilling into a cover crop (Will Illiffe, pers comm.). The USA experience is of varied success, as competition with the brassica crop can lead to reduced yields if the choice of cover and planting technique do not suit the cash crop (Hoyt, 1999; Price & Norsworthy, 2013). This varied success deters the majority of UK growers from moving away from plough based cultivations as establishment and final quality in field vegetable crops needs to be high. Growers are unwilling to bear the financial risk of reduced crop quality and yield if mistakes are made during initial transition to minimum tillage. Any loss in quality or yield per hectare is unlikely to be offset by savings made by reduced establishment costs. Therefore work would need to be done to demonstrate that minimum tillage is consistently successful, as well as guidance on the cover crop and establishment method to use.

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Volunteer potatoes are becoming an increasing problem, and growers are giving more thought to the best way to reduce volunteers before drilling the next crop. There is debate as to the best method; whether to leave them to be damaged by frost and predators before cultivation, or conversely, cultivate earlier to bury them and encourage them to chit so they can be sprayed off earlier.

Future actions: Evaluate strip-till and minimum tillage as establishment methods for field vegetables, which crops it is most suitable for, also evaluate the problems with reduced tillage and investigate ways to overcome it. In addition, evaluate different cultivation techniques and timings on the control of volunteer potatoes in the following crop.

Cover cropping

Cover cropping is becoming increasingly popular with many growers where they can manage the land and rotation, it is more difficult to manage where land is rented. It has been adopted for most in annual crops such as salads where the land would previously have been left fallow overwinter, as they slot more easily into the rotation where the cash crops are grown though spring to late summer. JepCo, a salads grower, have been trialling cover crops as part of AHDB's GreatSoils project, and have acknowledged that there may be weed suppression benefits. In the AHDB weed fellowship programme (CP 086) (Atwood, 2015) cover crops were trialled as a short term ley before baby leaf spinach and it appeared that there was some suppression of weeds, but the trials were unreplicated and would need to be repeated to be certain of consistent results. For weed suppression to occur the cover crop must establish well (3.2.7), as where there are any gaps weeds will still take advantage. This was seen in the grass/buckwheat mix in the CP 086 trials. Weed suppression during the cover crop presence was best in those containing clover which established cover quickly. A concern for field vegetable growers, especially those of fine seeded drilled crops is to ensure that the cover crop is broken down well enough in advance of drilling so that it does not block or interfere with the machinery. If used, cover crops are often sprayed off before being incorporated. A cover crop can also pose a threat as a volunteer species in the following cash crop.

Future actions: Further evaluate cover crops for effects on weed suppression, and evaluate the best type of cover crop for different rotational scenarios. This can be informed from other crops and literature reviews and the known biology (such as emergence patterns of the weeds) so that a narrower range of options are tested. This would be ideal for a participative 'Farmer Innovation Group' where the design, approach, recording and interpretation is shared between growers.

Intercropping or companion cropping

Intercropping or undersowing with a manageable species could suppress weeds in the non-competitive crops which are listed in the weed species section (Section 5). Rye/legume cover crops are commonly used in asparagus in Canada and USA to prevent soil erosion, but the rye is also thought to have allelopathic properties to help suppress weeds as well as improve soil quality.

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Future actions: Evaluate options for intercropping and assess their effects on weed competition.

Seed rates, plant spacing and row widths

Seed rates and plant spacing are often optimised to obtain the correct size and specification of product required by the customer, and maximise marketable yield per hectare. Seed houses carry out trials on these aspects to recommend the correct rate which the grower needs to meet customer requirements. With respect to weed control, the ability to be able to mechanically hoe the crop is also considered when deciding on plant spacing, row widths and seed rates.

Drilling and planting dates

These are driven by the seasonality of the crop in question, and the scheduled marketing window for the produce. Weed control is most challenging in early spring drilled crops which emerge before weeds have germinated, especially if the pre-emergence herbicide is ineffective in dry conditions. This is because there are limited post-emergence weed control options for many field vegetable crops. Therefore growers give particular attention to the fields which they select for early drilling and planting.

Manual removal of weeds

Hand weeding is frequently used across many vegetable crop types. It is very expensive (c. minimum £500/ha, and can be up to £2,500/ha in organic carrots where a 'lie on' (people lay on a frame which is moved across the field) weeder is used for repeated passes. Weeds can be severely detrimental to yield and production efficiency, and the limited range of herbicides and the high value of crops make hand weeding an essential approach to weed control and currently it is still within profit margins to carry out.

Mechanical weeding

Mechanical hoes are frequently used in salad crops and sometimes in brassica crops, but if hoeing is not required it is best not to disturb any residual herbicide that has been applied and may still be active. Hoeing is limited by ground conditions and crop growth stage. The type of hoe used varies from inter-row shallow cultivators guided by the operator or GPS, to more sophisticated vision guided hoes, such as the Garford Robocrop In-row weeder, which can weed around individual plants, and was trialled and developed in AHDB Horticulture project FV 266 (Grundy, 2007). The latter type is becoming more popular as more farms adopt RTK GPS and can plant with greater precision which allows them to be used with less risk of plant loss (Figure 14).

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Figure 14 Left. Inter-row hoe guided by GPS. Right. Garford In-row weeder

The vision guided baby leaf hoe is a new development from Garford which could also be useful in narrow row drilled root crops. In crops drilled with RTK GPS, the hoe can be accurately pulled through a crop with rows as narrow as sub 50 mm, and an accuracy of 5mm (Figure 15).

Figure 15 The Garford Robocrop baby leaf hoe

Thermal weeding

Thermal weeding such as flame weeding is widely used in organic field vegetable production primarily when producing a stale seed bed. Inter-row flame weeding is not widely used, but could be investigated. The drawback with flame weeding is the cost of the fuel when used on a large scale.

Electrical weeding in field vegetables is currently being investigated in a European-funded (H2020) project led by Ubiqutek, in collaboration with Steketee in the UK. The technology is controlling weeds in and between vegetable rows.

Controlling weeds in organic leeks by hot foam treatments was investigated by ADAS in the AHDB Horticultural weeds fellowship project (CP086), but results showed it was extremely slow and the volume of water required to transport across the field was not practical or economic.

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Future action: Investigate the possibilities of flame weeding for inter-row weed control.

Mulching

Plastic mulches are commonly used for weed control in cucurbit crops such as courgettes. This method is very effective in controlling most annual weeds within the rows. However, weeds can grow through the holes, and controlling weeds in the inter-row areas between the mulch will become difficult after the loss of diquat, which was the main method of post-planting weed control in cucurbits. Growers are investigating alternative methods of weed control between rows such as living mulches. Hand weeding is an option, but is expensive.

Another type of mulch which is occasionally used on organic farms is compost or woodchip and this is being evaluated in an EIP project on a Welsh organic vegetable farm (2018-19) for Horticulture Wales (Figure 16). It is also being evaluated by a current Innovative Farmers group. Cucurbit growers are evaluating straw as a mulch between rows, in addition to dwarf rye to outcompete weeds in the inter-row areas. This could be investigated for other wide row crops.

Figure 16 A celeriac plant after woodchip has been applied (Source: Chris Creed, ADAS Hort Wales), and straw being applied between rows of courgettes.

Non-recyclable plastic has to be disposed of through licenced waste contractors. Growers are seeking alternative options but implementing biodegradable plastics has proved more challenging than anticipated for some. Growers aim to achieve 100% replacement in the future, but it is a challenge to get the longevity of the plastic right. It can break down too fast and does not last the life of the crop, or too slow and poses a problem for following crops in the rotation. However, due to the limited options for weed control plastic mulch is commonly used in cucurbits, and growers endeavour to work to use recyclable plastic where possible as environmental regulations and concerns need to be met to comply with customers desires for environmentally sustainable farming approaches.

More permanent woven textile mulches such as Mypex are also very occasionally used where a crop may be grown on the same site year on year, and weed control will be a challenge. The use of Mypex is rarer as it is more expensive, but can provide a cost-effective solution in these niche longer term cropping situations, e.g. in a perennial crop such as rhubarb.

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Mulches are effective but barriers to their use would be cost, and also finding efficient methods of applying the mulch in different cropping situations. They also need to be recyclable where possible to be environmentally friendly.

Future actions: Evaluate the potential for use of mulch, either recyclable plastic, woodchip and straw mulches in a range of vegetable crops for weed control and effect on the crop.

Novel and emerging technology

AHDB Horticulture project CP 134 is developing "eyeSpot" where droplets of herbicide are only applied to the target weeds. This principle has been tested in small experiments, though the technology is currently some way off of development and commercialisation (Murdoch *et al*., 2017). Garford (in collaboration with Tillett & Hague) manufacture a vision guided spot sprayer. However, due to economics of investment and use currently favouring broadacre spraying it has currently not been as popular as the inter-row hoe (N. Tillett, pers comm).

Weeds can be mapped as in arable crops, but there are no methods which automatically detect weed species pertinent to horticultural crops. This is still done manually by the operator or ground truthed from imagery.

Field vegetables

In crop control

The use of conventional chemical herbicides remain a key part of weed control in non-organic field vegetables. Many of the herbicides authorised in field vegetables are as EAMUs (Emergency approval for minor use). Although crops are high value, they are minor crops when compared to the area of cereals and form only a small market for agrochemical companies. Therefore there are often only a limited number of herbicides available when compared to major crops such as cereals. Key active substances such as pendimethalin and metribuzin, which form the mainstay of many field vegetable herbicide programmes, are candidates for substitution (Table 9) (European commission, 2015). However, major manufacturers continue to support authorisation of these key actives as they recognise their importance. But the risk of losing authorisations due to these regulatory threats has led growers to continue to support weed control crop protection work, through a high proportion of trials in the first two years of the AHDB SceptrePlus program (CP 165) focussing on weed control. In Sceptre (CP 077) and SceptrePlus many of the products trialled are already authorised in other crops, but minor uses are being sought for field vegetables (e.g. diflufenican for use in carrots). However, there are one or two 'new' actives which are not yet authorised in the UK where products are being trialled and authorisations are being sought. For example benfluralin (Bonalan) and aclonifen (Bandur) are authorised for use in the EU for use in field vegetables but not yet in the UK. Pethoxamid is authorised in the UK, and has been trialled in field vegetables but the company are

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still developing the product, and until the authorisation process for major uses is completed it will not be available for minor crops in the UK.

Brassicas

There are many types of brassica crops and these vary from those which are grown for a few weeks e.g. broccoli, to those which are in the ground for a few months such as kale and Brussels sprouts. In 2017, there were 27,308 hectares of brassicas were grown in the UK (Defra, 2018a). They are grown at a range of row widths and plant populations depending on the species. In hand harvested crops such as brassicas, weeds can impede pickers physically. They also visually obscure the crop, reducing harvesting efficiency, and weeds such as nettles can deter pickers. Where excessive weed is present and heads are missed harvested yields can be reduced by up to 30%. The increased humidity in the canopy can also increase the risk of disease and weed seeds can contaminate the fresh product. Common problem weeds are listed below (Table 17).

Early crops under plastic are at the greatest risk from weed competition as the plastic or fleece cover provides an environment to increase weed germination and growth as well as increasing crop growth. It also makes it difficult to easily apply early post-emergence herbicides if they are needed. Careful field site selection is recommended for these early crops.

Table 17 Common weeds found in brassica crops.

Common name	Scientific name
Annual sow-thistle	*Sonchus spp.*
Charlock (SW)	*Sinapsis arvensis*
Common fumitory	*Fumaria offinalis*
Fat hen	*Chenopodium album*
Field penny-cress	*Thlaspi arvense*
Groundsel	*Senecio vulgaris*
Redshank	*Polygonum persicaria maculosa*
Scentless mayweed	*Tripleurospermum inodorum*
Shepherds purse	*Capsella bursa-pastoris*
Small nettle	*Urtica urens*

A combination of approaches for weed control are used as the limited range of authorised herbicides does not cover the full range of weed species likely to be present. Some brassica types, such as cauliflower, are more sensitive to herbicides than others, and a check in growth can cause anything from a minor delay to scheduling or in the worst case 'blindness'. Therefore care is needed with choice of product and timing of application for flower headed brassicas.

The approaches explained by Harvey *et al*., (1982) still influence practice today. He stated that "weed control requirements depend mainly on"

1) Whether the crop is drilled or transplanted
2) The time of year which it is sown or planted

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3) The length of time for which the crop occupies the land
4) Whether the leaves are heavily waxed, as in Brussels Sprouts, or have a less-developed wax layer, as in cauliflower"

Brassicas are grown on a range of soil types from sandy loams to silty clay loams. Pre-planting herbicides are sometimes used, generally either pendimethalin or pendimethalin + dimethenamid-P, but as the planter disturbs the residual soil layer weeds can emerge within the row after planting. So, alternatively growers also follow up with a post-planting application of metazachlor + clomazone. Some growers rely on this post-planting herbicide alone. The approach used depends on the weed species present and the known weed burden of the field. Selective herbicide products authorised for brassicas are shown in Table 18. Wing-P authorisation was gained as a result of the AHDB Horticulture FV 256 and Sceptre trials (Hanks & Knott, 2006; Knott, 2012). Corteva are developing a range of new herbicide products based on their Arylex active, of which Belkar (halauxifen-methyl + picloram) has been recently authorised for winter oilseed rape. Therefore it may be useful to trial in vegetable brassicas for safety and efficacy.

Table 18. Selective herbicides authorised for use in brassica crops. Care should be taken to check authorisations before use as some herbicides are not authorised for certain brassica types e.g. collards and kale.

Active ingredients	Example product	Target weeds
Residual herbicides		
clomazone	*Gamit 36 CS*	BLW
dimethenamid-P + metazachlor	*Springbok*	BLW and grasses
dimethenamid-P + pendimethalin	*Wing-P*	BLW and grasses
metazachlor	*Sultan 50 SC*	BLW and grasses
napropamide	*Devrinol*	BLW and grasses
pendimethalin	*Stomp 400 SC*	BLW and grasses
S-metolachlor	*Dual Gold*	BLW and grasses
Contact herbicides		
clethodim	*Centurion Max*	Grasses
clopyralid	*Dow Shield 400*	BLW (mainly compositae)
cycloxydim	*Laser*	Grasses
fluazifop-p-butyl	*Fusilade Max*	Grasses
pyridate	*Lentagran WP*	BLW

Future actions:

- Continue to evaluate new herbicide actives which are being developed for oilseed rape in vegetable brassicas to widen the range of actives available.
- Evaluate strip tillage effects on weed control and test if brassicas can be successfully established in a strip till system (so that the band of disturbance to pre-planting herbicide is minimised and/or can be applied at planting).

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- Investigate the possibilities of developing ALS tolerant vegetable brassica varieties, which are already available for OSR.

Alliums

Alliums covers leeks, bulb onions, salad onions and garlic of which approximately 10,333 hectares were grown in 2017 (Defra, 2018a). Alliums are slow growing and non-competitive especially early in growth, and at this crop stage also very sensitive to herbicides. With the exception of salad onions they are also quite long season crops staying in the ground from four to seven months and they never achieve full ground cover, therefore are one of the least competitive vegetable crops. Growers experience problems with the key weeds listed in Table 19.

Table 19 Common weeds found in allium crops.

Common name	Scientific name
Annual meadow grass	*Poa annua*
Annual sowthistle	*Sonchus spp*
Black-bindweed	*Fallopia convolvulus*
Black-grass	*Alopecurus myosuroides*
Chickweed	*Stellaria media*
Fat hen	*Chenopodium album*
Field pansy	*Viola arvensis*
Fools parsley	*Aethusa cynapium*
Groundsel	*Senecio vulgaris*
Redshank	*Polygonum persicaria maculosa*
Scentless mayweed	*Tripleurospermum inodorum*
Small nettle	*Urtica urens*

To minimise the likelihood of crop damage from herbicides a little and often approach is used in allium crops to maintain season long weed control. A programme of a residual herbicide, such as pendimethalin + dimethenamid-P (Wing-P) at reduced dose, followed by four to seven further herbicide applications is not uncommon. This helps cover the length of the cropping season and the lack of the competitiveness of the allium crop. These applications are frequently tank mixes of two or more active substances to cover the full weed spectrum and to minimise the risk of development of herbicide resistance. If graminicides are needed, these are alternated at appropriate intervals with actives targeting broad-leaved weeds. Graminicides de-wax the allium leaves and leave them susceptible to damage preventing tank-mixing and determining spray intervals. A list of selective herbicides approved in alliums is shown in Table 20.

Table 20 Selective herbicides authorised for use in allium crops. Care should be taken to check products before use as some herbicides are not authorised for certain allium types e.g. salad onions.

Active ingredients *Residual herbicides*	Example product	Target weeds
chloridazon*	*Pyramin DF*	BLW
chlorpropham	*Intruder/Cleancrop Amigo*	BLW and grasses

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dimethenamid-P + pendimethalin	*Wing-P*	BLW and grasses
isoxaben	*Flexidor*	BLW
pendimethalin	*Stomp 400 SC*	BLW and grasses
S-metalochlor	*Dual Gold*	BLW and grasses
Contact herbicides		
bentazone	*Basagran SG*	BLW
bromoxynil	*Buctril*	BLW
clethodim	*Centurion Max*	Grasses
clopyralid	*Dow Shield 400*	BLW (mainly compositae)
cycloxydim	*Laser*	Grasses
flumioxazine**	*Sumimax*	BLW and grasses
fluazifop-p-butyl	*Fusilade Max*	Grasses
fluroxypyr	*Starane Hi-Load*	BLW
glyphosate	*Roundup Energy, Roundup Flex, Roundup Powermax inter-row*	BLW and grasses
propaquizafop	*Falcon*	Grasses
prosulfocarb	*Defy*	BLW and grasses
pyridate	*Lentagran WP*	BLW and grasses

* Due to be unsupported for renewal in 2019, and stocks low at distributors

** Rarely used

Alliums are grown on a wide range of soil types from sandy loams to clay loams, while some leeks are grown in peat soils. Each requires a different approach to herbicide programmes to ensure crop safety and efficacy. For example, chlorpropham is particularly useful in organic peaty soils.

For those weeds not controlled by selective herbicides, some growers have invested in Inter-row shielded sprayers (Figure 17) to apply glyphosate between the rows (EAMU's 0354/2013, 2528/2013, 1305/2014).

Figure 17 A Micron varidome shielded sprayer in use in salad onions in the UK

Future actions:

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- Evaluate alternatives to glyphosate for inter-row control, such as pelargonic acid and carfentrazone ethyl, or pyraflufen-ethyl.
- Evaluate minimum tillage as an approach for establishment.

Root vegetables

Carrots and parsnips

Carrots and parsnips are grown on two main soil types; sandy loams or peat soils high in organic matter. This dictates the major areas of the UK where carrots and parsnips are grown, which is East Anglia, the Midlands and the Lancashire mosses. A total of 11,933 hectares of carrots are grown in the UK, and 2,969 hectares of parsnips. Weed control in non-organic carrot and parsnip crops relies very much on the use of a programme of herbicides, and until 2018 relied heavily on linuron (Garthwaite *et al*., 2018). This was in part due to its flexibility as a residual herbicide which also gave some contact activity giving efficacy from both pre- and post-emergence use. It gave control of key weeds (such as black-bindweed, groundsel and mayweed) and also controlled volunteer potatoes when tank-mixed with prosulfocarb. Typically carrots and parsnips are drilled after a stale seed bed is prepared, and then a pre-emergence herbicide is applied. After germination at least two follow up post-emergence herbicides are applied. A wick applicator (e.g. Weed Wiper) with a selective herbicide can occasionally provide effective control in carrot and, particularly, in parsnip crops where there is a height differential between weeds and crop (Figure 18).

Figure 18 Garford weed wiper in sugar beet (Left), and mayweed dying in a parsnip crop after ‘weed wiping’ with glyphosate (right).

Parsnips are less competitive than carrots as they are 10-14 days slower in germination and more sensitive to herbicides, therefore the loss of the linuron is most acute for parsnip crops. At present there are no effective post-emergence herbicides available to cover the full spectrum of weeds

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encountered. The most common weed species requiring control in carrots and parsnips are shown in Table 21 and the selective herbicides approved in both crops are listed in Table 22.

Table 21 Common weeds in carrot and parsnip crops

Common name	Scientific name
Black-bindweed	*Fallopia convolvulus*
Black-grass	*Alopecurus myosuroides*
Cut-leaved cranes-bill	*Geranium dissectum*
Fat hen	*Chenopodium album*
Fools parsley	*Aethusa cynapium*
Groundsel	*Senecio vulgaris*
Redshank	*Polygonum persicaria maculosa*
Scentless mayweed	*Tripleurospermum inodorum*
Small nettle	*Urtica urens*
Volunteer oilseed rape	*Brassica napus ssp oleifera*
Volunteer potatoes	*Solanum tuberosum*
White campion	*Silene latifolia*

Table 22 Selective herbicides authorised for use in carrot and parsnip crops. Care should be taken to check labels and recommendations before use.

Active ingredients	Example product	Target weeds
Residual herbicides		
clomazone	*Gamit 36 CS*	BLW and grasses
clomazone + pendimethalin	*Stallion Sync TEC*	BLW and grasses
isoxaben	*Flexidor*	BLW
metribuzin	*Sencorex Flow*	BLW and grasses
pendimethalin	*Stomp 400 SC*	BLW and grasses
Contact herbicides		
clethodim	*Centurion Max*	Grasses
cycloxydim	*Laser*	Grasses
fatty acids: pelargonic acid	*Finalsan inter-row use*	BLW
flumioxazine*	*Sumimax*	BLW and grasses
fluazifop-p-butyl	*Fusilade Max*	Grasses
glyphosate	*Roundup Energy, Roundup Flex, Roundup Powermax inter-row*	BLW and grasses
propaquizafop	*Falcon*	Grasses
prosulfocarb	*Defy*	BLW and grasses

** Rarely used due to risk of crop damage*

Inter-row hoeing and spraying is not currently widely used but may increase as growers consider alternatives to herbicides. Carrots and parsnips are frequently grown in twin or triple rows on a bed system, with four of these twin or triple rows per bed. Therefore even quite early in growth it becomes difficult to hoe without crop damage even with GPS as the carrots and parsnips are sown to maximise yield per ha and quickly ‘fill’ the bed. Sowing density is also used to manipulate the ideal root size required by retailers.

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Flame-weeding for a stale-seed bed and as a pre-emergence weed control method is popular in organically grown carrots as is inter-row hoeing (up to where it is practical) and hand weeding.

Future actions:

- Evaluate different row configurations and plant populations which would allow hoeing, but remain a cost-effective growing system.
- Investigate the use of adjuvants or other substances to 'hold' residual herbicides at the surface and increase crop safety.
- Investigate soil stabilisers to prevent the wind removing residual herbicides.
- Investigate whether herbicide applications in the dark could reduce crop damage.

Beets

Beetroot growers experience similar problems with weeds as sugar beet growers (with the exception of weed beet), and hence use many similar approaches to weed control (see section 4.4). Therefore authorisations are similar with the following exceptions: Dimethenamid-P and quinmerac are included in products for sugar beet such as Wing-P and Fiesta T, while pelargonic acid for inter-row application and s-metolachlor are authorised for use in beetroot but not sugar beet.

A concentrated sodium chloride solution and wetter applied to crops as a fertiliser will result in the control of weeds including volunteer potatoes.

Salads

Wholehead

Wholehead lettuce is grown on a wide range of soils and is usually transplanted, with 4,391 hectares planted in the UK in 2017 (Defra, 2018a). Plant spacing varies by type e.g. little gem will be planted closer together than iceberg. However, as mechanical weeding by hoe is frequently used, crops will be planted so that hoeing can be carried out easily as required, while still maintaining crop spacing to maximise heads per hectare. Mechanical hoeing is effective while weeds are small, but once they become larger and better rooted, they become harder to uproot and bury which is the primary method of weed control as described in the techniques section 3.

Mechanical hoeing is common as very few herbicides are authorised for post-emergence use and there are very few residual herbicides. Crops are only grown for a short period, with the crop in the ground from six weeks in summer to ten weeks for the latest crops in autumn. Although moisture and ideal growing conditions means the crop gains ground cover rapidly and should be competitive; weeds also germinate and grow rapidly. These compete with the crop and require control. Weeds also increase humidity in the lettuce crop, which increases the risk of a key disease issue for lettuce growers (downy mildew). As well as weed control reducing disease and crop competition it also reduces variation in head size at harvest. As the summer crops reach harvest very quickly, harvest

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intervals can restrict the use of herbicides, such as pendimethalin and propyzamide. Both have a harvest interval of 42 days when used at the on label rate. Therefore EAMUs 0375/17 and 2411/08 were gained for lower use rates with shorter harvest intervals to allow growers to maintain weed control in summer grown crops.

Broad-leaved weeds continue to be major problems for lettuce growers, particularly groundsel as it is in the *Compositae* family, and small nettle, chickweed, amaranth and polygonums are also frequent problems (Table 23).

Table 23 Common weeds found in wholehead salad crops.

Common name	Scientific name
Common amaranth	*Amaranthus retroflexus*
Common chickweed	*Stellaria media*
Fat hen	*Chenopodium album*
Groundsel	*Senecio vulgaris*
Knot-grass	*Polygonum aviculare*
Redshank	*Polygonum persicaria maculosa*
Scentless mayweed	*Tripleurospermum inodorum*
Small nettle	*Urtica urens*
Volunteer cereals	*Various species (barley, wheat, oats)*
Volunteer oilseed rape	*Brassica napus ssp oleifera*
Volunteer weed beet	*Beta vulgaris*
Willowherb	*Epilobium spp.*

A pre-emergence herbicide of pendimethalin, pendimethalin and dimethenamid-P or pendimethalin plus s-metalochlor is used after a stale seed bed. A follow up post-planting spray of propyzamide is frequently required. However, this does not cover all the weed species and mechanical hoeing and hand weeding is often required. A particular weed problem is groundsel. Since the lack of propachlor in March 2010, there is concern that resistance could develop due to the limited range of authorisations and a reliance on dimethenamid-P for groundsel control (Wallwork, 2016).

Table 24 Selective herbicides authorised for use in outdoor wholehead lettuce crops. Care should be taken to check authorisations before use.

Active ingredients	Example product	Target weeds
Residual herbicides		
chloridazon*	*Pyramin DF*	BLW
chlorpropham	*Intruder/Cleancrop Amigo*	BLW and grasses
dimethenamid-P + pendimethalin	*Wing-P*	BLW and grasses
pendimethalin	*Stomp 400 SC*	BLW and grasses
propyzamide	*Kerb Flo*	BLW and grasses
s-metolachlor	*Dual Gold*	BLW and grasses
Contact herbicides		
cycloxydim	*Laser*	Grasses

** Due to be unsupported for renewal in 2019, and stocks low at distributors*

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Future action: Evaluating and monitoring future resistance risks where modes of action are limited e.g. dimethenamid-P for control of groundsel.

Baby leaf

Baby leaf salad crops are frequently drilled and, as a good seedbed is important for establishment, these are most likely to be grown on light to medium textured soils. Baby leaf includes a range of salad crops with different species included in a single sowing (such as lettuce, chard, spinach and wild rocket), and 1,837 hectares were grown in 2017 (Defra, 2018a). All crops are harvested before eight true leaves, which defines the herbicide authorisations and products for use on these crops. As there are many different species, crop selectivity (safety) will vary by species and little information is available to guide growers except expert knowledge from specialist agronomists which is occasionally supplemented by results from AHDB-funded herbicide screens.

Crops are drilled at high densities to maximise weed competition and, as they are fast growing, this often helps outcompete some weeds. Growers experience similar weeds to wholehead lettuce, but in addition shepherd's purse (*Capsella bursa-pastoris*) is also a problem in baby leaf brassicas. There are also specific crops which are sensitive to certain herbicides which limits options. For example groundsel in wild rocket is hard to control because despite many authorisations for baby leaf crops, one of the only safe herbicides is napropamide and the rates which can be used (0.85 L/ha) do not control groundsel. Therefore, the main control of groundsel, and other weeds, in wild rocket is hand weeding just before harvest. However, groundsel is very similar in leaf shape to wild rocket and care is needed to ensure it does not contaminate the final product. Growers are very aware of this; highlighted by AHDB producing and circulating an awareness poster to assist identification at harvest and in the packhouse.

Herbicide authorisations for use in baby leaf are detailed in Table 25, but as discussed above not all are suitable for use on all crops due to species specific selectivity. Table 26 details reasons why authorisations are not used or are not suitable for the largest areas of baby leaf crop (wild rocket and spinach). Only four products are safe to use on baby leaf spinach, and two on baby leaf wild rocket. Restricted availability of safe and effective herbicides to use in baby leaf means that soil sterilisation, using Basamid, is frequently used and rotations in the following three years are planned to reduce weeds in crops with few available options – e.g. spinach, lettuce, wild rocket. Finishing with the crop that has the fewest weed control options, wild rocket, can work where the worst weeds are previously controlled in prior crops.

Table 25 Selective herbicides authorised for use in baby leaf salad crops including wild rocket. Care should be taken to check authorisations before use.

Active ingredients	Example product	Target weeds
Residual herbicides		
chloridazon*	*Pyramin DF*	BLW
chlorpropham	*Intruder/Cleancrop Amigo*	BLW and grasses

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clomazone	*Gamit 36 CS*	BLW and grasses
dimethenamid-P + pendimethalin	*Wing-P*	BLW and grasses
lenacil**	*Venzar Flowable*	BLW and grasses
napropamide	*Devrinol*	BLW and grasses
pendimethalin	*Stomp 400 SC*	BLW and grasses
propyzamide	*Kerb Flo*	BLW and grasses
s-metolachlor	*Dual Gold*	BLW and grasses
Contact herbicides		
cycloxydim	*Laser*	Grasses

** Due to be unsupported for renewal in 2019, and stocks low at distributors*

*** Use up date for pre-emergence authorisation is 28 February 2019*

Table 26 Selective herbicides authorised for use in baby leaf spinach and wild rocket crops with reasons why they are not used, and to indicate how this narrows the range of herbicides which can be used.

Active Ingredient	Example Product	Comments on suitability for use - Spinach	Comments on suitability for use – Wild Rocket
Chloridazon (commercial standard)	Pyramin DF	Likely to be lost through re-registration, product may be difficult to obtain for 2019	Not safe
chlorpropham	Intruder Cleancrop Amigo	Can stunt under some conditions – marginal crop safety	Not safe
clomazone	Gamit 36 CS	Possibility of bleaching causing crop quality issues	Possibility of bleaching causing crop quality issues
clopyralid	Dow Shield	Limited weed spectrum	Limited weed spectrum and distorts leaves
cycloxydim		Not authorised	Graminicide – limited weed spectrum
Lenacil (commercial standard)	Venzar Flow/500	EAMU for pre-em use lost after re-registration, possibility of post-em authorisation in pipeline	Not safe
napropamide	Devrinol	Limited spectrum at low rate	Safe but leaves groundsel at rate used
pendimethalin	Stomp Aqua	Not safe	Not safe
pendimethalin + dimethenamid-P	Wing-P	Not safe	Not safe
propyzamide	Kerb Flo	Limited weed spectrum, less effective in warm temperatures	Not safe
S-metalochlor	Dual Gold	Crop safety unknown, limited window of use	Not safe, limited window of use

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Steam sterilisation is used in the EU and in protected salad production, but is currently too slow to be economically viable for broadacre outdoor salads production in the UK.

Celery

Celery is grown mainly in East Anglia and Shropshire on peats and sandy loam soils, 946 hectares are grown in England and Wales (Defra, 2018a). The crop is transplanted, and there are two types; self-blanching and trench celery. The former and main type of celery can be grown on the flat, the latter trench celery is grown within a ridge, similar to a potato ridge. As with wholehead lettuce, mechanical hoeing is widely used as there are very few authorisations for the crop (Table 27). The crop shares common weed issues with wholehead lettuce.

Table 27 Selective herbicides authorised for use in celery crops. Care should be taken to check authorisations before use.

Active ingredients	Example product	Target weeds
Residual herbicides		
clomazone	*Gamit 36 CS*	BLW and grasses
pendimethalin	*Stomp 400 SC*	BLW and grasses
Contact herbicides		
pelargonic acid (pre-em use)	*Finalsan*	BLW
prosulfocarb	*Defy*	BLW and grasses

Cucurbits

Courgettes and pumpkins are only grown on a very minor scale at 2,357 hectares (J. Dyas. Pers. Comms.) but pumpkins in particular are increasing in popularity and area grown year on year recently. Similar species of weeds are an issue in both crops and are listed in Table 28. Both crops are planted on wide row spacings from 0.75cm – 1m, at approximately 10,000 plants per hectare as the crop needs space for canopy and fruits.

Table 28 Common weeds found in cucurbit crops

Common name	Scientific name
Annual meadow grass	*Poa annua*
Annual sowthistle	*Sonchus spp*
Black-bindweed	*Fallopia convolvulus*
Black-grass	*Alopecurus myosuroides*
Chickweed	*Stellaria media*
Fat hen	*Chenopodium album*
Groundsel	*Senecio vulgaris*
Knot-grass	*Polygonum*
Redshank	*Polygonum persicaria maculosa*
Scentless mayweed	*Tripleurospermum inodorum*
Small nettle	*Urtica urens*
Volunteer cereals	*Various species (barley, wheat, oats)*

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Courgettes

Courgettes are grown in a wide range of areas of the UK, and are commonly grown through polythene mulch as there are very few herbicides authorised for use in the crop (Table 29). Mulches were discussed in the previous section.

Table 29 Selective herbicides authorised for use in celery crops. Care should be taken to check authorisations before use.

Active ingredients	Example product	Target weeds
Residual herbicides		
clomazone	*Gamit 36 CS*	BLW and grasses
dimethenamid-P + pendimethalin	*Wing-P (inter-row)*	BLW and grasses
isoxaben	*Flexidor (courgette only)*	BLW
propyzamide	*Kerb Flo*	BLW and grasses
Contact herbicides		
pelargonic acid (pre-em use)	*Finalsan*	BLW

An inter-row spray is used to control weed between rows, dimethenamid-P + pendimethalin is used early post-planting to give early season control, and then this was followed by an inter-row application of diquat to control any later germinating weeds. With the revocation of diquat, growers are increasingly looking for alternative options for weed control in these inter-row areas including closer planting to increase crop competition, straw and living mulches as well as alternative mulch materials such as woodchip.

Pumpkins

Pumpkins are planted on a range of row widths from 0.5m to 1m. Some growers use plastic mulch as in courgettes, while others use no plastic at all but plant the crop so it can be mechanically hoed either one way, or in some cases both ways. Hand hoeing and hand rogueing is still very widely used.

Future action: Investigating the benefits and efficacy of using mulches, and strip till for pumpkins to provide alternative approaches for weed control (this has been trialled in the states).

Sweetcorn

Sweetcorn can be considered the same as a maize crop but with less authorisations for herbicides. In 2016, 2,495 hectares of sweetcorn was grown (Defra, 2018a). Cob quality is of importance so this is of high consideration within weed control programmes.

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Figure 19 Example of twin French rows for maize planting.

Sweetcorn is grown on twin French rows (Figure 19) configuration to facilitate plastic use on the early crops, however, it is not needed to be like that for later 'open' crops.

Changing row width would be of interest if the headers on the machines can facilitate it and if it increased yield per ha. Yield is measured in cob number per hectare and not in tonnes. A pre-emergence herbicide containing pendimethalin is frequently used on the earlier polythene covered crops, and once the polythene is removed a post-emergence herbicide application is then used combined with inter-row hoeing. Pre-emergence applications are less favoured on the later open crops as sometimes a single well-timed post emergence application can give good weed control. However, with this approach grass weed control relies on an ALS inhibitor (nicosulfuron), and if rotation between sweetcorn crops is tight then there will be a risk of development of herbicide resistance. For this reason, the use of a pre-emergence is recommended and is increasing.

Future action: Evaluate if weed control can be improved without compromising yield by increasing plant density, or reducing the width between rows.

Perennial veg – asparagus and rhubarb

Asparagus

In 2017, 2,470 hectares were grown (Defra, 2018a). Asparagus plantations are intended to be in the ground for at least 10 years, and in this time weeds can build up if they are not managed effectively. Site selection of a field as weed free as possible is key to maintaining a crop free of weeds for as long as possible. This is because once the crop is planted, weed control becomes more difficult. Once the crop is established, weed control is targeted by a range of approaches including herbicides pre- and post-harvest, hand rogueing, and overwinter living mulches between the rows. Row widths range from 1.2 to 2.0m. Re-ridging is also used to re-cover the crowns, but growers are increasingly questioning whether crops should be ridged or grown on the flat.

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Cover crops are increasingly being used for soil stabilisation (AHDB, 2018f) and have been studied in asparagus project FV 450 but UK growers have been trialling rye as it is thought to show allelopathy (Section 3). Rye overwinter cover crops are commonly used in Canada and Michigan to look at asparagus production (A. Huckle, Pers comm.). Overwinter cover crop commonplace in US and Canada largely for soil erosion but also used as a living mulch in their organic systems where a legume is included for nitrogen fixing.

Rhubarb

In 2017, 564 hectares of rhubarb were grown (Defra, 2018a). Rhubarb is grown on ridges in Yorkshire and re-ridging is used as a weed control method in these crops. While in other areas it is grown on the flat, and also planted on the 'square' so it can be hoed both ways.

Efficient and cost effective weed control is important in rhubarb, as with other crops, to prevent yield loss caused by competition for water, space and nutrients. The presence of weeds also impedes the harvest operation, leading to increased labour costs. Competition from weeds, and in particular perennial weeds, has increased in recent years with the loss of key herbicides such as dichlobenil and simazine. In addition, where weeds have developed resistance to currently approved herbicides, growers believe that their presence has led to a decrease in rhubarb crown size and yield in both forced and green pull crops.

Two projects (SF 129 and SF 161) have recently been funded by AHDB Horticulture to tackle the problem of weed control and guard against the development of resistance, by screening a number of herbicides with a likelihood of approval in the crop. The majority of rhubarb herbicide programmes are currently based on pendimethalin (Stomp Aqua) and propyzamide (Kerb Flo), and alternative options were needed to improve control of troublesome weeds such as Himalayan balsam, perennial nettle, field bindweed and mayweed.

In both rhubarb and asparagus crops there is a dormant period overwinter where weeds can subsequently flourish due to lack of competition from the crop. Glyphosate is widely used to control weed during dormancy as it can build up quickly if left unchecked. If untreated the increase in weed year on year will reduce yield and shorten the life of the plantation. Therefore alternatives to glyphosate should be sought

Future actions:

- Investigate the use of the biocontrol rust for Himalayan balsam on rhubarb
- Investigate alternatives to glyphosate for weed control over the dormant period

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4.1.2. Soft fruit

The main fruits associated with the soft fruit industry comprise strawberry, raspberry, blackberry, blueberry, blackcurrant, redcurrant and whitecurrant, and gooseberry crops. Soft fruit contributed 4.5% of the total UK crop output from 0.1% of the land farmed in the five years from 2009 to 2014 (The Andersons Centre, 2014), and despite being a high value crop, soft fruit growers tend to rely on off-label approvals for herbicides for weed control. Alternative methods for weed control in soft fruit include plastic and straw mulches, mowing and hand weeding.

Soft fruit crops may be grown in the soil or in containers, with the majority of blackcurrants, redcurrants and gooseberries grown in the soil. Strawberries grown in the soil are planted either in plastic covered raised bed rows or matted rows, where daughter plants are trained to grow in rows around the mother plant. The latter system has greater potential for weed control issues, with more inaccessible areas for weeds to become established. Raspberry crops grown in the soil can be produced from different rooting material, ranging from bare roots to long canes. Bare rooting material will suffer the greatest competition from weeds if not controlled. The same is the case for black currant cuttings that are stuck into the ground for rooting.

The longevity of the crop varies with crop type and cropping strategy; some strawberry and raspberry plants will be cropped for a single season and replaced the following season, whilst others will be cropped for a few years. In the case of bush fruit, such as blueberries and blackcurrants, the bushes will be kept for up to 15 years before being replaced. This has implications for the weed control strategy employed by the grower, increased duration of the crop will increase the weed burden if left unchecked.

Many weed species can be found in soft fruit crops (Table 30). Wind dispersed species can be a particular problem in containerised fruit production, whilst most weeds can be problematic in soil grown crops. Weeds such as black nightshade can be a contamination risk in blackcurrant crops, as the berries of both look very similar. Bindweed can swamp plantations, restricting plant growth and affecting future yields. Volunteer crops, such as oilseed rape, can be a problem alongside these weeds in land that has recently been in cultivation for other crops.

Table 30 List of weeds commonly found in soft fruit crops.

Common name	Scientific name
American willowherb	*Epilobium ciliatum*
Black nightshade	*Solanum nigra*
Cleavers	*Galium aparine*
Common chickweed	*Stellaria media*
Couch grass	*Elymus repens*
Creeping thistle	*Cirsium arvense*
Dock	*Rumex obtusifolius*
Field bindweed	*Convolvulus arvensis*

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Groundsel	*Senecio vulgaris*
Hairy bittercress	*Cardamine hirsuta*
Shepherd's purse	*Capsella bursa-pastoris*
Small nettle	*Urtica dioica*
Sowthistle	*Sonchus oleraceus*
Spear thistle	*Cirsium vulgare*
Willowherb	*Chamaenerion angustifolium*

Cultural control

Rotations

Some soft fruit growers rent land from arable or livestock farmers, which can aid in weed control through rotation. Careful site selection is needed if this approach is taken, as land that has previously had potatoes on it may harbour diseases that could infect soil grown raspberry and strawberry crops. This approach may not be possible for growers working on a smaller production area. Where a crop has been in the soil for a long period (e.g. bush fruit) and the site is to be replanted, a minimum of one year's break is advised to have the opportunity to gain control over perennial weeds.

Mulches

In general containerised soft fruit pots are placed onto weed suppression membrane on the ground, such as woven polypropylene. This is often used in conjunction with residual herbicides in order to control weeds in container-grown soft fruit. When planting a new blackcurrant plantations, growers can stick the cuttings through woven polypropylene or polythene sheeting. These coverings will supress weeds for the duration of the life of the sheeting (1-5 years depending on type), although care needs to be taken particularly in currants that as the bush grows the new base shoots are not restricted. This allows the bush to become established and create a canopy which can also supress less competitive weeds.

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

Living mulches are generally not used in soft fruit due to the difficulty of establishment and competition effects of the living mulch on the yields of the fruit.

Cover cropping

The use of cover cropping can be beneficial to supress weeds, provided that it can be easily killed off when required and is in place at the right time. This is not something that is widely used in the

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UK at the moment, although it may be worth considering, as there are a number of benefits to cover cropping, such as improved soil structure and an increase in organic matter. Using red fescue (*Festuca rubra*) and black medic (*Medicago lupulina*) cover crops prior to planting blackcurrant cuttings was found to supress noxious weeds in AHDB project CP086 (Atwood, 2017) with no effect on blackcurrant establishment, however the effects on yields over multiple seasons were not fully assessed.

Non-chemical control

Manual removal of weeds

Hand weeding is generally employed by smaller farms and those growing containerised fruit, where the numbers of pots and area to cover is relatively small, unless a large work force is available. Specific weeds may be targeted, as the labour cost for this method of weed control is high. Where bindweed becomes a problem in blackcurrants at harvest it is removed from the bushes by hand to stop the bindweed becoming tangled in the harvesting machinery. With limited herbicides available during the growing season weeds with large tap roots, such as docks (e.g. *Rumex obtusifolius*) or thistles, may have to be removed manually in order to stop seed set.

Mechanical weeding

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

Mowing

Mowing is often employed around the headland in a crop to stop weeds flowering and are used in both soil and containerised production, with timing of mowing critical to stop seed spread (AHDB Factsheet 05/18). Where vegetative alleyways are maintained in a crop, to reduce compaction from machinery and soil erosion, these will also be mown. In table top strawberry production the area underneath the gantry may be left as vegetation, which will be mown regularly to reduce humidity and the risk of disease, particularly if the crop is tunnelled. Mowing machinery is available where the mower head position can be altered to accommodate the table top legs. This weed control approach is useful for weed banks around the farm and between rows where there is a vegetative alleyway, however is generally impractical for weeds growing through a crop.

Thermal weeding

Thermal weeding methods include electric weeders, which have been tried in some blackcurrant crops with varying success. These are typically hand held or pulled along and electrify weeds

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causing scorch and death depending on the weed. An ongoing project is currently looking at the use of electric weeders in blackcurrants to control creeping thistles (*Cirsium arvense*) using tractor mounted weeders (EAFRD project 2018). Initial indications are promising, though further trials are being run to assess treatment timing and refine the equipment to make it suitable for use in blackcurrants. This may not work for other crops that would be sensitive to the electrical current. It is also going to be most effective in soil cropping conditions and where weeds are significantly taller than the crop.

Hot foam treatments have been trialled in other studies, such as for hardy nursery stock (HNS) in AHDB project CP 086 (Atwood, 2017) (ADAS, 2014), and have the potential for use in soil grown soft fruit. Multiple applications were necessary in this study in order to get good weed control. Trialling would need to be performed on each crop as each one will differ in their sensitivity to the treatment.

For any thermal weeding technique to be adopted by the soft fruit industry the technology would need to be able to be mounted on or pulled by a tractor or similar vehicle in order to make application as efficient as possible. Treatment timing and application numbers would need to be investigated in order for growers to get the best out of the technology.

Future action: Monitor trials being performed on electrical weeding in blackcurrants. Consider trialling hot foam treatments in soft fruit production, once technology and application methods have advanced. This could be in combination with guided weed control systems or robots.

Chemical control

Chemical herbicides are used in conjunction with other methods, such as plastic mulches, and are the most commonly used methods of weed control in soft fruit. With the increasing costs of labour and the lack of widely used alternatives, herbicides allow for cost effective and reliable weed control.

Existing chemicals

In soft fruit crops in the soil without plastic mulches generally have residual herbicides at the start of the season to reduce the numbers of germinating weed seedlings. This will generally be followed by a contact herbicide later in the year depending on the crop and is most common for bush fruit crops in the soil. The majority of the approvals listed in Table 31 for the different soft fruit crops are approved as an EAMU and may have specific restrictions for methods or areas of application. The most commonly used herbicides in the soft fruit industry from 2010 to 2016 were diquat, glyphosate, glufosinate-ammonium and pendimethalin according to Garthwaite *et al*., (2016a). Glufosinate-ammonium has been withdrawn since that pesticide survey report and diquat has also been withdrawn, with the final use up in 2020.

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Table 31 Herbicides authorised for use in soft fruit crops. Products will be authorised under each crop specific search term, some are for around crop use only. Care should be taken to check authorisations prior to use, products authorised as EAMUs are used at the grower's own risk. ✓= Full approval, ✓* = EAMU, - = no approval for crop.

	Active	Strawberry	Raspberry	Blackberry	Blueberry	Blackcurrant & redcurrant	Gooseberry
Contact acting	carfentrazone-ethyl	✓*	✓*	✓*	✓*	✓*	✓*
	clethodim	✓*	✓*	✓*	✓*	✓*	✓*
	clopyralid	✓*	-	-	✓*	✓*	✓*
	cycloxydim	✓	-	-	-	-	-
	diquat	✓	✓	✓	✓	✓	✓
	fluazifop-P-butyl	✓	✓	✓*	✓*	✓	✓
	glyphosate	✓*	✓*	✓*	✓*	✓*	✓*
	pelargonic acid	✓	✓	✓	✓	✓	✓
Residual acting	dimethenamid-P + pendimethalin	✓*	-	-	-	-	-
	flufenacet + metribuzin	-	-	-	✓*	✓*	✓*
	isoxaben	✓	✓	✓		✓	✓
	metamitron	✓*	-	-	-	-	-
	pendimethalin	✓	✓	✓	✓*	✓	✓
	propyzamide	✓	✓	✓	✓*	✓	✓
	s-metolachlor	✓*	-	-	-	-	-

New chemistries

Work has been done to identify further herbicides that may gain approval for use in blackcurrants in AHDB projects SF 012 and SF 154, as well in recent SCEPTREplus trials. SF 012 identified herbicides that subsequently gained approval for use in blackcurrants, however there have been losses to approved products in the intervening years. SF 154 identified rates of usage for carfentrazone-ethyl in strawberry during the dormant season, which resulted in an EAMU for its use in 2017. Wing P (dimethanamid-P + pendimethalin) has recently gained approval for use in strawberry crops and may be a useful chemical for other soft fruit crops if EAMUs can be attained. The SCEPTREplus programme of work will continue to identify new chemistries available for soft fruit production.

Alternatives to glyphosate

The usage of glyphosate across the soft fruit industry varies significantly depending on the crop. Glyphosate usage in strawberries and raspberries for example is low, and in these sectors diquat has the greatest usage. Blackcurrant growers were the greatest users of glyphosate in the soft fruit industry in the 2016 growing season (Garthwaite *et al*., 2016a). Alternatives are already being used, such as carfentrazone-ethyl and diquat and the amount used in blackcurrants equates to the same usage as glyphosate. The withdrawal of approval for diquat will result in carfentrazone-ethyl and

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pelargonic acid being the remaining alternatives for general weed control in the soft fruit industry. As mentioned above the SCEPTREplus programme of work is looking for new chemistries that can be brought to blackcurrants in the future.

Herbicide resistance

Herbicide products with different HRAC codes are applied to soft fruit where possible to reduce the risk of herbicide resistance developing. The risk of herbicide resistance will increase as more actives are lost in the future, if only few new actives are approved going forward.

Bioherbicides

Biopesticides have been well adopted for insect pests and fungal pathogens, however, this has not been the case for bioherbicides. In the UK only a few bioherbicides are currently approved for use, the actives of these include citronella oil and acetic acid (HDC Factsheet 18/14). At present these products are only approved for grassland, non-cropping areas (citronella oil), areas not intended to bear vegetation and hard surfaces (acetic acid) and not for fruit. A Defra funded project into bioherbicides (PS2153) indicated that inclusion of bioherbicides into a weed control programme could be beneficial, such as application along with traditional herbicides or multiple bioherbicide agents applied together.

Novel and emerging technologies

In field situations where there are no tunnels, such as in large blackcurrant plantations, aerial imagery (drones, satellite, and aeroplane) could be used to identify weed hot spots in fields and assess the efficacy of the weed treatments applied.

These could be used in conjunction with the new emerging area of robotic weeders in the future as the technologies advance. Technologies such as electric weeders have the potential for being implemented on robots.

Apps

Weed identification applications are available on smartphones. Some enable the user to take a photo and suggest possible weeds, giving botanical descriptions. These do not always give the correct identification and may require the user to do more research into the identified weed. Nonetheless these are useful tools that are probably underutilised by growers.

Future action: Simplify the weed identification apps to make them more user-friendly and ensure growers are aware of them and able to use the technology.

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Preventative weed control

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

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

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

Future action: Inform growers on all potential routes for weed infestation and issue guidance for control.

4.1.3. Tree fruit

Tree fruit systems include crops of plums, cherries, pears, cider and dessert apples. In 2017 the area covered by tree fruit production in the UK totalled 24,449 ha (Defra, 2017). Tree fruit orchards are in the ground for over 20 years, with apple orchards having a duration up to 30 years and as such these areas have a long period over which to accumulate weeds. Despite being a high value crop, soft fruit growers tend to rely on off-label approvals for herbicides for weed control. Alternative methods for weed control in tree fruit include organic mulches, mowing and tilling in organic production.

Weeds within soil grown tree fruit systems will compete with trees for light, space, soil moisture and nutrients. An approach of starting clean at orchard establishment is preferable in these crops to avoid competition that will affect vigour and ultimately yield. Weeds, such as plantains (*Plantago* spp.), can act as alternative hosts for significant pests of these crops, such as the rosy apple aphid that will migrate into an apple crop causing economic damage to the crop. The main weed species of orchards can be found in Table 32.

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Table 32 List of weeds commonly found in soft fruit crops.

Common name	Scientific name
Cleavers	*Galium aparine*
Couch grass	*Elymus repens*
Creeping thistle	*Cirsium arvense*
Dock	*Rumex obtusifolius*
Fathen	*Chenopodium album*
Groundsel	*Senecio vulgaris*
Plantain	*Plantago* spp.
Redshank	*Persicaria maculosa*
Sedges	*Carex* spp.
Small nettle	*Urtica dioica*
Sowthistle	*Sonchus oleraceus*
Spear thistle	*Cirsium vulgare*
Willowherb	*Chamaenerion angustifolium*

Cultural control

Mulches

Mulches are often used in orchards within the herbicide strip. These may consist of green compost, bark or clippings from alleyway mowing. Numerous studies have demonstrated the effectiveness of organic mulches in orchard situations, either alone or in conjunction with herbicide applications (Merwin *et al*., 1995; Hartley *et al*., 1996; Rifai *et al*., 2002; Neilson *et al*., 2014). These studies have evaluated the effects of mulches on the yield and quality of the fruit and found no difference when compared to herbicide application alone.

Where organic mulches, such as green compost, are added to the tree row RB209 guidelines (2019) should be followed to ensure that nutrient levels are not exceeded for the crop. If residual herbicides are still to be used within the strip organic mulches may affect the efficacy of the actives.

Living mulches, where a low competitive seed mix is sown in the strip at the time of orchard establishment, were trialled in the AHDB Weed Fellowship CP 086 (Atwood, 2017). Whilst some mixes performed well in terms of weed control all treatments resulted in a yield penalty at harvest compared to the standard herbicide application, indicating how sensitive tree fruit can be to competition. Similar effects were seen in a studies by Tworkoski & Glen (2012) and Tahir *et al*., (2015), where different living mulches caused smaller apples and lower yields when compared to herbicide application.

Cover cropping

The use of cover cropping can be beneficial to supress weeds, as well as creating an improved soil structure and an increase in organic matter. Using red fescue (*Festuca rubra*) and black medic

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(*Medicago lupulina*) cover crops prior to planting blackcurrant cuttings was found to supress noxious weeds in AHDB project CP 086 (Atwood, 2017) with no effect on blackcurrant establishment, however the effects on yields over multiple seasons were not fully assessed. This approach could be employed prior to planting of new tree fruit orchards provided that the cover crop is completely killed off before planting.

Non-chemical control

Mechanical

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

Tahir *et al*., (2015) trialled orchard floor management systems in an organic orchard including acetic acid application plus tilling, traditional mechanical tilling and a ‘sandwich’ system that combined a modified tillage system with a living mulch. The mechanical tilling was performed on a 1.5 m strip three times during the season. The ‘sandwich’ system had a living mulch established that was mown three times during the season with the clippings mulched on top, and a 40 cm strip tilled on either side. The three systems that included mechanical tilling performed better in terms of yield than a living mulch on its own.

Mowing

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

Mown alleyways are maintained within orchards, as this reduces herbicide applications, stabilises the soil and maintains soil structure. There has been more of a move towards having species rich alleyways in recent years that are mown less frequently in order to encourage natural predators in orchards (Cross *et al*., 2015).

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

Thermal weeding

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

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Raifi *et al*., (2000) evaluated steaming and flame weeding in an organic orchard, comparing it to mulching. Steam application provided some initial weed control, however this was reasonably short lived, with further applications necessary seven days after the initial application. Flame weeding provided good initial control of seedlings of annual weeds, but did not perform well on perennial or weeds with six or more true leaves. A driving speed of 2 km/hr provided the best weed control in the trial. Flame application should not be applied in conjunction with a mulch due to fire risks involved.

Hot foam treatments have been trialled in other studies, such as for HNS in AHDB project CP 086 (Atwood, 2017) (ADAS, 2014), and have the potential for use in tree fruit crops. Multiple applications were necessary in this study in order to get good weed control. Trialling would need to be performed on each crop as each one will differ in their sensitivity to the treatment.

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

Chemical control

In non-organic orchards trees are typically situated within a weed free strip that is maintained with residual and contact herbicides in conjunction with mulches during the season. Chemical control is widely used across the top fruit industry in order to achieve relatively cost effective and reliable weed control.

Existing chemistries

Over the period 2014 to 2016 there was a 20% increase in the usage of herbicides in orchards across the UK, which is linked to an overall increase in the area planted during this period (Garthwaite *et al*., 2016b). Herbicides with approvals for use in tree fruit orchards can be found in Table 33. The majority of these are off-label approvals, with some actives having a restriction of 365 day harvest interval (HI). The most commonly used herbicide in all tree fruit crops in 2016 was glyphosate (Garthwaite *et al*., 2016b).

Table 33 Herbicides authorised for use in tree fruit crops. Products will be authorised under each crop specific search term. Products listed under ‘Top Fruit’ and ‘Outdoor Top Fruit’ have 365 day harvest interval (HI). Care should be taken to check authorisations prior to use, products authorised as EAMUs are used at the grower’s own risk. ✓= Full approval, ✓* = EAMU, - = no approval for crop.

	Active	Apple	Pear	Cherry	Plum	Top fruit
Contact acting	2,4-D	✓	✓	-	-	
	clopyralid	✓*	✓*	-	-	
	diquat	✓	✓	✓	✓	
	fluazifop-P-butyl	✓*	✓*	✓*	✓*	
	fluroxypyr	✓*	✓*	✓*	-	
	glyphosate	✓	✓	✓	✓	

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	nicosulfuron					✓* 365 day HI
	pelargonic acid	✓	✓	✓	✓	
	prosulfocarb	✓*	✓*	✓*	✓*	
	flufenacet + isoxaflutole	-	-	-	-	✓* 365 day HI
	flumioxazine	-	-	-	-	✓* 365 day HI
	imazamox + pendimethalin	-	-	-	-	✓* 365 day HI
	isoxaben	✓	✓	✓	✓	
Residual acting	pendimethalin	✓	✓	✓	✓	
	propyzamide	✓	✓	✓*	✓	

New chemistries

The AHDB Weeds Fellowship CP 086 (Atwood, 2017) investigated new herbicides that could be brought to apple orchards, several safe and effective options were identified in the study, although further off label approvals have not been forthcoming and several herbicides have since been lost, such as glufosinate-aluminium. Wing P (dimethanamid-P + pendimethalin) has recently gained approval for use in strawberry crops and may be useful for tree fruit crops if EAMUs can be attained. The SCEPTREplus programme of work will identify new chemistries available for tree fruit production.

Alternatives to glyphosate

Glyphosate is the most commonly used herbicide across all tree fruit crops (Garthwaite *et al.*, 20016b). Some alternatives are already being used, such as 2, 4-D and diquat, however these equate to a small proportion of herbicides currently used and are often used in conjunction with glyphosate for adequate weed control. The withdrawal of approval for diquat will result in 2, 4-D and pelargonic acid being the remaining alternatives for general weed control in the tree fruit industry. As mentioned above the SCEPTREplus programme of work is looking for new chemistries that can be brought to tree fruit in the future.

Herbicide resistance

Herbicide products with different HRAC codes are applied to soft fruit where possible to reduce the risk of herbicide resistance developing. The risk of herbicide resistance will increase as more actives are lost in the future, if only few new actives are approved going forward.

Bioherbicides

Biopesticides have been well adopted for insect pests and fungal pathogens, however, this has not been the case for bioherbicides. In the UK only a few bioherbicides are currently approved for use, the actives of these include citronella oil and acetic acid (HDC Factsheet 18/14). At present these

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products are only approved for grassland, non-cropping areas (citronella oil), areas not intended to bear vegetation and hard surfaces (acetic acid) and not for fruit. A Defra-funded project into bioherbicides (PS2153) indicated that inclusion of bioherbicides into a weed control programme could be beneficial, such as application along with traditional herbicides or multiple bioherbicide agents applied together.

Novel and emerging technologies

In orchard situations where there are no tunnels, aerial imagery (drones, satellite, aeroplane) could be used to identify weed hot spots in fields and assess the efficacy of the weed treatments applied.

These could be used in conjunction with the new emerging area of robotic weeders in the future as the technologies advance. Technologies such as electric weeders have the potential for being implemented on robots.

Apps

Weed identification applications are available on smartphones. Some enable the user to take a photo and suggest possible weeds, giving botanical descriptions. These do not always give the correct identification and may require the user to do more research into the identified weed. Nonetheless these are useful tools that are probably underutilised by growers.

Future action: Simply the weed identification apps to make them more user-friendly and ensure growers are aware of it and able using the technology.

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Preventative weed control

Machinery should always be checked for cleanliness to prevent weed seeds being transferred on farm. Timing of weed control is important to ensure that weeds are dealt with before setting seed and preferably before flowering.

Future action: Inform growers on all potential routes for weed infestation and issue guidance for control.

4.1.4. Protected ornamentals

Protected ornamentals includes bedding and pot plants and HNS grown under protection, Crops are either grown on the floor of glasshouses or on benches, the weeds are present in gravel, between paving slabs or in cracks in the concrete under benches. Where crops are grown on the floor the ground may be made up and levelled with sand and gravel to provide a firm well drained base that is covered with a plastic woven matting to prevent weed growth. Alternatively plastic woven matting is laid directly over the soil. Weeds occur around stations particularly where there is a gap, in any rips or tears in the matting and where growing media collects on the surface of the matting.

Weed pressure and control differs within these crop groups however crop hygiene contributes significantly to weed control.

Bedding plants are typically bought in as plugs from specialist plant raisers, the majority are seed raised although some important Genus are raised from cuttings. Plugs are transplanted into six-packs or pots soon after they are delivered and are grown on until ready for sale. Winter bedding crops such as *Primula* are some of the longest on the nursery with some crops on the nursery for 3-4 months. Summer bedding crops have a much shorter turn around and are finished in a matter of weeks. Peat based growing media/coir typically makes up the growing media which is generally free of weeds, although low levels of weed seed are often present in the growing media. Growing media is supplied in bulk, wrapped in plastic to prevent weed contamination. Watering regimes are managed to minimise excess wetness which encourages weeds such as liverwort *(Marchantia polymorpha)* however weed contamination can still occur, particularly where windblown seed (e.g. *Salix)* blows in through the glass house vents. The crop is susceptible to herbicide damage so herbicides are not used. Due to the short term nature of cropping any weeds are physically removed which is sufficient to keep the crop clean.

Pot plant production includes potted Roses, Chrysanthemum, Begonia, Orchids and Poinsettia and other genus. Young plants are bought in from specialist plant producers as unrooted cuttings, plugs or micro propagated young plants. Plugs are potted on into a peat (or bark in the case of Orchids) based growing media which is generally free of weeds and are grown on for sale. Most crops are

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relatively short term with Orchids having the longest production cycle. Most of the crops are susceptible to herbicide damage and as weed pressure is low herbicides are not typically used, weeds are physically removed by hand to keep the crop clean.

Protected HNS, container grown. Typically either propagated in house or bought in as a plug or a liner. The production cycle can take up to 2 years from cutting to finished plant and a number of common annual nursery weeds can grow in the pots during this time (e.g. Groundsel *(Senecio vulgaris)*, Mouse eared chickweed *(Cerastium fontanum Baumg.* Subsp. *triviale)*, bittercress *(Cardamine* spp.), Willow seedlings *(Salix caprea)* and Willowherb *(Epilobium* spp.) Controlling weeds around the site, maintaining good levels of crop hygiene and preventing weeds contaminating irrigation water are very important cultural controls. Residual herbicide programmes backed up with hand weeding is the typical approach to weed control but there are limited residual herbicides available for use under protection e.g. flufenacet, isoxaben, metribuzin and dimethenamid-p + metazachlor.

Due to the nature of cropping, weed control techniques are limited to the following (herbicides only being relevant to protected HNS):

Hand Weeding

Hand weeding is used to compliment residual herbicide programmes and inter row cultivations where weeds are growing within the crop row and cannot be removed mechanically. Hand weeding is expensive so a range of other techniques are used to help minimise costs.

Mechanical weeders

Mechanical weeders are not used as they have not been developed for use in container grown crops. It is unlikely that they would be an effective option as damage to pots or packs cannot be tolerated as this would reduce the quality of the finished product. If a suitable vision guided mechanical weeder could be developed, weeds that had been removed would need collecting, as weeds and growing media on the production bed are a source of contamination for gravel or sand beds which could facilitate further weed growth.

Future action: Investigate the potential of electric weeding and mechanical solutions for HNS container grown crops as a spot treatment/alternative to hand weeding.

Bark mulches

These are routinely used in the production of container grown HNS and are applied via a machine immediately after potting, research has shown that these successfully reduce some weeds such as moss *(Funaria hygrometrica)* and liverwort *(Marchantia polymorpha)* (HDC, 2012). Herbicides are used for the control of other weed species.

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Wood fibre mulches

These are relatively new to the market as commercial products and are currently being trialled by nurseries, however it can be difficult to achieve a sufficient depth of mulch when plants are potted by machine as potting machines fill containers to the pot rim. These mulches may be better suited to specimen plants in large pots where mulches are applied by hand and a sufficient depth to prevent weed growth can be achieved. Wood fibre mulches contribute to weed control post potting but herbicides still need to be applied to achieve the desired level of control.

Biodegradable mulching spray

Researchers in Italy have developed a biodegradable mulching spray based on chitosan for weed control in the cultivation of containerised shrubs. It was applied with a compressed air spray gun at 2L/m² to an estimated thickness of 150 µm. More than two months after application the mulching spray effectively controlled weed growth in containers even under severe weed pressure. Three months after its application the mulch started to degrade which allowed the growth of some weeds in the containers but use if the mulch outperformed the herbicide control with oxadiazon granules (Giaccone, 2018)

Pot toppers

Pot toppers, typically (woven coir) are used largely on specimen pots to supress weeds as a physical barrier. Pot toppers have their limitations and can blow off however larger pot toppers are more effective as they are less likely to blow off or shrink from the edge of the pot.

Future action: Continue to investigate non-chemical alternatives for weed control, working with commerce to transfer research to commercially available products e.g. Chitosan biodegradable mulching sprays.

Existing chemistries

The following actives are approved for use in protected ornamentals, but there are some restrictions and obstacles to use as follows; dimethenamid-p + metazachlor (either at low rates or at 1 in 3 years), flufenacet, isoxaben (once per crop), metazachlor (either at low rates or at 1 in 3 years), metribuzin (no crop safety info – contact action and risk of root uptake so likely to be damaging so not really used). Dimethenamid-p + metazachlor can still be used under the long term arrangement for extension of use (LTAEU under protection), and these uses need reviewing and converting to EAMUs to secure their longer term usage. The AHDB Horticulture crop protection review highlights the fact that there will be reduced reliance on chemical herbicides as the number of available products continues to fall (AHDB, 2017c)

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Future action: Growers will need to be informed of the most efficient and crop safe weed control mixtures and where products should be utilised within weed control programmes. This is necessary to optimise the use of these key actives and maintain their long term efficiency.

Optimising use of existing chemistries

There is a need to maintain strict hygiene standards to optimise the use of existing chemistries through the prevention of herbicide resistance, reduced environmental impact and through precision application.

Future Action: As little or no monitoring of herbicide resistance has been done in protected ornamentals production, testing key weed species from multiple nursery sites would be worthwhile.

Precision application

Herbicides have typically been applied over the top of crops immediately after planting or early in the year whilst the crop is dormant. Some residual herbicides such as isoxaben and metazachlor can safely be applied over crop foliage as a summer top up treatment but both actives have recently had restrictions on the rate of use and the number of applications per crop.

Future Action: There is scope for brushing of weeds, identification and spot weeding with vision guided technology, laser/electric weeders other novel techniques that are likely to be crop safe. Precision application and placement of herbicides sprayed onto the surface of the growing media using automation to maximise efficiency and improve crop safety.

New chemistry

New chemistry is typically registered on major crops where there is a greater return on investment. Therefore as minor crop, horticultural crops typically rely on EAMU approvals to facilitate use. There may be new actives which could be relevant to protected ornamental production and the AHDB continues to review any possibilities as they arise.

Future actions: AHDB and agrochemical and biopesticide manufacturers to continue to work together to support the introduction of new herbicide active ingredients and EAMU applications for the crop

Assess any new chemistry's suitability for the control of key weeds of HNS under protection.

Commodity substances

Sodium hydrogen bicarbonate proved to provide post emergence control of liverwort *(Marchantia polymorpha)* when used at 122 kg/ha, it is now used by some growers to control liverwort *(Marchantia polymorpha)* in container grown crops (Atwood *et al*, 2016).

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Bioherbicides

Not currently used but currently research is investigating the effectiveness of *Phoma macrostoma* as a bioherbicide for use in cereal crops for broadleaved weed control of Sowthistle (*Sonchus arvensis*). Its broad spectrum weed control, short persistence, and low risk to the environment could make it an effective bioherbicide option (Hynes, 2018) for a variety of crops, including protected ornamentals. Pelargonic acid is not used but could be useful for inter-row or on hard standing areas in the absence of glyphosate. Care would need to be taken around crops not to scorch them as crop quality is paramount.

Future action: Trial any promising bioherbicides for efficacy and crop safety.

Seed meals

HNS 175 (AHDB, 2011) identified the fact that *sinapis alba* seed meals have the potential to reduce the cost of liverwort control by reducing manual removal

Future action: Further research and development of seed meal application and refining the dose rate is required before specific recommendations can be made.

Managing weeds in non-cropped areas

Weeds are typically managed proactively in such areas through the use of persistent residual herbicides such as Chikara (flazasulfuron) which typically provides up to five months residual control. Season long control is achieved through application of either top up residual herbicide or regular applications of contact herbicides. Weeds could potentially be managed without herbicides in non-cropped areas but this would increase time spent managing weeds. The season can be so hectic when the weather is good and the season is in full swing (particularly on bedding nurseries) that weed control gets neglected and weeds in non-cropped areas contribute to weed pressure.

4.1.5. HNS Field grown stock: Transplants and Budded crops

Budded crops are grown on a three year crop cycle, the rootstocks are either grown from seed (e.g. *Rosa)*, drilled directly in pre formed beds in the soil in April/May that has been sterilised with Basamid to minimise weed pressure and soil borne diseases on specialist nurseries. Seedlings are very sensitive to competition post germination and a limited range of residual and contact herbicides are crop safe. Alternatively rootstocks are produced on stool beds (e.g. *Malus)* and are clones, harvested after one year’s growth with some roots. Perennial weeds are problematic in stool bed production as the mother stock may remain in the same location for a number of years.

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Rootstocks; whether seed raised or clones the rootstocks are lifted, graded and cold stored in the autumn / winter following their first year of growth. Specialist nurseries often raise and supply rootstocks although some growers produce their own in house. Rootstocks are then planted into pre formed beds in the field in April/May and are budded between July and August depending on the species. Rootstocks are headed back the following February and the bud of the chosen clone grows away for one year prior to being lifted and sold as a maiden. Residual herbicides are applied post planting rootstocks, post budding and post heading back; pendimethalin, metribuzin, lenacil, isoxaben and metazachlor are key actives.

Transplants are raised from seed or cuttings. Seed raised Genus are typically grown for one year are then lifted, graded and cold stored prior to being replanted into prepared beds to grow on for 1 to two years. Depending on the genus, cutting raised stock is often left to grow on for two to three years prior to being lifted, graded and sold. Crop value is determined by height and weed pressure can severely restrict the potential height of many crops (especially in the first year of growth), effectively devaluing it.

Large and specimen trees are planted as large transplants or maidens that have been budded and grown elsewhere. The number of growing seasons depends on the required height and girth. Large trees are either lifted as bare root crops or are root balled whereas specimen trees are root balled. Crop value is determined by the girth of the trunk, weeds compete with the crop for water and nutrients and can reduce growth particularly in younger trees.

Cultural control

Rotations

Field grown HNS is typically rotated with either major arable crops or a grass ley, Perennial ground cover, if present would compete with the crop and interfere with lifting operations. Rotations help to manage weed populations but the crop spacing and the presence of bare soil enable annual weeds such as groundsel (*Senecio vulgaris*) to thrive therefore a robust residual herbicide programme is required. There are limited contact herbicides, particularly between September and March that can be used over the crop and the loss of diquat as a inter row treatment will be a significant blow.

Future action: Evaluate planting the crop using GPS or RTK guidance systems and the utilisation of non-chemical weed controls as inter-row treatments.

Tillage and cultivations

Stale seed beds are sometimes used but if the land is part of a wider rotation there is often limited time or opportunity to utilise tillage and cultivations, particularly in the year of planting as soils are often too wet prior to planting early in the year. Crops are typically grown on light soils (often with a low organic matter content) and additional tillage and cultivations; particularly on sloping sites can

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create other problems such as soil erosion. Ploughing is typically carried out in the autumn to bury previous crop residues (stubble or grassland after spraying off and any compost that has been applied) and allow winter frosts to break the soil down. Ploughing, in terms of weed control, is valuable as it buries freshly shed seed to a depth below which it cannot germinate. Cultivations in the spring prior to planting will bring some weed seed to the surface.

Inter-row cultivations and mechanical weeding are used during the growing season and are a viable option to supplement the limited range of contact herbicides authorised for use in the production of crops such as transplants. Cultivation between rows on closely spaced crops provides good weed control (Halcomb, 2009). Any perennial ground cover would interfere with lifting operations.

Future action: Evaluate the potential of cover crops which could be sprayed off with glyphosate prior to carrying out strip tillage where crop rows are to be planted to utilise the cover crop as a mulch. Free flowing mulch could be considered where the cover crop has been buried during planting (straw would be unsuitable as it would interfere with lifting machinery)

Stubble cultivations

Stubble cultivations are not currently widely carried out and could be utilised more for weed control after arable crops have been harvested the year prior to crop establishment. Closer collaboration between landowners and growers would help to maximise this technique potential as crops are often grown on rented land. Extra cultivations carry a cost but improved weed control through reduced weed pressure would make this worthwhile. Where perennial weeds are a problem the emphasis would need to be placed on controlling these with a suitable systemic herbicide (e.g. glyphosate) prior to carrying out stubble cultivations.

Cultivations

Ploughing or bed forming are often the primary cultivations as a deep rooting zone is needed to plant crops and enable them to establish. Non-inversion tillage is not widely used in HNS production as there is the common misconception that the technique would not provide sufficient depth to physically plant the majority of crops. Rooting depth need not be constrained through the effective utilisation of appropriate methods (e.g. strip tillage) and improvements in soil structure and organic matter levels should improve crop performance.

No-till or direct drilling is not appropriate for HNS crops, because soil sterilisation is routinely carried out prior to drilling seed raised crops as it helps to control weeds and increase crop vigour.

Future action: Evaluate the potential of non-inversion tillage in the production of HNS.

Cover cropping

Cover cropping using cereals such as oats is used by rose growers as a potential method of allopathic weed control, however the benefits (if any) are not well understood. Selective herbicides

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that control broad leaved weeds can be and are still used to help to reduce weed pressure from volunteer potatoes and broad leaved weeds in the cover crop.

Adding a cover crop in the rotation results in the need to rent land for longer however any reductions in weed pressure makes this worthwhile particularly where volunteer potato control is needed. This technique is used prior to planting rootstocks.

An alternative approach is to plant a longer term (typically three-year) ryegrass and clover lay to build fertility and reduce pressure from annual weeds. This is normally done on owned rather than rented land.

Intercropping or companion cropping

This technique has not been tried however crop vigour is reduced by competition and crop value of transplants is dependent on its height. Any intercropping would need to benefit the crop and would need to be easily killed off with a crop safe contact herbicide well in advance of lifting so that crop debris did not inter fear with lifting operations.

Future action: Evaluate the potential of intercropping for weed suppression in the production of HNS. A range of species would need to be evaluated alongside the performance of the HNS crop to determine if a suitable companion crop can be found

Non – chemical control - Manual removal of weeds

Hand Weeding

Hand weeding is used to remove annual weeds to compliment residual herbicide programmes early in the season before inter row cultivations start. Hand weeding also compliments inter-row cultivations where weeds are growing within the crop row and cannot be removed mechanically. Hand weeding is expensive so residual and contact herbicides or inter cultivations are preferential to help minimise costs.

Mechanical weeding

Mechanical weeding is not currently used in HNS because weed control is achieved through the use of herbicides.

Future action: Evaluate the potential of mechanical weeding in longer term field grown trees.

Electrical weeding

Not currently used due to the technology being very new, also concerns relating to health and safety. Has the potential for wider use and this technology could be used following its use in blackcurrants.

Future action: Evaluate electric weeders potential to control weeds between crop rows as a spot treatment to compliment hand weeding in the future.

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Hot water and Foam weeding

Not currently used but some leading growers expressing interest in this technique given the continual decline in herbicide options.

Steaming

Not currently used in the UK as chemical soil sterilants are available for both control of weed seed and soil borne diseases. The method has been used in field HNS production in Germany but is expensive and time consuming. If remaining soil sterilants are withdrawn this technique may be used in the UK.

Mulching

Some crops are grown through plastic mulches e.g. field grown maiden trees with a two year production cycle however plastic mulches are high cost and disposal of waste plastic creates large volumes of waste.

Future action: Evaluate free flowing biodegradable mulches as an alternative to residual herbicides.

Chemical control

Existing chemistries

The residual herbicide lenacil is still used under the long term arrangement for extension of use (LTAEU), and needs reviewing and converting to an EAMU to secure the long-term future of the active. The AHDB Horticulture crop protection review highlights the fact that there will be reduced reliance on chemical herbicides as the number of available products continues to fall (AHDB 2017d)

Future action: Growers will need to be informed of the most efficient and crop safe weed control mixtures and where products should be utilised within weed control programmes. This is necessary to maximise the use of these key actives and maintain their long term efficiency.

Optimising use of existing chemistries

Herbicides have typically been applied over the top of crops immediately after planting or early in the year whilst the crop is dormant. Some residual herbicides such as isoxaben and metazachlor can safely be applied over crop foliage as a summer top up treatment but both actives have recently had restrictions on the rate of use / number of applications per crop.

Future Action: Precision application and placement of herbicides sprayed onto the surface of the soil using automation to maximise efficiency and improve crop safety.

Investigate precision application and placement of herbicides as band treatments between crop rows for improved efficacy and crop safety.

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New chemistry

A new active to the UK HDC H46 has potential for use in field grown HNS and will be included in HNS 198 trials during 2019 (AHDB, 2019). Previous work in HNS with aclonifen highlighted its potential and recent work in HNS 198 (Atwood, 2016) has proved its crop safety on a limited range of field grown HNS.

Future actions: AHDB and agrochemical and biopesticide manufacturers to work together to support the introduction of new herbicide active ingredients and EAMU applications for the crop such as aclonifen, pethoxamid, metobromuron and HDC H46. The SCEPTRE plus model could be followed to support the HNS industry.

Bioherbicides

Not currently used but currently research investigating the effectiveness of *Phoma macrostoma* as a bioherbicide for use in cereal crops for broadleaved weed control, including thistle (*Cirsium arvense*), Sowthistle (*Sonchus arvensis*), and bindweed (*Convolvulus arvensis*). Its broad spectrum weed control, short persistence, and low risk to the environment could make it an effective bioherbicide option (Hynes, 2018) for a variety of crops, including HNS.

Future action: Trial any promising bioherbicides for efficacy and crop safety.

4.1.6. Flowers and bulbs

The production of plants and flowers (ornamentals) comprised around 12% of the total output of UK crops in the five years 2009 to 2013 (Andersons, 2014). It is an important sector within UK agriculture and horticulture, although it is often overlooked, and there has been very little research into alternative methods of weed control.

British grown cut flowers are a high value product. However, when it comes to weed control, growers generally rely on the use of off-label herbicides through EAMUs (Extension of Authorisation for Minor Uses) or LTAEU (Long Term Arrangements for Extension of Use). Despite the crops' high value, they are minor crops when compared to major arable crops, and therefore only form a small market for agrochemical companies. Alternative methods of weed control for cut flower growers are generally hand weeding and cultivation, which are both expensive, and unreliable in wet conditions (ADAS, 2015).

Some cut flowers are drilled and some are transplanted from modules, inevitably these crops are shallow rooting and particularly vulnerable to herbicide damage (AHDB, 2017b). Crop spacing and drilling/transplanting timings will depend on the species being grown. In bulb production (e.g.

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narcissus) usual practice is to plant bulbs in bands of 20-25 cm width in ridges 76 cm apart. Planting timings for bulbs are species dependent.

Effective weed control is extremely important for cut flower growers. Weeds will compete for water and nutrients, reducing the quality and yield of a commercial crop, and they can also harbour pests and diseases which can then move into the crop. Some crops can remain in the ground for a number of years; narcissus crops for three or more years, peony for up to three years, and Gladiolus may be left down for several years. For bulb crops, weed growth reduces the yield and quality of both flowers and bulbs, and impedes both flower picking and bulb lifting. Research in narcissus has shown that the period after flower harvest, when the bulbs are increasing in size and initiating flowers, is particularly important to keep weed free. Where weeds are not controlled after picking, flower yields can be reduced by up to 25% the following year, with a 13% reduction in bulb yield (AHDB, 2013).

There are a number of weeds commonly found in cut flower crops, which are listed in Table 34. Volunteer crops can also be problematic if cut flowers are grown on land that has recently been used for other crops (e.g. Oilseed rape).

Table 34 List of weeds commonly found in cut flower crops.

Common name	**Latin name**
Shepherd's purse	*Capsella bursa-pastoris*
Fat Hen	*Chenopodium album*
Creeping thistle	*Cirsium arvense*
Black-bindweed	*Fallopia convolvulus*
Common fumitory	*Fumaria officinalis*
Red dead-nettle	*Lamium purpureum*
Redshank	*Persicaria maculosa*
Knotgrass	*Polygonum aviculare*
Groundsel	*Senecio vulgaris*
Black nightshade	*Solanum nigrum*
Sow thistle	*Sonchus* spp.
Chickweed	*Stellaria media*
Scentless mayweed	*Tripleurospermum inodorum*
Small nettle	*Urtica urens*
Common field speedwell	*Veronica persicae*

Cultural Control

Rotations

In the cut flower sector, some growers will rent land from arable farmers, in order to maintain crop rotations, which provides one of the key methods of weed control. For growers with a smaller production area, rotation on this scale may not be possible, but there could be the opportunity for crop rotation (e.g. with field vegetable production).

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Crop cultivars

The majority of the drilled cut flower crops, and bulbs, are poor competitors with weeds, particularly at their early growth stages as they can be slow to develop. Some crops, such as Bupleurum and cornflower, compete well with weeds once initially established, reducing the need for follow-up herbicide treatments (AHDB, 2017b). Transplanted modules have the benefit of faster establishment, which will enable them to outcompete weeds.

Future actions:

- Consider the use of transplanted modules over direct drilling.
- Consider varieties that show competitive traits over weeds.

Cover cropping

The use of cover cropping can be beneficial to supress weeds, provided that it can be easily killed off when required and is in place at the right time (3.2.7). This is not something that is widely used in the UK at the moment, although it may be worth considering, as there are a number of benefits to cover cropping, such as improved soil structure and an increase in organic matter. Using leguminous cover crops between rotations of cut flowers can not only supress weeds but could also reduce the need for nitrogen supplied by fertiliser, manures or other sources.

Non-Chemical Control

Manual removal of weeds

Hand weeding and rogueing is still important in the cut flower sector, and for many small farms, remains the main method of weed control. For long-term perennial crops such as peony, the requirement for hand weeding (with some mechanical cultivation) is much greater than crops in the ground for less time. With few herbicide options available to growers, the control of weeds such as creeping thistle (*Cirsium arvense*) growing within and between the rows is virtually impossible without damaging the crop, requiring manual removal.

Mechanical weeding

Mechanical weeding is used in some crops, but if it is not required, it is better to leave the soil undisturbed to maintain the residual herbicide layer. The most common method of mechanical weeding is inter-row shallow cultivators guided by the operator or GPS, but there are now more sophisticated machines such as the Garford Robocrop In-row weeder, which can weed around individual plants. This was trialled and developed in AHDB Horticulture project FV 266 (Grundy, 2007). This is becoming more popular in field vegetable production, and this method of mechanical weeding could also be taken up by the cut flower industry.

Future action: Evaluate and then demonstrate the use of new mechanical weeding machinery such as the Garford Robocrop In-row weeder.

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Thermal weeding

Various studies have been conducted by ADAS investigating the weed control efficacy of an electric weeder in the amenity sector, field vegetables and blackcurrants. The results showed that the handheld device controlled common nettle (*Urtica dioica*), broad-leaved dock (*Rumex obtusifilius*) and creeping thistle (ADAS, 2014c). There is scope for this to be used in cut flower crops, although as in other cases care would need to be taken to ensure there was no damage to the crop. It may be useful to use as a type of spot treatment in problem areas where damage to the crop can be avoided.

The use of hot foam was also trialled on HNS in AHDB funded project CP 086 (ADAS, 2014c), which gave some promising results, although multiple applications were needed. As with electrical weeding, there is the potential for use in cut flower crops, although some species may prove too sensitive.

Future action: Consider trialling electrical weeders and hot foam treatments in cut flower production, either as a spot treatment in problem areas, or when the crop is well established.

Chemical Control

In the cut flower sector, herbicide applications are still the primary method of weed control. Without suitable herbicides, production costs could be prohibitive. In narcissus production for example, if weed cover prevents picking narcissus flower buds, or if it is impossible to lift bulbs because weeds clog machinery, then the worst case is a crop loss of 100% (Knott, 2012).

Existing chemistries

Generally, residual herbicides are applied as soon after drilling or planting as possible. Herbicide products authorised for use on outdoor cut flowers are shown in Table 35. There are a few selective, foliar-acting, herbicides authorised for use on cut flowers, but due to the range of crop species grown, there is a great range of sensitivity to these products between crops. Some crops, such as Bupleurum and cornflower, compete well with weeds once initially established, reducing the need for follow-up treatments. For other less competitive crops, or slow germinating crops such as larkspur, further treatments of residual herbicides may be applied to extend weed control once the crop has emerged and developed to a sufficient size (AHDB, 2017b). For a number of weed species, chemical control options are limited, for example with creeping thistle (*Cirsium arvense*), control currently relies on the use of a few residual herbicides, directed sprays of Dow Shield 400, and hand weeding (ADAS, 2014c).

Table 35 Selective herbicides authorised for use in outdoor cut flower crops. Products will be authorised under the heading 'Outdoor Ornamental Plant Production'. Care should be taken to check authorisations prior to use, and test on a small area first if using a product for the first time, as some flower species can be sensitive to herbicide applications.

Active ingredients	Example product	Target weeds

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Residual herbicides		
chlorpropham	*Intruder*	BLW
clomazone	*Gamit 36 CS*	BLW
dimethenamid-P + metazachlor	*Springbok*	BLW and grasses
dimethenamid-P + pendimethalin	*Wing-P*	BLW and grasses
isoxaben	*Flexidor 500*	BLW
lenacil	*Venzar Flowable*	BLW
metamitron	*Goltix 70 SC*	BLW
metazachlor	*Butisan S*	BLW and grasses
metribuzin	*Sencorex Flow*	BLW and grasses
napropamide	*Devrinol*	BLW and grasses
pendimethalin	*Stomp 400 SC*	BLW and grasses
S-metolachlor	*Dual Gold*	BLW and grasses
Contact herbicides		
bentazone	*Basagran SG*	BLW
clethodim	*Centurion Max*	Grasses
desmedipham + ethofumesate + phenmedipham	*Betanal Expert*	BLW and grasses
fluazifop-p-butyl	*Fusilade Max*	Grasses
phenmedipham	*Betasana SC*	BLW and grasses
florasulam	*Boxer*	BLW

The latest Pesticide Usage Survey Report for Outdoor Bulbs and Flowers in Great Britain was published in 2009, covering the 2008/09 cropping season. The most extensively used herbicides were glyphosate (non-selective), accounting for 35% of the herbicide-treated area, linuron (11%), pendimethalin (11%) and chlorpropham (11%) (Garthwaite *et al*., 2009). The recent loss of linuron, and increasing restrictions on the use of some products, means that for some growers, the need to investigate alternative methods of weed control is now required, reducing the reliance on herbicides if possible.

For bulb crops, there are only a handful of EAMUs which specifically state that the herbicide is safe for use on bulb crops, for example Kerb Flo (propyzamide) EAMU 0207/13. Most product labels state 'Outdoor Ornamental Plant Production' but unless narcissus or bulbs are specified on the label, this use is at the growers own risk, which adds to the difficulty of finding suitable herbicides for weed control within bulb crops.

Optimising use of existing chemistry

The main method of herbicide application is to apply residual herbicides over the whole planting area immediately after drilling or planting. This has its restrictions, as some plant species can be very sensitive to the current herbicides authorised for use, and to avoid damaging the crop, growers will often apply a lower rate. Whilst this is safe to the crop, it also results in a shortened duration of effective weed control, and many growers find that a top-up treatment is required. Spot treatments can be utilised, particularly in problem areas, where weed populations are high. This is often done with a knapsack and handheld lance. However, in the field vegetable sector, precision application (spatially targeted) is becoming more common and this is something that would be of great benefit in field-grown cut flowers. Within SceptrePlus, a trial has been funded for 2019 looking at precision spraying between the rows of a drilled sweet william crop. Sweet william is a sensitive crop, which

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makes it a good candidate for trialling this method. If successful, this would allow growers to either apply a higher rate of herbicide (i.e. closer to the full label rate), or possibly apply herbicides that have proved to be too damaging in the past, to ensure safe, effective weed control.

New chemistries

The development of new chemistries for the cut flower sector is slow. Typically, actives will be trialled and authorised in arable and vegetable crops first, before being tested on cut flowers, and then possibly granted an EAMU authorisation. In recent years, work has been funded by AHDB to examine some new herbicide actives (SceptrePlus), which are authorised for use in the EU for use in field vegetables but are not yet authorised in the UK, and although some results were promising the approval process is lengthy.

Herbicide resistance

Of the 15 commonly found weeds in cut flowers crops in the UK (Table 34) there are herbicide resistant populations of fat hen, groundsel, black nightshade, chickweed, and scentless mayweed. Outside of the UK there are also herbicide resistant populations of Shepherd's purse, creeping thistle, knotgrass, sow thistles, and small nettle (Heap, 2019; Table 36).

Although in the UK these resistant populations are found in crops other than cut flowers there are some resistant populations found in nurseries outside of the UK and there is a precedence for resistance evolution in these species. Therefore there is a chance that herbicide resistance could evolve in populations of these weeds in cut flower crops. Additionally, as little research is conducted in this area of cut flower, there is also the possibility that resistant populations are already present, but have not been identified.

Currently, herbicide products with different HRAC codes will be applied where possible, to help reduce the risk of herbicide resistance developing. However, if more actives are lost in the future, with few new actives coming through, then the risk of herbicide resistance will increase.

Table 36: From Heap (2019), world-wide cases of herbicide resistance found in the top 15 weed species of UK cut flower crops (see Table 34), where species is missing there are no known cases of resistance

Common name	Latin name	Herbicide resistance	Crops resistant populations found
Shepherd's purse	*Capsella bursa-pastoris*	Photosystem II inhibitors ALS inhibitors	Orchards, alfalfa Cereals, roadsides
Fat hen	*Chenopodium album*	Photosystem II inhibitors*	Crop lands*, maize, sugar beet, nurseries, mint, potato
		Synthetic auxins	Maize
		ALS inhibitors	Cereals, soy bean
Creeping thistle	*Cirsium arvense*	Synthetic auxins	Pastures, crop lands
Knotgrass	*Polygonum aviculare*	Carotenoid biosynthesis Photosystem II inhibitors	Apples Maize, crop lands
Groundsel	*Senecio vulgaris*	Photosystem II inhibitors*	Orchards*, maize, fruit, mint, railways, roadsides, vegetables, nurseries,
		ALS inhibitors	Cereals, fruit

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Black nightshade	*Solanum nigrum*	Photosystem II inhibitors* PSI electron diverters	Maize*, crop land, pastures Sugar cane, vegetables
Sow thistle	*Sonchus* spp.	Photosystem II inhibitors ALS inhibitors Glyphosate Synthetic auxins	Maize Cereals, vegetables, pastures Cotton, fallow Cereals
Chickweed	*Stellaria media*	Photosystem II inhibitors Synthetic auxins* ALS inhibitors*	Maize Cereals* Cereals*
Scentless mayweed	*Tripleurospermum inodorum*	ALS inhibitors*	Cereals*
Small nettle	*Urtica urens*	Photosystem II inhibitors	Vegetables

* Cases of herbicide resistance in the UK

Future action: Monitor for potential cases of herbicide resistance, particularly in species where resistance has been found in other crops

Bioherbicides

At present, Pelargonic acid is authorised for use in ornamental plant production as Finalsan Plus, but it is not widely used as results can often be mixed when compared to conventional herbicides. This may be due to the fact that as with biofungicides and bioinsecticides, the conditions for use are stricter than with conventional herbicides. Good even spray coverage is essential, and Finalsan Plus is most effective against small, actively growing weeds. Weeds also need to be dry before application. Finalsan Plus does not have a long-term effect and therefore re-emergence of affected weeds may occur, resulting in the need for a repeat application 40-60 days later.

Alternatives to glyphosate

The most extensively used herbicide according to the 2009 Pesticide Usage Survey Report for Outdoor Bulbs and Flowers in Great Britain was glyphosate, accounting for 35% of the herbicide-treated area (Garthwaite *et al*., 2009). The main use is either on uncropped areas, or applications when the crop is 'dormant' or not exposed to green material being treated. Since 2009, whilst glyphosate is still used, there are more alternatives being used, mainly to burn-off foliage when the crop dies down (i.e. diquat and carfentrazone-ethyl). With the impending loss of diquat, the use of carfentrazone-ethyl is likely to rise. In AHDB-funded project HNS PO 192 (Talbot *et al*., 2016), carfentrazone-ethyl (as Shark), was found to be safe when used on sweet william, which are very sensitive to herbicides. Some initial scorch was observed but the plants soon grew away from this and produced a marketable crop, and this product has proved to be very useful to growers.

Genetic Tools

Genetically modified crops

Currently, no herbicide tolerant Genetically Modified Crops (GMCs) are approved to be commercially grown in the European Union (ISAAA, 2018). When it comes to breeding in ornamental crops, a key objective is the creation of new flower colours, either to complete the range in a particular crop or replace an existing cultivar with a better performing genotype of the same colour (Chandler, 2007).

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This has been done for carnations, the first transgenic violet-coloured carnation expressing the F3’5’H gene was originally marketed in Australia in 1996, followed by Japan and the United States (Anderson, 2013). In the UK, cut flower carnations IFD-25958-3 and line IFD-26407-2 were approved for importing by the European Food Safety Authority in 2015 (Horticulture Week), although this authorisation did not cover cultivation. Suntory-owned Florigene wants to export carnations genetically modified for petal colour and herbicide tolerance. Although these cultivars were genetically modified to create new flowering traits (e.g. petal colours), the marker used to select the modified cells was the additional insertion of the surB gene, which confers ALS inhibitor resistance (ISAAA, 2018, Table 16). The insertion of this trait into the modified flowers would enable the use of ALS inhibitors in the carnation crops for additional weed control. It is also highly likely that any future genetically modified cut flowers would also carry an herbicide resistance trait.

Preventative weed control

Ensuring efforts are made to keep machinery clean is important to prevent weed seeds from being transported around the farm.

Ensuring that crop-free areas are well maintained (e.g. field headlands, around the edges of polytunnels) is important to prevent seed spreading into cropped areas.

The use of green compost applied around the crop could be used to supress weeds, although this is not common practice, and with some sensitive plant species there could be issues with phytotoxicity.

4.2. Cereals and Oilseeds

Cereals and oilseeds is a group containing a range of crops commonly grown on farms in the UK, including wheat, barley, oats, rye, triticale, oilseed rape, and linseed. In 2018 the cereal growing area in England was 1.64 million ha of wheat, 338,000 ha of winter barley was, 478,000 ha of spring barely, and 137,000 ha of oats. The area of oilseed rape grown in England were 564,000 ha of winter oilseed rape and less than 8,000 ha of spring oilseed rape (Defra, 2018b). Most crops are sown in narrow rows (<25cm), except for oilseed rape where 50cm is common (4.2.1, AHDB, 2018c). Poor weed control in oilseed rape can reduce yields from 3% to 73% depending on crop vigour (Cook *et al*., 2015).

The main weed species that cause problems in UK cereal and oilseed crops are: black-grass (*Alopecurus myosuroides*), Italian ryegrass (*Lolium multiflorum*), brome grasses (*Bromus* and *Anisantha* spp.), wild-oats (*Avena* spp.), annual meadow grass (*Poa annua*), field poppy (*Papaver*

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rhoeas), chickweed (*Stellaria media*), and mayweed (*Matricaria* and *Tripleurospermum* spp.). Volunteer cereals and oilseed rape can also cause problems in following crops.

A recent online survey of farmers and agronomists by Davies & Hull (2018) to assess the presence and distribution of brome weeds across the UK found that black-grass was still the most problematic grass weed in arable farming, followed by *Anisantha* species (great and sterile brome), although results were in favour of identifying problematic brome populations. Grass weed problems were also found to vary by region, with black-grass the most problematic grass weed in the East, East Midlands, and South East of England, *Anisantha* species in the South West, Yorkshire/ Lancashire, and the North of England, and annual meadow grass in Scotland and Northern Ireland.

Other surveys have shown changes in weed populations in arable farming over the past 40-50 years. Potts *et al*., (2010) found that weed species in Sussex cereal fields changes significantly between 1968-2005, as a result of herbicide use and herbicide resistance, with an increase in the presence of black-grass, sterile brome, soft brome, wild-oats, poppy, fumitory, and sun spurge (*Euphorbia helioscopia*). Hawes *et al*., (2010) found that annual meadow grass, chickweed, and field pansy (*Viola arvensis*) were the three most common weed species in conventional, integrated, and organic arable farming in Scotland. However, surveys of some problematic species have not been conducted for a number of years, for example, the last assessment of the distribution of Italian ryegrass populations as weeds was conducted in 1981 (Froud-Williams & Chancellor, 1982), with recent assessments only of resistant populations (Hull *et al*., 2014).

4.2.1. Cultural control

Rotations

Simple, non-diverse crop rotations lead to the selection of one or two dominant weed species in a field, this has been the case in the UK and Europe where rotations consisting of mainly winter cereals have become dominated by black-grass. More diverse rotations result in better control of black-grass and other grass weeds found in cereals and oilseeds (Fried *et al*., 2008; Colbach *et al*., 2010; AHDB, 2014).

Introducing different crops into a cereal and oilseed rotation can help control weeds by allowing for the use of different cultural control techniques (e.g. delayed drilling, spring cropping), differences in the levels of crop competition (discussed below), and use of different herbicide actives. For example, the introduction of sugar beet into the rotation can increase mechanical weed control options and introducing potatoes can increase crop competition (AHDB, 2017a).

Using oilseed rape in rotation with cereals allows for the use of different herbicide modes of action to control grass weeds, including metazachlor, carbetamide and propyzamide to which there is no

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known resistance in the UK. However, these herbicides have been found in water and extreme care needs to be taken when using these herbicides to protect water ways (AHDB, 2018c).

Introducing spring cropping into the rotation can help improve black-grass and other grass weed control. Lutman *et al*., (2013) found that spring wheat could have a 78-96% reduction in black-grass plant counts compared to winter wheat. Freckleton *et al*., (2018) demonstrated a reduction of black-grass density when spring barley was included in a rotation, they attributed the reduction to avoiding crop establishment in the main germination period in autumn and that cultivations and seedbed preparation in the spring remove most of the plants. They also highlighted the competitiveness of spring barley, with its rapid growth and high biomass production, which can suppress weed development. Zeller *et al.,* (2018) conducted rotation trials over a five year period including zero, 25% and 50% spring crops. They reduced black-grass populations by zero, 33% and 50% respectively.

Recently there has been an interest in introducing livestock into the arable rotation, which offers an opportunity to decrease the black-grass seed bank (AHDB, 2018a). This option is further discussed in section 3.2.2.

Crop species

Crop choice can have an influence on weed control due to the competitiveness of the crop against weeds, potential allelopathy, and the number of herbicide actives available for use in the crop.

Wheat is a competitive crop, although it can be less competitive than other cereal crops, such as barley (Bertholdsson, 2005; Cook & Roche, 2018). There are many herbicide options available for use in winter and spring wheat crops, although wide-spread resistance has been identified to many of the actives available, particularly in black-grass (BCPC, 2018; Heap, 2018).

Barley is a highly competitive crop (Watson *et al*., 2006) and is also potentially allelopathic (Bertholdssen, 2005). There are many herbicides actives available for use in barley, but these are more limited than in wheat, and herbicide resistance in grass weeds is widespread (BCPC, 2018).

Oats are usually more competitive than wheat and barley, and like barley are potentially allelopathic (Seavers & Wright, 1999). Fradgley *et al*., (2017) that found oats are more resource efficient and competitive than other cereals. There are however, fewer herbicide actives available for use in oat crops (BCPC, 2018).

Triticale crops can have similar or slightly lower levels of weed competition than oats and barley (Davies & Welsh, 2002; Dhima *et al.,* 2007). Rye is also highly competitive, but has fewer herbicide options compared to wheat and barley (AHDB, 2017a; BCPC, 2018).

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Oilseed rape is a highly competitive crop early in the growing season. Although, its competitiveness depends on the level of establishment achieved and the autumn and winter growing conditions. In late winter, pigeons can strip the plants allowing further emergence of weeds in the spring. At the end of the season when the leaves fall, further weeds can germinate. Spring crop establishment may be delayed by cool conditions at drilling (AHDB, 2018c). There are fewer herbicide options available for use in oilseed rape compared to cereal crops, but different actives such as propyzamide can be used, helping with weed control in rotation (BCPC, 2018; AHDB 2018c).

Winter linseed crops have a relatively small leaf area and are therefore susceptible to weed competition, particularly from broad-leaved weeds, but a spring application of amidosulfuron can control cleavers and chickweed before yield is affected (MAFF, 2001). There are fewer herbicide options available for use in linseed crops than other crops (BCPC, 2018).

Crop cultivars

The competitiveness and weed suppressive ability of cereal crops can be dependent on establishment rate, tillering ability, and early leaf area index. As well as below ground traits, such as root competition, although this area has been less studied (Andrew *et al*., 2015). To be useful for selection of competitive crop cultivars these traits must be heritable and consistent across different environmental conditions (Fradgley *et al*., 2017).

Andrew *et al*., (2015) reviewed the potential for competitive cereal cultivars as a tool for integrated weed management, highlighting the need for predictive approaches to assess the weed competitive traits of new cereal cultivars, and a ranking system to allow growers to select cultivars with competitive traits. A view also supported by Watson *et al*., (2006). However, this ranking system would need to relate to the traits and characteristics different cultivars possess and not a cultivar itself as they are continually replaced (Seavers and Wright, 1999).

Murphy *et al*., (2008) compared 63 cultivars of spring wheat for five potential competition traits, including plant height, leaf area index, juvenile growth habit, coleoptile length and thousand grain weight and for the ability of these cultivars to achieve high yields, suppress weeds and withstand mechanical cultivation. The results indicated that modern cultivars commonly had a higher grain yield than historical cultivars, however their ability to suppress weeds in the rotation was found to be slightly lower, indicated by an increase in weed biomass. This finding was supported by Korres & Froud-Williams (2002) who evaluated the competitive ability against chickweed of six winter wheat cultivars at a range of seed rates. The study found that two older cultivars (Maris Widgeon and Maris Huntsman) showed more effective weed suppression than other varieties. In particular, the study found that height conferred the greatest competitiveness of the crop to weed populations. In line with this study, Lemerle *et al*., (1996) found that taller varieties of winter wheat with higher dry matter production and, high tiller numbers were the most competitive against annual ryegrass (*Lolium*

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rigidum). Straw height and stem density were the most important traits in this interaction and were both associated with weed tolerance and increased yield in the presence of weeds. However, a strong relationship between increased height and interception of photosynthetically active radiation (PAR) has not always been found (Andrew *et al*., 2015). Some shade tolerant weeds (e.g. ivy-leaved speedwell) can thrive under tall cultivars (Gooding *et al*., 1993).

The Grains Research and Development Corporation (GRDC) have developed new wheat varieties with high early vigour, a larger flag and upper leaves (Figure 20) (Rebetzke *et al*., 2018). The varieties are in trial in 2018 and it is expected they will become available from 2023 (Lee, 2018). Future work will look at a more competitive root architecture and chemical control through allelopathy.

Figure 20: Super-size' flag leaf in weed-competitive CSIRO wheat breeding line W470201 (L) and commercial wheat Mace (R) at Roseworthy, SA, in 2016 (Rebetzke *et al*., 2018).

Dhima *et al*., (2010) compared 29 six-row and 21 two-row barley cultivars for competition with winter wild-oat (*Avena sterilis* spp. l*udoviciana*) and German-madwort (*Asperugo procumbens*). The most competitive six-row cultivars reduced fresh weight of both weeds by 61-75% compared to the least competitive six-row cultivar. The most competitive two-row cultivars reduced weed fresh weight by 59-76% compared to the least competitive cultivar. However, there was a weak relationship between morphological traits and the competitive ability of the barley cultivars, with early vigour possibly having the greatest effect on barley competitive ability. Cook & Roche (2018) comparted a six-row and a two-row barley cultivar for competitiveness against black-grass, finding that head counts were lower in the 6-row barley plots, with the critical competition phase occurring after winter. However, competitive ability may vary more between six-row cultivars than two-row cultivars. When comparing 29 barley cultivars in competition with oats, Watson *et al*., (2006) found that competitiveness varied mostly in six-row cultivars, which represented both the least and most competitive cultivars, whereas

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two-row cultivars generally showed intermediate levels of competitiveness. Yield loss for these cultivars ranged from 6% to 79%, with dwarf and hull-less cultivars the least competitive.

Fradgley *et al*., (2017) investigated the weed suppressive ability of five husked and three naked oat varieties over four years (2009-2013), finding that there was a significant interaction between crop variety and early season weed cover in husked but not naked oats.

Little research has been conducted on the impact the different weed competitive abilities of oilseed rape cultivars in the UK, but evidence from Canada suggests that hybrid oilseed rape cultivars can be up to twice as competitive against grass weeds compared to open pollinated cultivars at high weed densities (Zand & Beckie, 2002).

Future action:

- Produce a ranking system to allow growers to select cereal cultivars based on their weed competitive traits.
- Consider research into the difference in competitive abilities of different oilseed rape cultivars.

Tillage and cultivations

Cultivating too early after harvest can actually increase weed burdens in the following crop and help replenish the weed seedbank and prevent dispersal loss and seed predation from the soil surface. 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 (AHDB, 2018c). Moss (1980b, 1987) 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. Similarly, Gruber *et al*., 2010 found that seedbank decline of oilseed rape is 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.

Some oilseed rape herbicides, such as propyzamide, work best when the crop is established by shallow cultivation (AHDB, 2018c). In Denmark inter-row cultivations have often replaced chemical weed control in oilseed rape crops, with hoes mounted on S-tines or shanks (Melander *et al*., 2005).

Compared to non-inversion tillage, mouldboard ploughing can reduce the number of black-grass plants in the following winter wheat crop by an average of 69%, whereas direct drilling may increase the density by 16%. However, there can be high variability for black-grass control for these methods, for example control in mouldboard ploughing can vary from -82% to 96% compared to non-inversion tillage (Lutman *et al*., 2013).

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The IWMPraise H2020 project is currently investigating the effectiveness on weed control of using non-till crop establishment in field beans and oilseed rape, and the influence of non-till systems on grass weed control in spring crops in the UK (IWMPraise UK, 2018).

Cover crops

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, but that larger weeds such as fat hen (*Chenopodium album*) are less affected as they outgrow the height of cover crops (Kruidhof *et al*., 2008). However, recent research has shown that the main impact that 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 (Cussans & Storkey, 2018). For example, Agrovista (2017) found that nitrogen application to spring wheat following a fallow increased black-grass head counts, but the effect was not seen in plots drilled into a cover crop, possibly as a result of the cover crop residue minimising soil disturbance at drilling. Cover crop studies by Kruidhof *et al*., (2008) also found that delayed sowing in combination with a stale seedbed considerably reduced weed pressure in all plots regardless of cover crop.

Seed rates

Increasing seed rates can help increase levels of crop competition and account for yield losses associated with delayed drilling. Lutman *et al*., (2013) indicated that increasing winter wheat seed rates from 100 to 200 or 300 plants m^2 decreased black-grass head numbers by 17% and 32% respectively (Figure 21). As wheat density increases the level of variability in control also increases, this was attributed to lack of data and the variability of the weed's response to crop density. The tillering ability of black-grass is reduced by increased density of crop fertile tillers and less so by seed rate. In wheat, hybrid barley and conventional 2-row barley autumn crop densities reduced the population of black-grass in the autumn (Figure 22, S. Cook, pers comm).

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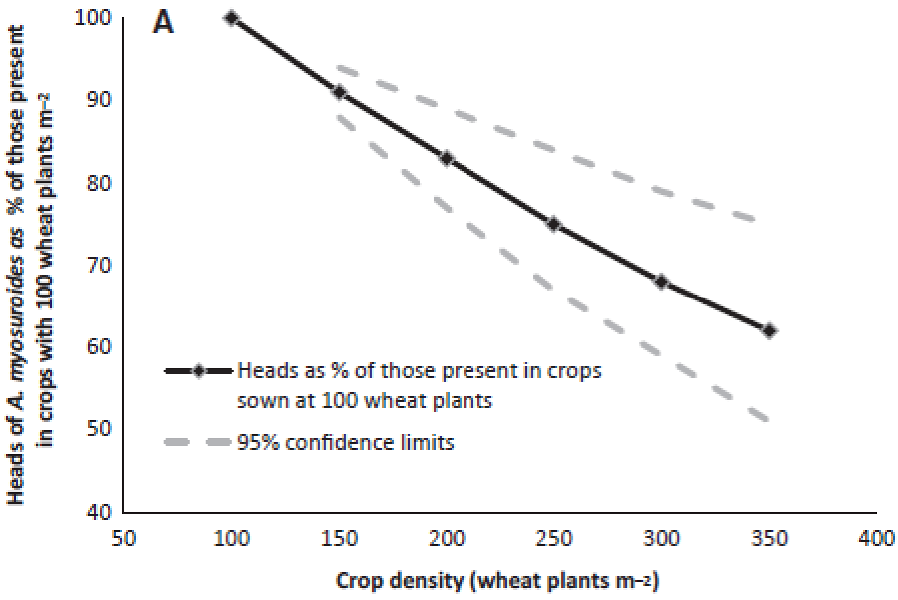

Figure 21: From Lutman *et al*., (2013). Relationship between crop density and black-grass heads/m² expressed as a percentage of those present at 100 crop plants m² (plus 95% confidence intervals)).

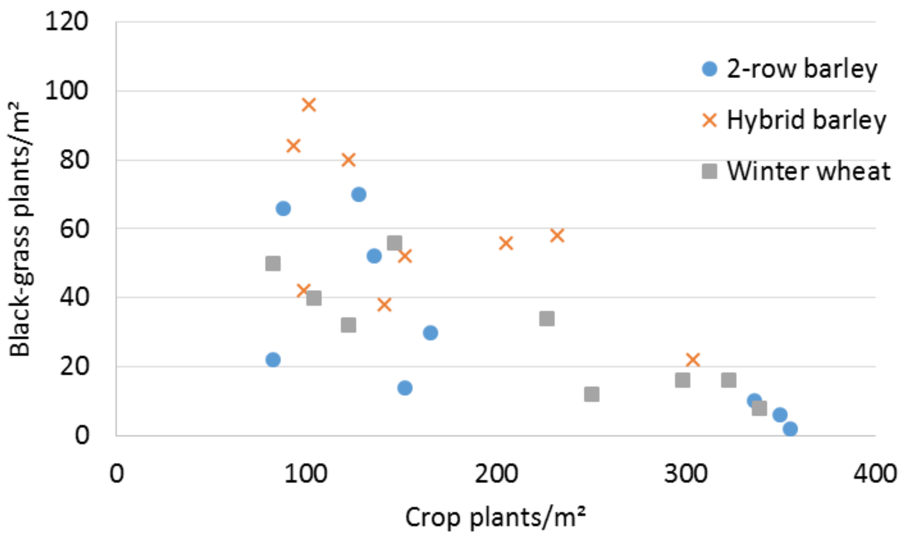

Figure 22: The effect of increasing winter wheat, hybrid barley seed rate and 2-row barley seed rate on the population of black-grass plants in the autumn.

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 (Sim *et al*., 2007). Cook *et al*., (2015) found that in the absence of herbicides increased seed rates coupled with narrow rows could reduce weed populations and increase yields, but that 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.

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Row width

The impact of wide and narrow row spacings on weed control in cereals are not clear. Rasmussen (2003) found that there was no difference in weed biomass in row widths of 12 and 24cm in winter wheat. Rasmussen (2004) found that weed control was increased in winter wheat sown at a row width to 24cm when a combination of inter-row hoeing and harrowing was used, compared to harrowing alone in a 12cm spaced crop. Blair *et al*., (1997) showed that weed density was greater in the wider rows (25cm). Under organic conditions, Drews *et al*., (2009) also found that weeds were more suppressed at a row spacing of 12cm compared to 24cm, and also that row orientation (north-south or east-west) had no effect on weed growth. Chancellor & Peters (1976) reported conflicting conclusions as to the effect of row spacings on the competitive effects of wild-oats. However, the overall impression is that wider spacings (c 24cm) may lead to slightly less competitive crops and greater weed density.

For oilseed rape Cook *et al*., (2015) found that where weeds were well controlled, row widths could be increased to 48cm without impacting yield and allowing for the use of cultural control options such as inter-row hoeing.

Drilling dates

Delayed drilling of winter oilseed rape crops significantly reduces crop competition and suppressive ability against volunteer cereals and weeds, resulting in higher weed densities and reduced yields (Lutman & Dixon, 1991; Lutman *et al*., 1999). Whereas where crop establishment is good early drilling can increase crop biomass and competitiveness. For example Sim *et al*., (2007) found that flower head density of Italian ryegrass increased from 226 head/m^2 when oilseed rape was sown in early September to 633 heads/m^2 in the crop sown two weeks later.

The effects of drilling date for grass weed control in cereals varies depending on the species present. For control of wild-oats, delayed drilling extends the period for which seed predation and early germination can take place, for Italian ryegrass delayed drilling reduces populations as most seeds emerge by November, and for annual meadow grass delayed drilling has little effect (AHDB, 2017a). Lutman *et al*., (2013) found in a meta-analysis of black-grass control in winter wheat that delaying drilling until the end of October significantly decreased black-grass plant numbers by at least 50%. The effect of delayed drilling on plant head counts was less clear, head counts decreased in crops drilled in late October compared to September, but head counts increased again in crops sown in November and December, likely as a result of reduced crop competition.

As well as the influence of crop establishment and competition, the benefits for black-grass control obtained by delayed drilling cereal crops can also be dependent on seed dormancy. Weather conditions during seed ripening will determine the dormancy of black-grass seeds shed that year.

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Warm dry weather at ripening will lead to low seed dormancy and rapid germination with 90% of seed emerging 30 days after drilling. Cold wet weather will lead to high dormancy and protracted germination with 90% of seed emerging 60 days after drilling. In low dormancy years delayed drilling allows for maximum black-grass emergence and control before drilling. In high dormancy years early drilling will encourage crop competition (AHDB, 2017a).

Despite the increased benefits for weed control, it is often the case that growers are reluctant to delay drilling cereal crops due to the chance that heavy rain and wet soils will prevent machinery being able to access fields resulting in no crop being drilled. Seed coating for delayed germination is one innovation that could potentially overcome this and still allow for some of the benefits related to delayed drilling dates. Seeds are coated in temperature activated polymers that regulate water uptake until a pre-determined temperature threshold is reached (Pedrini *et al*., 2017). However, these coatings are often used to delay germination until soils are warmer, rather than cooler, and would therefore be more effective for use in drilling spring crops in the autumn (Johnson *et al*., 1999). An alternative would be to use seed coats that decayed over a set period of time, preventing seeds from water uptake for a month after sowing (Stendahl, 2005). Some research into delaying wheat (Stendahl, 2005) and spring oilseed rape (Willenborg *et al*., 2004) germination has been conducted, but not in the UK.

Future action: Investigate the potential for temperature activated polymer seed coats and decaying seed coats to delay cereal seed emergence.

4.2.2. Non-chemical control

Manual removal of weeds

Hand rogueing can be a useful weed control method within cereals. It is most feasible at low weed populations, for example hand rogueing of wild-oats has been carried out for many years and is suitable for densities of less than one plant per 10 m^2 (Rolston, 1981). Rogueing is especially recommended where a new weed has appeared in a field as rogueing fields where an infestation is low will prevent population increases in future years (Thill *et al.,* 1994). This is particularly the case for black-grass as any newly present populations are highly likely to have been introduced from an existing herbicide resistant population (AHDB, 2014).

Weed control is particularly important for seed certification purposes or farm saved seed. Gooding (2017) claimed that for this purpose hand rogueing of seed crops can be economic, particularly if it safeguards the field for future use in growing seed crops. It is also important to note that grass weeds are also alternative hosts for cereal pests and diseases which impact quality. This could be included in decision schemes as to whether it is economic to hand rogue within a crop for IPM.

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There are, however, draw backs to hand rogueing. The stem extension period in some cereal weeds can be protracted, meaning that rogueing may have to be conducted in cereals on multiple occasions, increasing costs. Furthermore, to prevent weed seed return the whole plant must be pulled and removed from the field increasing costs (Rolston, 1981). Hand rogueing is also labour intensive and therefore can be expensive. Rogueing black-grass in severely infested fields can cost around £86/ha (NFU, 2016), but rogueing winter wild-oats can be as low as £34/ha (Organic Research Centre, 2019). Conversely, as weed seed return and therefore weed pressure is reduced the cost of rogueing can fall, for example in 2016 a Lincolnshire farmer spent ~£32/ha rogueing black-grass from winter wheat, but in 2017 costs reduced to £26/ha (Adama, 2019; Table 37).

Table 37: From Adama (2019). Costs associated with hand rogueing black-grass across a Lincolnshire farm in 2016 and 2017

Crop	Rogueing costs in 2016 £/ha	Rogueing costs in 2017 £/ha
Winter wheat	32	26
Spring barley	40	37
Spring wheat	53	47
Highest cost/ha	186	89
Lowest costs/ha	19	18
Mean across all crops (including sugar beet)	56	38

Future action: Assess any reduction in grass weed levels, particularly black-grass, over a number of years of hand rogueing, and conduct a cost-benefit

Mechanical weeding

Spring-tine weeders are the most commonly used form of mechanical weeding used in UK organic cereals, with weeding often conducted in the spring reducing weed densities by 5% to 90% depending on the species present (Davies & Welsh, 2002). Two to four harrowings using stiff tines can give 69-95% weed control in winter wheat (Bond *et al*., 2003).

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 (AHDB, 2016c). 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 (Bond *et al*., 2003). Therefore, yield losses related to weed pressure and crop damage as a result of mechanical weeding need to be assessed. For example, Rasmussen (2003) found that where weed pressures were low the use of mechanical weeding reduced wheat yields possibly as a result of crop damage, or the need for wider row spacing, but there was no associated yield loss where weed pressure was high.

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The Royal Agricultural University has more recently been conducting mechanical weeding trials in winter wheat using an Opico harrow comb weeder, Garford RoboCrop inter row hoe, TRP Rotanet, and the Combcut weeder (Agricology, 2017). However, none of the mechanical weed control options used gave yield advantages over the untreated control plots, a finding supported by previous studies (Davies & Welsh, 2002; Cannon, 2018). 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 (Davies & Welsh, 2002).

In France mechanical weeding was evaluated between 2003 and 2006, reported in Cook *et al*., (2015) and this led to advisory information being produced by Terres Inovia (2008) for its use on maize, oilseed rape and cereals and ITAB (2013) for use in winter cereals, linseed, maize, winter beans and barley. Videos and information can be found at http://www.terresinovia.fr/colza/cultiver-du-colza/desherbage/lutte-mecanique/

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 (Melander *et al*., 2005). 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 (Cook *et al*., 2015). 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 (3.5.1) (Melander *et al*., 2013).

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 (Melander *et al*., 2013).

Future actions:

- Assess weed thresholds in cereals where the yield losses are higher than those related to the use of mechanical weeding and yield benefits are gained by mechanical weeding
- Improve mechanical weeders for use in cereal crops to reduce the need for post-emergent herbicides

Thermal weeding

Little research has been conducted on the application of thermal weeding in cereal and oilseed crops, with no thermal method demonstrating economically viable potential for use compared to chemical weed control (Melander *et al*., 2017). Due to narrow rows and similar crop-weed plant sizes, for cereals and oilseeds flame weeding to remove weed seedlings on stale seedbeds would be the

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most effective thermal method. However, evidence suggests that flame weeding is most effective on broad-leaved weeds, with grasses less susceptible due to the position of their meristem (growing point) (Cisneros & Zandstra, 2008). Therefore, it is unlikely that flame weeding stale seedbeds as an alternative to using glyphosate will provide adequate control of grass weeds, such as black-grass, Italian ryegrass, and bromes.

There could be the potential for use of microwave treatments to cereal and oilseed crop stale seedbeds in the UK for weed seed destruction. Khan *et al*., (2018) tested the effectiveness of soil microwave treatments of stale seedbeds on weed establishment in dryland wheat crops in Australia. Microwave treatments raised soil temperatures to 75-80ºC and weed levels, including wild-oat and rigid ryegrass, in the following wheat crop were reduced by 65% to 80%.

In 2012, a small test was conducted to assess the practicality of using an electrical weeder above an onion crop to control black-grass flower heads that had emerged above the crop. The initial outlook was promising, with the electrical weeder making contact with the black-grass flower heads and not the crop. The experiment was not repeated, but suggests that electrical weeding could potentially have a role in preventing grass weed seed return in cereal crops where there is a height differential (L. Tatnell, Pers. Comm.).

Future action:

- Investigate the potential for flame weeding for use on stale seedbeds as a possible alternative to glyphosate including an evaluation of environmental impacts, costs, and efficacy.
- Investigate the use of electrical weeding for preventing weed seed return in crops where a spatial difference is possible between the crop and weed.

Allelopathy

White *et al*., (2016) reviewed the use of cover crops, including examples of crops and their allelochemicals. A total of 44 compounds have been identified as potential allelochemicals in barley, and studies have found that spring barley residues can reduce weed densities by up to 90% compared to bare soils (White *et al*., 2016). Bertholdsson (2005) found that allelopathic activity in barley and wheat could explain 7% to 58% and 0% to 21%, respectively, of genotypic variance in weed control between different cultivars. Oat crops also appear to have allelopathic effects on weeds (Seavers & Wright, 1999). In a greenhouse study using 24 oat cultivars, Grimmer & Masiunas (2005) reported reduction in the emergence of fat-hen (*Chenopodium album*) and shepherd's-purse (*Capsella bursa-pastoris*) of 27% to 47% and 2.3% to 24% respectively.

Research has been conducted in Sweden investigating differences in allelopathy between wheat cultivars, for potential use in integrated weed management of black-grass. Cultivars with high levels of allelopathy reduced black-grass biomass by up to 50% compared to cultivars with low levels of

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allelopathy. However, herbicide resistant black-grass populations were less affected than herbicide sensitive populations (Bertholdsson, 2012). Similar to this, there is currently a PhD project at Rothamsted Research investigating the production of potential allelopathic chemicals by black-grass and crops, with the intent to develop novel weed control strategies that exploit the interactions of these compounds (Rothamsted Research, 2019).

Species in the Brassicacea family are also reported to have allelopathic potential. For example, isothiocyanates from Turnip-rape (*Brassica rapa*) mulch have been found to significantly suppress black-grass germination (White *et al*., 2016). However, evidence for the use of the allelopathic potential of Brassicaceae in controlling arable grass weeds is mixed. In field trials, Cussans & Storkey (2018) investigated the effect of incorporating the residues of a biofumigant mustard cover crop on reducing weed germination and subsequent growth, finding that there was no consistent biofumigant effect for Italian ryegrass, wild-oats, meadow brome, sterile brome, or black-grass.

Biological control

There are a number of invertebrate species that have been found to feed on black-grass, ryegrass, brome, and meadow grass weeds, but not crop species. For example, the gall midges *Stenodiplosis geniculati*, *Contrarina merceri*, and *Dasineura alopecuri* appear to affect *Alopecurus* species, *Oscinella vastori* appears to affect Italian ryegrass and other ryegrass species, and the leaf miner *Cerodontha muscina* appears to affect brome and meadow grass species (Biological Records Centre, 2018). However, some of these reports originate from the 1930s and 1940s without any recent research conducted on these invertebrate species and their potential effect on crops and the environment.

Future action: Investigate native invertebrate species that feed on and/or parasitise seeds of grass weed species, but do not affect crops, and how these species could be exploited.

Weed seed control

A weed surfer machine can be used for weed seed control before crop harvest and without the destruction of the crop. Wild-oats cut at early flowering and two weeks later had nil and 36-100% of seeds viable in 2008 and 2009 (Pawsey, 2009). The cut weeds have the potential to regrow, the crop can be damaged and yield reductions could occur. When used on black-grass in winter wheat, the field was cut in June and hit about 80% of heads, removing about 50% of them (Allen-Stevens, 2016).

In Australia 85% annual ryegrass seed, 77% great brome seed, and 84% wild-oat seed was retained at crop maturity of wheat for harvest weed seed destruction (HWSD). However, 28 days after crop maturity only 41% of brome seed and 39% of wild-oat seed was retained on plants, compared to 63% of ryegrass and 79% of wild-oat seed, suggesting that if HWSD were to be used successfully

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on brome grass weeds and wild-oats in the UK harvesting of heavily infested fields would need to be harvested earlier than other fields (Walsh & Powles, 2014).

A chaff tramliner has been trialled in the UK by Frontier and E W Davies Farms Ltd and results in 2017 indicated that the device can deal with the amounts of chaff produced and that populations of black-grass were higher in the chaff lines (Frontier, 2018). Frontier estimated that 30-50% of black-grass seed were still in the heads at harvest in a crop of hybrid winter barley. In 2018 only 23% of black-grass seed remained on the heads at harvest, the method has shown some promise and could possibly be more effective in early maturing crops.

Future action: Continue to investigate the use and potential efficacy of harvest weed seed control options in the UK.

4.2.3. Chemical control

Existing chemistry

The recent pesticide usage survey results showed that 98% of wheat crops receive a herbicide, in 3.1 applications containing 4.5 products and 6.7 active substances (Garthwaite *et al*., 2017a). Most herbicides are applied in the autumn (September-November) and in the spring (March-May), the most common herbicides applied are detailed in Table 38. Herbicide applications to winter barley were made at similar timings to wheat with a lower overall usage (Table 38).

Applications to spring barley were made between March and June, with a similar number of active substances being applied to winter barley. Oats, includes both winter and spring sown with herbicides being applied September to November and again in March to June. Applications were generally made against broad-leaved weeds including cleavers (Table 39). A proportion of the glyphosate applications to spring barley and to oats was for crop desiccation. Herbicides were applied to rye and triticale at similar timings as those made to oats, as both cereals are grown on a small area there is fewer choice of herbicides for weed control.

In oilseed rape, herbicide applications to the winter crop were made from August through to March, the most common products were a pre-emergence herbicide followed by a graminicide (propaquizafop) then propyzamide, a residual herbicide applied in October/November either alone or in mixture with aminopyralid. Glyphosate is also often used either pre planting and/or as a desiccant (Table 40; Garthwaite *et al*., 2017a). In linseed most herbicides are applied between April and June, glyphosate is also used for crop desiccation. Since the survey in 2016 usage has changed with clethodim now being used more frequently in oilseed rape.

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Table 38: Herbicide usage on cereals and oilseeds in the United Kingdom

Crop	Percentage of area treated with herbicides	Number of spray rounds applied to crops	Number of products applied	Number of active substances applied
Arable crops				
Wheat[1]	98.2	3.1	4.5	6.7
Winter barley	98.2	2.7	3.9	5.4
Spring barley	97.2	2.5	3.5	5.0
Oats[1]	91.2	2.1	2.7	3.9
Rye	89.4	2.3	3.3	4.5
Triticale[1]	98.9	3.1	4.0	5.5
Oilseed rape[1]	98.2	3.7	4.4	5.6
Linseed[1]	92.3	3.8	4.4	4.6

[1] Includes winter and spring sown crops

Table 39: The common active substances used for cereal crops in the United Kingdom (including on stale seedbeds). Taken from Garthwaite *et al*., 2017a

Active ingredient	Wheat	Winter barley	Spring barley	Oats	Rye	Triticale
Glyphosate	✓	✓	✓	✓	✓	✓
Diflufenican + flufenacet	✓	✓			✓	✓
Fluroxypyr	✓		✓	✓		✓
Diflufenican	✓	✓			✓	
Pendimethalin		✓			✓	✓
Mecoprop-P			✓	✓		
Pinoxaden		✓	✓			
Iodosulfuron-methyl-sodium + mesosulfuron-methyl	✓					
Diflufenican + flupyrsulfuron-methyl				✓		
Florasulam + fluroxypyr				✓		
Metsulfuron-methyl + thifensulfuron-methyl			✓			
Metsulfuron-methyl + tribenuron-methyl				✓		✓

Table 40: The common active substances used for oilseeds crops in the United Kingdom (including on stale seedbeds). Taken from Garthwaite *et al*., 2017a

Active ingredient	Oilseed rape	Linseed
Glyphosate	✓	✓
Propaquizafop	✓	
Propyzamide	✓	
Aminopyralid + propyzamide	✓	
Dimethenamid P + metazachlor/quinmerac	✓	
Clethodim		✓
Bromoxynil		✓
Amidosulfuron + iodosulfuron-methyl-sodium		✓
Amidosulfuron		✓

Crop desiccation

Crop desiccation of cereals and oilseeds using non-selective herbicides, such as glyphosate, can reduce the presence of perennial weeds such as couch (a very effective timing for good control) and

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volunteer potatoes and late growing annual weeds. When glyphosate is used for crop desiccation, weeds are only effectively controlled if weeds are green and actively growing (AHDB, 2018d). Additionally, as discussed above in spot spraying a reduction in weed seed return to the seed bank will only be effective if grass weeds are treated at the appropriate growth stage.

Optimising use of existing chemistries

Black-grass, bromes, and ryegrass, are the main grass weeds that spot spraying is used for in cereals and oilseed crops in the UK, often to prevent seed return and reduce costs in future crops. Lutman *et al*., (2002) calculated that spot spraying black-grass patches with a non-selective herbicide over a ten year period could result in a saving of £3-£20/ha/year, depending on the level of black-grass infestation. Monsanto (2018) suggested that spot spraying 1m^2 of feed wheat would result in a loss of as little as £0.10/m^2 and prevent up to 30,000 seeds being returned to the soil seedbank. Using non-selective herbicide to spot spray weed patches resistant to post-emergence herbicides could help prevent the spread of herbicide resistance within a field. However, this could also increase the risk of glyphosate resistance evolution, as treating weeds at larger growth stages can reduce efficacy (3.4.3 & 3.4.7).

As well as spot spraying, there has also been a move towards the precise application of pre-emergence and post-emergence herbicides related to weed maps. For example, an automated machine vision system, eyeWeed (discussed in 4.2.4), has been developed in the UK for black-grass mapping and precision applications of pre- and post-emergence herbicides. The system creates maps based on the spatial variation in black-grass flower/seed head density within a field using cameras mounted on farm machinery, which can be used in the following growing season for patch spraying, as research has shown that black-grass patches are stable from year to year (Murdoch *et al*., 2014). In addition to using weed maps for precision herbicide application other in-field maps, such as soil maps could also be used. Recently, Metcalfe *et al*., (2017) showed control of black-grass (*Alopecurus myosuroides*) by pre-emergence herbicide was greatly affected by soil organic matter and increased control could be achieved by adjusting rates to account for variation in soil organic matter across a field in relation to soil mapping. Although more in-field research is needed, the relationship between herbicide efficacy/ degradation and soil organic content has been a subject of interest for some time (Stevenson, 1972), with Lehmann *et al*., (1992) finding that degradation time of a sulfonamide herbicide increased from 2-4 weeks to 1-3 months when soil organic carbon was above 2.5%.

There has been interest in using weed wipers for the control of grass weeds in cereal crops (Hutchinsons, 2016). In cereals the control of black-grass, is difficult as the height differential is often nor great enough to minimise damage to the crop and maximise kill of black-grass. Wild-oats (*Avena* spp.) are taller timing is important to ensure that they have not set seed before treatment occurs.

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The critical timing to use weed wiping to prevent grass weed seed return in cereal crops is when weeds are flowering and before seeds are filled (Hutchinsons, 2016).

Future actions:

- Evaluate the point where it becomes economically unviable to patch spray based on the weed flower head threshold.
- Confirm the best weed growth stage for grass weed patch spraying, is it effective after seed set?

New chemistries

BASF plan to release Luximo^{TM}, a herbicide containing cinmethylin in the UK in 2021. Luximo^{TM} will be a residual grass weed herbicide applied pre-emergence of the crop, and controls black-grass and ryegrass in winter cereals. There is no known cross-resistance to cinmethylin, but management and stewardship will be required to prevent it (BASF, 2018a).

Herbicide resistance

Herbicide resistant weeds are one of the main weed control issues for cereals and oilseeds. Herbicide resistance can be tested for using a number of different methods (discussed in 3.4.8). At present in the UK there are 15 weed species resistant to eight different herbicide modes of action, including ALS inhibitors, ACCase inhibitors, and photosystem II inhibitors (Heap, 2018). Herbicide resistant populations of black-grass are estimated to affect 20,000 UK farms across 35 counties, Italian ryegrass affects >475 farms across 33 counties, and wild-oats affect >250 farms across 28 counties (Hull *et al*., 2014, Figure 23). In 2018, a UK Italian ryegrass population with enhanced metabolic resistance was found to be resistant to flufenacet (Heap, 2018). ALS-inhibitor resistance has also been confirmed in more than 70 poppy (*Papaver rhoeas*) populations, 12 mayweed (*Tripleurospermum inodorum*) populations, and 40 chickweed (*Stellaria media*) populations (Tatnell *et al*., 2016).

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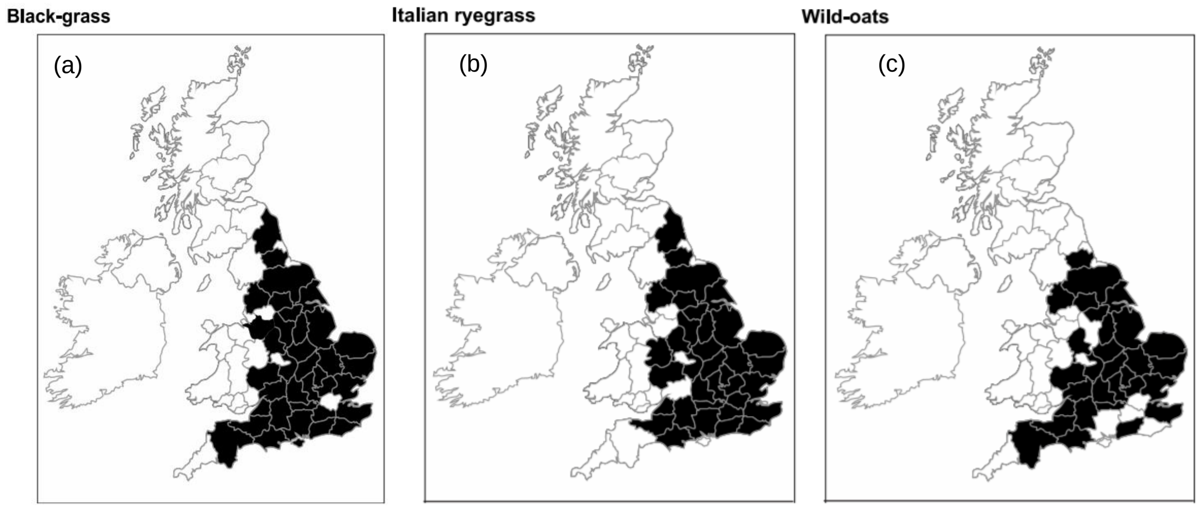

Figure 23: From Hull *et al*., (2014). UK counties with confirmed herbicide resistant populations of (a) black-grass, (b) Italian ryegrass, and (c) wild-oats.

In a few arable situations herbicide resistance has become so severe there are no more cost- or technologically-effective herbicide options left. Previously, problematic weeds may have been treated with a herbicide with a new mode of action, but for both practical reasons (resistance and a lack of new modes of action) and regulatory/commercial reasons (loss of actives through regulation) this is becoming more difficult (Moss, 2010; Duke, 2012). There is also the potential for new cases of herbicide resistant weeds, as shown by the recent discovery of flufenacet resistant Italian ryegrass (Heap, 2018), showing that ongoing monitoring for resistance is needed.

Currently there are research projects focused on the potential for herbicide resistance in UK brome species (led by ADAS (AHDB & commercial partners RD-211200059, 2017-2021)), prevention of glyphosate resistance in the UK (led by ADAS (AHDB & commercial partners RD-2140006131, 2015-2020)), and the black-grass research initiative (BGRI) (BBSRC & AHDB) which has just come to an end (http://bgri.info/, a consortium led by Rothamsted Research). Recent UK research projects have also included the prevention of widescale increase of ALS-resistant broad-leaved weeds (Tatnell *et al*., 2017) and PhD projects on ALS-inhibitor, ACCase-inhibitor, and glyphosate resistance in black-grass (Lynch, 2014; Davies, 2015; Knight, 2015).

Future action: Further UK research could focus on resistance monitoring, evaluating the success of resistance prevention strategies, and extensive knowledge transfer to growers and advisors.

Bioherbicides

Bioherbicides could potentially offer alternative chemical control options to synthetic chemistry in cereals and oilseeds. A one year, DEFRA-funded study in 2014 found that black-grass was affected

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by a specific strain of bacterial wilt (*Xanthomonas translucens* pv *graminis* (Xtg)), with one isolate giving 50% reduction in biomass. As this was a pilot study Xtg was not further developed, but it showed promise as a bioherbicide as it is a specialised pathogen and therefore would be unlikely to cross infect cereals, as a bacteria it is cheap and easy to culture, and provided reasonable control (Defra, 2014). There is also currently research investigating the effectiveness of *Phoma macrostoma* as a bioherbicide for use in cereal crops for broad-leaved weed control, including thistle (*Cirsium arvense*), sowthistle (*Sonchus arvensis*), and bindweed (*Convolvulus arvensis*). Its broad spectrum weed control, short persistence, and low risk to the environment could make it an effective bioherbicide option (Hynes, 2018). However, bioherbicides often have low efficacy, are typically species specific and are costly, and consequently uptake is low, as discussed in 3.4.9.

4.2.4. Novel and emerging technology

Arable weeds are generally distributed in patches, while herbicides are applied uniformly (Berge *et al.,* 2012). Therefore, there is scope for the use of site specific weed management (SSWM) for cereal and oilseed crops. Lopez-Grandos (2011) claimed that real-time SSWM includes two approaches: (i) a weed detection-tractor-sprayer combination (usually used for extensive crops such as cereals) and (ii) a small autonomous vehicle that integrates detection and control of weeds also in a unique and simultaneous operation (robotic weeding) (usually used for high value crops such as tomatoes).

Site specific weed management (manual)

Apps are available for easy manual recording and mapping of weeds within cereal, such as iSOYLscout (3.6.4). The scouting app allows users to map by drawing, GPS tracing, or simply photographing weeds in the field. This could be used pre-harvest when weeds are apparent within a crop (black-grass or brome) or earlier in the year, post-drilling (Food and Farming Futures, 2018).

Satellite imagery

Castillejo-Gonzalez *et al.,* (2014) used satellite images to map wild-oat patches at the field level (15 wheat fields) and at region level (entire satellite scene of 80 km^2) with accuracies between 80% and 99%. With similar technology, de Castro *et al.,* (2013) mapped cruciferous weed patches in 263 winter wheat fields, which covered approximately 2656 ha, obtaining global classification accuracies of 89–91%.

Within field detection of weeds in cereals

In general, in field detection of weeds in cereals is less effective at discriminating weeds in seeded crops (Fennimore *et al*., 2014), crops planted in narrowly spaced rows (e.g. wheat) or weeds growing within crop rows (Torres-Sanchez *et al.,* 2014). Nevertheless, recent advances in machine-learning algorithms combined with pattern and feature selection techniques have offered excellent results for

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between- and within crop-row weed detection and classification (Xue *et al*, 2012 Hung *et al.,* 2014; Perez-Ortiz *et al.,* 2016).

The eyeWeed system uses cameras mounted on ground-based farm machinery (e.g. sprayers) with the goal of automating the process of creating the geo-referenced maps of identified black-grass patches without needing corroboration from ground truthing (Murdoch *et al*., 2014).

Economics

A study determining the economic feasibility of weed mapping systems was completed by Lausen *et al., (*2017). The study demonstrated it is possible to perform image acquisition for weed mapping for a total cost ranging from approximately 2.4-6.6 €/ha. The study also suggested that tractor based setup seems significantly cheaper than the all-terrain vehicle setup for identifying cereal weeds.

Future action: Continue the development of satellite and within field detection technology to distinguish between grass weeds and cereals

4.2.5. Digital tools

Prediction modelling

A number of prediction models have been developed for use in measuring the effectiveness of management strategies for black-grass control. Metcalfe *et al*., (2018) have developed a model using factors such as variation in soil type to identify areas of the field that are more vulnerable to infestation, which could enable site-specific within field management of black-grass. Freckleton *et al*., (2018) have developed a model to measure the effectiveness of management interventions for black-grass on a regional scale, finding that rotational strategies need to be carefully evaluated against spatiotemporal (area and time) variation to be effective for black-grass control. A detailed black-grass prediction model (AlomySys) has also been developed in France, which could potentially be used in the UK. The model predicts the influence of soil environment, cropping system, soil seed distribution, seed survival, and seed dormancy on emergence flushes (Colbach *et al*., 2006).

Many herbicide resistance models have also been developed for use in arable rotations. However, as the development and spread of target site resistance and non-target site resistance differ, models have to be developed for each resistance mechanism, cropping system, herbicide active/ mode of action, and weed species. For example, Cavan *et al*., (2000) developed a model combining cultural, mechanical, and herbicide strategies to predict the time to resistance development in black-grass. Neve (2008) developed a model to understand the evolution and management of glyphosate resistance, which could potentially be updated for use in the UK with results for more recent research (e.g. Davies & Neve, 2017; Davies *et al*., 2018; and 'Managing the resistance risk to retain long-term effectiveness of glyphosate for grass-weed control in UK crop rotations', led by ADAS (AHDB &

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commercial partners RD-2140006131, 2015-2020)). The PERTH model (Polygenic Evolution of Resistance to Herbicides) is also a model that could potentially be adapted for use in the UK for outcrossing, annual weeds (Renton *et al*., 2011).

The use of prediction and herbicide resistance models such as these for black-grass and other weed control in cereals and oilseeds could increase the use and effectiveness of precision herbicide application, rotations for weed control, cultivations, and uptake of resistance prevention strategies. However, these models can only be impactful with knowledge transfer to farmers and in some cases demonstration sites to show growers the effectiveness of their predictions.

Decision support systems

Like prediction models, decision support systems (DSS) can be used by growers and advisors to guide their weed control decision making process in advance of a single crop or in their whole arable system. A number of DSS are available in the UK for use in arable rotations, ranging from simple tools, such as the Dow Kerb weather window (http://uk.dowagro.com/category/oilseed-rape/kerb-weather-data/), to more complex DSS, such as Weed Manager, which was designed to take into account rotations, herbicide use and cultivations (Parsons *et al.,* 2009). There are also DSS that have been developed in European cereals and oilseed cropping systems that have the potential to be adapted for use in the UK. DSS-IWM, is an online system to support reliable decisions based on local conditions, mechanical and herbicide options, validating dose-response functions under field conditions in maize and winter wheat (http://ict-agri.eu/node/36643). DSSHerbicide (www.DSSHerbicide.de) is another reasonably simple DSS that has been developed for winter wheat in the Southern Baltic region of Europe. It requires simple inputs of weed presence, density, and predicted minimum and maximum temperatures, and gives outputs on recommended herbicides, rates, and expected levels of control. Adaptation of these existing systems to the UK would take less effort than developing new systems, but would still require field trial validations, model adaptation for UK conditions, and extensive grower demonstrations to encourage uptake, as discussed in 3.6.2.

Internet tools and Apps

The use and transferability of internet tools and Apps for use by UK cereals and oilseeds growers and advisors is dependent on the tools and Apps themselves. Tools and Apps that provide growers and advisors information on weed biology can easily be used in the UK without adaptation to the UK or the need for regular updating. Additionally, unlike prediction models and DSS, the information provided in internet tools and Apps is not as dependent on the region they are developed in, with growers and advisors able to read and uptake the information they need. However, caution will be required by the user when using internet tools and Apps not developed for their specific region, especially relating to control techniques.

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4.2.6. Genetic tools

Herbicide tolerant crops

Currently in UK cereals and oilseeds, the only herbicide tolerant crop available is imidazolinone tolerant Clearfield® oilseed rape. In the 2017/18 growing season Clearfield oilseed rape had a 10% UK market share (BASF, 2018b). Although, there are no herbicide tolerant cereal varieties currently available in the UK, but there are ACCase tolerant wheat varieties available in the USA. CoAXium™ is a wheat production system where quizalofop tolerant varieties have been created through induced mutagenesis using ethyl methanesulfonate (Ostlie *et al*., 2015; CoAXium, 2019).

The use of ALS tolerant oilseed rape can increase weed control options, particularly for hard to control broad-leaved weeds. Although, herbicides containing aminopyralid, propyzamide, and Arylex can provide control for many broad-leaved weeds including poppies, mayweed, and chickweed in oilseed rape crops. However, they do not provide control for charlock, a species closely related to oilseed rape (Dow AgroSciences UK, 2019; University of Hertfordshire, 2019), whereas the ALS chemistry available in Clearfield® oilseed rape can control charlock without damaging the crop (BASF, 2019a).

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 (Krato & Petersen, 2012b). There is also a large 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 (as discussed above) (Lamichhane *et al*., 2017). However, growers using Clearfield® oilseed rape must follow strict stewardship guidelines to help manage herbicide resistance and crop volunteers (BASF, 2019b).

Future actions:

- Assess and monitor weed species shifts and potential resistance evolution in UK grown herbicide tolerant oilseed rape
- Assess the potential for the use of herbicide tolerant wheat in the UK, including cost-benefit analysis and potential herbicide resistance

Genetically modified crops

Although no genetically modified crops (GMCs) are currently grown in the UK, this situation may change once the UK has left the European Union. Areal *et al*., (2015) recently reviewed the

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environmental and economic impacts of introducing GMCs to the UK, with a focus on cereals and oilseeds.

A number of GMCs with herbicide tolerant traits, which could potentially be cultivated in the UK have already been approved for use in countries outside of the EU, including glyphosate tolerant oilseed rape and maize (Table 15). The cultivation of these crops in the UK could potentially provide economic benefits to growers, but are dependent on the situation. Areal *et al*., (2015) found that under high weed pressures and in large fields, the use of herbicide tolerant oilseed rape in the UK could result in large financial benefits compared to conventional varieties. However, these gains were not seen in smaller fields where the cost of buffer zones, to prevent gene flow between the GM-oilseed rape and other oilseed rape crops and wild relatives, eroded profits.

Most of the GMCs that could be grown in the UK for weed control are glyphosate resistant (Table 15). With extensive resistance to multiple herbicide modes of action in UK weed species, in particular black-grass, but no confirmed cases of glyphosate resistance, it is likely that if glyphosate tolerant GMCs were to become available in the UK uptake would be high. As there are no glyphosate resistant weed populations in the UK, initially, the use of glyphosate tolerant GMCs could potentially provide high levels of weed control, like their early use in the USA, Australia, and Canada. However, like in these countries, it is highly likely that with the use of glyphosate tolerant GMCs glyphosate resistant weeds will quickly evolve, unless stewardship to prevent or at least slow the evolution of glyphosate resistance is of high priority (Harker *et al*., 2012; Heap, 2018). For oilseeds and cereals, this would particularly be the case for black-grass, which has been shown to respond to glyphosate selection in controlled conditions (Davies & Neve, 2017), sterile brome (*Anisantha sterilis*), which has been shown to be evolving glyphosate resistance in the UK (Davies *et al*., 2018), and ryegrass species (*Lolium* spp.), which are prone to glyphosate resistance evolution (Heap, 2018).

Some research has been done on the impact on weed communities of introducing herbicide resistant oilseed rape, sugar beet, and maize to the UK, finding that weed densities in GM oilseed rape crops were 20% lower than in conventional varieties following weed control treatments, but were not lower overall (Heard *et al*., 2003a; Heard *et al*., 2003b).

If GM oilseed rape were to be grown in the UK there would be the possibility that the crop could cross pollinate with the closely related weed species charlock (*Sinapsis arvensis*) causing further weed issues. However, experiments in France between GM oilseed rape varieties and charlock found that in ‘normal conditions’ the probability that a flower had a probability lower than 10^{-10} of producing hybrid seed, showing that these risks are small and could be mitigated with integrated weed management (Lefol *et al*., 1996).

Although not related to weed control, the John Innes Centre (2019) have applied to DEFRA for consent to conduct field trials on GM wheat to increase iron transport, and CRISPR edited oilseed

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rape to investigate the function of an existing gene. If successful, the application for these trials could potentially allow for further trials into these technologies for weed control in the UK.

CRISPR technology

CRISPR could potentially be used in the management of weeds in cereals and oilseeds, either through the development of herbicide tolerant cereal and oilseed varieties, which currently fall under the same regulatory umbrella as GMCs and would have similar environmental and weed control impact. CRISPR technology could also potentially be used in weed control to remove existing herbicide target site resistance mechanisms in weed species through a gene drive event, particularly in grass weeds. However, the herbicide mode of action would not be able to be used while the CRISPR mechanism is spreading through the population (drive event), and management of the newly sensitive populations would need to be carefully managed to prevent resistance evolution again. CRISPR gene drives could also be used to increase the impact of other weed control strategies, for example seed shedding black-grass could be delayed to increase the effectiveness of harvest weed seed control (Neve, 2018).

The effectiveness of CRIPSR gene drives will be influenced by weed species biology. A gene drive will work best in outcrossing species, such as black-grass, but not very well in selfing species, like bromes and wild-oats. The effectiveness of gene drives will be affected by the persistence of resistance individuals in the soil seedbank. With this in mind black-grass and ryegrass species have been identified as a priority for CRISPR gene drives (Neve, 2018).

4.3. Potatoes

Potatoes are a spring planted crop grown on wide rows or occasionally in beds. Weeds can reduce the yield and quality of potatoes by decreasing size, weight and number of tubers (Arnold *et al*., 1998) particularly where crop cover is reduced by weed competition. The average potential yield loss is around 34% (Oerke, 2006). Potatoes are very susceptible to weed interference during two phases of growth, firstly the early growth stages due to slow emergence, and again at the end of the growing season when the canopy opens up (Love *et al*., 1995). Some weeds, notably cleavers (*Galium aparine*), and bindweed (*Fallopia convolvulus*), can grow though the crop and smother the canopy. Tall weeds such as fat hen (*Chenopodium album*), oilseed rape (*Brassica napus*), creeping thistle (*Cirsium arvense*), sowthistles (*Sonchus* spp.) and many grass weeds can emerge through the canopy and compete for nutrients, light and water. Even weeds which do not emerge through the canopy can compete with the crop for nutrients if present in sufficient numbers. The presence of weeds at the end of the growing season can interfere with crop desiccation, and/or slow the process of harvest.

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Potatoes can be good competitors with weeds once crop canopy expansion begins and are often considered a “cleaning” crop in the rotation (Bond & Grundy, 2001). Managing weeds without herbicides requires an integration of methods and strategies and a change in how weeds are perceived (Boydston, 2010).

4.3.1. Cultural control

Rotations

Weed control for potatoes should begin with control of problematic perennial weeds elsewhere in the rotation. In particular, growers should attempt to control creeping thistle and sow thistle in other crops in the rotation because there are few control options for use in potatoes that are effective against these weeds. The length of time between potato crops is usually determined by the presence of pests, especially potato cyst nematode (PCN), rather than of weeds. The use of some potato herbicides in the current year, like metribuzin and rimsulfuron can restrict cropping choices in the year of application.

No recent research work has been done to look at the effects of rotations on weed control.

Cultivations

Potato seed tubers are normally deep planted in ridges, or occasionally in beds, which allows for both pre-emergence and post-emergence cultivations and ridging operations (Vangessel & Renner, 1990). No recent work has been done to look at the effects of cultivations on weed control, but there has been work looking at cultivations to alleviate compaction (Silgram *et al*., 2015)

Seed, planting, pests and diseases

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 less likelihood of late germinating weeds proving 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. It is important that the planter is operating efficiently to produce a reasonably uniform, competitive plant stand. PCN will slow canopy expansion and perhaps final canopy size too, thereby reducing competitiveness with weeds.

Bed planting can also be used to provide earlier canopy cover that will increase competitiveness with weeds. In bed plantings canopy closure is commonly 15 to 20 days earlier than traditionally planted rows (Hopkins *et al*., 2006).

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Future action: Examine the effect of row width on the date of canopy closure and weed control.

Cover crops

There is interest in the use of cover crops prior to potatoes in the UK. Cover crops can improve soil structure and take up nitrogen (N) which would otherwise be lost via leaching over-winter when ground is bare. A cover crop may allow N to be released to the next spring sown (potato) crop (Silgram *et al*., 2015). In this work there were no significant effects of the use of cover crops on subsequent potato yield, tuber size or quality. Although cover crops can affect weed populations (3.2.7) this was not assessed in the study by Silgram *et al*., (2015). In Italy, rapeseed and ryegrass (*Lolium* spp.) cover crops were the most efficient weed suppressors. Weed biomass was less than 1% of the total biomass produced by the cover. The cover crops also reduced weed emergence in the following potato crops (Campiglia *et al*., 2009).

Where stone separation occurs, vegetation associated with the cover crop tends to be removed with the stones, but it can also lead to the removal of a significant amount of soil from the potato bed Therefore, cover crops with significant biomass need to be largely destroyed by cultivation or glyphosate prior to potato seedbed preparation.

Consideration should also be given to the species of cover crop grown as it could be a host for common pests and diseases of potatoes and other crops in the rotation. For example, anecdotally it has been reported that many cover crops can be a host for wireworm and FLN, and some “biofumigation” crops can be hosts for club root.

Future action: Evaluate the use of a cover crop prior to potatoes for weed suppression and effects on soil pests and diseases.

Intercropping or companion cropping

Rajalahti *et al*., (1999) evaluated the potential of ridging, in combination with intercropping cover crops, to control weeds in potato. 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 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.

Future action: The use of intercropping should be monitored in other crops and considered for use in potatoes if more information becomes available.

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Crop cultivars

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 (Mohler, 2001). Colquhoun *et al*., (2009) reported differences among ten potato cultivars in their ability to tolerate weeds and retain tuber yield in the presence of weeds. Crop cultivars with fast developing canopies, large leaf area index, and tall height generally suppress weed growth and tolerate weeds better than less competitive cultivars (Cavalieri *et al*., 2017). At the present time, Markies in particular is noted in the UK for this effect.

Future action: Competitive cultivars could be selected for in breeding programmes, but their use depends on the suitability of the produce for the target market.

4.3.2. Non-chemical control

Mechanical weeding

In organic crops, it is common to rake over the ground post-planting and when weeds are at the cotyledon stage. This has the effect of ripping-out weeds on the top of the ridge and burying those in the bottom. A 12 m rake can weed 80 ha per day in good conditions. A cultivator/ridger is then used a minimum of twice, commonly three and perhaps even four or more times post-emergence. This method has been shown to be one of the most effective weed control strategies in potato (Mohler, 2001). As organic crops do not usually have the nutritional supplies of conventional crops, especially nitrogen, canopy development is usually slower and sometimes never complete, and so additional passes are going to be required to control weeds. A two row cultivator/ridger can realistically only manage 14 ha per day with the first post-emergence pass. Typically this reduces to about 9.5 ha per day with a 2nd pass and just seven ha's per day with a 3rd or subsequent pass. The lower speed with later passes is due to the need to avoid crop canopy damage. Large six row equipment can manage proportionately more, but requires sophisticated and therefore expensive RTK GPS-controlled equipment with a relatively large tractor (typically 150 kW) 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 in potatoes always seems to be effective. In the UK, three years of experiments with one, two or three passes were done (Kilpatrick, 1995). A single pass reduced weed biomass by 59-87%, two passes by 85-87% and three passes by 70%. The yield response depended on the weed pressure i.e. at a low weed pressure cultivation for weed control reduced the yield, and at high weed pressures cultivation increased crop yield. There were no major differences between yield response to chemical and mechanical weed control. In Denmark, 0, 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

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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. Yield responses were variable. Mechanical weeding causes moisture loss from the soil, and when this is done repeatedly, that loss can be significant for the crop. In addition, mechanical weeding can damage crop root systems.

Future action: With the loss of some important potato herbicides, mechanical weeding particularly in conjunction with guidance technology, such as real time kinematics (RTK), should be evaluated for use in conventional crops.

Mulching

Clear plastic or white “fleece” has sometimes been used to promote crop earliness, with residual herbicides being applied just before it is laid. The fleece is then removed soon after crop emergence. However, the dry soil surface promoted by these covers often means at best indifferent weed control. It would be possible to use black instead of clear plastic, and remove it as the crops emerge. 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 then taking up plastic is expensive, and disposal/recycling are additional issues (Ballingall & Ironside, 2009). Therefore, this technique is only applicable to small areas of niche high value crops.

Thermal weeding

Thermal weeding is sometimes used in organic potato crops where it is too wet to rake pre-emergence. The work rate is slow and consumption of LPG is typically within the range 120 to 250 L/ha, which means the carbon footprint is very significant. This technique can also be used to desiccate organic crops (and weeds) prior to harvest.

A thermal flame spot weeder has been developed and trialled in Denmark (Poulson, 2018), using on-board cameras to identify weeds which then activate small burners. Current research investigating the benefits of flame weeding in vegetable systems is being done in a European H2020 funded project IWMPraise (2016) and results from this need to be monitored for further use in potatoes.

Future action: Keep a watching brief on thermal weed control methods as they develop. This is most likely to be in combination with guided weed control systems or robots.

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4.3.3. Chemical control

Existing chemistry

In the latest pesticide usage survey done in 2016 (Garthwaite *et al*., 2017a) the most used herbicides were diquat, linuron, metribuzin, glyphosate and carfentrazone-ethyl (Figure 24). On mineral soils, weed control for the bulk of the GB area relies on diquat (typically 2.0 L/ha of a 200 g/L product) mixed with a combination of residual herbicides, usually applied at the beginning of crop emergence. The residuals used will depend on cost, anticipated weed spectrum, variety (especially sensitivity to metribuzin, and to a lesser extent clomazone), and soil type. The very large area treated with diquat, which is more than twice the UK area of potatoes, reflects its use as a desiccant as well as an herbicide (Figure 24).

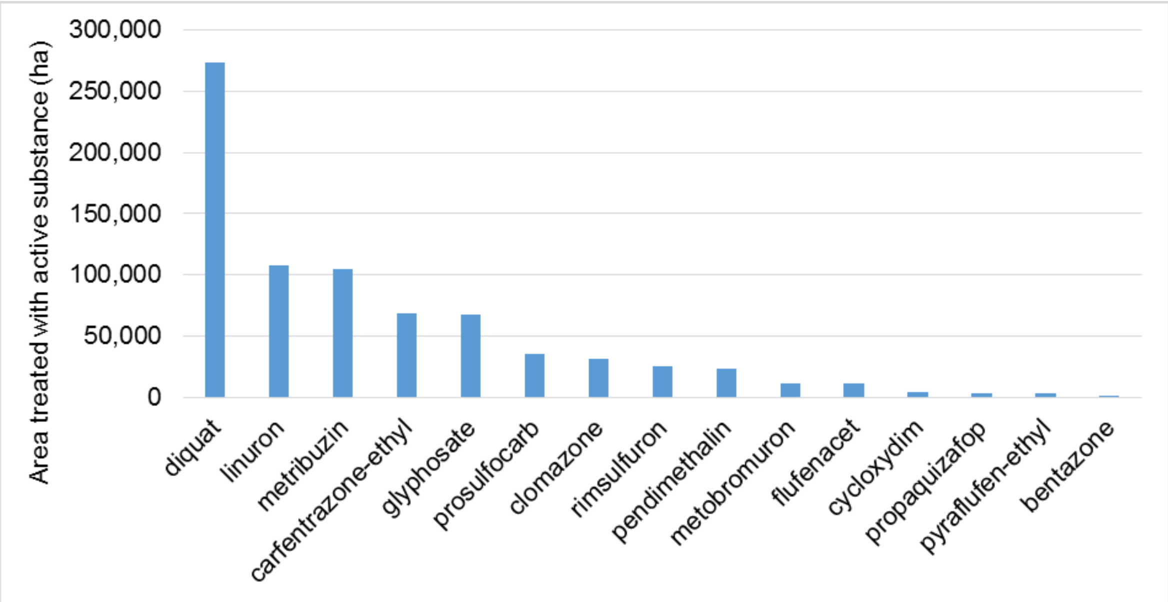

Figure 24 The area of potatoes treated with herbicides in the UK in 2015 (PUS Stats, 2018). (Area treated refers to the active substance treated area. This is the basic area treated by each active substance, multiplied by the number of times the area was treated).

Residual herbicides

Residual herbicides commonly used in potatoes are clomazone, flufenacet, linuron, metobromuron, metribuzin, pendimethalin and prosulfocarb (Table 41). With the exception of linuron, these residuals are usually applied at less than full label rate. The loss of linuron (its last year of use was 2018) may mean its replacement with metobromuron, because both belong to the same chemical group (substituted ureas) and therefore have a similar, though not identical, weed spectrum. Alternatively, because of cost, other active ingredients may be used at higher rates than is currently common practice.

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Table 41 Currently authorised actives and mixtures for use in potatoes for broad leaved and grass weed control

Active Ingredient	HRAC group	Residual	Contact
Bentazone	C3		✓
Carfentrazone-ethyl	E		✓
Clomazone	F3	✓	
Clomazone + metribuzin	F3 + C1		
Cycloxydim	A		✓
Diquat	D		✓
Flufenacet	K3	✓	
Glufosinate-ammonium	H		✓
Metobromuron	C2	✓	
Metribuzin	C1	✓	
Pendimethalin	K1	✓	
Propaquizafop	A		✓
Prosulfocarb	N	✓	
Pyraflufen-ethyl	E		✓
Quizalofop-P-ethyl	A		✓
Quizalofop-P-tefuryl	A		✓
Rimsulfuron	B		✓

On sands and very light soils (coarse sandy loam or lighter), the water soluble herbicides metribuzin and clomazone (1,165 and 1,102 mg/L @ 20˚C, respectively) are prone to being moved down the soil profile following heavy rain soon after application and being taken up by potato roots, causing crop damage. The risk of this happening restricts the rates which can be applied on these soil types. At the other end of the water solubility spectrum, the activity of pendimethalin (0.33 mg/L) and to a lesser extent of prosulfocarb (13.2 mg/L) can be poor when soil surfaces are dry in the first two weeks or so after application.

Contact herbicides

The loss of diquat after 2019 will probably mean its replacement with carfentrazone or pyraflufen. Herbicides in this group (HRAC E) may be harsher than diquat on emerged foliage, and if that proves to be the case, then the timing of herbicide application will need to be a few days earlier than commonly occurs at present. This will in turn put more pressure on the residual herbicides, perhaps resulting in more post-emergence application.

Black-grass

Where black-grass (*Alopecurus myosuroides*) is a problem, and, anecdotally it is an increasing problem in potato crops, then it is common to apply glyphosate post-planting but pre-emergence of the crop (so as to avoid translocated crop damage) and use flufenacet + metribuzin as a co-formulated product as the residual. Again this cannot be used where the variety is very sensitive to metribuzin. Flufenacet is also very effective as a residual herbicide against cleavers.

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Post-emergence herbicides

Major competitive weeds emerging after herbicide application on mineral soils are often black-bindweed and cleavers. Historically, either bentazone or rimsulfuron were used to control both, although in more recent years the use of bentazone has declined significantly due to its cost relative to rimsulfuron, and lack of new variety sensitivity testing. Rimsulfuron can be used on all potato crops, except seed, whereas bentazone is variety specific. Following work in Holland, there is a trend towards mixing low rates of metribuzin with rimsulfuron except where the variety is very sensitive to metribuzin. The activity of rimsulfuron is very temperature dependant, and improves in warm conditions. Rimsulfuron will nearly always cause some delay in canopy expansion, and that delay is made more severe if it is applied under conditions of high temperatures and high light intensities. Because of SU resistance within black-grass populations, the activity of rimsulfuron applied post-emergence of this weed is often very poor, when it does little more than slightly stunting it. The addition of propaquizafop to rimsulfuron does help suppress black-grass, despite “fop” resistance in populations of this weed.

High organic matter soils

On soils with a significant percentage of organic matter, say 10% or more, it is common to incorporate metribuzin in the seedbed pre-planting, and then apply either diquat alone or a mixture of diquat and metribuzin at the start of crop emergence. Again, metribuzin cannot be used on very sensitive varieties. It is then normal to follow-up with a cultivator/ridger usually just once, but sometimes twice, post-emergence to control late germinating competitive weeds such as fat hen, black-bindweed, redshank (*Persicaria maculosa*), pale persicaria (*Persicaria lapathifolia*), and increasingly black-grass as well. Rimsulfuron is commonly used post-emergence too, although it only suppresses rather than controls many of the broad-leaved weed species at which it is targeted, requiring cultivation to complete the process.

Pre-harvest herbicides

Pre-harvest weed control occurs during crop desiccation. With diquat being lost to the industry at the end of 2019, carfentrazone, pyraflufen and glufosinate ammonium are alternatives either alone or in combination with flailing. Glufosinate ammonium can only be used as a band spray after flailing for this purpose. Pelargonic acid has approval for use as a desiccant in the US and there is some development work underway which may lead to UK approval at a future date

Herbicide resistant weeds

The inclusion of potatoes in the rotation is largely beneficial for the control of herbicide resistant weeds, particularly where ALS resistance is present (HRAC group B) as there is only one herbicide in this group, rimsulfuron (Table 43). The high levels of metribuzin use (HRAC C1) in the crop will

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increase the risk of exposing already resistant weeds and increase further the risk of developing resistance in annual meadow grass (*Poa annua*), fat hen and groundsel (*Senecio vulgaris*). Resistance to this group has already been seen in the UK in these species (see section 5.4.3 sugar beet).

Future action:

The withdrawal of diquat will have a significant effect on early weed control in potatoes. Alternatives need to be evaluated.

Variety sensitivity testing to herbicides needs to be included in herbicide programme evaluation.

New chemistries

A new herbicide (SP01644) containing the active substance aclonifen, is being prepared for the market by Bayer (CPM, 2018). An application for registration has been submitted to the Chemicals Regulation Division (CRD) for a maximum rate of 3 L/ha pre-emergence. This active has been used in Europe for more than 15 years. It is a residual with a broad spectrum of activity, promising good control of small nettle (*Urtica urens*), brassica weeds, fat hen, orache (*Atriplex patula*)and a range of polygonum species, with a useful contribution to the control of mayweed (*Tripleurospermum inodorum*) and grassweeds (from seed).

4.3.4. Novel and emerging technologies

Aerial imagery (satellite, aeroplane, drones) can be used to identify weedy areas and measure the response to management tactics. Drone imagery has been used in the field to identify disease in potato (Gibson-Poole *et al*., 2017) and weeds (Sabzi et al., 2018).

Weed control with self-propelled robots is a fast developing area. Sensing weed technology is well developed and this is being combined with a wide range of weed control measures such as lasers and herbicide spot sprays. Naio technologies have developed an autonomous weeding robot ‘Oz’ that can be fitted with spiked harrows to weed potato ridges (NAIO, 2019)

Future action: Keep a watching brief on developing technologies, liaise and interact with industry and research establishments.

4.3.5. Genetic tools

In potatoes, there are no herbicide tolerant varieties being developed. It seems unlikely that such varieties will appear in the foreseeable future, given public reaction to the technique, and the much higher breeding priorities of resistance to blight and PCN.

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Future action: Keep a watching brief on genetic tools, liaise and interact with industry and research establishments.

4.3.6. Preventative weed control

New weeds can be introduced to the field by machinery, seed contamination of other crops and organic manures and digestate. Cereal straw spread to protect crops from frost, notably overwintered carrots, can be sources of new weed introductions, especially herbicide resistant black-grass. Contractor-operated combines and straw balers have often been implicated in the spread of black-grass seed. Many weed species can be spread from field to field on cultivation equipment and harvesting machinery. Large quantities of soil can be transported from farm to farm and machinery should be thoroughly cleaned to minimise this risk.

Future action: Inform growers on all potential routes for weed infestation and issue guidance for control. Research is required to quantify the effects of different types of organic manure on weed seed survival and spread.

4.4. Sugar beet

Sugar beet is spring sown in March/April and precision drilled on 45-50 cm rows, with 14-20 cm between plants in the row (BBRO, 2018b). Crop canopy closure usually occurs in June. The crop is sensitive to competition during the early stages of growth, root yield can be reduced by 26-100% by weeds that emerge within eight weeks of sowing or within four weeks of the crop reaching the two-leaf stage (Schweizer & Dexter, 1987). When sugar beet plants reach GS18, or weeds emerge eight weeks after sowing there is likely to be less effect on yield. Scott *et al*., (1979) estimated that once sugar beet reached GS14-16 stage, weeds could reduce yields by about 1.5% per day for the next six weeks. The most frequently occurring weeds in sugar beet taken from Heard *et al*., (2003b) are detailed in Table 42, since then black-grass (*Alopecurus myosuroides*), volunteer oilseed rape and volunteer potatoes have become more prevalent and increased herbicide costs where they occur (P Chambers, Pers. Comm.). Most weeds encountered in sugar beet crops are predominantly spring germinating, but there are subtleties between the emergence periods which can cause problems necessitating a programme of up to six herbicide applications being applied in the first 60 days after drilling. Herbicides/weed control constitutes up to 69% of the cost of spray costs (Redman, 2018).

An additional weed problem encountered is weed beet, this is present in 82% of crops (BBRO, 2018b), densities of only 1 plant/m² can reduce root yields by 11.7% (Longden, 1989) through shading and competition for water and nutrients .

Table 42 The most commonly occurring 12 weed species occurring in spring sown sugar beet, after ‘cost effective’ weed control in 2003.

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Sugar beet	Common name	Latin name
1	Fat hen	*Chenopodium album*
2	Annual meadow-grass	*Poa annua*
3	Knotgrass	*Polygonum aviculare*
5	Redshank	*Persicaria maculosa*
8	Chickweed	*Stellaria media*
4	Common field speedwell	*Veronica persicaria*
7	Field pansy	*Viola arvensis*
9	Shepherds purse	*Capsella bursa pastoris*
6	Black-bindweed	*Polygonum convolvulus*
10	Sow thistle	*Sonchus spp.*
11	Red dead nettle	*Lamium purpureum*
12	Groundsel	*Senecio vulgaris*

Taken from Heard *et al.*, 2003b

Recent changes in product approvals and availability mean growers will need to make significant adjustments to their current weed control programmes.

In the short term, the aims for all sugar-beet advisers and growers wishing to control weed beet remain to:-

1. Prevent introductions
2. Stop further multiplication of existing infestations
3. Exhaust infested sites of viable seed populations.

4.4.1. Cultural control

Rotations

Rotations are one of the key factors in controlling weeds. Schweizer & Zimdahl (1984) showed that the seedbank of annual weeds can decline by 96% over a six-year period in a rotation containing sugar beet, maize and spring barley. Weed beet populations are likely to increase rapidly where beet are grown one year in three rather than one year in five (Bond & Turner 2007). Weed beet seed can remain in the seedbank for at least seven years (Gunn, 1982; Longden, 1993), annual decline estimates varied between 30 and 75% (Landová *et al.*, 2010; Longden & Breay, 1995; IRS, 2010; Sester *et al.*, 2006). Targeting these troublesome weeds should be a priority and this requires an understanding of their biology.

The effects of rotation are linked closely with cultivations and herbicide use and all techniques can be utilised to reduce the number of weed seeds in the seedbank.

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Tillage and cultivations

To achieve maximum yield it is critical that the plant population of sugar beet does not fall below 100,000 established plants/ha (BBRO, 2018c). The main objective of cultivations is to optimise rapid emergence and this requires preparation of a good seedbed by loosening the soil, weed control, burying plant residues and incorporating manures etc. Movement of soil is beneficial for weed control, but is subject to seasonal rainfall patterns and is limited by the periodicity of emergence of each weed species. The law of diminishing returns applies to repeated cultivation, with the greatest stimulation of germination from the first cultivation and successively smaller effects from subsequent ones (Cook *et al*., 2013). Currently the majority of sugar beet is established following ploughing (Ecclestone & Wright, 2014) which helps to bury freshly shed seed to a depth below which it cannot germinate. However, non-inversion tillage is now being used more frequently, to reduce costs and this can have a greater effect on weed numbers than ploughing after the primary cultivation due to minimal soil disturbance. Shallow cultivations to a maximum of 5 cm in the spring will provide light which will encourage germination (Longden, 1980; Desplanque *et al*., 2002; Sester *et al*., 2006) and shallow or no cultivations will keep more seeds in this soil layer and lead to quicker depletion of the seed bank by germination (Roberts & Feast, 1973). Longden (1974) showed that depletion of weed beet seed was quicker in the top 5 cm of soil (eight years) than at a greater depth (15 years).

The current move towards improving soil structure and increasing organic matter (GREATsoils, 2018) may lead to strip tillage and direct drilling being more commonplace in the UK, as these systems help to reduce the number of weeds present (Cooper, 2014). They minimise soil movement but there have been problems with optimising their use on farms (Ecclestone & Wright, 2014). Thriplow farms (2018) have tried to establish sugar beet using this system for a few years and have not been very successful citing poor weather and unmatched drill and cultivation passes as possible reasons. Introduction of strip tilling and direct drilling could lead to the inclusion of cover crops prior to sugar beet and these could be used to supress weeds.

Future action: Evaluate minimal cultivation systems such as direct drilling and strip tillage for establishing sugar beet and assess their effects on weed populations.

Cover cropping and allelopathy

Sugar beet, being a spring crop, provides an excellent opportunity for establishing a cover crop over the winter prior to drilling, preventing nitrate leaching and protecting soils from erosion. However, the presence and destruction of a cover crop conflicts with cultivation and the requirement for good establishment of the crop. Killing the cover crop and drilling the sugar beet directly would be most beneficial to weed control, but several workers have shown problems with crop establishment. Petersen & Rover (2005) showed that the presence of a winter hardy cover crop decreased the field emergence of sugar beet and the remaining plants were difficult to control with selective herbicides.

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They also showed that rotary band tillage reduced the weed density when compared to conventional seedbed preparation. The lowest weed density was observed in a straw mulch system. A German study compared the effects of drilling sugar beet directly into a cover crop of wheat or rye, with conventional tillage in spring. Seedling growth after emergence was slower with direct drilling (Richard *et al*., 1995). Presence of cover crop residues on the surface reduced spring weed numbers by up to 83% compared with the un-mulched control. In a dry spring, sugar beet emergence was improved by the presence of a mulch due to moisture retention by the soil (Kunz *et al*., 2017b).

Consideration should also be given to species that act as hosts for common pests and diseases of sugar beet such as cereal crops hosting powdery mildew and brassicas hosting beet cyst nematode (BCN).

Future action: Evaluate the use of a cover crop prior to sugar beet for weed suppression.

Intercropping or companion cropping

Barley has been intercropped successfully with sugar beet as a technique for preventing wind erosion as long as the barley is sprayed off prior to it competing with the beet (Fornstrom & Miller, 1996, Defra, 2005). Kunz *et al*., (2016) sowed broad-leaved species, Black medic (*Medicago lupulina)*, *Trifolium subterraneum* and a mixture of grasses perennial ryegrass (*Lolium perenne)* and Meadow fescue (*Festuca pratensis)* at two and 30 days after drilling sugar beet and showed that living mulches could reduce herbicide input up to 65%. Weed suppression of fat hen (*Chenopodium album*), black-bindweed (*Polygonum convolvulus)* and knotgrass (*Polygonum aviculare*) was highest with *Trifolium subterraneum*. Kunz (2017b) identified there were opportunities for the use of living mulches for early-season weed control but herbicides would also be needed.

Future action: The use of intercropping should be monitored in other crops and considered for use in sugar beet as more information becomes available.

Crop cultivars

Current sugar beet varieties are poor competitors against weeds, particularly at early growth stages, due to their low populations, slow shoot development (particularly in cold seasons) and limited height. Paolini *et al*., (1999) thought that rapid leaf development at early growth stages to intercept light was a requirement of a competitive variety but Stevanato *et al*., (2011) attributed improved competition to superior rooting traits that resulted in better water and nutrient uptake. This could be linked with the existing work that is evaluating rooting traits for nutrient uptake (Sparkes, 2014). BBRO demonstration farms had a range of varieties sown over six rows, a range of canopy characteristics indicated that some varieties may be more suitable for weed suppression than others (BBRO, 2018a)

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Future action: Evaluate varieties in existing variety trials for competitive traits against weeds by excluding herbicides from small areas.

Drilling dates

There is little room for delaying sowing date in sugar beet for weed control, IRS (2010) in the Netherlands reported there were fewer weed beet in late drilled crops. Emergence of weeds and weed beet seed mainly depends on soil temperature and moisture (Sester *et al*., 2006). If temperatures in spring are high, more weed beet seed will emerge and will be destroyed by delayed tillage and use of a non-selective herbicide. Bolters in sugar beet can be minimised by drilling varieties prone to bolting after mid-March (Longden, 1980).

For optimal development in the field, sugar beet need to emerge quickly and form an even stand. Environmental influences such as low soil temperatures or crusting of the soil surface can slow down crop emergence and early development. Seed priming can lead to faster and more uniform emergence and primed seed is sold commercially in the UK (Germains, 2018). Bezhin *et al*., (2018) evaluated seed priming as a method to accelerate emergence and the effect of improved early growth on weed control. The technique worked under controlled conditions but did not work in the field.

Seed rates

Crop and weed population densities were identified as key drivers of sugar beet yield and quality (Mahmood & Murdoch, 2017). Spatial variability in plant populations was strongly and negatively associated with weed density suggesting that the areas of low plant population allowed more space for new weeds to emerge in summer resulting in greater weed competition (Kropff *et al*., 1992). Weed control is an obvious target for precision farming, through improving plant establishment in weedy patches or increased weed control in these areas.

4.4.2. Non-chemical control

Manual removal of weeds

Hand pulling and rogueing is still important for the control of weed beet, bolters, wild oats and black-grass at low infestations. Cutting weed beet at soil level with a sharp spade or similar tool is an alternative to pulling. At the pre-flowering or flowering stage BBRO recommend the weed beet and bolters should be pulled, or have their stem broken close to the root and left on top of the crop to die. After flowering the recommendation is to remove plants from the field.

Longden (1987) indicated that plants should be moved from the field as seed may have set. Manual weeding is still a valuable way of removing the last few weeds within a crop.

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Mechanical weeding

Mechanical weeding is frequently used to kill weeds inter-row, but there have been developments in machinery to control weed intra-row. Kunz *et al., (*2018) evaluated camera steered mechanical weed control, they used ducks-foot blades in the inter-row combined with four different mechanical intra-row weeding elements and a band sprayer. Average weed densities in the untreated control plots were from 12 to 153 plants m² with fat hen (*Chenopodium album*), black-bindweed (*Polygonum convolvulus*), and field pennycress (*Thlapsi arvense*) the most abundant species. Camera steered hoeing resulted in 78% weed control compared to 65% using manual guidance. Mechanical intra-row weeding controlled up to 79% of the weeds in the crop rows. Weed control efficacy was highest in the herbicide treatments with almost 100% killed where herbicide band-applications were combined with inter-row hoeing. However, it was reported that crop yields were reduced where mechanical weeding was used.

Tugnoli *et al*., (2002) showed that it was possible use inter and intra-row mechanical weeding of sugar beet at GS14-16 and remove the need for a pre-emergence herbicide application. This could be combined with low doses of post-emergence herbicides on the row. This work showed no effects on yield or quality of the crop. Removal of all herbicide applications was not possible due to the presence of weeds within the row and the authors stated that a move to completely mechanical control was not possible. Additional weed control would come from combining mechanical weeding in the inter-row area with band application of herbicides in the intra-row area. Kunz *et al*., (2017a) showed that band spraying in combination with inter-row hoeing reduced herbicide input by 50 to 75% compared to uniform herbicide applications. Weed control efficacy was 72% in the conventional herbicide treatments, 87% for the combination of weed hoeing and band spraying, 78% for precision hoeing with camera steering and 84% for precision hoeing with GNSS-RTK (Global Navigation Satellite system- Real time Kinematic). The use of automatic steering can increase the speed of weeding from 4km/hr (manual steering) to 7-10 km/hr (automatic steering) (Kunz *et al*., 2015). Weed hoeing using automatic steering technologies reduced weed densities in sugar beet by 87% compared to 85% weed control efficacy in with conventional weeding systems.

Future action: Evaluate camera or RTK guided inter and intra-row mechanical weeding combined with and without band spraying.

Mowing and cutting, for weed seed control

The tall flower spikes of weed beet allow height selective control by both pulling and cutting (Longden, 1993). Cutting bolters or weed beet is optimal when done three times at two week intervals starting 14-28 days after flowering (Longden, 1980; 1982). Delaying cutting to 42 days after flowering results in viable seed already being present. Cutting should start at 20 cm above the crop, and further cuts should be made progressively lower until the final cut is just above the crop canopy. A rotary

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cutter (weed surfer) has been developed to remove the flower heads of bolted weed beet growing in sugar beet crops (Anon, 2000).

Thermal, electrical, flame, hot water and hot foam

Flame weeding has a lot of disadvantages being cost-intensive and inefficient. A thermal flame spot weeder has been developed and trialled in Denmark (Poulson, 2018), on board cameras identify weeds and small burners are activated. Current research investigating the benefits of flame weeding in vegetable systems is being done in a European H2020 funded project IWMPraise (2016) and this needs to be monitored for use in sugar beet.

Electrical weeding for the control of bolters was first developed in the 1980's (Diprose *et al*., 1985), the electro-thermal machine killed between 38 and 41% of bolters compared with 65% for the chemical applicator. The use of electricity to kill weeds has been further developed in recent years with Ubiqutek (2018) in partnership with Steketee & Zasso (Zasso, 2018) developing machines to use in agriculture but none are yet commercially available.

Hot foam has been patented by Weedingtech™ (2018) but recent work by ADAS (2013b) identified improvements were required in treatment speed, application timing and tractor mounted equipment. This would allow multiple rows to be treated simultaneously so it could be used in arable crops.

Microwave and laser technology is developing and could be suitable for use in sugar beet crops.

Future action: Keep a watching brief on thermal weed control methods as they develop. This is most likely to be in combination with guided weed control systems or robots.

4.4.3. Chemical control

Chemical control currently remains as the key method for controlling weeds in sugar beet and the industry has been threatened by the withdrawal of two of the most commonly used herbicides, phenmedipham and desmedipham.

The recent withdrawal of neonicotinoid seed dressings has led to growers increasingly asking about mixing insecticides with herbicides. There is a lack of information in this area particularly regarding water volumes and potential crop damage.

Weed wiping

Weed wiping can be a successful method of controlling weed beet, volunteer potatoes and other weeds that grow taller than the crop (McWhorter, 1970; Dale, 1979). Travel in both directions is necessary to apply sufficient herbicide (glyphosate) for a good kill. In recent years weed wipers have been tried as a control method for black-grass (Farmers guide, 2016). For all weeds the differential in height between the crop and weed is sometimes not great enough and there is a danger of

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damaging the crop. Another factor to consider is timing as applications have to be made before seed is viable, so for black-grass the weed has to be treated before the 1st week in June. Repeated applications may needed as further tillers appear above the height of the crop.

Only glyphosate is authorised for use for weed wiping in the UK, but in New Zealand and Canada metsulfuron, clopyralid, triclopyr and picloram have been trialled (Harrington & Ghanizadeh, 2017) and could be alternatives for use in sugar beet.

Absence of phenmedipham and desmedipham – decision making process and guidance

Phenmedipham (PMP) is the main sugar beet herbicide used in the UK (Figure 25) and has been used since the 1970's. In 2015 it was applied to 242,759 ha of beet (approximately 100,00 ha of the crop was grown), 33% of the crop received two applications and 57% received three applications. It is included in the majority of mixes available to growers. Desmedipham (DMP) became available in the early 1990's and is only available with PMP in mixtures and was applied to 181,869 ha in 2015 (Figure 25). Both PMP and DMP are contact herbicides and are applied post-emergence of the weeds.

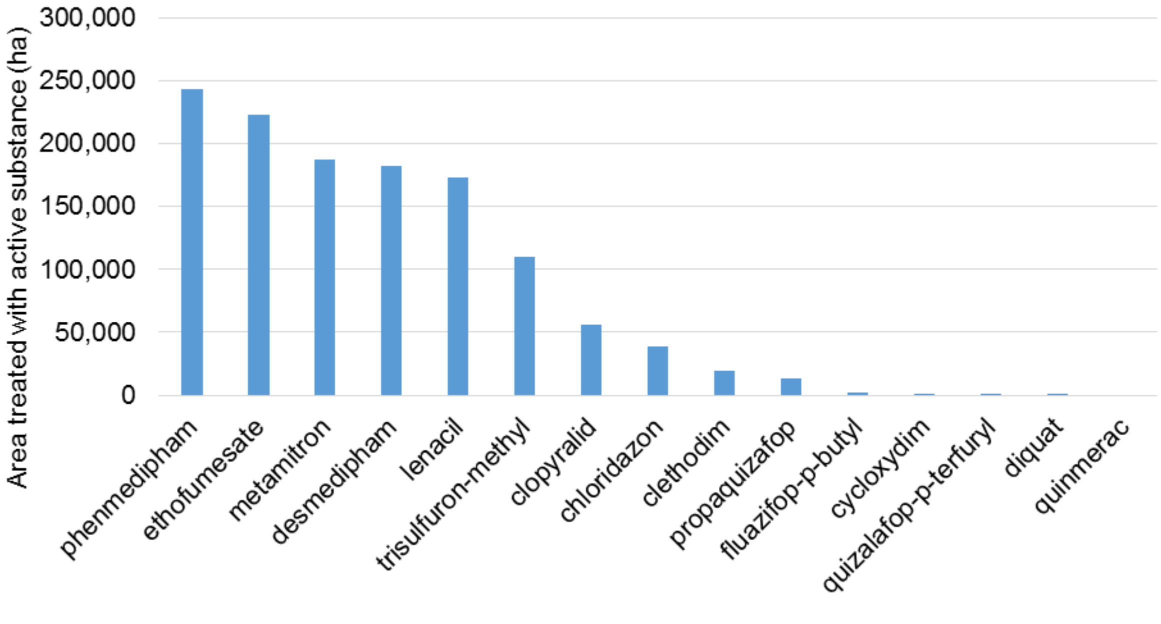

Figure 25 The area of sugar beet treated with herbicides in the UK in 2015 (PUS Stats, 2018). (Area treated refers to the active substance treated area. This is the basic area treated by each active substance, multiplied by the number of times the area was treated)

A wide range of herbicides are available for use in sugar beet (Table 43), the majority for post-emergence application. In general herbicide programmes typically include a contact (always PMP +/- DMP) plus an activator (ethofumesate) and a residual component. Triflusulfuron-methyl & clopyralid may also be added to control specific weeds. All contact herbicides applied post-emergence are more effective in dry conditions than the residuals. Pre-emergence herbicides require moisture to work effectively and during dry conditions, such as spring 2018, growers have been

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reluctant to make applications post drilling. Loss of PMP and DMP will place more reliance on the residual components of post-emergence mixtures which will in turn be more affected by lack of soil moisture. The synergistic nature of mixing actives has given high levels of weed control and allowed the dosage of individual components to remain low (although obviously higher in the Broadacre approach than the FAR approach for example (see Table 44 for definitions). Pre-emergence herbicides can be applied (normally straight after drilling) and can be can be mixed in with a total graminicide and/or nitrogen fertiliser. They do not provide season-long control and typically are used to sensitise weeds to the post-emergence applications and give more leeway for the timing of post-emergence applications. Post-emergence weed control in recent years has relied on mixes of actives either formulated by the manufacturer or mixed on farm to provide broad spectrum weed control.

Crops typically receive two to four post-emergence applications for broad-leaved weed control with some receiving a prior application pre-emergence. Additionally specific graminicides are applied depending on the weeds present. If lower doses are used then more applications are usually required (FAR system at one extreme – Broadacre approach at the other) (Table 44).

Table 43 Currently authorised actives and mixtures for use in sugar beet for broad-leaved and grass weed control

Active substance	HRAC group*	Pre-emergence	Post-emergence
Diquat (Use up by 2020)	D	✓	
Chloridazon (not available in 2019)	C1	✓	
Chloridazon + metamitron (not available in 2019)	C1+C1	✓	
Chloridazon + quinmerac (not available in 2019)	C1+O	✓	✓
Ethofumesate	N	✓	✓
Ethofumesate + metamitron	N+C1	✓	✓
Metamitron	C1	✓	✓
Metamitron + quinmerac	C1 + O	✓	✓
Clethodim	A		✓
Clopyralid	O		✓
Cycloxydim	A		✓
Desmedipham + ethofumesate + lenacil + phenmedipham	C1 + N + C1 + C1		✓
Desmedipham + ethofumesate + phenmedipham	C1 + N + C1		✓
Desmedipham + phenmedipham	C1+C1		✓
Dimethenamid-P + quinmerac	K3 + O		✓
Ethofumesate + metamitron + phenmedipham	N + C1 + C1		✓
Ethofumesate + phenmedipham	N+C1		✓
Fluazifop-P-butyl	A		✓
Lenacil	C1		✓
Lenacil + triflusulfuron-methyl	C1+B		✓
Phenmedipham	C1		✓
Propaquizafop	A		✓
Quizalofop-P-ethyl	A		✓
Quizalofop-P-tefuryl	A		✓
Triflusulfuron-methyl	B		✓

*HRAC Group: The Herbicide Resistance action committee has classified herbicides are according to their target sites, sites of action, similarity of induced symptoms or chemical classes.

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Table 44 Outline of herbicide strategies for sugar beet (BBRO, 2018c)

System	Components	Weed size	Intervals	Comment
FAR	Phenmedipham/ Activator (ethofumesate)/ Residual	Early cotyledon stage until the weed flush is over.	Multiple (4 or 5) applications of herbicides, 7-10 days apart, at relatively low doses	Difficult to recognise the end of the weed flush. Fitting in with other farm spraying.
Active	Broad spectrum herbicides containing multiple a.i.s	Early true leaf	10-14 days between sprays	Control under a wide range of conditions.
Broadacre	Robust broad-spectrum herbicides. Sometimes includes a pre-emergence.	Expanded cotyledon stage, followed by a second application at two leaves.	14 days	
Standard managed approach	Usually includes a pre-emergence spray, multiple low doses (two or three). Herbicides selected for weed species present.	Expanded cotyledon stage	10-14 days between sprays	Lack of spray days Difficult to treat wide range of weed species.

The availability of broad-spectrum weed control has meant there is little need to vary mixes from field to field and fewer requirements to identify small weeds. Mixtures can be tailored for later applications if certain weeds are escaping control at earlier applications.

Current herbicide status

The number of actives available for pre-emergence use has diminished in recent years. Chloridazon (the most frequently used pre-emergence) is no longer in production for 2019. Fiesta T, a chloridazon + quinmerac mix, is no longer available. Volcan Combi (chloridazon + metamitron) stocks can be used but it will also be withdrawn in 2019. Chloridazon is also subject to a restriction on dose, a maximum total dose of 2.6 kg/ha of chloridazon may only be applied every third year on the same field.

Diquat usage has reduced over recent years but it has recently been withdrawn, it will be sold until 04 May 2019 and can be used until 04 February 2020.

The pre-emergence use of lenacil has recently been removed, but it can still be applied post-emergence. It is widely used (Figure 25) as the residual component of many mixtures. A recently introduced restriction on use (it may only be applied once in the same field every three years) will add to the complications in planning herbicide programmes.

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Quinmerac, ethofumesate and metamitron can be applied both pre- and post-emergence (Table 43). Quinmerac is available with metamitron as Goltix Titan from Adama and as Kezuro from BASF. Kezuro will only be available from a small number of distributors in 2019. BASF registered two new sugar beet herbicides in 2018, Topkat and Tanaris, containing dimethenamid-P + quinmerac. However, these will only available via a very limited number of distributors (I Ford, Pers. Comm.).

The restriction on the use of ethofumesate (the maximum total dose must not exceed 1.0 kg/ha of the active ingredient in any three year period) is particularly difficult to work around, and growers are wary of applying too much active pre-emergence as they need to be able to use it in post-emergence mixes. Where black-grass is an issue then growers can apply 0.5 kg/ha pre-emergence as that is where it is most effective.

Metamitron used to be applied on its own as an early post-emergence application with oil added to aid contact activity. Adjuvants have been used to aid contact activity in post –emergence herbicides especially in dry conditions or where difficult or large weeds were present. If PMP & DMP are withdrawn then adjuvant use could become more important hopefully to enhance the contact activity of the remaining actives. However the adjuvants currently used, mainly mineral or rape oil based, can reduce selectivity and increase crop damage especially on small beet or after a period of rapid soft growth. The advice on rates of oil to add (zero above 21°C) has been based on the maximum air temperature on the day of spraying (BBRO, 2018c)

Triflusulfuron-methyl is available as a single active (Debut, Shiro, Upbeet) or in mixture with lenacil (Debut plus, Safari Lite WSB). The straight active has always been recommended for use in a tank mix with PMP (also +/- DMP, +/- ethofumesate, +/- residual, +/- clopyralid) as it is an ALS inhibitor and this is good practise. There is limited information on the activity of the active substance alone, the original dossiers to support the registration are based on three applications of 15gms active (30gms product) in mixture with an adjuvant. This makes it difficult to isolate the exact spectrum of the active alone as the product was developed for use in combination with other modes of activity and in programmes with multiple applications. Based on commercial feedback the weeds controlled by triflusulfuron are detailed in Table 45 (S. Cranwell, Pers. comm.). It may be that triflusulfuron-methyl + ethofumesate + lenacil for example (there are other possibilities) will be a robust mix but there is little information on this without PMP.

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Table 45 Triflusulfuron activity based on treating small (cot-2 lvs) actively growing weeds.

Susceptible		Moderately susceptible	Moderately resistant
Amsinkia	Nettles (all spp)	Annual. mercury	Black-bindweed
Black nightshade	Parsley piert	Bugloss	Campion
Charlock	Redshank	Coltsfoot (S)	Chickweed
Cleavers	Scarlet pimpernel	Creeping thistle (S)	Corn buttercup
Corn marigold	Shepherds needle	Docks	Corn spurrey
Cranesbills	Shepherds purse	Field pansy	Fat hen
Field pennycress	Speedwells	Fumitory	Field bindweed
Flixweed	Spurges	Knotgrass	Grasses
Fools parsley	Vol carrot	Nipplewort	Horsetail
Forget-me-not	Vol OSR	Pale persicaria	Mugwort (S)
Groundsel	Vol parsnip	Poppy	Orache
Hedge parsley(S)	Vol potatoes	Runch/w radish	Wild mint
Mayweeds	Wild carrot	Sow thistle	

Clopyralid will continue to be a useful active for control of volunteer potatoes, thistles (*Cirsium* spp.), mayweed species (*Matricaria* spp. and *Tripleurospermum* spp.) and provide some control of black-bindweed. It has often been added to mixes but also has been used as a single active. There is a restriction that applications should be completed by end of June.

New herbicides or possible re-introductions for sugar beet in the UK

Clomazone is an active is already authorised for use in Europe. The manufacturer has reported leaf 'bleaching', and similar symptoms have been seen when the active has been used in oilseed rape. This is likely to make it unacceptable to UK beet growers.

Chlorpropham has been used in beet previously and is awaiting a decision at the Standing Committee on Plants, Animals, Food and Feed (SCoPAFF) (Anon, 2019). This active could come back into use in beet crops.

Historically tri-allate was a useful herbicide option in sugar beet, not only for grass weed control but also for some broad-leaved weeds. Gowan Crop Protection are hoping to pursue use on this crop again in the UK and as part of a larger European programme. It is likely that Avadex Factor (450CS) will be the potential product developed for the crop but timelines are unclear at the moment.

A concentrated sodium chloride solution and wetter applied to crops as a fertiliser will result in the control of weeds including volunteer potatoes.

Future action:

The availability of herbicides for broad-leaved weed control with the removal of PMP and DMP, will be limited to ethofumesate, lenacil, triflusulfuron-methyl, clopyralid, metamitron, quinmerac and dimethenamid-P. Growers will need to be informed of the most effective weed control mixtures and programmes optimising the use of these actives whilst maintaining their longer-term efficacy.

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The use of adjuvants and safeners with single actives and mixtures should be assessed to maximise efficacy and minimise crop damage particularly if PMP and DMP are withdrawn.

The importance of seedbeds being weed free at drilling by application of a non-selective herbicide, such as glyphosate should be demonstrated, although the approval of glyphosate will be up for revision on 12 December 2022. BBRO should seek active involvement in projects looking at alternatives to glyphosate.

Absence of phenmedipham and desmedipham – weeds of particular concern

PMP controls a wider range of weeds than DMP, their main strengths are black-bindweed, fat hen, charlock (*Sinapis arvensis*) and ivy-leaved speedwell (*Veronica persica*). The International Institute of Sugar Beet Research (IIRB) Weed Control Group released the following statement about the possible withdrawal of PMP in 2018: '*From our experiences weeds such as fat hen, common orache (*Atriplex patula*), black-bindweed, cruciferous weeds (*Brassicaceae*), annual mercury (*Mercurialis annua*) and amaranth (*Amaranthus*) species would become very difficult to control without phenmedipham*'.

If PMP/DMP were no longer available there is a lack of current independent information available on how well the other constituents of the mixes would perform in the absence of the main contact element and in a range of field conditions (especially with varying weather conditions). The individual components of the mixes (other than PMP +/- DMP) are rarely applied on their own post-emergence, so there is little recent field experience of their strengths and weaknesses.

Removal of PMP and DMP (HRAC group C1) would not reduce the number of HRAC groups already available B, C1, K3, N and O (Table 46), but it would change the balance of herbicides used. Increased usage of triflusulfuron-methyl (group B, ALS) and greater reliance on metamitron (Group C1) would increase the risk of exposing already resistant weeds and increase further the risk of developing resistance.

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Table 46 Common sugar beet weeds showing resistance in the UK or Europe to herbicide groups used in the UK

Common name	Latin name	B Triflusulfuron-methyl	C1 Metamitron lenacil	K3 Dimethenamid -P	N ethofumesate	O Clopyralid Quinmerac
Annual meadow grass	*Poa annua*		*E, UK*			
Black-grass	*Alopecurus myosuroides*	*UK*	*E*	*E*	*E*	
Chickweed	*Stellaria media*	*UK*	*E*			*UK*
Fat hen	*Chenopodium album*	*E*	*E, UK*			
Groundsel	*Senecio vulgaris*	*E*	*E, UK*			
Knotgrass	*Polygonum aviculare*		*E*			
Shepherds purse	*Capsella bursa pastoris*	*E*	*E*			
Sow thistle	*Sonchus spp.*	*UK*	*E*			

E – Europe, UK, United Kingdom

Future action:

Conduct a survey of weed occurrence in sugar beet fields. This could be done by asking growers to participate by leaving some small untreated areas. Weed presence could be scored, and data sent to a central point for analysis. This would provide an invaluable basis for improving the knowledge of the current and potential challenges faced by growers.

Understand the effectiveness of herbicides as single actives, products and tank mixes on a range of commonly occurring weeds (as identified in the survey). A combination of field experimentation along with more controlled container-based studies will enable a wider range of weeds and environmental conditions (such as high and low temperatures, wet and dry soil conditions) to be tested.

Assess the resistance risks of mixes/programmes based on actives with a high risk of resistance, e.g. ALS herbicides, and the importance and availability of 'modifiers' in these programmes. A range of grass and broad-leaved weeds need to be included in these assessments, together with the risks of using high risk active substances in other crops in the rotation. All three recommendations are interlinked, along with the implication of greater ALS use (4.4.4).

4.4.4. Novel and emerging technologies

Aerial imagery (satellite, aeroplane, drones) can be used to identify weedy areas and measure the response to management tactics. Unmanned Aerial Vehicle imagery has been used to identify crops and weeds in the field in sugar beet (Lottes *et al*., 2017a; Mink *et al*., 2018).

Weed control with self-propelled robots is a fast developing area. Sensing weed technology is well developed and this is being combined with a wide range of weed control measures such as lasers and herbicide spot sprays.

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The Bonirob V3 robot has been used successfully in sugar beet and can distinguish between crop plants and weeds (Lottes *et al*., 2016, 2017b). The EU Smartbot project (Suh *et al*., 2018) addressed volunteer potato control in sugar beet and detected 98% of the weeds.

Future action: Keep a watching brief on incoming technologies, liaise and interact with industry and research establishments.

Digital

The BBRO weed identification App is available on smartphones. It describes 137 broad-leaved and 35 grass weed species in sugar beet. It has an identification section which is very complicated to use and requires a good understanding of botany. The weed descriptions vary widely with some being simple but most being complicated. Photographs of weeds and seeds are included.

Future action: Simplify the BBRO weed identification App and make it more user-friendly.

Preventative weed control

Preventing ingress of weeds onto the farm is vitally important and can occur through the application to crops of manures, composts and digestate.

Machinery should always be cleaned to prevent weed seeds being moved around the farm. Contractors machines such as beet harvesters coming onto farm should also be cleaned before use.

Weeds growing in non-cropped areas should be controlled to prevent the spread of seed elsewhere.

Future action: Inform growers on all potential routes for weed infestation and issue guidance for control.

4.4.5. Genetic tools

In the near future, the main genetic tools that will be available to sugar beet growers will be ALS-tolerant varieties (as discussed below). There are also genetically modified (3.7.2) glyphosate and glufosinate tolerant sugar beet varieties grown in Canada, USA and Japan (Table 15; ISSA, 2018). Although, these varieties are not available in the UK under current legislation (European Commission, 2001), the situation could potentially change once the UK has left the European Union. If GM herbicide tolerant (HT) sugar beet were to be grown in the UK glyphosate would be able to be used in-crop for weed control. However, as discussed in section 3.7.2, GM glyphosate tolerant crops need to be used in conjunction with integrated weed management to prevent herbicide resistance (3.4.7). There is already precedent set for the evolution of glyphosate resistant weeds in GM sugar beet, for example tall waterhemp (*Amaranthus tuberculatus*) in GM glyphosate tolerant sugar beet in the USA (Heap, 2018). Although tall waterhemp is not a weed in UK sugar beet crops, the related green amaranth (*Amaranthus viridis*) is and may be more likely than other weeds to evolve

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glyphosate resistance in GM sugar beet crops. Heard *et al*., (2003b) did not identify any problem weeds in work conducted on glyphosate herbicide tolerant sugar beet in the UK.

Lutman *et al*., (2005) explored the effect of including herbicide resistant genes in sugar beet, and the movement of these genes to weeds, in particular, weed beet. They concluded that the key strategy was prevention and removal of bolting beet plants to minimise the risk of the creation of HT weed beet.

As discussed (3.7.1) there is a high risk of the evolution of ALS resistant weeds where ALS-tolerant sugar beet crops are used. CRISPR technology (3.7.3) could potentially be used in conjunction with ALS-tolerant sugar beet in the UK for gene drives to remove target site ALS resistant mechanisms. However, this technology is currently classified as genetic modification and as such is under the same regulation as GM crops. Additionally, as discussed in section 3.7.3 there are ethical issues surrounding gene drives in wild populations. CRISPR gene drives could also not be used in weed beet due to cross pollination issue with the crop.

Future action: Keep a watching brief on genetic tools, liaise and interact with industry and research establishments.

Implications and robustness of ALS tolerant varieties

Conviso® Smart is a weed control system in sugar beet comprising two components:

- Varieties tolerant to ALS herbicides
- Herbicide containing ALS inhibitors – 'Conviso® One' is the first proposed product

In spring 2016, two KWS Conviso® Smart varieties entered BBRO Recommended List trials in the three year system for testing and recommendation, both are rhizomania tolerant & one is BCN tolerant. Currently KWS have six varieties in the National list/Recommended list trial system. The first variety is anticipated to make the recommended list when the crop committee next convenes in January 2019 and should therefore be on the list for 2020 drilling season (R. Bradbury, Pers. comm.). SES Van Der Have were given access to a long-term licence for the technology in May 2017 and will produce further varieties.

The herbicide, Conviso® One, is a mixture of two HRAC group B active substances foramsulfuron (50g/L) and thiencarbazone-methyl (30 g/L). Foramsulfuron is available in the UK as a component on Maister for use in maize, thiencarbazone-methyl is available in Europe. Foramsulfuron is mainly a leaf contact herbicide whereas thiencarbazone-methyl works via leaf and soil with a residual effect.

Conviso® One is applied either as a single 1 litre/ha spray at the two-four-leaf stage of fat hen (a marker weed), or alternatively a split dose as two 0.5 litre/ha applications – the first at the two-leaf

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stage of fat hen and the next 10-14 days later. It can be applied up to the six leaf stage of weeds. It can be used in dry conditions where a longer window of residual activity may be required and soil activity lasts for 15 days (Götze *et al*., 2018). The herbicide can be mixed with other products to increase the weed spectrum controlled. Bayer are yet to receive registration for the ALS actives in the UK, this is likely to be delayed by the UK leaving the EU in March 2019.

A wide range of weeds are controlled by Conviso® One compared to a standard tank mix in sugar beet (Figure 26). Its strengths include annual mercury, perennial sowthistle (*Sonchus arvensis*) and volunteer-potato (*Solanum tuberosum*). Weaknesses include brassicas including volunteer oilseed rape, speedwells (*Veronica persica*, *Veronica hederifolia*), black nightshade (*Solanum nigrum*), sowthistle, creeping thistle (*Cirsium arvensis*) and knotgrass (Balgheim, *et al*., 2018, Stibbe & Wegner, 2017). Grass weeds were well controlled with Conviso® One performing much better than the standard tank mix (Balgheim, *et al*., 2018, Figure 27).

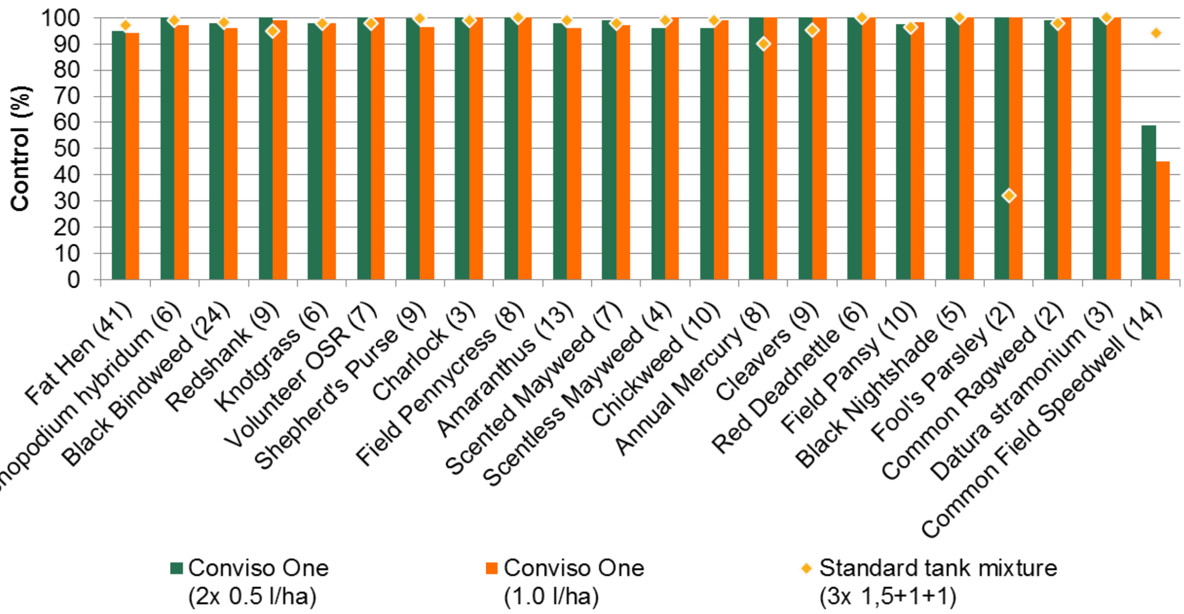

Figure 26 Weed species controlled by Conviso® One as either a single or split application compared to a standard tank mixture (3 applications of 1.5 l/ha Betanal maxxPro + 1 l/ha Goltix SC/WG/Gold + 1 l/ha Mero (wetter). 53 European trials. Number in brackets is the number of trials conducted. Source: Bayer

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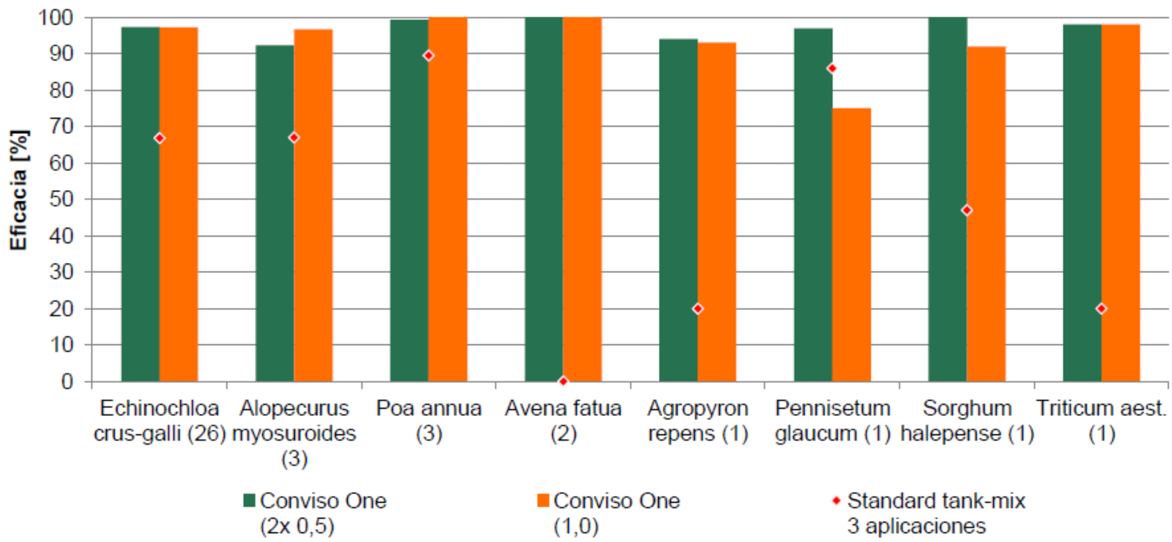

Figure 27 Grass weed species controlled by Conviso® One as either a single or split application compared to a standard tank mixture (3 applications of 1,5 l/ha Betanal maxxPro + 1 l/ha Goltix SC/WG/Gold + 1 l/ha Mero (wetter). 53 European trials. Number in brackets is the number of trials conducted. Source: Arcones (2017)

Conviso® Smart system will allow control of non-ALS tolerant weed beet. Stewardship will need to include the control of bolting ALS tolerant sugar beet to prevent ALS tolerant weed beet becoming established as a problem.

The crop following harvest of a Conviso® Smart sugar beet crop and planted in autumn of the same year will have to be winter wheat. In the following year peas, field beans, conventional sugar beet, spring barley, spring wheat, soya, spring oilseed rape (wait one year), potatoes (wait one year), mustard (as green manure) winter oilseed rape can be grown (Stibbe & Wegner, 2017).

Implications on weed beet

Introduction of the Conviso® smart varieties and associated herbicides will offer an opportunity to grow sugar beet in fields with a high burden of weed beet. The wide application window allows late germinating beet to be controlled. A similar system introduced in oilseed rape (Clearfield®) comprising of an ALS tolerant variety and herbicides containing imazamox have allowed oilseed rape to be grown on land with a high burden of brassica weeds and volunteer oilseed rape. In the Conviso® smart system long-term reduction of weed beet seed bank is possible, but only if new bolters are prevented or subsequently pulled and removed from the field. This was identified as a key management change to be made when Lutman *et al*., (2005) considered the introduction of glyphosate tolerant beet into the rotation. Weed control strategies need to be increasingly crop rotation-oriented and practical solutions should be promoted to control volunteers. Control of volunteer crop plants needs to be included in a stewardship programme.

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Implications for resistance

The use of the Conviso® One herbicide alone to control weeds would result in increased selection pressure on a wide range of weeds. The use of a single herbicide over the landscape for an extended period will change the weed flora, and increase the selection of herbicide-resistant weed biotypes (Lamichtane *et al*., 2017). Resistance to ALS herbicides has already been recorded in several common weeds in UK arable crops (Table 47) and is seen in a wider range of weeds in Europe that also occur here. Currently there is only a single group B herbicide (ALS inhibitors), trisulfuron-methyl, authorised for use in sugar beet.

Increased reliance on a single mode of action herbicide group increases selection pressure and could lead to the increased level of resistance in a wider range of species. The use of a post-emergent ALS inhibitor herbicide alone was always the weakest treatment with the lowest amount of control of known resistant poppy populations (Tatnell, *et al*., 2017). Grass weeds occur in low numbers in sugar beet and resistant broad-leaved weeds occur in hotspots. However, occurrences of herbicide resistance in broad-leaved weeds in the UK are probably under reported. The same species of weeds do occur in both sugar beet and winter wheat within the rotation (Figure 28), and with the increase in the area of spring cereals a greater number of spring germinating weeds are likely to be encountered.

Table 47 Weeds occurring in UK rotations with resistance to ALS herbicides (HRAC group B)

Common name	Latin name	Europe	UK
Black-grass	*Alopecurus myosuroides*	✓	✓
Chickweed	*Stellaria media*	✓	✓
Common poppy	*Papaver rhoeas*	✓	✓
Fat hen	*Chenopodium album*	✓	
Groundsel	*Senecio vulgaris*	✓	
Italian ryegrass	*Lolium multiflorum*	✓	✓
Meadow and rye brome	*Bromus*		✓ *(suspected)*
Oilseed rape	*Oilseed rape (Clearfield®)*		
Perennial ryegrass	*Lolium perenne*	✓	
Scented mayweed	*Matricaria recutita*	✓	
Scentless mayweed	*Tripleurospermum inodorum*	✓	✓
Shepherds purse	*Capsella bursa pastoris*	✓	
Sow thistle	*Sonchus spp.*	✓	✓
Sterile brome	*Anisantha sterilis*	✓	✓
Wild-oat	*Avena fatua*	✓	✓
Winter wild-oat	*Avena sterilis*	✓	✓

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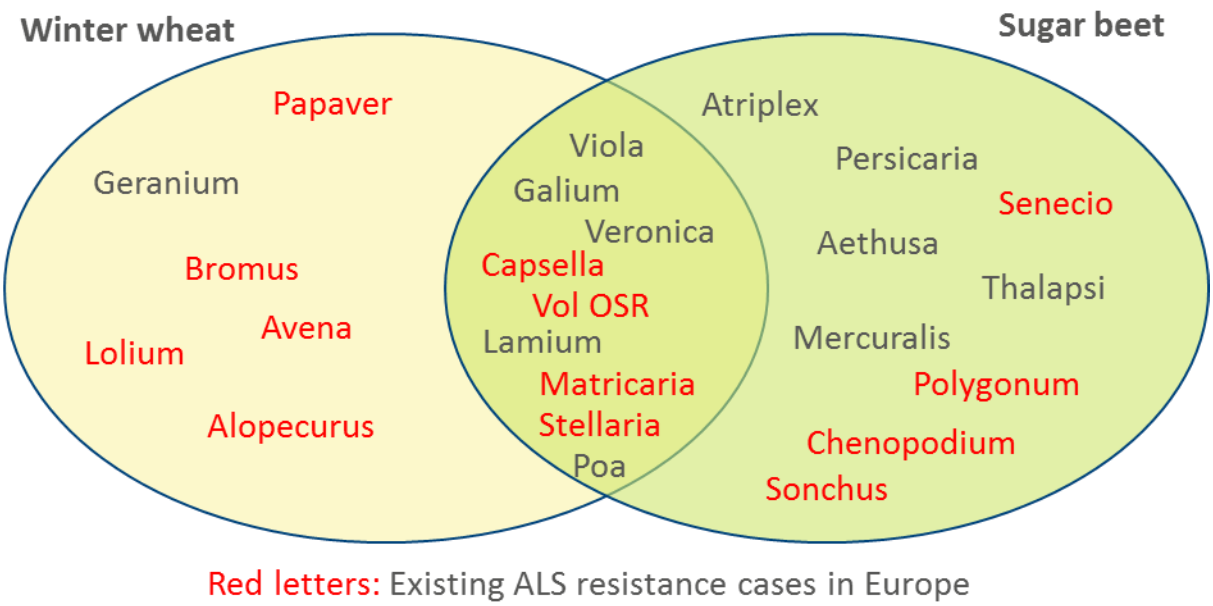

Figure 28 Overlap of the major weed species found in winter wheat and sugar beet, indicating those where ALS resistance is known (Adapted from Collavo *et al*., 2017)

Beckie *et al*., (2008) showed that growers who included three or more crop types on their farm had significantly less incidence of herbicide resistant weeds compared with those that grew less than three. Tatnell *et al*., (2017) showed that a non-ALS programme gave the highest control of both ALS-resistant and susceptible poppy populations, which in turn reduced the risk of selecting for herbicide resistance. Therefore improving crop diversity and changing herbicide strategies to lower risk options slowed the further development of herbicide resistance. Herbicide tolerant crops are most effective and sustainable as a component of an integrated weed management (IWM) system (Lamichtane *et al*., 2017). IWM uses a combination of cultural and chemical control options to manage weeds. A stewardship programme will be necessary and is planned following proactive weed resistance management strategies (Conviso® Smart, 2018; Stibbe & Wegner 2017): This will:

- Use agronomic measures to:
  1. Ensure high efficacy to avoid weed seed production
  2. Keep the soil weed seed bank at a low level
- Cultivate soil to a minimum of 10 cm after harvest of the preceding crop
- use a non-selective herbicide before sowing if necessary
- use a cover crop to reduce weed pressure if possible
- Adopt a varied crop rotation
- Rotate different herbicide mode of actions: Use at least one non-ALS inhibiting herbicide pre-emergence or early post-emergence herbicide active on grasses and dicotyledonous weeds in a 3-year crop rotation containing winter cereals.
- Use the full dose rate to achieve complete kill.
- Use the herbicide at the appropriate recommended growth stage of the weeds

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- In difficult conditions e.g. drought, use appropriate mixing partners to ensure maximum weed control.

Additionally measures need to be taken to guide farmers in optimising the use of this valuable new technology.

In the UK there is a high risk that ALS-resistant black-grass could be present in sugar beet fields. Herbicide resistant black-grass occurs on the majority of 20,000 farms where herbicides are used routinely for its control (Hull *et al*., 2014). In 2013 all three types of resistance were shown to occur in approximately half the samples assessed (Figure 29). Herbicide-resistant Italian ryegrass occurs on >475 farms in 33 counties of England covering the major beet growing areas, the main mechanism is enhanced metabolism but target site resistance to group A and B has been recorded (Hull *et al*., 2014). In wild-oats the occurrence of resistance is lower with resistance being recorded to HRAC groups A and B (Hull *et al*., 2014). Increasing tolerance to ALS herbicides has been recorded in *Bromus* species (L Davies, Pers. Comm.).

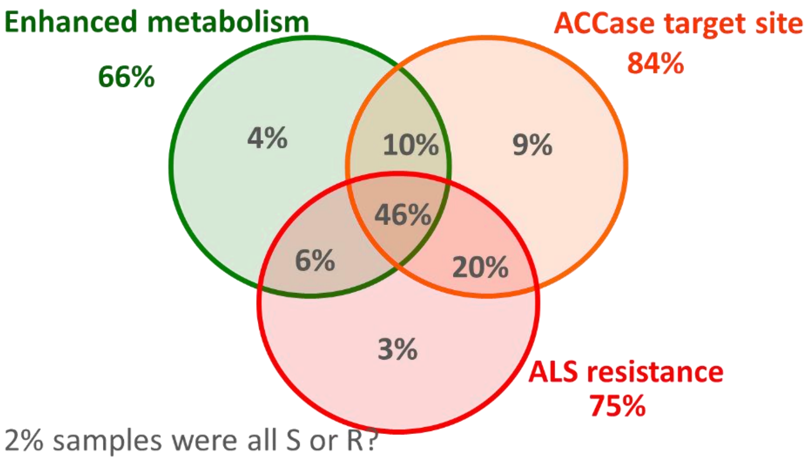

Figure 29 Proportion of black-grass samples that were resistant (RR or RRR). A total of 122 non-random populations, collected in 2013, were tested (Hull *et al*., 2014).

With resistance to group B being recorded in all commonly occurring grasses the reliance on a single herbicide with a single mode of action to control a wide range of weeds is a method that will efficiently select for resistance. The range of graminicides available in sugar beet is limited to mainly group A herbicides (ACCase which includes the 'fops' and 'dims') (Table 48). As there is already resistance to group A in black-grass, Italian ryegrass and wild oat, control will be compromised. The use of group A herbicides is also restricted to a single use of any one product in a season, a further application can be made of a different product aimed at different weeds, and this is to reduce the development of resistance. Ethofumesate has been shown to be effective for black-grass control both pre- and post-emergence. Whilst metamitron offers some activity pre-emergence it is more effective when applied post-emergence. Both these actives should not be relied upon to control grass weeds alone as the levels of control are low. The effectiveness of these chemicals will be affected

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by EMR resistance. Ethofumesate is also authorised for use on winter wheat and herbage seed and this offers a further complication as its usage is restricted to a maximum total dose not exceeding 1.0 kg/ha ethofumesate in any three year period.

Triflusulfuron-methyl (Debut/Shiro) has been shown to have some effects on black-grass when used in combination with Betasana Trio (phenmedipham + desmedipham + ethofumesate) (UPL, 2014).

The IIRB Weed Control Group stated that ‘without PMP and DMP, the new ALS system will lead to selection of resistance to ALS inhibitors in a range of weed species. The use of PMP and DMP is necessary for resistance management and could fill in a few gaps in the efficacy spectrum of the proposed ALS product’.

Table 48 Pre- and post-emergence grass weed control in sugar beet

Active Substance	HRAC group	Black-grass	Bromes	Italian ryegrass	Wild oat	Annual meadow grass
Clethodim	A	S	S	S	S	S
Cycloxydim	A	S	S	S	S	R
Ethofumesate	N	S	MS	R	MS	S
Fluazifop-P-butyl	A	S	S	S	S	NC
Metamitron post	C1	S	NC	NC	S	S
Metamitron pre	C1	MR	NC	NC	R	S
Propaquizafop	A	S	S	S	S	MS
Quizalofop-p-ethyl	A	S	S	S	S	NC
Quizalofop-P-tefuryl	A	S	NC	S	S	NC

S = Susceptible MS = Moderately susceptible MR = Moderately resistant R = Resistant NC = No claim of control (Taken from BBRO, 2018b)

Future action:

In Conviso® Smart sugar beet the control of ALS resistant grass weeds such as black-grass and broad-leaved weeds such as fat hen will be high risk. Reliance on Conviso® One alone will expose the populations to post-emergence applications of Group B herbicides. Mixtures with chemistry from other groups are necessary due to potential cross-rotation resistance issues to ALS chemistry. ALS herbicides are widely used in most other crops in the rotation including Clearfield® OSR. The proposed stewardship programme may include both mandatory and recommended practices but additional support for growers is necessary. This should include:

- Education programs to maintain and improve knowledge of weeds and their management describing implementation and integration of weed management practices, which may include diversification of crop systems, cultivations, use of cover crops, stubble management and stale seed beds, zero tolerance for weed escapes in some crops, and herbicide resistant weed management strategies.
- Development of the stewardship programme with Bayer including development of best management practices, on-farm demonstrations, grower and advisor education and awareness

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of longer term risks where herbicide resistant weeds are most likely to evolve. This should cover all available herbicides.

There is a lack of information in UK conditions of the efficacy of Conviso® One and the following questions need to be answered:

- How robust are two applications for season long weed control across all soil types for all weed species?
- What will happen on soils which continually produce weed flushes late into the season, or where summers are wet?
- How robust is volunteer potato control especially control of daughter tubers?
- How effective are mixtures and programmes of foramsulfuron and thiencarbazone-methyl (Conviso® One) with other actives such as PMP, DMP, metamitron, ethofumesate, lenacil and Clopyralid? Also how effective are mixtures and programmes without PMP and DMP. There is much that can be learned through desk review and previous work which should be used to test a narrower range of sugar beet specific scenarios.

4.4.6. Summary of future actions

Short-term

- The availability of herbicides for broad-leaved weed control with the removal of PMP and DMP, will be limited to ethofumesate, lenacil, triflusulfuron-methyl, clopyralid, metamitron quinmerac and dimethenamid-P. Growers will need to be informed of the most effective weed control mixtures and programmes optimising the use of these actives and to maintain their longer-term efficacy.

- The use of adjuvants and safeners with single actives and mixtures should be assessed to maximise efficacy and minimise crop damage particularly if PMP and DMP are withdrawn.

- BBRO and the agrochemical and biopesticide manufacturers should work together to support the introduction of new herbicide active substances and for the crop such as clomazone, chlorpropham and tri-allate. Sugar beet is classed as a major UK crop and generally not eligible for Extensions of Authorisation for Minor Use (EAMU) authorisations (in accordance with Article 51 of Regulation (EC) 1107/2009) (CRD, 2019). BBRO should consider whether this is an approach that levy payers would support and benefit from.

- Conduct a survey of weed occurrence in sugar beet fields. This could be done by asking growers to participate by leaving some small untreated areas and collating data on weed presence. This would highlight the potential challenges being faced by growers.

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- Simplify the BBRO weed identification app and make it more user friendly

- Inform growers of all potential routes through which weeds can infest a farm and issue guidance on preventative measures.

- The recent withdrawal of neonicotinoid seed dressings has led to growers increasingly asking about mixing insecticides with herbicides. There is a lack of information in this area particularly regarding the required water volumes and potential crop damage.

- There is a lack of information in UK conditions of the efficacy of Conviso® One, the following questions need to be answered:
    - How robust are two applications for season long weed control across all soil types for all weed species?
    - What will happen on soils which continually produce weed flushes late into the season, or where summers are wet?
    - How robust is volunteer potato control especially control of daughter tubers?

    - Assess the resistance risks of mixes/programmes based on actives with a high risk of resistance, e.g. ALS herbicides, and the importance and availability of 'modifiers' in these programmes. A range of grass and broad-leaved weeds need to be included in these assessments, together with the risks of using high risk active substances in other crops in the rotation.

Medium term

- Understand the effectiveness of herbicides as single actives, products and tank mixes on a range of commonly occurring weeds (as identified in the survey). A combination of field experimentation and container-based studies will enable a wider range of weeds and environmental conditions (such as high and low temperatures, wet and dry soil conditions) to be tested.

- Evaluate minimal cultivation systems such as direct drilling and strip tillage for establishing sugar beet and assess their effects on weed populations

- Evaluate the use of a cover crop prior to sugar beet for weed suppression.

- Evaluate varieties in existing variety trials for competition against weeds by excluding herbicides from small areas.

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- Evaluate camera or RTK guided inter and intra-row mechanical weeding combined with and without band spraying

- The importance of need to start clean at drilling by application of a non-selective herbicide, such as glyphosate should be demonstrated, although the approval of glyphosate will be up for revision on 12 December 2022. BBRO should seek active involvement in projects looking at alternatives to glyphosate.

- Keep a watching brief on genetic tools, liaise and interact with industry and research establishments.

- Control of ALS resistant grass weeds such as black-grass and broad-leaved weed such as fat hen in Conviso® Smart sugar beet will pose major risks and weed populations will be exposed to post-emergence applications of Group B herbicides. Mixtures with chemistry from other herbicide groups is necessary to minimise potential across rotation resistance issues to ALS chemistry. ALS herbicides are widely used in most other crops in the rotation including Clearfield® OSR. The proposed stewardship programme may include both mandatory and recommended practices but additional support for growers is necessary. This will include:
    - Education programs to maintain and improve knowledge of weeds and their management describing implementation and integration of weed management practices, which may include diversification of crop systems, cultivations, use of cover crops, stubble management and stale seed beds, zero tolerance for weed escapes in some crops, and herbicide resistant weed management strategies.
    - Development of the stewardship programme with Bayer including development of best management practices, on-farm demonstrations, grower and advisor education and awareness of longer term risks where herbicide resistant weeds are most likely to evolve. This should cover all available herbicides.

Long term

- The use of intercropping should be monitored in other crops and considered for use in sugar beet as more information becomes available.

- Keep a watching brief on thermal weed control methods as they develop. This is most likely to be in combination with guided weed control systems or robots.

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4.5. Grassland

In all grassland and pasture (upland, short-term or permanent), weed control is essential particularly of perennial weeds. In all these systems once perennial weeds are established, control becomes more difficult as they often spread and create more of a problem, taking time, effort and money to resolve (IBERS, 2013).

Grassland management will always require a period of reseeding to ensure the sward remains productive. This can be completed by two methods: complete destruction and creation of a new ley, or overseeding. Results of an AHDB survey in 2016 led to a 'Grassland reseeding guide' (AHDB, 2016b). This document is a practical guide to re-establishing grassland, including a pasture improving decision scheme and weed control advice. In all systems, ensuring competitive seedling establishment and reducing the opportunity for weed establishment and spread is essential.

Key weeds within grassland systems:

The AHDB reseeding survey results reported that the top five problematic weed species before reseeding were thistles (36%) (*Cirsium* spp.), docks (*Rumex* spp.) (26%), buttercups (*Ranunculus* spp.) (15%), chickweed (*Stellaria media*) (11%), and nettles (*Urtica* spp.) (9%) (AHDB, 2016b).

Creeping thistle (*Cirsium arvense*) and spear thistle (*Cirsium vulgare*) are also both listed as injurious species in the Weeds Act (1959). Creeping thistle spreads mainly by underground creeping rhizomes, whilst spear thistle has a tap root and spreads by seed (SRUC, 2014). There is a comprehensive guide to controlling creeping thistles by non-chemical methods in the FIBL & ORC Technical guide by Dierauer *et al*., (2016).

Docks are one of the most problematic species in grassland (SRUC, 2014) and are listed in the Weeds Act (1959), so control is required by the landowner. They have a large tap root and produce a large amount of seed if left uncontrolled. The seed will readily germinate at any time of the year when the opportunity arises, as docks exploit bare areas and can tolerate trampling by livestock. Dierauer (2018) provides a detailed review of dock control.

Although not mentioned in the AHDB reseeding survey bracken (*Pteridium aquilinum*) is very competitive weed and is widespread on neutral to acid soils (ADAS, 1980). Its vigorous growth and dense foliage shade out other vegetation (Pakeman & Marrs, 1993). It has extensive persistent rhizome systems that can grow deeply and extend laterally several feet a year (ADAS, 1980). Additionally, dense litter builds up under bracken and this prevents most other vegetation from establishing. Stewart *et al.,* (2005), reviewed available methods for bracken control.

The biology, management and control of a wide range of perennial weeds is detailed in a review document as part of a Defra-funded research project (Defra, 2008). The review document also

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contains details of European organic projects on perennial weed management. The voluntary initiative has also produced a detailed control method for each weed type in grassland, including docks and thistles.

Weed control when establishing a new ley or reseeding will be discussed separately within this section. Upland grassland, which in this review will be regarded as permanent grassland, will be covered as an additional sub-topic.

4.5.1. Cultural control

Rotations

Rotational weed management is only applicable to short term grassland within a crop rotation, and excludes permanent grassland and upland areas. A break crop, like stubble turnips or kale, can be used to avoid a grass-to-grass reseed, however any weed control benefits from this are incidental as the main use of break crops in grass rotation is to break any pest lifecycles and also provides useful additional feed (AHDB, 2016b).

The AHBD reseeding survey (AHDB, 2016b) found that only about 8% of reseeds were following brassicas. The three most common previous crops were permanent grass (33.3%), cereals (21.6%) and temporary grass (17.1%).

Tillage and cultivations

Ploughing and deep cultivations

The standard practice of ploughing 20 cm deep and cultivating when establishing grassland results in inversion of mature docks with stem, crown and root. Burying the docks with regular ploughing weakens the plants, but will not kill them, and regrowth will occur (Dierauer, 2018).

The regenerative potential of creeping thistle after cultivation depends on the nutrient reserves in the roots (Dierauer *et al*., 2016). The higher the amount of reserve material, the greater the re-sprouting potential. The content of reserve material in thistle roots follows a seasonal cycle, with a low point in spring after sprouting (Figure 30). As a result, spring ploughing is significantly more damaging to thistles than in autumn or winter.

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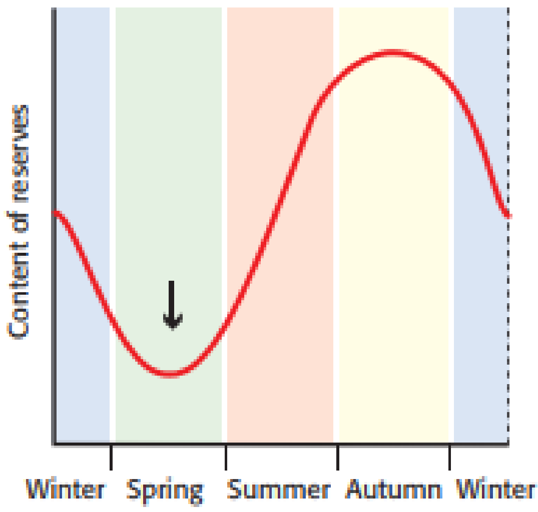

Figure 30: Yearly profile of thistle energy reserves. Source: Dierauer *et al*., 2016

Natural England (2008) advise that on suitable areas, bracken cover can be significantly reduced by ploughing between late June and early August. Inverting deep furrows exposes bracken rhizomes over winter, for control prior to a spring sowing. Deep tine cultivation in two directions has been used to successfully controlled bracken without ploughing (Natural England, 2008). In new British woodland, only deep ploughing is effective for bracken control, and costs 150-600 €/ha, compared to herbicide costs of 150-1500 €/ha (Willoughby *et al.*, 2009). However, as some regeneration will occur, so a follow-up programme using alternative control methods must also be used.

Ploughing and deep cultivations are advisable for grassland in rotation, especially on flat and shallow land. It is not feasible on permanent pasture unless severe weed infestation is found, and the land is not restricted by legislation. Furthermore, the use of heavy machinery is not possible in many marginal and upland areas. For these areas, alternative mechanical control should be prioritised.

Shallow cultivation

One extremely effective method for restoring highly dock-infested pasture land is by using some form of cultivation that cuts the crown off the weed and brings the roots onto the soil surface where they dehydrate. Repeated shallow cultivations will bring the dock crowns to the soil surface, knock off attached soil, disturb and desiccate the plants and finally kill them. It may require six to eight weeks to adequately dry out the dock crowns. Dry weather in summer is essential for such a dock treatment in the UK. Such intensive 'fallow' treatment must be followed by a competitive crop to avoid re-establishment of docks (Dierauer, 2018).

Cover cropping and allelopathy

Evidence suggests that some grassland weeds, such as musk thistle (*Carduus nutans*), inhibit desired forage species through allelopathy (Wardle *et al.,* 1993, 1994, 1996).

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Buckwheat appears to have an allelopathic effect on mature docks, significantly reducing their vigour (Dierauer, 2018), which could be utilised within a grassland rotation. However, in a thorough review of allelopathy in grassland by Da Silva *et al.,* (2017) no information could be found regarding whether allelopathy had been considered in the management of pastures, as well as in restoration of grasslands.

Crop cultivars and mixes

Choosing the correct seed mix, for a specific location, soil type and water availability is critical for establishing and maintaining grasslands. This will ensure limited damage to soil structure, avoid bare patches and overgrazing risks, which would allow the competitive nature of weeds to dominate and reduce the chance of a successful ley establishment. For example; the grasses fescue and timothy can grow at low temperatures, so are more competitive in an upland environment (AHDB, 2015a). Additionally, clovers are predominantly winter active, and compliment many grassland seedlings and reduce bare patches. A study by Tracy *et al.,* (2004) found consistent negative relationships between forage species diversity and weed abundance. The results suggested that maintaining both productive pasture communities (>150 g/m of above ground biomass) and an evenly distributed array of forage species should be combined to effectively reduce weed invasion.

IBERS (2013) and AHDB (2015) provide detailed information and advice for selecting crop varieties.

Cultural weed control in new leys

There are two main timings to re-sow or establish new leys in the UK, autumn (August to October) and spring (March to May), with advantages and disadvantages to both (Table 49). The best method is ploughing deeply to bury surface trash and then reseeding, however with modern varieties it is possible to use direct drilling or under sowing methods with minimal cultivations. Prior to ley seeding and during ley destruction, repeated deep cultivation can be used to destroy the root systems of thistle, docks, nettles and bracken, if these have been a problem previously (IBERS, 2013). This system is most effective when roots are collected to prevent regrowth.

Table 49: Advantages and disadvantages of establishing new leys in the autumn or spring (Dow AgroSciences, 2018a)

	Autumn	**Spring**
Advantages	Minimal impact on grazing as land not taken out of production at peak growth times. Seedbed has time to settle over winter, allowing good structure to form. Good weed control if done early and you catch weeds when they are still actively growing.	Higher probability of good conditions for establishment. As grass is actively growing it can better out-compete weeds. No heading in first season.

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Disadvantages	Significant weed competition from late reseeds. Narrower window for good establishment.	Losing peak growth by taking field out of production at this time. Soil does not have time to settle before carrying stock.

A good firm seedbed is needed for grass seed establishment. The soil surface can be rolled to achieve this as a fluffy surface is not ideal and will result in poor establishment. There is a high economic investment required so it should be done properly to ensure the return on investment is realised in the shortest time scale.

There are a number of aspects that influence the establishment of a grass ley including weed control, nutrient and water availability and variety choice. When creating a new ley, soil disturbance allows the opportunity for seedlings from within the seed bank to emerge. Weeds will immediately compete with the emerging grasses and many annual broad-leaved weed species such as chickweed and mayweed and grass weeds such as annual meadow-grass can be very vigorous at inhibiting grass growth and resulting in a less productive sward (SRUC, 2014). Chickweed is especially troublesome in new leys, and can reduce ryegrass content by 50% (IBERS, 2013). Chickweed is spread by seed, and can complete up to six life cycles in one year, with the potential to flower every month of the year (Grime *et al*., 1988).

AHDB (2015) recommend the following cultural practices to manage the risk of weeds competing with new leys:

- Graze with young cattle soon after establishment to reduce the first flush of weeds. Cattle are advised as they are not selective feeders and will not leave seedlings too short.
- Graze well before winter to avoid winter kill which leaves bare patches for weeds to establish.
- Use clover to help reduce bare ground in which weed seedlings can grow.
- Create a dense sward by combining sowing rates and variety selection to help prevent dock establishment as the seeds of this weed are dependent on light to germinate.
- Combine a mix of cutting and grazing.
- Avoid over grazing, as damaged tillers will reduce grass competitiveness.
- Avoid soil compaction (and reduced grass competition) to help discourage docks.
- Prevent the relocation of nitrogen into lower soil layers with the cultivation of catch crops or well-established winter crops. Replace failed catch crops and avoid bare fallow (Dierauer *et al*., 2016).

Cultural control in existing pasture

Although prevention is the most effective measure against perennial weeds, once grassland has established, it is important to target weeds as they inevitably build up over time.

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Focus on preventing established weed spread (AHDB, 2015a) by:

- Monitoring weed establishment.
- Removing stock in wet conditions to avoid poaching (where docks can thrive).
- Mixing cutting and grazing.
- Avoiding over grazing, as damaged tillers will reduce grass competitiveness.
- Using clover to help reduce bare ground where weed seedlings can grow.
- Creating a dense sward by combining sowing rates and variety selection to prevent germination of dock seeds that are dependent on light to germinate.
- Avoiding soil compaction (and reduced grass competition) will help discourage docks.
- Over seeding where necessary.

Spread of creeping thistles, which becomes a problem as the ley ages, are most effectively prevented by frequent competition for light, nutrients and water. This can be achieved by balanced crop rotations, water-permeable soils, dense plant stocking, and frequent mowing for forage production.

If rushes have developed within existing or long term pasture, this is a sign of poor drainage or low soil pH (AHDB, 2013) and can be improved by liming or improving drainage (mole ploughing). In a report, exploring upland hay meadows for biodiversity (Pinches *et al*., 2013) it was concluded that further research is required to determine why populations of rush species have increased in upland hay meadows.

Future actions:

- Further work is needed on grassland management especially in upland areas, where soil improvement and herbicide application to ferns/rushes is key to competitive grass establishment.

Cultural control- uplands

Upland grasslands offer challenging conditions for grass to establish. Air temperatures are low, and the length of the growing seasons are short. Coupled with this, annual rainfall tends to be high, and soil quality poor because of leaching. As a result, weeds have more opportunity to establish, if hardy, and can compete with newly seeded grass.

AHDB (2015) suggest the following cultural controls to promote grass seedling competitiveness in upland areas:

- Variety selection- focus on varieties with winter hardiness and the ability to grow at low temperatures e.g. fescues and timothy.

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- Soil management- as upland permanent grazing tends to be on poorer acidic soils prone to leaching; lime and phosphate deficiencies can limit seedling growth. Spring applications of nitrogen fertiliser can promote rapid growth, however this is highly dependent on soil temperature, and ensuring the ground is not too wet (limit compaction).
- Timing of re-seeding is possible only in late spring (April –May) or late summer (July-August) due to risk of new seedlings to frost.
- Avoid overgrazing- exposure of bare ground and poaching will promote perennial weeds.

As well, as challenging growth of grass seedlings, the steep terrain, presence of rocks and soil conditions limit some management practices (especially the use of heavy machinery) and in extreme cases make them totally impractical.

Furthermore, the importance and dominance of some weeds increases, for example bracken, which reduces the quantity and quality of forage area.

4.5.2. Non-chemical control

Manual removal of weeds

In permanent pastures with a weak proliferation of docks, digging out and tilling is the most effective control method (Dierauer, 2018). The ideal time for single plant control is at the dock's rosette stage (Farming connect, 2019). From the 5-6 leaf stage onwards, docks cannot be controlled by grazing or competition from pasture grasses. It is possible to remove 90-150 weeds per hour, and if this is done properly about 90% of these will be killed (Dierauer, 2018).

Hand rogueing is a useful way of controlling weeds which are poisonous to livestock, such as ragwort, where complete removal is necessary. However, these weeds have long taproots so there is the risk of leaving some of the root system in the ground (especially in dry conditions) from which weeds can regenerate.

Hand pulling as part of a bracken control strategy, is rarely used as it is very labour intensive. Nevertheless, hand pulling can be an effective control strategy for smaller patches of bracken and should not be completely discounted (SNH, 2014).

Mechanical weeding

Harrowing/hoeing

In new lays, harrowing in the autumn and sowing grass/clover seed to fill gaps will prevent chickweed establishment (Farming Connect, 2019). If thistles are the dominant weed a hoe should be used instead of harrow to avoid cutting and spreading rhizomes Dierauer *et al*., (2016), as this will spread the problem further within the field.

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Dock twirler

The Swiss 'dock twirler' is a further development of the German dock-tiller (model MEV). Three contra-rotating spiral-shaped spikes clasp the dock 30 cm deep (Dierauer, 2018). The machine pulls the dock plant out of the ground and the root is then separated by hand from the attached soil (about 0.8 kg). The machine must be mounted to a 1.6 t heavy (small) excavator or yard loader. More than 90 % of docks can be achieved with careful execution and it is possible to remove 120–180 plants per hour. No re-growth of the dock plants is found. This is therefore as effective as and quicker than hand pulling. However on slopes, the use of the dock twirler is restricted.

Future actions: Examine the potential of dock twirler' in horticulture, as the appearance of remaining plants would not be effected, however impact on rooting systems would need to be accessed.

Crushing and treading by livestock

Bracken can be partially controlled by crushing using all-terrain vehicles and rollers. Natural England (2008) advise that, if used, this technique should be completed twice yearly or can be used as a follow up on areas treated with herbicides. Special bracken crushing rollers fitted with deep cross-ribs (e.g. Cuthbertson, Holt), or purpose built machines (e.g. Landbase, Bracken Bruisers) may be available locally.

Additionally, winter-feeding can be used to attract livestock onto bracken sites so that weed buds and developing fronds are damaged by stock treading (cattle are more effective than sheep) and the litter is disturbed and broken up which encourages frost penetration to the rhizomes. This is not a reliable method but can help damage surviving fronds as a follow-up on sprayed areas (Natural England, 2008). Rushes can also be partially controlled by livestock treading (AHDB, 2013).

Mowing and cutting, for weed seed control

Weed surfer methods could be used for all taller weed species. Topping before plants can flower and set seed helps control thistles, docks, buttercups, bracken and nettles. Topping reduces the spread of thistles and nettles, however, they may still spread via roots (AHDB, 2015a). Topping will not control chickweed because the plants flower close to the ground. Ragwort should never be topped where livestock are grazing as it increases palatability of the weed (IBERS, 2013).

Bracken cannot be controlled by cutting alone. However, cutting twice in a season can weaken rhizomes and allow grazing. Some areas (steep terrain and where boulders are present), are not suitable for cutters (Natural England, 2008).

As a method, cutting would need to be incorporated into an IWM system to achieve the best overall weed control. However, it is effective for reducing the energy stored within tubers and rhizomes and

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limiting the spread by seed, which could increase the success of alternative methods, especially where non chemical options are required.

Thermal, electrical, flame, hot water and hot foam

Electrical weeding

ADAS investigated the weed control efficacy of an electric weeder in the amenity sector, field vegetables and blackcurrants for the control of common nettle, broad-leaved dock and creeping thistle. All of these are problematic weeds for grassland. The method was found to be effective; and a 1.3 m tall creeping thistle touched by the probe in the middle of the stem, took 25 seconds to be killed. For a broad-leaved dock at 1.5 m tall, the comparable time to kill the weed was 34 seconds (ADAS, 2014b).

A hand held lance could be used instead of a knapsack sprayer and the height differential between mature (flowering) weeds and grassland would be suitable for a tractor mounted set-up. Furthermore, it was highlighted that as much of UK grassland occurs in high rainfall areas near reservoirs and watercourses, the use of an electrical weeder would also contribute significantly to a reduction in pesticide leaching. This offers a practical solution to tackling troublesome grassland weeds.

ADAS (2014a) completed an economic assessment of electric weed control for grassland. It was concluded that it could be used for the control of perennial weeds such as thistles, docks and nettles as these appear as discrete patches or as single plants. Further research is therefore required.

Future actions: Investigate the use of electrical weeding on perennials in grassland, including effective long term usage and quantification of root damage. Electrical weeding could be a useful component of an IWM strategy.

Steam/hot water

The machine for the application of hot water and steam to dock plants was developed by Agroscope in Switzerland (Dierauer, 2018). A hot water – steam mixture of 90–95°C is applied around the dock root with a rotary nozzle for at least 10 seconds. The contact with the hot water kills the root to a depth of about 12 cm and seeds in the immediate vicinity are also killed. The technique is about 80 % effective and most successful in dry soil. It is possible to control 120–180 plants per hour but this method leaves 4 cm small holes in the ground.

Hot water/steam treatment is quicker but slightly less effective than hand weeding but does have the benefit of killing seeds within the immediate of the target weed. With further research, this method could be a realistic replacement for spot treatments in grassland.

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Controlled burning can be used, at the appropriate time of year (winter months), to manage gorse and broom. Moorland burning is used to manage heather by removing older material and competitive grasses (B. Hunt, Pers. Comm.) provided appropriate muirburn legislation is complied with.

Future action: A comparison of hot water/steam techniques with electrical weeding should be done to investigate which is likely to be most effective as a spot treatment.

Freezing

In a study by Mahoney *et al., (*2014) field and greenhouse experiments were conducted to evaluate the use of liquid carbon dioxide to freeze weeds within turf. They found that annual weeds (such as chickweed and cleavers) were better controlled than perennials. Freezing affected turf grass growth with all species tested showing >30% damage. However, no damage was recorded at 28 days after treatment so grass plants were able to recover. It was finally concluded that liquid carbon dioxide does have potential to be used as an alternative method of weed control.

Future actions:

- As bracken is not tolerant of hard frosts, it would be worth investigating the use of liquid carbon dioxide is an alternative control method.
- The efficacy and cost of freezing should also be compared with other cultural methods of weed control.

Biological Control

Dierauer, (2018) reviewed the biological control for docks (Table 50) and Bond & Turner (2004) reviewed animal control (Table 51).

Table 50: Biological control of docks using fungi, insects and livestock (Source: Dierauer, 2018)

Control	**Mode of operation**	**Effect/performance**	**Suitability as a method**
Fungi	Rust and leaf-spot fungi attack the dock's leaves and can weaken the plant	*Uromyces rumicis* (a rust fungus) can reduce the weight of plant stems and leaves by 30–50% given artificial infection. *Ramularia rubella* (*septoriosis*) results in the leaves dying. It can reduce the roots' weight by up to 50 %	The fungi are not UV-stable and can easily be washed off the dock plants. Their potential for dock control is therefore rated as low

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Fiery clear wing moth	Fiery clearwing (*Pyropteron chrysidiforme*) can cause the dock to die. The moths lay eggs on the plants and the larvae feed on the roots.	In Europe, infestations of up to 80 % of plants were observed in field tests. But in general, the performance has not been convincing so far	The method is still being developed and practical trials are underway.
Dock beetle	Larvae feed on dock leaves. A single beetle eats 3 to 5 cm^2 of leaf surface per day.	With three to four generations per year, the beetle can completely skeletonise and weaken dock plants. The beetle only occurs in permanent pastures. However the beetle cannot kill dock plants.	Strategies have been developed for promoting the dock beetle in permanent pastures such as delaying cutting until the larvae have buried themselves in the soil to pupate. Leaving strips of grassland uncut to ensure a food supply for the beetle from spring to autumn

Table 51: Biological control in bracken. Adapted from Bond & Turner (2004)

		Effect/performance	**Suitability as a method**
Pigs	After ploughing, pigs expose rhizomes, and some are eaten (Salisbury, 1961).	Effective in deep soils.	An alternative food source needs to be available to prevent the animals eating only the toxic bracken. This limits the use of pigs for biological control.
Caterpillars	Caterpillars of two South African moths; *Conservula cinisigma* and *Panotima* sp. (Lawton, 1988)	The feeding period of these caterpillars is much earlier in the year than any native British species. This coincides with when the bracken is most vulnerable. No field trials have been conducted	Limited success
Fungi	Fungal pathogens *Ascochyta pteridis* and *Phoma aquiline* cause curl-tip disease of bracken (Burge & Irvine,1985).		Limited success

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Future action: Investigate biological control options for dock control, including pathogens and pests highlighted in the table above.

4.5.3. Chemical control

Existing chemistry

Herbicide usage in grassland is generally low. A higher proportion of newly sown leys were treated with herbicides (30%) than grassland which was two to five years old (7.0%), permanent pasture (4.9%) or rough grazing (1.9%) (Barker *et al*., 2018). The majority of grassland remains untreated with herbicides.

For new sown leys most herbicides (Table 52) are applied between March and October for general weed control, in particular for chickweed and docks. Undersown new leys receive herbicides during May and June again predominantly for general weed control (Barker *et al*., 2018). Approximately 70% of new sown leys remain untreated. Older leys (two-five years) receive herbicides (Table 52) mainly between March and September with 92% remaining untreated (Barker *et al*., 2018). The targets are a wide range of broad-leaved weeds including nettles, thistles, docks, rushes and ragwort (Barker *et al*., 2018).

Permanent pasture receives few herbicides with 95% remaining untreated. Herbicides (Table 2) are applied between April and August targeting docks, thistles, nettles, ragwort and rushes (Barker *et al*., 2018). Only a small area of rough grazing receives herbicides, with applications made between April and August (Table 52). The weed targets are similar to those in permanent pasture with the addition of bracken (Barker *et al*., 2018).

Table 52: Active substances applied to grassland

	New leys direct sown	New leys undersown	Leys 2 to 5 years old	Permanent pasture	Rough grazing
2-4, DB	✓	✓			
Tribenuron-methyl	✓	✓			
Fluroxypyr	✓	✓			
Glyphosate	✓				
Mecoprop-p	✓				
Florasulam/fluroxypyr		✓			
Fluroxypyr		✓	✓	✓	
Fluroxypyr/triclopyr			✓	✓	✓
Clopyralid/Fluroxypyr/triclopyr			✓	✓	✓
Clopyralid/triclopyr			✓	✓	✓
Amidosulfuron			✓		
MCPA				✓	✓
Asulam					✓

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a) Chemical control in establishing new grass leys

Weed control options at this stage include selective herbicides, a few of which can be applied as early as three grass leaves. Other herbicide treatments require the ley to be over one year old before an application is made, which can result in a high level of weed competition. Applications in the autumn to smaller weeds should achieve high efficacy and allow the sward to grow more vigorously in the spring, leading to a much more productive and economic ley. Spot treatments are also commonly used for perennial weed species such as docks and thistles (Dow AgroSciences, 2018b).

b) Chemical control in grassland rejuvenation

When rejuvenating grassland for successful weed control it is essential to remove weed competition and allow for over seeding for establishment in poorer areas of the field. If perennial weeds, in particular docks and thistles that are very large, cultural control (i.e. topping/cutting) should be used first before applying a selective herbicide, or spot treating with a knapsack sprayer particularly if the weed threshold is relatively low (for thistle below 5% cover).

Weed wiping can be useful where reseeding is difficult due to soil type or the field is in an environmentally sensitive area. It is also ideal where there is a restricted area of pasture or high stocking levels do not allow for the stock exclusion period required by selective broad-leaved herbicides. Treated poisonous weeds, (including ragwort, hemlock, water dropwort and bracken) must be removed or allowed to completely degenerate before re-grazing or conserving (SRUC, 2014).

c) Upland chemical control

Although herbicides may be available for the management of weeds in upland perennial grassland the main challenge is their application. Use of conventional tractor mounted/trailed sprayers is frequently impractical, if not dangerous. When conventional hydraulic boom sprayers are used they are typically mounted on all-terrain vehicles. In many situations it is not easy to use boom sprayers so spot spraying, with a knapsack or handheld CDA sprayer, or weed-wiping are possible alternatives.

Herbicides include:

- Grassland selective (Table 52)
- Asulam (Emergency use for bracken control)
- Glyphosate

Bracken control is limited to spot spraying and weed wiping using non selective glyphosate.

The cost of control of rushes ranges from £35/ha for weed wiping with glyphosate, to £500/ha for full reseeding (AHDB, 2013). This means it may not be economic to control common rush. Furthermore, AHDB (2013) claim that environmental payments on most upland farms are a key income stream so

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chemical control may not be permitted in some areas and the timing and scale of mechanical topping may be restricted.

Common rush is moderately susceptible to selective hormonal herbicides, such as MCPA. These chemicals, can be applied with a boom sprayer but this , must be done with care, as they will damage or kill most broad-leaved plants, including clover (AHDB, 2013).

Future of asulam

Asulam uniquely offers selective control of bracken and can be applied aerially over challenging terrain often found in rough grazing uplands (Bracken Control Group). However, the future availability of this herbicide cannot be guaranteed, as approval for its use ended in December 2012 due to concerns over its presence in watercourses. From 2014 to 2019, temporary, annual arrangements were put in place to allow the emergency approval and use of asulam for bracken control to continue (Bracken Control Group). The Bracken Control Group is continuing to work to promote the value of this herbicide for bracken control.

Alternatives to the use of asulam

The potential loss of asulam led a number of interested parties to evaluate alternatives. This work predominantly focused on the use of sulfonyl urea herbicides, however, a UK authorisation for such use is unlikely due to water issues (B. Hunt, Pers. Comm.). Tribenuron (Spartan or Express 75% DF) is one example of a sulfonylurea herbicides that was tested and gave effective long-term control of bracken in blueberry fields, and has been registered for use for this purpose in Canada (Jensen & Specht, 2008).

There are a limited number of studies that compare the efficacy of asulam with alternative herbicides and these were reviewed by Stewart *et al.*, (2005).The most feasible alternative asulam is a selective spray of glyphosate. Work on the evaluation of various glyphosate formulations for the control of bracken has continued, as has work on the development of various novel herbicide applicators (B. Hunt Pers. Comm.).

Mechanical weed control:
The use of asulam could be replaced by: ploughing, cutting, bruising, electrical or biological control (see sections above).

In the review by Stewart *et al.,* (2005), cutting twice a year was more effective than asulam application in four out of five studies. There was also evidence that mixed methods of weed control can also be more effective than asulam alone. In a review of British woodlands, bracken control using cutting was estimated to cost 600-2000 €/ha over a five year period in comparison with 150-

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1500 €/ha for herbicide use (Willoughby *et al.*, 2009). Cutting was thought to weaken and supress bracken, rather than killing it (Green, 2003).

Future actions:

- Promotion of alternatives to asulam, or novel application technologies to limit the environmental impact of the chemical.
- The effectiveness of long term mechanical strategies (e.g. cutting, bruising) need to be compared to asulam application.

Weed wiping

Weed wiping (3.4.5) can be useful where reseeding is difficult due to soil type or in environmentally sensitive areas or where clover needs to be conserved, which is common within grassland. Weed wiping is ideal where restricted pasture or high stocking levels do not allow for the stock exclusion period required by selective broad-leaved herbicides. In conservation areas, such as nature reserves, environmental groups are using glyphosate to selectively remove invasive weeds by weed-wiping leaving desirable species untouched (B. Hunt, Per. Comm.).

Weed-wipers can manage rushes more efficiently than conventional boom sprayers using less chemical with a dramatic reduction in spray drift and minimal runoff to watercourses (AHDB, 2013). Weed wipers are also advised for controlling bracken, either on ATV or tractor mounted rotating pressurised systems (Natural England, 2008). There are examples of several water companies; including Welsh water (2018) and Northern Ireland Water (2018), offering to hire weed wipers to farmers for free to reduce the amount of pesticides reaching water and their impact in sensitive areas.

The use of weed wipers are effective and practical for grasslands and uptake is likely to increase if water companies are prepared to continue to provide equipment free of charge.

Bioherbicides

Anjum & Bajwa (2007), found sunflower extracts to be effective for control of docks. Furthermore, Leptospermone (from *Callistemon citrinus*) and Sarmentine (from pepper) have both been found to negatively affect curly dock (Soltys *et al.,* 2013). Bioherbicides could be of use in grassland where weed wiping and spot spraying is already used. However, not all bioherbicides are sufficiently profitable under field conditions for widespread use (Soltys *et al.,* 2013). Consequently they are unlikely to be adopted in the near future. Use of bioherbicides for grass weed control is more likely to be driven by transferable substances from other agricultural sectors such as horticulture.

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In a review of bioherbicides by Green (2003), it was claimed that considerable research has already been conducted within the UK to find a pathogen capable of bracken control. It further states that there is more potential to find root infecting organisms, but as extensive manipulation of the soil environment is required, this approach is unfeasible for managed upland, and is best suited to high input agricultural sites. It was concluded that bracken is not a suitable target for bioherbicide programmes.

4.5.4. Novel and emerging technologies

Satellite imagery

Ali *et al.,* (2016), reviewed methods for grassland monitoring approaches (Figure 31), including both ground-based and remote sensing methods. While ground-based methods are very useful for grassland monitoring on a local scale, and for providing values for model development and calibration of *ex situ* data, they are subjective, time consuming and are only feasible (or applicable) for small scale assessment (Xu *et al.*, 2008). Ali *et al.,* (2016) concluded that satellite remote sensing could be used for the retrieval of grassland biophysical parameters, including biomass, quality, growth, land cover, degradation, grazing capacity, as well as mapping and monitoring for conservation and management. They further claimed that the application of very high-resolution data for remote sensing-based precision agriculture approaches to grassland is now evolving to the same level of maturity as in arable agriculture. However, but more work needs to be done on communicating the benefits and opportunities to the farming community.

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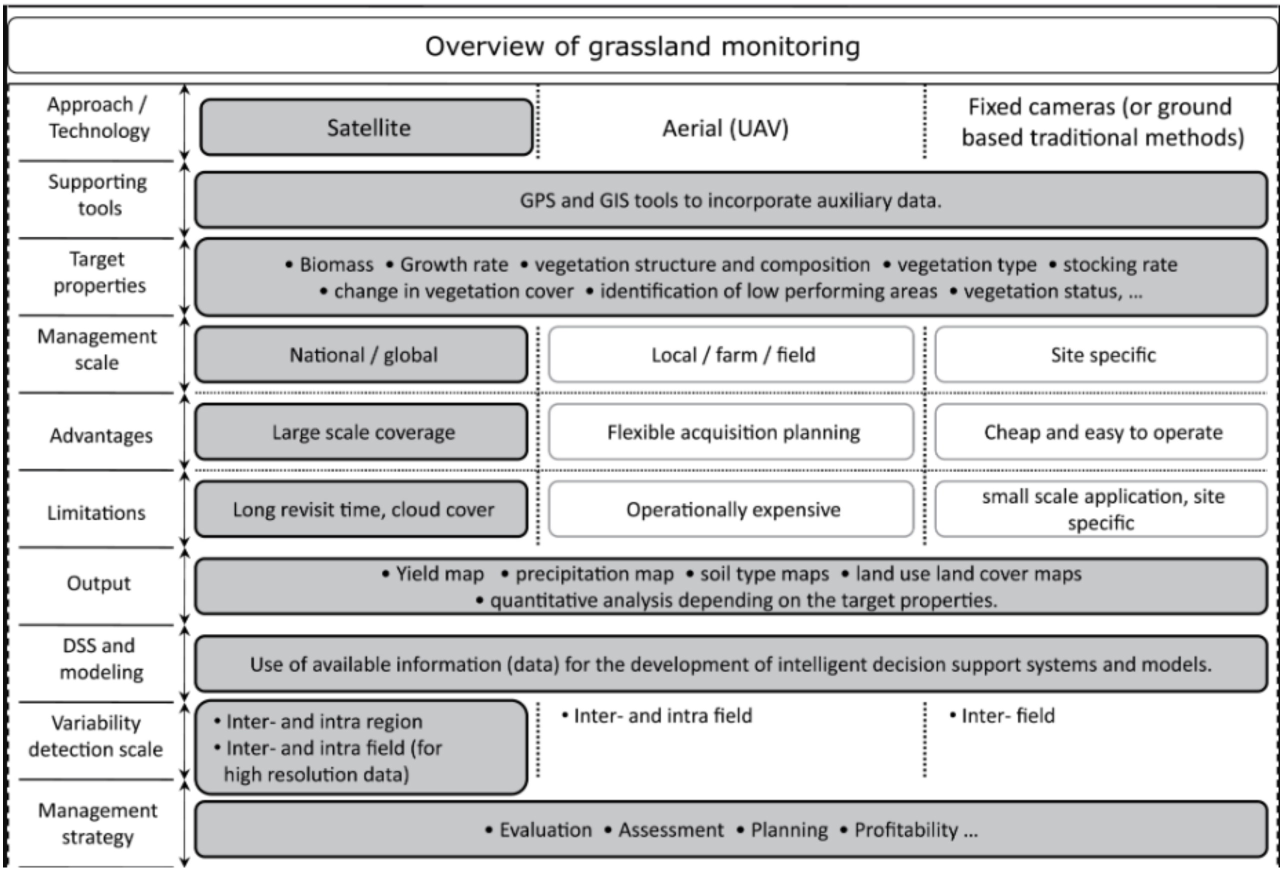

Figure 31 Overview of grassland monitoring. Source: Ali *et al., (*2016)

Drones and UAVs

In other countries, such as Australia, New Zealand and Asia, drones are used for selective spraying of grassland, where they can replace labour-intensive control methods and in situations where terrain and/or ground conditions rule out the use of conventional or even specialist vehicles. Drone AG have developed the DJI Agras system which has the capability to selectively spray herbicides. The drone can hold 10kg of chemical and can spray 3-4 ha/ hour.

Crop Angel Ltd (http://cropangel.com/) is a company developing unmanned aerial vehicles (UAVs) for practical agricultural applications, particularly for aerial spraying of chemicals for bracken control and spot spraying. This is intended be done on sensitive sites where any other form of application by machine or on foot with a knapsack would damage the environment, and on areas where it is difficult or impossible to use helicopters.

It is important to note that spraying chemical from drones within the UK has not yet been legalised by CRD. However, trials are being conducted by a consortium of farm drone enthusiasts and other interested parties, using this technology; specifically targeted at bracken control on inaccessible hill sides and in upland areas important for sheep production. Drone AG and Crop Angel are working

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with the legislative bodies so that UAVs can be used efficiently and safely to increase agricultural and horticultural output in the future.

This technology could be utilised for grassland weed control. However, there are currently substantial legislative barriers to implementation. Furthermore, the costs of the drones, operating systems and current training is likely to be in excess of what can be afforded for upland areas.

Future Action:

- Completion of trials for drone spraying for bracken control.
- Cost benefit analysis of precision spraying glyphosate and asulam in comparison with alternative methods.
- Development of possible health and safety and legislation frameworks for drone usage.
- Economic analysis of the practicalities of using hi-tech approaches on grassland, especially where margins can be small, and economic investment is limited.

Automated machinery and robotics

Van Evert *et al.,* (2011), developed a prototype robot to selectively remove broad-leaved docks (*Rumex obtusifolius*) from grassland. It navigated by following a predefined path using centimetre-precision global positioning system (GPS). Broad-leaved dock was detected using a camera and image processing, and then destroyed by a cutting device. Field testing showed that the accuracy of weed detection was 93% and effective control (where the weeder was positioned within 0.1 m of the taproot) occurred in 73% of cases.

Similarly, Binch & Fox (2017) developed an automated grassland precision sprayer for docks and stinging nettles. This was further refined, to use in combination with UAVs for detection, to reduce the time required to survey for weeds (Binch *et al*., 2018). This combination of UAVs for detection and all-terrain robot for precision spraying, circumnavigates the current limitations of UAV usage for herbicide spraying within the EU.

Future action: Investigate the commercial availability of the Binch & Fox automated precision sprayer for docks in the UK.

4.5.5. Digital tools

Modelling

A study conducted by Magda *et al.,* (2017), used modelling of grassland to predict best management practices for weeds whilst promoting yellow rattle (*Rhinanthus minor*). This technology could be

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important for grassland areas designated as SSSI or receiving payments such as Countryside Stewardship Schemes.

Pottier *et al.,* (2004), developed a model for predicting bracken control across the UK: the model produced satisfactory results in two areas, (1) the broad scale ranking of untreated sites in terms of biomass, and (2) the approximate ranking of control treatment at three of the six sites. This should be used as a management tool for large areas, where funding is restricted, to help make informed decisions on controlled methods. However, they warn that national climate data is not reliable enough to use for routine bracken performance predictions at the site level (especially where peculiar micro-climates exist), although predictions for many sites are adequate.

Internet tools and apps

Dow AgroSciences have created a Grassland Weed app to help identify weed and estimates cost and solutions of their removal (http://uk.dowagro.com/grassland-weed-app-now-available/).

In Australia, portable apps has been developed called “Pasture from space” (http://www.pasturesfromspace.csiro.au/) which provides estimates of pasture production during the growing season by means of remote sensing. Satellite data is used to accurately and quantitatively estimate pasture biomass or feed on offer (FOO) and pasture growth rate (PGR) estimates. Estimation of PGR and FOO using remote sensing provides temporal and spatial information on feed resources allowing producers to more effectively manage their land and potentially raise the productivity and profitability of their businesses. As information is received electronically (email or web based), near real time decisions can be made. However, this does not specifically target weed management.

Originally established in 1999, the GrassCheck (http://www.agrisearch.org/about-grass-check) project aims to provide high quality, up-to-date grass information to assist farmers with grassland management decisions and support improvements in grass utilisation on Northern Ireland (N.I.) livestock farms. This is being trialled with famers throughout the UK in 2019. However, currently this does not specifically target weed management, but does provide weather and growing data to reduce overgrazing and therefore the potential for weeds to establish.

4.5.6. Genetic tools

In New Zealand, AgResearch have developed grasslanz (http://www.grasslanz.com/Home.aspx). They focus entirely on innovative solutions for grassland production including: plant varieties, plant gene research and grass endophytes. They aim to develop and commercialise innovative plant technologies, including those offered by plant biotechnology. Although not specific to weed control, increasing the competitive nature of grasslands could change and improve how weed control in pastures is managed.

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4.6. Legumes

This section covers combining peas, vining peas, winter and spring beans. Combining and vining peas are sown between February and April at target populations of 65-70 and 100 seeds/m² respectively, in rows up to 20cm wide. Winter beans are drilled or broadcast and ploughed in at target populations between 18-28 seeds/m² between mid-October and early November. Spring beans are sown on narrow rows (12-25cm) from late February onwards at target populations between 50-65 seeds/m².

Spring-grown pulses provide an extended window for cultural and stale seedbed techniques in the fight against black-grass (*Alopecurus myosuroides*) and other pernicious weeds. Pulses also have the advantage that they widen the choice of chemistry available for grass weed control.

Winter beans are considered to be more competitive than spring beans or peas because of their ability to branch and cover the space between the rows.

4.6.1. Cultural control

Most of the land is autumn ploughed either prior to legumes or in the case of winter beans to establish them, which in many cases helps reduce weed problems. The exception is if ploughing brings to the surface higher weed populations than are in surface layers. Land with high black-grass populations destined for vining pea production may well be avoided.

All weeds should be sprayed off prior to drilling as per normal practice for a spring crop. Perennial weeds would be addressed in the previous crop before any major soil cultivations.

Rotations

Legumes are generally grown within a cereal rotation. Problematic weeds in legumes can be targeted in other crops in the rotation as there are significantly more active substances available for weed control in wheat and barley. Including legumes as part of a double break, e.g. spring beans after oilseed rape, can be more effective in controlling black-grass.

As peas can be late drilled, herbicides are often applied during the late spring/summer. To avoid residue problems many specific pre-emergence herbicides require deep cultivation to minimise their potential impact on the following crop.

Tillage and cultivations

There is increasing interest in and adoption of shallow tillage to establish legume crops. Depending on soil conditions following the previous crop, fields should be sub-soiled to remove any compaction

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as peas are particularly sensitive to compaction. Processors and Growers Research Organisation (PGRO) experience indicates that these techniques appear to reduce weed emergence but do not remove the need to apply herbicides. Commercially, some farmer groups have over the last two or three years tested several types of shallow tillage drills with varying degrees of soil movement in front of the coulters. These have not had any noticeable effect on weed pressure.

In a recent PGRO experiment, combining peas were sown after ploughing in the autumn or after leaving the stubble uncultivated and subsoiling. The following spring, crops were either direct drilled or cultivated then drilled (Scrimshaw, 2011). Stubble areas received glyphosate before drilling and a pre-emergence was applied to all areas. Weed populations were lower following direct drilling. Yields were similar between all non-plough treatments indicating that establishment of peas was possible without ploughing in fields with good soil structure.

Future action: Evaluate minimal cultivation systems such as direct drilling and strip tillage for establishing legumes and assess their effects on weed populations. This is relevant for a wide range of crops.

Cover cropping

There is little recent research to direct growers to a particular cover crop species or mixture of species for maximum benefit to pulse crops or vegetable legumes. UK and European research on the use of cover crops to influence soil-borne disease control is at an early stage and there is currently little guidance available in relation to the benefits of individual species, or cover crop establishment and cultural practices (PGRO, 2018). PGRO currently recommends that if legumes are being grown in the crop rotation they should not be included in any cover or catch crops within the rotation, this is due to disease issues (PGRO, 2018d). PGRO is currently undertaking research to evaluate whether legumes can be used in cover or catch crops without any detrimental effects on the following legume crops.

A current EIP-Agri funded project (PGRO, 2018e) is examining the effect of autumn cover crops (brassica species, phacelia, cereals and legumes) on following vining pea crop focussing on soil health. This has demonstrated that cover crop mixes which give good ground coverage reduced weed numbers, not particularly in the peas but in the following cereal (PGRO, Pers. Comm.).

Future action: Further evaluate the use of a cover crop prior to legumes for weed suppression,

Intercropping or companion cropping

Inter cropping can provide peas with a scaffolding that improves standing ability. In 2017 peas were grown with intercrops of spring oats, barley and oilseed rape, there was an indication that the intercrops supressed weed levels. Work is continuing into 2018 using varying rates of oats and spring

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beans (PGRO, 2018f). It was observed that compared to pea only plots intercropping did not suppress bindweed. The level of weed suppression may have been affected by an insufficiently high population of the partner crop. The balance between the populations of pea and partner crop will be critical bearing in mind the poor competitive ability of peas. Howard (2016) stated that peaola, a mixture of peas and oilseed rape is viable in the UK. This used peas as the main crop with the oilseed rape helping to prevent lodging. An additional benefit was fewer flea beetles.

Weed suppression in barley intercropped with peas was compared with peas or barley alone in five European countries (Italy, UK, Denmark, France, and Germany) (Corre-Hellou *et al*., 2011). Fat-hen (*Chenopodium album*) and charlock (*Sinapis arvensis*) were the two dominant weed species and their intensity and biomass were reduced in intercropped plots compared with plots in which peas were grown on their own or those that were kept fallow.

Bulson *et al*., (1997) and Wolfe *et al*., (2013) showed improved weed suppression when autumn-sown faba beans were intercropped in comparison with sowing wheat or beans in monoculture. A further consequence of improved weed suppression was that soil inorganic N was used for grain production in the non-legume intercropping partner instead of weed biomass (Hauggaard-Nielsen *et al.,* 2001).

Future action: The use of intercropping and companion cropping should be evaluated using legumes

Crop species and varietal choices

Legumes lack competitive ability, as they are slow to cover the ground and smother weeds. Peas are particularly non-competitive and breeding has focussed on increasing yield and improving lodging and disease resistance. Grevsen (2000) in Denmark found differences between pea cultivars for weed suppression, the least competitive being semi-leafless types. Jacob *et al*., (2016), working in Canada, stated that as a consequence of breeding to improve agronomic traits, a point may have been reached where the competitive ability has been bred out of field peas or that there is insignificant variation for traits that confer competitive ability between cultivars. However, the traits that conferred competitiveness in semi-leafless peas could not be identified.

Work was done to investigate the competitiveness of different pea varieties for organically produced vining peas in the early 1990's. Commercial pea varieties change frequently, and this work has not been repeated using newer varieties. Other studies to evaluate varietal competitiveness have delivered inconsistent results.

Peas are inherently poor competitors for much of their early development. This could be improved if varieties could be bred that established more rapidly.

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Beans are more competitive than peas but current breeding programmes are focussing on yield, winter hardiness and, resistance to lodging and disease.

Future action: Determine if differences in the speed of establishment between modern varieties is likely to be a worthwhile area for future research. Undertake a review of growers to determine if there is interest in growing pea or bean varieties that could compete with weeds.

Seed rates

Increasing seed rates has been shown to improve weed control in all legumes. There has been little recent work on this in the UK but it has been researched elsewhere. In Canada increasing combining pea populations from 38 plants/m² to 150 plants/m² decreased weed biomass (volunteer barley) by 59% (Strydhorst *et al*., 2008), similar decreases were recorded by Townley-Smith *et al*., (1994), Grevsen (2000) and Lemerle *et al*., (2006). Similarly increasing plant population in spring beans from 22 plants/m² to 90 plants/m² decreased weed biomass (volunteer barley) by 53% (Strydhorst *et al*., 2008). Beans were less competitive than peas and achieving high bean yields required herbicide treatment. Increasing the plant populations of vining peas decreased the incidence of weeds and at the highest plant populations there were virtually no weeds (White & Anderson, 1974).

Although increasing seed rate can supress weeds this has to be balanced against seed cost and achieving optimum yield. Excessive plant populations can lead to increased disease levels and lodging.

Future action: Revisit work on legume seed rates, in combination with row widths to establish if they can be optimised for weed suppression.

Row widths

Commercial row widths for legumes range from 15cm to 25cm and are often determined by the type of drill used. Wider rows offer a larger window of opportunity to use inter-row, guided mechanical and herbicide applications using optical techniques (Section 3.3.1), but narrow rows improve the competitive ability of the crop with weeds. The yield of peas declines if row widths are increased above 20cm (PGRO, 2017; PGRO, 2016b) Narrower rows (15 cm) in vining peas promote quicker canopy formation which could be useful for improving weed suppression (Scrimshaw, 2014). In 2013, spring beans were sown on 12, 24 and 48cm row widths with seed rates of 20 and 40 seeds/m². Herbicides were applied to the inter-row gap and imazamox + pendimethalin was compared with glyphosate (PGRO, 2014). As the inter-row spaces increased yield declined and it was clear that spring beans did not compensate for the 48cm row width.

In winter beans broadcasting and ploughing are used to establish about 50% of crops (PGRO, 2017) but the remainder are drilled conventionally.

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Future action: Can row width be manipulated to improve weed suppression and optimise yield in legumes? Would double/triple close rows with the option to control weeds in the inter-row spaces be beneficial?

Drilling dates

There is considerable opportunity to establish pea or bean crops on a wide range of dates. The optimum sowing date for winter beans is later than for either cereals or oilseeds, which provides a wider window for pre-crop weed control. Delaying autumn drilling will delay crop emergence and allows a longer period for the use of non-selective herbicides on the crop, to control late germinating weed flushes. Delaying spring drilling will allow early germinating spring weeds to be controlled. Spring peas and particularly vining peas are drilled according to a drilling plan over a period between late February to late May/early June; a period when many weeds typically germinate (Figure 32).

Figure 32 Emergence periods of weeds in spring

4.6.2. Non-chemical weed control

Manual removal of weeds

Manual removal of weeds is possible throughout the life of the crop but currently this is uneconomic unless growers are paid a large premium to produce organic peas. If volunteer potatoes (*Solanum tuberosum*) are present, then manual removal may be the only option. There is one product to control potatoes in peas, but it has a 42-day harvest interval. Potato volunteers can produce pea sized berries, if these toxic contaminants are present in the harvested crop they result in crop rejection.

Mechanical weeding

Work was undertaken by PGRO in the 1990's using an Einbock tined weeder in combining peas. Results showed that mechanical weeding could be as effective as pre-emergence herbicide applications but was very dependent on the set-up of the equipment, soil conditions, weed species and the crop growth stage. Early passes at growth stage BBCH 12 to 13, in the direction of sowing,

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was most effective and caused minimal crop damage. Later passes at growth stage BBCH 15 caused greater levels of crop damage and plant loss.

Mechanical weeding is used successfully by Alan Webster in spring beans (PGRO, 2016a). In late May/early June, when the crop is approximately 15-20 cm tall and just before the rapid extension period, it is spring-tined grassland harrowed. After a week the crop has recovered and the process is repeated in the opposite direction. The mechanical weeding process ensures that any freshly emerging weeds are destroyed just before stem extension and crop canopy closure. Alan says "*it is not for the faint hearted as it looks a right mess and we probably lose up to 10% of the leaves. But the plants recover quickly and it ensures the best possible weed control. It never fails*."

Mechanical weed control is traditionally practiced and may be an option for winter beans. Between 1990 and 1992 a series of trials were done by ADAS in winter beans at two sites. The cultivators used were harrows at a depth of 2-4 cm and a Vi-till or flexitine at 7-10 cm depth. Treatments were applied early (4-6 nodes) or late (6-9 nodes). Plant population was reduced slightly at Boxworth but at Drayton there were significant plant losses where the flexitines were used, possibly linked to the wetter soil conditions (Figure 33). Winter beans can regenerate from basal buds if they are snapped off.

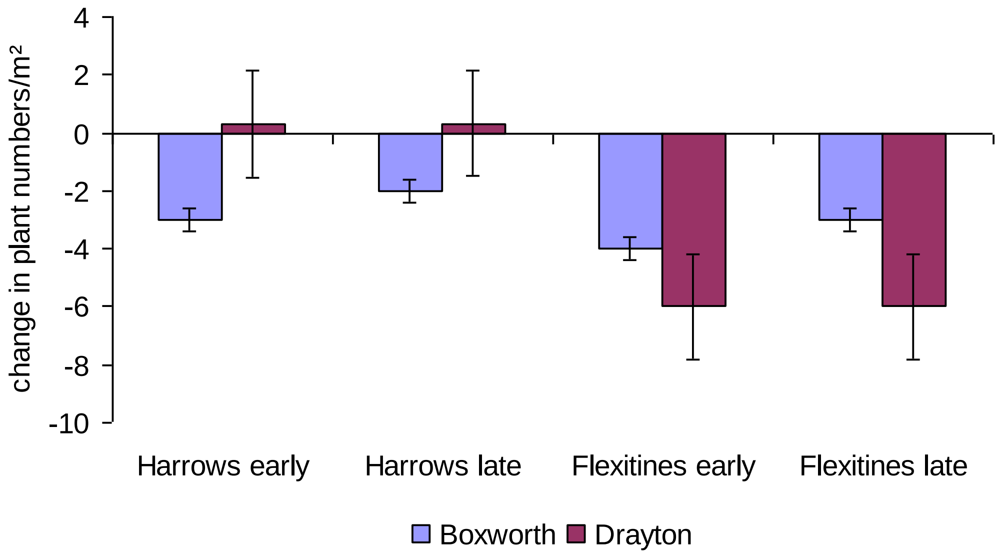

Figure 33 Plant losses due to mechanical weeding in winter beans compared to herbicide use.

The flexitine generally reduced weed numbers to a greater extent than the harrow. Smaller weeds were more vulnerable than larger ones and those with tap roots such as fool's parsley (*Aethusa cynapium*) and knotgrass (*Polygonum aviculare*) were better controlled by the deeper cultivations. Mechanical weeding can provide a reasonable level of weed control provided the weeds are small and there is enough tilth to cover them. A cultivation in the spring can also stimulate a further flush

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of weeds but more competitive crops can smother these out. Generally yields were unaffected by mechanical weeding as beans were able to recover from being covered with soil.

Thermal, electrical, flame weed control, hot water and hot foam

In all row crops, particularly where rows are wider (25 cm) the use of thermal technology can be considered. Flame weeding has a lot of disadvantages, being expensive, slow and inefficient. A thermal flame spot weeder has been developed and trialled in Denmark (Poulson, 2018), on board cameras identify weeds and small burners are activated. Current research investigating the benefits of flame weeding in vegetable systems is being done in a European H2020 funded project IWMPraise (2016). The results of this need to be reviewed for their applicability to legumes.

The use of electricity to kill weeds has been further developed in recent years with Ubiqutek (2018) in partnership with Steketee & Zasso (2018) developing machines to use in agriculture but none are yet commercially available.

Hot foam has been patented by Weedingtech™ (2018) and has been used for weed control. However, recent work by ADAS (2013b) has identified that improvements are required with regard to treatment speed, application timing and tractor mounted equipment. These refinements would allow multiple rows to be treated simultaneously.

Microwave and laser technology is developing and could be suitable for use in legume crops.

Future action: Keep a watching brief on thermal weed control methods as they develop. This is most likely to be in combination with guided weed control systems or robots.

4.6.3. Chemical control

In legumes the use of a pre-emergence herbicide is preferred method of weed control as it removes weed competition early in the life of the crop and improves the control of some weeds e.g. knotgrass and annual meadow-grass (*Poa annua*). However soil moisture is required for good efficacy.

Prior to the use of post-emergence herbicides crops should be well waxed to minimise crop damage.

Existing chemistry

Ninety seven percent of dry harvest pea crops received an herbicide, in 3.5 applications containing 4.8 products or 5.5 active substances. Most applications were made between February and July to control broad-leaved weeds, specific applications were made to control black-grass, charlock (*Sinapis arvensis*) and wild-oats (*Avena fatua*) (Garthwaite *et al*., 2017a).

In peas, weeds are generally controlled with a programme of pre- and post-emergence herbicides (Table 43.). The use of the pre-emergence herbicides, clomazone, pendimethalin and imazamox,

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removes early weed competition and improves control of knotgrass and annual meadow grass, moist soil at application is vital. Linuron is no longer available for use. Post-emergence herbicides are limited to bentazone and MCPB (PGRO, 2018a). In peas oilseed rape and volunteer potatoes are difficult to control. For oilseed rape pre-emergence pendimethalin is effective or pendimethalin + imazamox, or post emergence MCPB or bentazone provided it is applied before the rape has 4 leaves. In weedy crops at harvest a desiccant may be needed. There is no option to selectively kill volunteer potatoes in combining peas.

Table 53. Currently authorised actives and mixtures for use in peas and beans for broad leaved and grass weed control

Active Ingredient	HRAC group	Combining peas	Vining peas	Spring beans	Winter beans
Bentazone	C3	✓	✓	✓	✓
Carbetamide	K2			✓	
Clomazone	F3	✓	✓	✓	✓
Clomazone + pendimethalin	F3+K1	✓			✓
Cycloxydim	A	✓	✓	✓	✓
Diquat	D	✓		✓	✓
Fluazifop-P-butyl	A	✓	✓	✓	✓
Flumioxazin	E		✓		
Imazamox + pendimethalin	B+K1	✓	✓		
MCPB	O	✓	✓		
Pendimethalin	K1	✓	✓		✓
Propaquizafop	A	✓		✓	✓
Propyzamide	K1			✓	
Prosulfocarb	N			✓	✓
Quizalofop-P-ethyl	A	✓	✓		
Quizalofop-P-tefuryl	A	✓		✓	✓
S-metolachlor	K3		✓		✓

In vining peas most herbicides are applied between May and July (Garthwaite *et al*., 2016c). Those most commonly used are detailed in Table 54. Applications were made for general weed control, with black-grass, volunteer oilseed rape, borage (*Borago officinalis*) and cranesbill (*Geranium* spp.) specifically mentioned. Weed control is best from pre-emergence herbicides but most of these have a requirement for deep cultivations or ploughing before the next crop. Clomazone, pendimethalin, imazamox are permitted as is S-metolachlor (EAMU) but linuron is no longer authorised (PGRO, 2018c). Post-emergence herbicides are limited to MCPB and bentazone. Again oilseed rape can be a problem and volunteer potatoes. The production of potato true seed can contaminate the produce and specific control measures need to be taken to prevent this (PGRO, 2018c). Flumioxin can be applied under an EAMU to supress berry production.

Ninety six percent of field beans received an herbicide, in 2.5 applications containing 3.4 products or 4.2 active substances, fewer herbicides than dry harvest peas. Herbicide applications to winter

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field beans were made between September and November and February to June (Garthwaite *et al*., 2017a), spring beans were treated between February and June. Weeds controlled were grass and broadleaved species including black-grass and wild-oats. The most common herbicides applied are detailed in Table 54.

Post-emergence herbicides in field beans are limited to a single active substance, bentazone, so control of weeds with pre-emergence applications is essential. As with peas, there are restrictions on the lighter soil types (PGRO, 2018b). Linuron is no longer available for use in field beans so pre-emergence herbicides are limited to propyzamide, clomazone, imazamox and prosulfocarb (EAMU). Dual Gold (S-metolachlor), can be used under an EAMU on spring beans only. Propyzamide gives good control of grass weeds including herbicide resistant black-grass. Oilseed rape control is limited to applications of bentazone onto small plants.

In all crops several graminicides can be used to control grass weeds.

Table 54 Top five most common formulations applied to legumes species.

Active ingredient	Dry harvest peas[3]	Field beans[3]	Pea and bean crops[1,2]
Glyphosate	✓	✓	✓
Imazamox/pendimethalin	✓	✓	✓
MCPB	✓		✓
Bentazone	✓		✓
Pendimethalin	✓	✓	
Clomazone/linuron		✓	✓
Clomazone		✓	

[1]vining peas (87% of the total), broad beans, French beans, peas for picking, runner beans and edible-podded peas including mange-tout.
[2]Garthwaite *et al*., 2016c, 3Garthwaite *et al*., 2017a

Glyphosate is used prior to drilling and as a pre-harvest desiccant. The recent loss of diquat will have a significant effect on weed control and desiccation. Glyphosate can be used as an alternative but it is much slower acting than diquat (10-14 days compared to 3-7) days and it cannot be used on seed crops.

Although there are occasional reports of glyphosate being used in bean crops, there is no authorisation for its use to control weeds. It is risked because in some situations glyphosate only stunts and delays the crop rather than kills it; and weed control is as effective as in non-crop situations.

Optimising use of existing chemistry

Chemical control currently remains as the key method for controlling weeds in legumes. Optimising their use is important and simply providing a fine seedbed and rolling post drilling will improve pre-emergence weed control.

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The performance of herbicides could be improved through addition of water softeners and adjuvants to improve weed control and crop safety. PGRO did work on the use of adjuvants with bentazone to reduce rates of application and costs whilst maintaining acceptable control. This work has not been used to change the label.

Future action: There could be more work done to investigate how herbicide performance in legume crops could be improved through the use of crop safeners, water conditioners and adjuvants.

Spot spraying

Vision guided spot spraying of glyphosate for control of volunteer potatoes has been used successfully in vining peas (Scrimshaw, 2014). This project demonstrated the usefulness of spot applications of glyphosate using an optically guided weeder that could differentiate between the crop (vining peas) and developing volunteer potatoes. This work allowed Extensions of Authorisation for Minor Use to be obtained for Roundup Energy and Roundup Flex when applied using the Tillett and Hague Technology Ltd equipment. Wider rows led to a greater window of opportunity for applications, but the equipment is expensive and at the time when the work was undertaken, it was not easy to calibrate to spot treat potato volunteers.

Future action: Keep a watching brief on developing technologies, liaise and interact with industry and research establishments

Precision application

There may be potential for precision application of currently approved selective herbicides, such as bentazone applied post-emergence. It may reduce the need for ‘blanket’ applications if better targeting could be achieved. Quantities applied could be reduced using this technology. Crop development would influence how this might be practically be used, enabling applications at later crop growth stages.

Use of contact herbicides and a residual through an inter-row hooded sprayer has been considered and seems feasible.

Future action: Keep a watching brief on developing technologies, liaise and interact with industry and research establishments

Weed wiping

In theory weed wiping could be used to control volunteer potatoes and other tall weeds and should be effective if they are taller than the legume crop. The research could be done in parallel with similar work in field vegetables. Weed wiping has not been used before in legumes.

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New chemistry

Given the status of vining peas and other field vegetables as minor crops in the UK, future pesticide developments are unlikely to be specifically targeted for use in these crops, although EAMU's are often sought following approval in other crops, if residue data is available. EAMU's are possible in combining peas as they too are a minor crop. Field beans are not a minor crop and full label approvals would be required.

There are active substances available elsewhere in the world which are used in peas and could be useful in the UK. PGRO have tested a range of actives which have shown promise whilst others have caused crop damage, these have included salflufenacil, imazamox alone, imazethapyr and dimethenamid - P are examples.

Future action: Work with AHDB to evaluate herbicides for minor uses in legumes

Pre-harvest weed control

Control of weeds prior to harvest in combining peas, spring and winter field beans is traditionally done using diquat. Sales of diquat will cease by 4 May 2019, with a use-up period for growers up to 4 February 2020. Glyphosate can be used as an alternative but not on seed crops, and has the additional advantage of perennial weed control. The approval of glyphosate will be up for revision on 12 December 2022 and its loss would have significant effects on legume production. As an alternative there could be a return to swathing or, in the long-term, breeding for more determinate rapid drying varieties.

In vining pea seed crops, diquat is the only active available for desiccation and after its withdrawal there will be no alternatives for vining peas grown for seed production. Salflufenacil has been used in Canada on phaseolus beans (Soltani *et al*., 2013) but is currently not approved for use in Europe (European Commission, 2019) and it may not be appropriate for seed crops. There is a need to evaluate alternatives to diquat for desiccation in legumes.

Future action: Evaluate alternatives to diquat and glyphosate for crop desiccation.

4.6.4. Novel and emerging technologies

Aerial imagery (satellite, aeroplane, drone) can be used to identify weedy areas and measure the response to management tactics in legume crops.

A confidential project has recently started in peas and beans to investigate the use of remote sensing and advanced data analysis to improve crop production. Black-grass can be detected as well as general weed infestations which can allow GPS assisted 'spot'/variable herbicide applications.

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Weed control with self-propelled robots is a fast developing area. Sensing weed technology is well developed and this is being combined with a wide range of weed control measures such as lasers and herbicide spot sprays.

Future action: Keep a watching brief on developing technologies, liaise and interact with industry and research establishments.

4.6.5. Digital tools

Apps

The PGRO app (PGRO, 2019) allows the pictorial recording of crop/weed issues to a location and provides reference information and contact information for more detailed guidance if required.

Genetic tools

Genetic modification has not progressed as well in legumes as it has in other crop species.

Future action: Keep a watching brief on genetic tools, liaise and interact with industry and research establishments.

4.6.6. Preventative weed control

It is vitally important to prevent the ingress of weeds onto farms 3.8

Weed seed control

Weed seed control could be appropriate for combinable crops, it needs to be evaluated.

4.7. Maize

In 2016 197,000 ha of maize was grown in the UK, 76% of the area grown was for forage, 19% for anaerobic digestion, 3% for grain and 2% for game cover (Barker *et al*., 2018).

The importance of weed competition in maize depends on the crop growth stage, the amount of weeds present, the degree of water and nutrient stress, and the weed species. Small weeds reflect far-red light and trigger changes in the growth of the neighbouring maize plants (Liu *et al*., 2009).

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The critical period for weed control is during the first six weeks after emergence (AHDB, 2015b), delaying weed control results in significant reductions in yield (Figure 34).

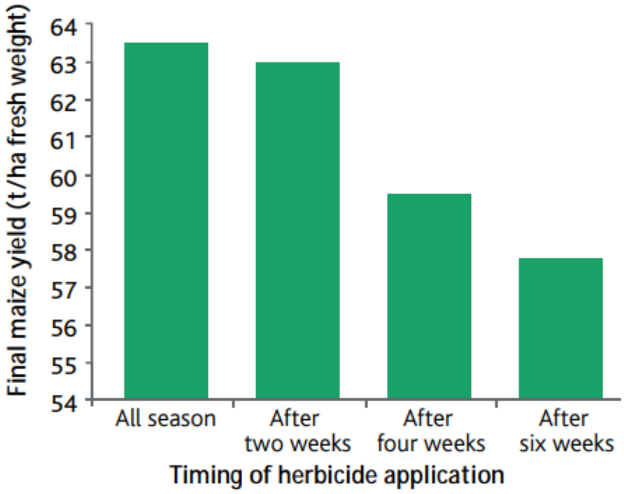

Figure 34 Maize growers association weed control trial taken from AHDB, 2015b

Maize is generally sown when soil temperatures at drilling depth (8-12cm) reach a minimum of 8°C for at least 5-7 days, which usually occurs between mid-April and mid-May (AHDB, 2015b). Standard row width is 76cm but depends on the machinery available for other operations. Target plant density is around 100,000 plants/m².

4.7.1. Cultural control

Rotations

Maize can be grown repeatedly on the same field, but harvest is early enough, it can fit well into a rotation with cereals and grass leys. As in other crops increasing crop diversity in rotations containing maize reduced weed populations. In Canada continuous cropping of maize was compared with a maize/barley rotation over a six-year period using both no tillage and ploughing. When the rotation started with maize (after a glyphosate application) and was followed by barley, numbers of broad-leaved weeds, grasses, annual weeds, and perennial weeds were consistently lower in the ploughed treatment than in the no-tillage treatment. However, when the rotation started with barley and did not receive an application of glyphosate in the barley year, weed levels were consistently higher throughout the experiment (Carter *et al*., 2002). In Slovakia, continuous maize was compared to a range of rotations containing maize, spring barley, winter wheat and peas over a 7 year period. Total weed density generally decreased with increasingly diverse rotations (Demjanová *et al*., 2009).

As rotations change then cultivations change, both Demjanová *et al*., (2009) and Doucet *et al*., (1999) noted that crop rotation plays a lesser role in the regulation of weed density compared to changing cultivations.

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Tillage and cultivations

As maize is sensitive to compaction and compacted soils lead to poor establishment most fields prepared for maize are ploughed. The secondary cultivation depends on the site and local conditions, however stale seedbed management can be very effective at reducing weed populations (AHDB, 2015b).

While most maize is precision-drilled following the plough, an increasing area is being established with non-inversion tillage, direct drilling and strip tilling (University of Reading, 2014). However, stopping ploughing can increase weed populations. Morris *et al*., (2010) showed not ploughing has led to a higher level of grass weeds. Buhler *et al*., (1994) recorded increases of field bindweed (*Convolvulus arvensis*) and dandelion (*Taraxacum officinale*) after 14 years of reduced tillage compared to conventional (ploughed) continuous maize. In Canada, the density of weeds increased over a 6-year period of no-tillage compared to ploughing, especially perennial species (dandelion (*Taraxacum officinale*) and couch (*Elytrigia repens*)) (Carter et al., 2002). Demjanová *et al*., (2009) recorded lower total weed density where ploughing used compared to reduced tillage systems (no ploughing). It was noted that the main benefit of conventional tillage is highly significant decline of perennial weeds.

Future action: Evaluate the establishment of maize after non-inversion tillage and direct drilling.

Cover crops

The inclusion of cover crops would be primarily for the prevention of soil erosion, improvement of soil organic matter content and capture of nitrogen but they have been shown to have value for weed suppression. In Italy cover crops were sown in September, mown and incorporated in May and followed by maize. Weed populations were assessed 4 weeks after drilling. Compared to the weed-covered control, weed density decreased approximately by 42%, 44% and 47%, respectively, in maize following hairy vetch (*Vicia villosa*), subclover (*Trifolium subterraneum*) , and ryegrass (*Lolium* spp.) cover crops but weed biomass was reduced by 31%, 40% and 94% respectively. The greater reduction in density after ryegrass was attributed to lower mineral N content in the soil and possibly an allelopathic effect of ryegrass against weeds (Caporali *et al*., 2004). Similar results have been shown by Rosa (2014) in Poland but increased weed populations were seen by Brozović *et al*., (2018) in Croatia. Abdin *et al*., (2000) showed that inter-row cultivation and cover crops was variable depending on the level of weed infestation, the growing conditions and location, stating that cover crops provided additional weed control but inter-row tillage or some herbicide application may still be necessary.

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Intercropping and companion cropping

Maize crops have a high proportion of bare soil that is susceptible to erosion and run off. Howard, (2016) concluded that cover crops and intercropping could be a useful tool in the crop for, recycling N that would otherwise leach over winter, weed suppression, support harvest traffic and so reduce compaction, and increase carbon sequestration. Grass can be sown successfully at the 6-8 leaf stage of maize using a lower seed rate (50% of normal) (Impey, 2015). In a Defra funded study (Defra, 2015b) three ground cover and cultivation treatments were done at two sites over two years. Conventional plough based cultivation was compared to strip tillage into a cover crop of perennial ryegrass, strip tillage into a biodiverse cover crop and non-inversion tillage. The cover crops were oversown into the previous maize crop. The principal aim of the trial was to reduce soil erosion overwinter and increase biodiversity within the maize crop. Whilst soil erosion was reduced under the cover crops compared to bare ground, maize yield were decreased by 80-90% where the crop was strip tilled into the cover crops. Agrovista, (2018), in an unreplicated trial, tested intercropping with tall fescue (*Festuca arundinacea*) sowing 3 rows between maize sown at 75cm centres, 15cm was left between the maize and the grass to prevent the grass from smothering the crop. Presence of the grass help suppress weed emergence. Sowing a perennial ryegrass/tall fescue mix later when the maize was at 4-6 leaves, reduced yields by 7% due to disturbance of the maize roots (Agrovista, 2018).

Future actions:

- Cover crops and intercropping are valuable for inclusion in the maize crop because they are effective at reducing nitrate, phosphorus and sediment losses to surface water and nitrate losses to ground water in the winter after maize harvest.
- Strip tilling into established ground cover is effective at increasing biodiversity and reducing weed cover but can be detrimental to yield. Further work needs to be done in this area to optimise the use of cover crops and intercropping in maize.

Row widths

Standard row widths are 76cm but have been sown as close as 25cm, narrowing the rows result in earlier canopy closure with taller plants and greater weed suppression ((Flenet *et al*., 1996). Mhlanga *et al*., (2016) reviewed a range of experiments and reported improved weed suppression came from decreasing row width.

Future action: There is an opportunity to consider the reduction of row width to improve weed suppression.

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Seed rates

As the population density of maize increases, the amount of light that reaches the soil is reduced, influencing emergence, growth, and development of weeds (Teasdale, 1995). Mhlanga *et al*., (2016) reviewed a range of experiments in maize and reported that increasing plant population reduced weed biomass by 23-99%, improved suppression came from decreasing row width.

4.7.2. Non-chemical control

Mechanical weeding

Maize, is planted in widely spaced rows and making it a suitable crop for use of mechanical weeding. Mechanical weeding is widely used in the US but not so much in the UK. As such there is much potential for mechanical weeding, crops can be mechanically weeded at multiple growth stages as demonstrated in the Table 55 below:

Table 55: Opportunities for mechanical weed control in maize

Time:	Pre-sowing	Week 1-2	Week 3-5	At 60% cover	Until harvest
Crop stage:	-	Sub surface shooting	Crop 1-4 leaves	4-6 leaves (20cm)	>60% cover
Weeds stage:	White filaments	Cotyledon	2-4 leaves	6 leaves	Flowering and seed bearing
Machinery and setting:	Harrow	Harrow	Harrow/ Finger or torsion weeder / pneumat	Finger or torsion weeder / Pneumat Ridger (hoeing)	Hand weed only
Other comments:			Risk of covering small plants	High ridges required	-

Source: Van der Schans *et al*, (2006)

Pannacci & Tei (2014) evaluated the effects of mechanical and chemical methods (spring-tine harrowing, hoeing, hoeing-ridging, split-hoeing, finger-weeding, over row herbicides & inter-row hoeing, overall herbicides) on weed control and maize yield. They showed it was possible to halve the amount of herbicides with no loss in weed control efficacy and crop yield, by combining chemical weed control in the row with hoeing inter-row. Where no herbicides were used, mechanical methods effectively control weeds without harming the maize crop. Pannacci & Tei (2014) found the best technique was hoeing-ridging, which gave excellent control of both inter- and intra-row weeds and could hinder the development of uncontrolled weeds, reducing their competitive ability and seed production.

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Kunz *et al*., (2018) evaluated inter- and intra-row mechanical weeding in eight experiments in Germany. Camera steered hoeing resulted in 78% weed control efficacy compared to 65% using machine hoeing with manual guidance. Mechanical intra-row elements controlled up to 79% of the weeds in the crop rows. The main weeds were fat hen (*Chenopodium album*), black-bindweed (*Polygonum convolvulus*) and field pennycress (*Thlapsi arvense*).

Mechanical weeding is an attractive option for weed control in maize and should be evaluated further particularly in conjunction with guided technology such as RTK.

Thermal, Electrical, Flame, Hot water and Hot foam

Due to the wide row width and late drilling date maize is particularly suited to inter-row weeding techniques hot foam and flame weeding (3.3.4) have been found to be effective for maize. A study conducted by Ulloa *et al.,* (2010), suggested that maize was tolerant to flaming and therefore has potential for weed control in organic sweet maize production, especially at the seven-leaf crop growth stage.

Future action: Keep a watching brief on thermal weed control methods as they develop. This is most likely to be in combination with guided weed control systems or robots.

4.7.3. Chemical control

In maize, herbicides were the most frequently applied pesticide, with nicosulfuron, glyphosate, mesotrione/terbuthylazine and pendimethalin the most frequently used (Figure 24). The majority of herbicides were applied between March and June (Barker *et al*., 2018, Figure 24). Maize is not sown until April-May, allowing ample time to prepare a stale seedbed and control any emerging weeds with glyphosate. Most herbicide use was targeted at general weed control with specific mentions of grass weeds, bindweed, thistles and volunteer potatoes.

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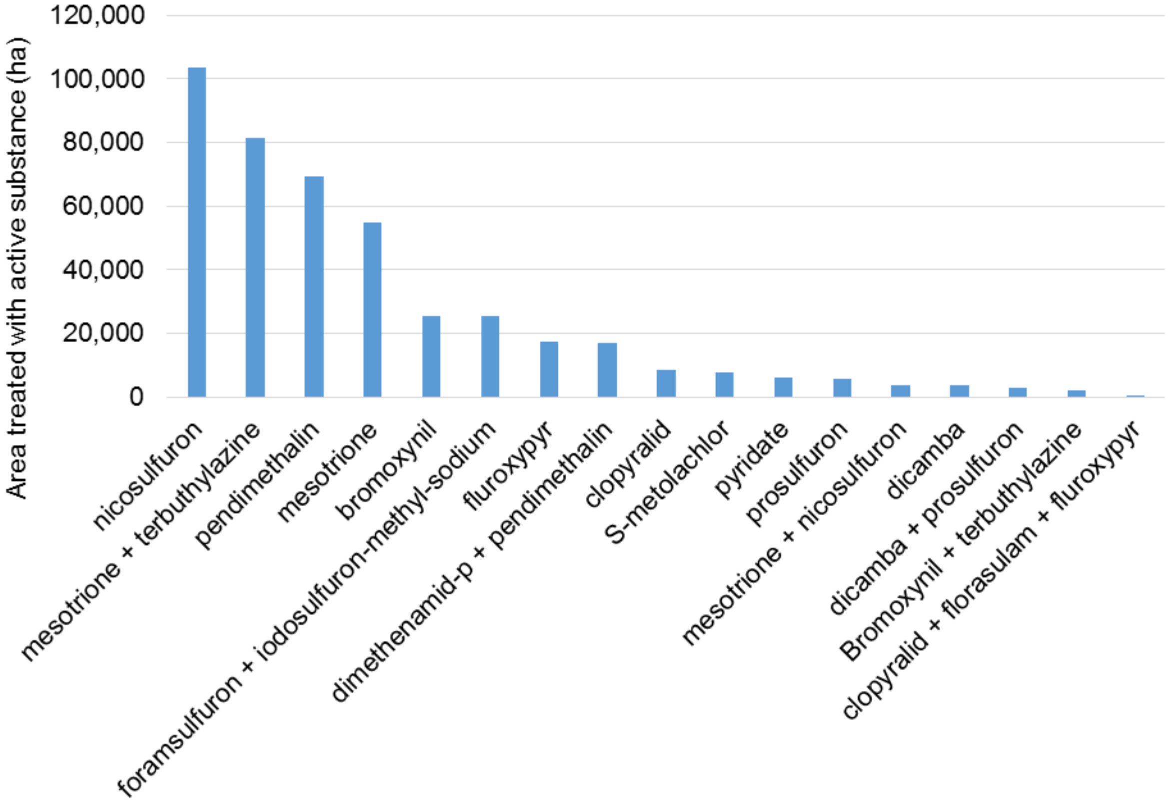

Figure 35 The formulation treated area of maize treated in the UK in 2016 (Barker *et al*., 2018). ('Treated area' is the gross area treated with a pesticide, including all repeat applications.)

Existing chemistries

A range of pre- and post-emergence herbicides are authorised for use in maize (Table 43). Pre-emergence herbicides are less frequently used than post-emergence herbicides, but in some situation they can be beneficial.

- In maize planted under plastic
- Where control of weeds prior to drilling has been compromised.
- Where a particular weed problem is expected and a sequence of herbicides will provide better control e.g. black-grass control
- Where prompt application of a post-emergence herbicide is unlikely to happen. A pre-emergence delays weed emergence so allowing more time to apply a post emergence.
- Where crop damage is expected, the post emergence can be delayed until the crop is more advanced and crop damage can be reduced.
- To sensitise weeds to the post-emergence herbicide

The choice of a pre-emergence is generally determined by the amount of moisture present. Where moisture is limited pendimethalin is preferred as it is more persistent. When moisture is plentiful crop

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and weed emergence will be quick and a stronger pre-emergence is needed, such as products containing dimethenamid-p + pendimethalin or S-metolachlor + pendimethalin.

Where no pre-emergence has been used it is critical to apply the herbicide to weeds at the cotyledon stage. Herbicides should be tailored to the weeds present, containing mesotrione + terbuthylazine, nicosulfuron, mesotrione or bromoxynil at a rate depending on the species present.

Where a pre-emergence has been used post emergence sprays should be applied when the first weeds are between the cotyledon stage, but no later than 2-4 leaves of the maize crop. The product choice depends on the pre-emergence used and the species expected, following a good pre-emergence any further weeds can be removed using bromoxynil or mesotrione + terbuthylazine.

Black-grass control always starts with the use of a pre-emergence, pendimethalin or flufenacet + isoxaflutole, followed by foramsulfuron + iodosulfuron-methyl-sodium with a wetter.

Specific weeds can be targeted, fluroxypyr for cleavers and chickweed, prosulfuron for knotgrass, redshank and mayweed, bromoxynil for redshank, fat hen and groundsel, foramsulfuron + terbuthylazine for black nightshade.

As in other crops the use of ALS inhibitors (HRAC group B) are subject to restriction and cannot be used in sequence with any other ALS inhibitors.

Table 56: Currently authorised actives and mixtures for use in maize for broad leaved and grass weed control

Active Ingredient	HRAC group	Pre-emergence	Post-emergence
flufenacet + isoxaflutole	K3+F2	✓	
pendimethalin	K3	✓	
S-metolachlor	K3	✓	
dimethenamid-p + pendimethalin	K1+K3	✓	✓
2,4-D	O		✓
bromoxynil	C3		✓
clopyralid	O		✓
clopyralid + florasulam + fluroxypyr	O+B+O		✓
dicamba	O		✓
dicamba + prosulfuron	O+B		✓
fluroxypyr	O		✓
mesotrione	F2		✓
mesotrione + nicosulfuron	F2+B		✓
pyridate	C3		✓
rimsulfuron	B		✓
prosulfuron	B		✓
mesotrione + terbuthylazine	F2+C1		✓
foramsulfuron + iodosulfuron-methyl-sodium	B+B		✓
nicosulfuron	B		✓

There are a high number of ALS inhibitors (HRAC group B) used in maize particularly targeted at the control of grass weeds such as black-grass. Additional use of group B herbicides within a rotation that includes maize with arable crops increases the risk of development of herbicide resistance in

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grass weeds such as black-grass and broad-leaved weeds such as fat hen, poppy and mayweeds. Mixtures with chemistry from other groups are necessary due to potential cross-rotation resistance issues to ALS chemistry.

Future action: Education program to maintain and improve knowledge of weeds and herbicide resistant weed management strategies. This should include the implementation and integration of cultural weed management practices, which may include diversification of crop systems, cultivations, use of cover crops, stubble management and stale seed beds.

New chemistries

The following actives and mixtures are approved for use in maize but are not currently available (UKPG, 2019): Bromoxynil + terbuthylazine, bromoxynil + prosulfuron, Dicamba + nicosulfuron, dimethenamid-p, isoxaflutole, flufenacet, foramsulfuron, iodosulfuron-methyl-sodium, mesotrione + S-metolachlor, terbuthylazine, nicosulfuron + thifensulfuron-methyl, thifensulfuron-methyl and tembotrione

Precision application

The wide-spaced rows of maize make it a suitable candidate for the precision application of herbicides between rows. A hooded sprayer could be used whilst the maize is small, at this time the crop is sensitive to some herbicides and applications can check growth.

4.7.4. Novel and emerging technologies

Weed detection in maize

Images from unmanned aerial vehicles have been used to successfully map weeds for use in site specific herbicide application (Pena *et al.*, 2013; Castaldi *et al.* 2017). Castaldi *et al., (*2017) reported a range of herbicide savings between 14% and 39% as compared with a uniform application.

Additionally, there are numerous methods for in field detection of weeds in maize crops as presented in Table 57 below.

Table 57: Methods for detecting weeds in maize crops

Crop size	Technique	Sensor	Reference
Early stage	Fluorescence imaging	Spectrometer	Longchamps *et al., (*2010)

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Early stage	Ultrasound	Ultrasonic	Andújar *et al., (*2011a, b)
Vegetative	Laser imaging	LiDAR-TLS	Andújar *et al., (*2013)
Vegetative	3D imaging	RGB-D	Andújar *et al., (*2016)

Adapted from Fernandez-Quintanilla *et al., (*2018)

Automated weed control and robotics

Automated machines, have been developed and tested specifically for maize. Kunz *et al., (*2018) evaluated camera steered mechanical weed control in maize. Camera steered hoeing resulted in 78% weed control efficacy compared to 65% using machine hoeing with manual guidance. The most abundant species weeds found throughout the untreated controls were fat hen (*Chenopodium album*), black-bindweed (*Polygonum convolvulus*), and Field pennycress (*Thlapsi arvense*). Mechanical intra-row elements controlled up to 79% of the weeds in the crop rows. Weed control efficacy was highest in the herbicide treatments with almost 100% followed by herbicide band-applications combined with inter-row hoeing.

Additionally, Frasconi *et al., (*2014) developed an automated machine that performs both inter row using a rigid tool, and selective flaming to provide weeding within maize rows. Other weeding robots that could be used on maize include; Ecorobotix and FaaS (small robot company).

4.7.5. Genetic tools

Herbicide tolerant crops

Herbicide tolerant maize varieties have been developed, specifically imidazoline resistant maize, which is sold as Clearfield® corn in the USA (Tan *et al*., 2005; BASF, 2019c). Although Clearfield® corn is not sold in the UK, Clearfield® oilseed rape is. If uptake of Clearfield oilseed rape is wide enough, there could be the commercial potential to introduce the cultivation of Clearfield® corn as well.

Genetically modified maize crops have been approved for use in other countries, which could potentially be grown in the United Kingdom for weed control. Many maize varieties have been produced with glyphosate and glufosinate tolerance. Maize has the most registered GM varieties of any crop, and herbicide tolerant maize varieties are authorised for cultivation in seventeen countries (Table 15). Although genetically modified maize is authorised for import into the European Union no herbicide tolerant varieties are authorised for cultivation. However, maize varieties modified to contain *Bacillus thuringiensis* genes for invertebrate pest control are cultivated in Spain (ISAAA, 2018), potentially leading the way for other genetically modified maize varieties to be cultivated.

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5. Weed species biology

For each weed species the key strengths and weaknesses in their lifecycle have been identified (Table 58), the information has been taken from the AHDB horticulture weed identification guide and AHDB/BASF encyclopaedia of arable weeds. The most suitable methods for the control of individual species is also identified (Table 59).

Table 58 Individual weed species, the crop in which they are most problematical in and the strengths and weaknesses of each weed

Common Name	*Latin name*	Crop	Strengths	Weaknesses
Annual Meadow grass	*Poa annua*	spring crops Soft fruit, Bedding, Nursey stock, Field veg, sugar beet	Germination all year round Quick life cycle (6 weeks) Regrow from fragments Long seed production	Cannot germinate from depth
Black-bindweed	*Fallopia convolvulus*	spring crops, WW, soft fruit, field vegetables	Long term seedbank Regrow from fragments Large no. seeds	Frost sensitive poor rooting at seedling stage
Black-grass	*Alopecurus myosuroides*	WW, WOSR	Medium term seed bank Flowers pre-harvest High seed production	Readily geminates and 80% in autumn One generation per year
Bracken	*Pteridium* spp.	Grassland	Rhizome growth Often grows in steep banks which makes control difficult Effective at shading other crops	New shoots susceptible to freezing if uncovered
Brome (sterile and great)	*Anisantha sterilis* and *Anisantha diandra*	WW, WOSR	Strengths competitive in early stages of growth. Spring germinators can set seed. Likes reduced cultivations. Over winters	Cannot germinate from depth Germination inhibited drought Dormancy quickly lost (light) Dark required for germination Short term seed bank One generation per year
Brome (meadow, soft rye)	*Bromus commutatus, Bromus hordeaceus,* and *Bromus secalinus*	WW, WOSR	Viable in straw due to late germination staggered emergence Large no. seeds	Burial enforces dormancy Short term seed bank Cannot germinate from depth
Charlock	*Sinapis arvensis*	WW, WOSR, Soft fruit, field vegetables	Long persistency in seedbank. High seed production. Short lifecycle. Germinates most of year. Can survive mild winters. Same family as OSR. Highly competitive. Tap rooted.	Hairy leaf to trap herbicide when young. Small seedlings shallow rooting

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Cleavers	*Galium aparine*	WW, WOSR, Soft fruit, Tree fruit, nursery stock, field vegetables	Germinates autumn and spring. Frost tolerant. Very competitive. Chokes crops. Seeds moved in grain. Difficult to clean from grain. Germinates from depth. High seed production	Shallow rooted when small, fibrous roots.
Common chickweed	*Stellaria media*	WOSR, Spring crops, Soft fruit, Bedding plants, Nursery stock, Field veg, Grassland, sugar beet	Many generations in a year. Germinates all year round. Survives winter. Roots from stems. Moved by birds, seed, vegetatively. High seed production.	Small roots when small, germinates after cultivation.
Common couch	*Elytrigia repens*	WW, SC, Soft fruit, Tree fruit, nursery stock, field veg	Spread by rhizomes and stolons, and seed Long germination and growing period (only dormant over winter) highly competitive High seed production	Sensitive to glyphosate Seedlings sensitive to crop completion/shading Short-term seed bank
Common fumitory	*Fumaria officinalis*	Soft fruit, field vegetables	Long term seedbank	Mainly germinates in spring. Single generation per year small seedlings
Common nettle	*Urtica dioica*	Perennial crops and grassland	spreads by stolons, grows from fragments Perennial Rapid growing seedlings Tough roots and rhizomes High seed production	seed less important, does not flower in first year grows in patches Germination delayed in closed vegetation germinates mostly from bare soil Intolerant to poor soil fertility Does not tolerate trampling
Common orache	*Atriplex patula*	Spring crops, Broadleaf crops, soft fruit, Nursery stock, Field veg	tap-rooted persistent in seed bank High seed production Viable of ingestion by birds and animals	grows above the crop spring germinating small seedlings doesn’t overwinter
Common poppy	*Papaver rheas*	WOSR, Most crops, Soft fruit	high seed production, autumn and spring germination, frost tolerant, Long term seed bank, herbicide resistance	Small seedlings can be easily removed

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Common sorrel	*Rumex acetosa*	Soft fruit, bedding, nursey stock, grassland	Spreads vigorously Spread from seed and root fragments Very difficult to remove from pots tolerant of shade fibrous root system Seeds survive ingestion Can germinate in dark High seed production	Not persistent in seed bank
Crane's bill	*Geranium* spp.	WOSR (competitive, cereals	Herbicide control (variable) High seed production (explosive pods spread over wide area) Protracted germination period Autumn germinating and can overwinter Medium term seed bank	susceptible to Sulfonylureas not highly competitive
Dandelion	*Taraxacum agg.*	soft fruit, fruit trees, nursery stocks, grassland	tap-rooted Long germination and flowering period High seed production Viable of ingestion by birds and animals multiple generations a year Wind dispersed overwinters Can regrow from root fragments	Germinates quickly Short-term seed bank
Docks	*Rumex* spp.	Soft fruit, Tree fruit, Nursery stock, Field vegetables, Grassland	Grows in compacted wet soils Overwinters as rosette. Can be a short term perennial. Reproduce by seeds (twice a year) and root fragments. Seed survives in slurry and manures. Germinates all year round.	small seedlings before tap toot develops Large rosettes very different to surrounding crop
Fat hen	*Chenopodium album*	Spring crops, Soft fruit, Field vegetables, sugar beet	Seeds spread by crop contamination, birds and mammals Highly persistent in seed bank long germination period (although only spring plants set seed) High seed production Stout tap root Tolerant to glyphosate Even very small plants can flower	Can be tall and grow above crops

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Field bean	*Vicia faba*	Winter wheat	Germinates in autumn/spring and overwinters Germinate from depth	Not persistent in seed bank if controlled in crop Entrance only as volunteer from previous cropping
Field bindweed	*Convolvulus arvensis*	Soft fruit, field vegetables	Persistent perennial weed Roots overwinter Can regenerate from root fragments Long term seedbank	Roots can be susceptible to freezing Seed set is unlikely in UK. Glyphosate Does not persist in long grass leys Seedlings and first-year plants are easier to control than older plants but even 3-week-old seedlings are able to regenerate from the root Leaves and stems difficult to wet with herbicides
Field horsetail	*Equisetum arvense*	Soft fruit, tree fruit, nursey stock, grassland	deep rooted rhizomes perennial Long growing period High spore production Strong competitor fungicidal properties Plants extracts can inhibit germination of 30 grasses species	Not competitive in tall crops intolerant to shading Horsetail does not respond as quickly as cereals to increased soil fertility
Speedwells	*Veronica spp.*	WOSR, Horticulture, soft fruit, wine growing, field vegetable, sugar beet	Germinates All year round. Several generations per season. Shoot fragments able to grow roots. High seed production. Long flowering season Long term seed bank	small seedlings, Not competitive fibrous roots
Fool's parsley	*Aethusa cynapium*	Soft fruit, Field vegetables, grassland	germinates all Spring/summer Cannot control with hormone herbicides Long term seedbank	
Goat willow	*Salix caprea*	Soft fruit, bedding, nursery stock	Deep rooting of seedlings Germinates April to August New potted stock provide ideal conditions for establishment Seeds can travel over a long distance	short flowering period

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Groundsel	*Senecio vulgaris*	Soft fruit, Tree fruit, Bedding, Nursery stock, Field vegetables, grassland	Can overwinter tough stems when fully grown Difficult to control selectively as brassica, but ok in cereals Strong tap root/fibrous	
Hairy bitter cress	*Cardamine hirsuta*	Bedding, nursery stock	Exploding seed pods Stick seeds when wet are easily transported Life cycle only 5-6weeks Moderate seed production Long flowering and germination periods stem fragments can re-root seedlings overwinter	
Hedge mustard	*Sisymbrium officinale*	WOSR, brassicas	Can overwinter tough stems when fully grown Difficult to control selectively as brassica, but ok in cereals Strong tap root/fibrous High seed production Long term seed bank	Light and stratification of seeds is required for germination Germination supressed by low nitrogen
Italian ryegrass	*Lolium multiflorum*	Winter wheat, WOSR	Spring and autumn germination Can Overwinter Post emergence Resistance seen High seed production thrives in crop rotation with pasture	Cannot germinate from depth
Knot-grass	*Polygonum aviculare*	Spring crops, Soft fruit, Tree fruit, Nursery stock, Field vegetables, sugar beet	Seed survive ingestion by birds Can regenerate after cutting Spring cultivation can increase plant no. Long term seed bank Residual herbicides do not work well High seed production	Only one generation per year Autumn germinating seeds not frost tolerant Low temperature required to break dormancy Susceptible to hormone and contact herbicides
Loose silky bent	*Apera spica-venti*	Cereals	Resistant light seeds travel a long distance Persistent in seed bank Seeds shed before crop matures which makes control difficult 92% efficacy of control is required for chemical control to reduce pops	Only germinates in autumn Not persistent in seed bank Grows in clumps

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Mayweeds	*Matricaria recutita and Tripleurospermum inodorum*	Winter wheat, OSR, Spring crops, Soft fruit, field vegetables	Long-term seedbank High seed production Germination all year round Can survive short term leys Overwinters survives ingestion by worms and some still viable after cattle Some tolerance to flaming Highly competitive with crops	Attacked by insects newly emerged plants slow growing
Oilseed Rape	*Brassica napus ssp. Oleifera*	winter wheat, Spring crops, Soft fruit, Field vegetables	Long term seed bank High seed production overwinter spring and autumn germinations Very competitive Thrives in reduced tillage Difficult to control selectively in brassica, but ok in cereals	Seedlings weak
Pale persicaria	*Persicaria lapthifolia*	Spring crops, Soft fruit, Nursery stock, Field vegetables	Persistent in seed bank Emergence to flowering takes 6 weeks High seed production Viable after ingestion by birds and rabbits Can survive up to 6 months in water	Spring germination only Stratification required for germination Light promotes germination susceptible to arbuscular-mycorrhizal fungi
Pansy	*Viola* spp.	Spring crops, Soft fruit, Nursery stock, Field vegetables, sugar beet	Persistent seeds Explosive seed head Overwinter prolonged germination period	Shallow germination Structurally weak
Parsley-piert	*Aphanes arvensis*	Winter wheat, Soft fruit	Germinates all year round Long term seedbank young plants overwinter drought resistant Promoted by reduced cultivation and direct drilling Long flowering period Viable after ingestion by cows	Require light to germinate Does not tolerate lime
Perennial ryegrass	*Lolium perenne*	Winter wheat	Germinates all year round Continues to grow through winter More common where pasture is in rotation	Short seed longevity Susceptible to glyphosate

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Pineapple weed	*Matricaria discoides*	Spring crops, Winter crops, Soft fruit, field vegetables	Forms dense mat, choking plants High seed production Germinates all year round Long term seed bank Can grow on compacted soils can germinate after flash of light Can overwinter Promoted by no till	Shallow germination Structurally weak
Potato	*Solanum tuberosum*	Spring crops	Tubers Can be poisonous to humans and livestock Only physical control in vegetable crops, fruits and legumes	Only occurs as volunteers, so easily predicted susceptible to very hard frost
Prickly sow-thistle	*Sonchus asper*	soft fruit, tree fruit, bedding, nursery stock, field vegetables	Wind dispersed From germination to seed set only 10weeks High seed production Long term seed bank Seeds viable after eaten by birds/cows/worms If cut early in the year, can produce further flower stalks Strong taproot Long seed production	Light to stimulate germination Seeds susceptible to soil solarisation Attacked by a range of insects
Ragwort	*Senecio jacobaea*	Grazing, hay production	High seed production Long term seed bank can survive grazing and transported by sheep Can live for up to 5 years Long flowering period Spreading rootstock Deep rooting	Seed not dispersed far from parent Takes more than 2 years to flower Flowering shoots not frost hardy Plants do not tolerate soil disturbance
Red dead nettle	*Lamium purpureum*	Spring crops, Soft fruit, Tree fruit, Nursery stock, Field vegetables	Long germination period long flowering period- found "in fruit for 8 months of year" Can overwinter Can reshoot after spring cultivations and go on to establish/set seed Long term seed bank Encouraged by minimal cultivation	Needs light to geminate cannot germinate from depth Not very competitive and can be shaded out

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Redshank	*Persicaria maculosa*	Spring crops, Soft fruit, Tree fruit, Nursery stock, Field vegetables, sugar beet	Seeds remain on plant and can contaminate grain During cultivations, plant fragments can root at the nodes self-pollinating Very persistent in seed bank Unharmed if eaten by horse, cattle and deer, birds Moderate seed production Seeds Can float in water Taproot	Frost susceptible shallow germination Only germinates in spring/early summer
Rushes	*Juncaceae*	Grassland	Competitive once established Long term seed bank Can form dense patches which limit grazing once large Encouraged by over grazing	Grows in wet habitats only Benefits from wet summers
shepherd's-purse	*Capsella bursa-pastoris*	OSR, Soft fruit and field vegetables, sugar beet	Germinates all year round Flowers most of year plants overwinter Well transported seeds Many generations a year seedling 2-6 leaves are tolerant to flaming Very long seedbank High seed Production flower spikes cut prematurely can still produce viable seed	Stratification plus light needed to break dormancy shallow germination
Small nettle	*Urtica urens*	Broadleaf crops, Soft fruit, field vegetables, grassland	Plants can overwinter in sheltered areas Seeds transported by animal ingestion Long term Seedbank High seed production Tolerant to heavy shading	Poorly competitive in vigorous cereal crops susceptible to frost
Smooth sow thistle	*Sonchus oleraceus*	Winter crops	High seed production Long germination period Long term seed bank flowers self-fertile If cut in flower seeds maybe viable in flower for 5 months of the year Can withstand moderate frosts Partly viable after ingestion by birds Topping stems can lead to more flowering stems	Light to stimulate germination seedlings do not like shading cannot withstand repeated trampling often grazed by rabbits/hares Attacked by a range of insects, fungi and bacteria

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Spear and creeping thistle	*Cirsium* spp.	WOSR, spring crops, cereals, Grassland, grassland, Soft fruit, Tree fruit, Nursery stock, Field vegetables	Perennial Extensive creeping rhizomes which can regenerate Waxy leaves reduce herbicide adhesion High seed production Long term seedbank	Less likely to set fertile seeds than other thistles (3% viable)
Weed beet	*Beta vulgaris*	Sugar beet	High seed production Long-term seedbank If cut in flower seeds maybe viable Topping stems can lead to more flowering stems	Grows above beet crop Uncompetitive in non-beet crops Seeds perish on surface
Wheat	*Triticum aestivium*	WOSR, Spring crops	Germinate in spring/autumn Cannot be controlled with herbicides in other cereals	On generation per year Seed unlikely to remain viable for more than two years
Wild carrot	*Daucus carota*	Perennial crops	Persistent in seedbank Abundant seeds Over winter strong tap root in second year	susceptible to insect attack Biannual
Wild radish	*Raphanus raphanistrum*	WOSR, spring crops, Soft fruit, field vegetables	Found in manures Moderate seed production Long term seed bank Tap root If grazed/chopped can regrow from root Drought resistant	Not frost tolerant but will persist in a mild winter Susceptible to typical brassica pests e.g. cabbage stem beetle
Wild-oat	*Avena fatua*	WW, WOSR, Spring crops (all competitive), Soft fruit	Long and variable germination period Resistant to frost winter and wild oats can occur in same field Can emerge from depth (10-15cm) More persistent in soil than other grasses Resistant populations well spread Can regrow, so whole plant removal required	Preventing seed return enables populations to decrease within 2-3 years (but labour intensive) small plants frost sensitive, so delayed sowing possible susceptible to competition at early growth stages
Willow herbs	*Epilobium* spp.	Soft fruit, tree fruit, bedding, nursey stock	Seeds dispersed over large distances Long germination period High seed production After germination produces root stems Reproduction by seed and lateral root stems can regenerate from root fragments Perennial	Shallow germination short term seedbank

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Table 59 The most suitable methods for controlling individual weed species and the crops they are most likely to be problematical in

			Non-chemical										Cultural									
Common Name	*Latin name*	Crop most likely to be problematical in.	weed wiping (above crop)	Ploughing	Harrow/cultivate/till (shallow)	Stale seed bed and cultivate	Stubble and seedling	Mowing/Cutting	Clean machinery	In field weeding	Flaming/steaming	Hand weed includes Hortic	Varied Crop Rotation	change of sowing date	Competitive crop/ground cover	Mulching (all)	Break crop or long term ley	Grazing	Seeds left at surface	Good harvesting practise	increase sowing rates/ decrease	Resistance recorded in UK
Annual Meadow grass	*Poa annua*	Spring crops, Soft fruit, Bedding, Nursey stock, Field veg, sugar beet		M		L				L	M				M							Y
Black-bindweed	*Fallopia convolvulus*	Spring crops, WW, soft fruit, field vegetables, sugar beet		L	M	L	M	M	L	L												N
Black-grass	*Alopecurus myosuroides*	WW, WOSR		H			M	M	M	M		M	H	H	M		H					Y
Bracken	*Pteridium* spp.	Grassland	H	M	M			M		M	M				L			M				N
brome (sterile and great)	*Anisantha spp*	WW, WOSR		H		M	H	M	L	L			M	M	M				M			Y
Brome (meadow, soft rye)	*Bromus* spp.	WW, WOSR		H		M	H	M	L	L			M	M	M				M			Y
Charlock	*Sinapis arvensis*	WW, WOSR, Soft fruit, field vegetables	H	M	H	H	M	H		H	H	H		L								N
Cleavers	*Galium aparine*	WW, WOSR, Soft fruit, Tree fruit, nursery stock, field vegetables		M	M	H	M	M		M	M	M	H	L								N
Common chickweed	*Stellaria media*	WOSR, Spring crops, Soft fruit, Bedding plants, Nursery stock, Field veg, Grassland, sugar beet				H		M	M	H	M	H			L			M			L	Y
Common couch	*Elytrigia repens*	WW, Spring crops, Soft fruit, Tree fruit, nursery stock, field veg		L	M	M	H	H	L	L			H	L			H	H				N
Common fumitory	*Fumaria officinalis*	Soft fruit, field vegetables				H				H	H	M		H		H						N
Common nettle	*Urtica dioica*	Perennial crops and grassland			L	L		M		M								M				N

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			Non-chemical										Cultural										
Common Name	*Latin name*	Crop most likely to be problematical in.	weed wiping (above crop)	Ploughing	Harrow/cultivate/till (shallow)	Stale seed bed and cultivate	Stubble and seedling	Mowing/Cutting	Clean machinery	In field weeding	Flaming/steaming	Hand weed includes Hortic	Varied Crop Rotation	change of sowing date	Competitive crop/ground cover	Mulching (all)	Break crop or long term ley	Grazing	Seeds left at surface	Good harvesting practise	increase sowing rates/ decrease	Resistance recorded in UK
Common orache	*Atriplex patula*	Spring crops, Broadleaf crops, soft fruit, Nursery stock, Field veg			H	L				M	H	M					H	H				N
Common poppy	*Papaver rheas*	WOSR, Soft fruit		M	M	M	L			M	H	H	M									Y
Common sorrel	*Rumex acetosa*	Soft fruit, bedding, nursey stock, grassland								L		L					X	L				N
Crane's bill	*Geranium* spp.	WOSR (competitive, cereals		M		H	H			M	M	M	H	L								N
Dandelion	*Taraxacum agg.*	soft fruit, fruit trees, nursery stocks, grassland		H	L	M	M	L		M												N
Docks	*Rumex* spp.	Soft fruit, Tree fruit, Nursery stock, Field vegetables, Grassland	H	M	H		M	M	H	M	H	H	L		M		L	M	X			N
Fat hen	*Chenopodium album*	Spring crops, Soft fruit, Field vegetables, sugar beet	L	L	M	M	M		M	M	H	M	M	L								N
Field bean	*Vicia faba*	Winter wheat																	H			N
Field bindweed	*Convolvulus arvensis*	Soft fruit, field vegetables		M		M	L		M	L	H		L				H	H				N
Field horsetail	*Equisetum arvense*	Soft fruit, tree fruit, nursey stock, grassland		L	X	X	X	L								L						N
Fool's parsley	*Aethusa cynapium*	Soft fruit, Field vegetables, grassland				H				H	H	M	M				M					N
Goat willow	*Salix caprea*	Soft fruit, bedding, nursery stock										H										N
Groundsel	*Senecio vulgaris*	Soft fruit, Tree fruit, Bedding, Nursery stock, Field vegetables, grassland, sugar beet			M	H	M			H	H	H	M		M		M					N
Hairy bitter cress	*Cardamine hirsuta*	Bedding, nursery stock			M			M	M	M		H						L				N

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			Non-chemical										Cultural									
Common Name	*Latin name*	Crop most likely to be problematical in.	weed wiping (above crop)	Ploughing	Harrow/cultivate/till (shallow)	Stale seed bed and cultivate	Stubble and seedling	Mowing/Cutting	Clean machinery	In field weeding	Flaming/steaming	Hand weed includes Hortic	Varied Crop Rotation	change of sowing date	Competitive crop/ground cover	Mulching (all)	Break crop or long term ley	Grazing	Seeds left at surface	Good harvesting practise	increase sowing rates/ decrease	Resistance recorded in UK
Hedge mustard	*Sisymbrium officinale*					H		M		M												N
Italian ryegrass	*Lolium multiflorum*	Winter wheat, WOSR		L	L		M		H				L	M			H					Y
Knot-grass	*Polygonum aviculare*	Spring crops, Soft fruit, Tree fruit, Nursery stock, Field vegetables, sugar beet		L		M	M			M	M		L									N
Loose silky bent	*Apera spica-venti*	Cereals		M	X					M			M	M			H					Y
Mayweeds	*Matricaria recutita and Tripleurospermum inodorum*	Winter wheat, OSR, spring crops, Soft fruit, field vegetables		M	M	M	X			H	M	M	L								M	Y
Oilseed Rape	*Brassica napus ssp. Oleifera*	winter wheat, Spring crops, Soft fruit, Field vegetables			H	H	H			H	H	H	H						H			N
Pale persicaria	*Persicaria lapthifolia*	Spring crops , Soft fruit, Nursery stock, Field vegetables		M	M	M				M	M	M	M									N
Pansy	*Viola* spp.	Spring crops, Soft fruit, Nursery stock, Field vegetables, sugar beet			M	H	H	H		M	H	M	L									N
Parsley-piert	*Aphanes arvensis*	Winter wheat, Soft fruit		H	H	H				M	H	M	H				M					N
Perennial ryegrass	*Lolium perenne*	Winter wheat							H									H				N
Pineapple weed	*Matricaria discoides*	Spring crops, Winter crops, Soft fruit, field vegetables			M	M			M	H	H	M										N
Potato	*Solanum tuberosum*	Spring crops			H					H			M		M		M			H		N
Prickly sow-thistle	*Sonchus asper*	soft fruit, tree fruit, bedding, nursery stock, field vegetables, sugar beet		H	M	M	H			M	M	L						M				Y
Ragwort	*Senecio jacobaea*	Grazing, hay production		H	H	H		M		M		M			L			M				N

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			Non-chemical										Cultural									
Common Name	*Latin name*	Crop most likely to be problematical in.	weed wiping (above crop)	Ploughing	Harrow/cultivate/till (shallow)	Stale seed bed and cultivate	Stubble and seedling	Mowing/Cutting	Clean machinery	In field weeding	Flaming/steaming	Hand weed includes Hortic	Varied Crop Rotation	change of sowing date	Competitive crop/ground cover	Mulching (all)	Break crop or long term ley	Grazing	Seeds left at surface	Good harvesting practise	increase sowing rates/ decrease	Resistance recorded in UK
Red dead nettle	*Lamium purpureum*	Spring crops, Soft fruit, Tree fruit, Nursery stock, Field vegetables, sugar beet			H	H				H	H	H			H							N
Redshank	*Persicaria maculosa*	Spring crops, Soft fruit, Tree fruit, Nursery stock, Field vegetables, sugar beet			M	M			H	H	M	M			H						H	N
Rushes	*Juncaceae*	Grassland	H					M							M	X		H				N
shepherd's-purse	*Capsella bursa-pastoris*	OSR, Soft fruit and field vegetables, sugar beet			H	H	H			M	H	M						L				N
Small nettle	*Urtica urens*	Broadleaf crops, Soft fruit, field vegetables, grassland			M	H		L		H	H	M						L				N
Smooth sow thistle	*Soncus oleraceus*	Winter crops, sugar beet			M			M		H			M		M		H	H				N
Spear and creeping thistle	*Cirsium* spp.	WOSR, Spring crops, cereals, Grassland, grassland, Soft fruit, Tree fruit, Nursery stock, Field vegetables	M	L	M		M	M		L			M	M	L				X			N
Speedwells	*Veronica spp*	WOSR, Horticulture, soft fruit, wine growing, field vegetable, sugar beet		L	M	H	M			H	H	M				M						N
Weed beet	*Beta vulgaris*	Sugar beet	H					H				H	H	L					M			
Wheat	*Triticum aestivium*	WOSR, Spring crops			M	H							M									N
Wild carrot	*Daucus carota*	Perennial crops			M	M		M				M					M					N
Wild radish	*Raphanus raphanistrum*	WOSR, spring crops, Soft fruit, field vegetables		M		H	M			H	H	H		L	M							N
Wild-oat	*Avena fatua*	WW, WOSR, Spring crops (all competitive), Soft fruit		L	L	H	L		M	M		M	H	L			M		H		M	Y
Willow herbs	*Epilobium* spp.	Soft fruit, tree fruit, bedding, nursey stock				H		L		H	H	M				M		H				N

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Opportunity for control : L- Low M - Moderate H - High X - no control

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6. Recommendations and priorities

Increase access to and use of current knowledge

Growers are probably unaware of all the information that is available to them to help with weed management. That knowledge is often kept within the individual sectors (e.g. crops or horticulture).There is much relevant work on weeds that was once funded by MAFF or Defra and it is often hard to find, with only the current researchers knowing of its existence and so it will be lost when they leave the industry. Peer reviewed information is unavailable to many whom it could be beneficial. Consequently making better use of existing knowledge is a very high priority. Enabling greater access to it should be a high priority and eroding barriers between different cropping sectors through putting the weed biology at the centre of the knowledge will enable good progress in all sectors. Decision support tools that incorporate up to date information on weed management could also be developed. A targeted central location storage for weed control that covers all crop sectors should be developed with simple messages that would also harness farmer-to-farmer knowledge learning.

Link practical knowledge better with fundamental research

As in many other science disciplines there is too great a gap between those who undertake fundamental research and those who are looking to apply their findings in practice. There is huge scope to derive more benefits from research. To do so needs more involvement of those with an in-depth and practical understanding of weed management in the setting of project objectives. A good example would be to better focus research on those areas where gaps in the understanding of weed biology are hindering the development of better control options.

Maximise herbicide availability

The availability of herbicides continues to decline. Further actives will be withdrawn and there are unlikely to be many new herbicides to replace them. Good stewardship of current active substances is vital and requires companies, regulators and users to work together to retain them through continued support and prevention of bad practice.

Retaining product efficacy by minimising resistance and ensuring good practice, is something over which agronomists and growers have considerable ‘control’. Much is known about the risks of weeds developing resistance to herbicides. Pro-active identification of the high risk uses/situations which could select for resistance should be a priority. Weed management strategies for these high risk situations should be agreed and communicated widely and monitoring of weed species shifts and

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emerging cases of herbicide resistance in relation to herbicide use and other integrated weed management strategies is needed

Agree funding for Integrated Weed Management (IWM)

Both growers and politicians recognise the need to maximise non-chemical control of weeds and develop integrated weed management. However, research in these areas typically does not attract commercial funding. To ensure future development of sustainable weed management solutions will require collective funding from farmers/growers and/or those promoting non-chemical approaches. The availability of suitable funding mechanisms to drive what are often too costly and less effective options is not an industry priority. However, if government and industry can work together it will be possible to make more progress than is currently the case.

Weed research and approaches to control need to be considered more strategically

Reviewing and compiling information for this review has highlighted how the current approach to weed control is very often based on the use of herbicides against specific weeds and/or in specific crops. It is very clear however, that as with nutrient and soil management there is considerable scope for a more strategic approach that is relevant to the whole cropping system which can then be deployed in specific crops. A key recommendation is that there should be a more strategic approach to weed research and control.

Putting weed biology/weed life cycles at the heart of control strategies will enable more rapid progress across multiple crops. Interventions need to target the weakest stage of the weed lifecycle, whilst maximising the tolerance of the current and future crops. A cross-sector, multi-annual approach is therefore vital.

Understand selectivity between crops and weeds

All technologies require a differential selectivity between the crop and the weed. Development of appropriate techniques will build on those principles. Selectivity can be achieved by a number of routes:

- **Spatial selectivity** is a major opportunity for chemical and non-chemical approaches and irrespective of the crop we need to be able to identify one from the other. The wider the row spacing the greater the opportunities. This could be optical and ground or satellite based. Additionally alternative ways of highlighting where the crop is ('plant marking') should be considered, such as by seed treatments or genetic. We now have much better location within fields and that is already very helpful. Agreeing criteria and operating speeds is a key need to enable wider deployment of all technologies

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- **Temporal selectivity** enables treatments to be made when crops are more tolerant or weeds more sensitive. Just as pre-emergence herbicides are widely used, such approaches should be considered for non-chemical approaches.

- **Crop and weed tolerance** is critical for herbicides, but also for non-chemical approaches. Information on what it takes to kill a weed and what it takes not to kill a crop will be vital considerations in enabling current and new non-chemical approaches, but also in prioritising herbicide options. The screening of herbicides for minor crops could be advanced, and cost minimised, through a more strategic approach which considers weed and crop tolerance independently and enables a more focussed approach to deliver quicker results. In parallel the regulatory issues of using herbicides on a wider range of crops will need to be addressed and requires a combined grower, regulator and retailer approach.

Within each individual section of the review there are key future actions highlighted. These have been collated as a list in Appendix 1 with a suggested funding route included. Where possible these have been sorted into short, medium and long-term requirements.

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8. Appendix 1: Knowledge gaps and future actions

Key

Timescale: *ST=Short term, MT = Medium term, LT = Long term;*

Scale of impact: *L = Low, M = Medium, H = High*

Likelihood of progress: *L = Low, M = Medium, H = High*

8.1. Altering row widths and seed rates to improve competitiveness

Crop	*Future action*
Horticulture	Evaluate different row configurations of carrots and parsnips and plant populations which would allow hoeing, but remain a cost-effective growing system.
Legumes Maize	Can row width be manipulated to improve weed suppression and optimise yield?
Potatoes	Examine the effect of row width on the date of canopy closure and weed control.

Funding sources: Information is already available although some of it may be dated and from outside the UK. The subject area would benefit from KE and further research to support the knowledge gaps.

Constraints: Effects on yield and market requirements for produce size.

Timescale	ST	Scale of impact	H	Likelihood of progress	H

8.2. Improving the competitive ability of grassland against weeds through soil management

Crop	*Future action*
Grassland	Further work is needed on organic grassland management especially in upland areas, where soil improvement and herbicide application to ferns/rushes is key to competitive grass establishment.

Funding sources: A limited market for individual research projects, this area could benefit from information collected from soil projects or a co-ordinated farmer's group approach.

Constraints: size of market

Timescale	LT	Scale of impact	L	Likelihood of progress	L

8.3. Non inversion tillage, strip tilling and direct drilling – establishment of crops by non-traditional methods

Crop	*Future action*
Sugar beet	Evaluate minimal cultivation systems such as direct drilling and strip tillage for establishing crops and assess their effects on weed populations

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Horticulture	Evaluate strip-till and minimum tillage as establishment methods for field horticulture crops. Which crops it is most suitable for? Also evaluate the problems with reduced tillage and investigate ways to overcome it.
Horticulture	Evaluate different cultivation techniques and timings on the control of volunteer potatoes in the following crop.
Horticulture	Evaluate strip tillage effects on weed control and test if brassicas can be successfully established in a strip till system (so that the band of disturbance to pre-planting herbicide is minimised and/or can be applied at planting).
Horticulture	Evaluate strip till for pumpkins to provide alternative approaches for weed control.
Horticulture	Consider the use of transplanted flower modules over direct drilling
Horticulture	Evaluate the potential of non-inversion tillage in the production of HNS.
Legumes Maize	Evaluate the establishment of legumes and maize after non-inversion tillage, strip tilling and direct drilling
Horticulture	Evaluate planting the crop using GPS or RTK guidance systems and the utilisation of non-chemical weed controls such as hot water mulching, electrical weeding or foam weeding as inter – row treatments.

Funding sources: Information is already available from the UK. The subject area would benefit from KE and further research to support the knowledge gaps.

Constraints - none

Timescale	MT	Scale of impact	H	Likelihood of progress	H

8.4. Physical alternatives to herbicides for in-crop weed control including between crop rows, spot treatment and patch spraying.

Crop	*Future action*
All crops	Investigate the potential for thermal techniques such as, electrical, flame or hot foam weeding techniques for use on **stale seedbeds, between crop rows and spot treatment** – environmental impacts, costs, and efficacy.
All crops	Investigate the use of electrical weeding for preventing weed seed return
All crops	Identify the weed density threshold for patch spraying of weeds to prevent weed seed return, economic gains/losses, levels of potential weed seed returned
Cereals Oilseeds	Assess any reduction in grass weed levels, particularly black-grass, over a number of years of hand rogueing, and conduct a cost-benefit analysis
Cereals Oilseeds	Assess weed thresholds in cereals where the yield losses are higher than those related to the use of mechanical weeding and yield benefits are gained by mechanical weeding
Cereals Oilseeds Potatoes Maize	Evaluate, mechanical weeding particularly in conjunction with guidance technology, such as real time kinematics (RTK).

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Cereals Oilseeds	Investigate the potential for temperature activated polymer seed coats and decaying seed coats to delay cereal seed emergence
Grassland	The effectiveness of long term mechanical strategies (e.g. cutting, bruising) need to be compared to asulam application for bracken control.
Grassland	Investigate the use of electrical weeding on perennials in grassland, including effective long term usage and quantification of root damage.
Grassland	Investigate the use of liquid carbon dioxide as an alternative control method for bracken control.
Horticulture	Carry out further research on seed meals and their potential to contribute to weed control in container production. Particularly for Liverwort *(Marchantia polymorpha)*.
Horticulture	Evaluate brushing of weeds, identification and spot weeding with vision guided technology, laser / electric weeders other novel techniques that are likely to be crop safe in protected ornamentals.
Horticulture	Evaluate electric weeders potential to control weeds between crop rows as a spot treatment to compliment hand weeding in the future.

Funding sources: Information is already available and research is continuing in this area. It is limited by a lack of commercially available kit.

Constraints – Availability of kit

Timescale	ST	Scale of impact	H	Likelihood of progress	M

8.5. Biological control

Crop	*Future action*
Rhubarb	Investigate the use of the biocontrol rust for Himalayan balsam control.
All crops	Investigate native invertebrate species that feed on and/or parasitise seeds of grass weed species, but do not affect cereals, and how these species could be exploited.
All crops Grassland	Investigate biological control options for perennial weed control, such as dock, thistles and nettles.

Funding sources: Progress in this area is slow in field crops. This area would benefit from more fundamental research in the search for suitable organisms.

Constraints - Legislation

Timescale	LT	Scale of impact	L	Likelihood of progress	L

8.6. Use of cover crops

Crop	*Future action*
Sugar beet Legumes	Evaluate the use of a cover crop prior to the crop for weed suppression.
Horticulture	Further evaluate cover crops for effects on weed suppression, and evaluate the best type of cover crop for different rotational scenarios.

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Horticulture	Evaluate the potential of cover crops which could be sprayed off with glyphosate prior to carrying out strip tillage where crop rows are to be planted to utilise the cover crop as a mulch.
Potatoes	Evaluate the use of a cover crop prior to potatoes for weed suppression and effects on soil pests and diseases.
Maize	Cover crops are valuable for inclusion in the maize crop because they are effective at reducing nitrate, phosphorus and sediment losses to surface water and nitrate losses to ground water in the winter after maize harvest.

Funding sources: There is a wealth of existing information on the use of cover crops but less is directed at the effects on weed control and in the UK situation. This can be informed from other crops and literature reviews and the known biology (such as emergence patterns of the weeds) so that a narrower range of options are tested. This would be ideal for a participative 'Farmer Innovation Group' where the design, approach, recording and interpretation is shared between growers.

Constraints – No specific constraints.

Timescale	ST	Scale of impact	H	Likelihood of progress	M

8.7. Intercropping and companion cropping

Crop	*Future action*
All crops	Evaluate options for intercropping and assess their effects on weed competition.
Legumes	The use of intercropping and companion cropping should be evaluated in legumes, not just for weed suppression but also to take advantage of the value nitrogen fixing crops bring to the rotation.

Funding sources: Currently a topic of limited ongoing research in the UK, whilst many farmers are trying it on farm. A review of the current situation would be worthwhile so that a research project could test a narrow range of options. This would be ideal for a participative 'Farmer Innovation Group' where the design, approach, recording and interpretation is shared between growers.

Constraints - none

Timescale	ST	Scale of impact	H	Likelihood of progress	H

8.8. Physical mulches

Crop	*Future action*
Horticulture	Evaluate the potential for use of free flowing biodegradable mulches such as recyclable plastic, woodchip and straw mulches in a range of vegetable crops for as an alternative to residual herbicides for weed control and effects on the crop.

Funding sources: This work could compliment cover crops and intercropping research.

Constraints - none

Timescale	MT	Scale of impact	M	Likelihood of progress	L

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8.9. Competitive cultivars

Crop	*Future action*
All crops	Evaluate varieties in existing variety trials for competition against weeds by excluding herbicides from small areas.
All crops	Produce a ranking system to allow growers to select cereal cultivars based on their weed competitive traits.
Horticulture	Consider flower and bulb varieties that show competitive traits over weeds
Potatoes	Competitive cultivars could be selected for in breeding programmes, but their use depends on the suitability of the produce for the target market.

Funding sources: Development of competitive cultivars for weed control has not been a priority. Since the introduction of hybrid barley the opportunity for further development in other crops has increased. This area will tend to be driven by commercial companies.

Constraints – Commercially driven

Timescale	ST	Scale of impact	H	Likelihood of progress	M

8.10. Specific problems created by loss of active substances

Crop	*Future action*
Sugar beet	The availability of herbicides for broad-leaved weed control with the removal of PMP and DMP, will be limited to ethofumesate, lenacil, triflusulfuron-methyl, clopyralid, metamitron quinmerac and dimethenamid-P. Growers will need to be informed of the most effective weed control mixtures and programmes optimising the use of these actives and to maintain their longer-term efficacy.
Sugar beet	The recent withdrawal of neonicotinoid seed dressings has led to growers increasingly asking about mixing insecticides with herbicides. There is a lack of information in this area particularly regarding the required water volumes and potential crop damage.
Grassland	Promotion of alternatives to asulam, or novel application technologies to limit the environmental impact of the chemical.
Grassland	Completion of trials for drone spraying for bracken control.
Grassland	Cost benefit analysis of precision spraying glyphosate and asulam in comparison with alternative methods.
Grassland	Economic analysis of the practicalities of using hi-tech approaches on grassland, especially where margins can be small, and economic investment is limited.

Funding sources: The loss of a herbicide can have little effect of a range of alternatives are available, where no alternatives are available then the effect could be serious. Support from the Levy bodies would be preferable to give impartial testing of all alternatives, particularly where physical methods of control have to be incorporated.

Constraints – prior information of losses, Legislation

Timescale	MT	Scale of impact	M	Likelihood of progress	L

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8.11. Improving herbicide performance – water conditioning products and adjuvants

Crop	Future action
All	The use of adjuvants and safeners with single actives and mixtures should be assessed to maximise efficacy and minimise crop damage
All	Investigate the use of adjuvants or other substances to 'hold' residual herbicides at the surface and increase crop safety.
All	Investigate soil stabilisers to prevent the wind removing residual herbicides.

Funding sources: An area for commercial funding where a benefit can be seen. Outside of this for smaller markets impartial funding should be secured. The benefit to a range of crops should be sought rather than crop specific research.

Constraints – market, legislation

Timescale	ST	Scale of impact	H	Likelihood of progress	M

8.12. Chemical alternatives to glyphosate and diquat

Crop	Future action
Sugar beet	The importance of the need to start clean at drilling by application of a non-selective herbicide, such as glyphosate should be demonstrated, although the approval of glyphosate will be up for revision on 12 December 2022. BBRO should seek active involvement in projects looking at alternatives to glyphosate.
All crops	Evaluate alternatives to diquat and glyphosate for stale seedbed creation and crop desiccation
Horticulture	Evaluate alternatives to glyphosate for control of weeds between the crop rows.
Horticulture	Investigate alternatives to glyphosate for weed control over the dormant period in rhubarb and asparagus
Potatoes	Evaluate alternatives for the loss of diquat for early weed control in potatoes.

Funding sources: Funding in this area is already underway to look for alternatives to diquat. Glyphosate is a key active in UK farming and alternatives need to be in place before 2022.

Constraints – Legislation

Timescale	ST	Scale of impact	H	Likelihood of progress	H

8.13. Precision application of herbicides

Crop	Future action
Horticulture	Precision application and placement of herbicides sprayed onto the surface of the protected ornamentals growing media using automation to maximise efficiency and improve crop safety.

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Horticulture	Investigate precision application and placement of herbicides as band treatments between crop rows for improved efficacy and crop safety.
Grassland	Investigate precision application by targeted spot spraying/non-chemical treatment.

Funding sources: Band spraying has already been evaluated to a limited extent in arable crops and information can be provided through KE. Band sprayers are available and their use is limited by the label recommendations use of herbicides. Where needs are identified then these areas should could supported by industry or levy bodies.

Constraints - Legislation

Timescale	MT	Scale of impact	L	Likelihood of progress	L

8.14. Retaining current herbicides, evaluating new herbicides and assessing the potential of new herbicides for use in minor crops.

Crop	*Future action*
Horticulture	Inform growers of the most efficient and crop safe weed control mixtures and which and where products should be utilised within weed control programmes.
Sugar beet	Understand the effectiveness of herbicides as single actives, products and tank mixes on a range of commonly occurring weeds. A combination of field experimentation and container-based studies will enable a wider range of weeds and environmental conditions (such as high and low temperatures, wet and dry soil conditions) to be tested.
Horticulture	Continue to evaluate new herbicide actives which are being developed for oilseed rape in vegetable brassicas to widen the range of actives available.
Horticulture	Assess any new chemistry's suitability for the control of key weeds under protection.
Potatoes	Variety sensitivity testing to herbicides needs to be included in herbicide programme evaluation.
Legumes	PGRO to work with AHDB to evaluate herbicides for minor uses in legumes

Funding sources: This area is already supported by funding from AHDB with support for commercial companies. This area needs to be supported across crops to streamline the process, and use information on weed susceptibilities already known.

Constraints – Commercial confidentiality, legislation

Timescale	ST	Scale of impact	H	Likelihood of progress	H

8.15. Monitoring of changes in weed species and herbicide resistance development

Crop	*Future action*
All crops	Weed surveys in crops would highlight the challenges being faced by growers and could be used to target herbicides and control measures for evaluation.
All crops	Conduct 'resistance audits' in crops where herbicide withdrawal has increased the reliance on actives with a high risk of resistance, e.g. ALS herbicides. A range of grass

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	and broad-leaved weeds need to be included in these audits, together with the risks of using high risk active substances in other crops in the rotation.
All crops	Monitor shifts in weed species in the UK, to highlight emerging problems
All crops	Monitoring for emerging cases of herbicide resistance in UK weed species: changes in resistance levels and new cases of resistance
All crops	Evaluate the success of resistance prevention strategies, including extensive knowledge transfer to growers and advisors

Funding sources: Herbicide resistance is a headline subject and attracts funding from fundamental, levy and commercial sources. Herbicide resistance is responsible for significant yield losses and increases in variable costs. The subject area would benefit from KE and further monitoring.

Constraints - none

Timescale	LT	Scale of impact	M	Likelihood of progress	H

8.16. Sensing and predicting the need for weed control.

Crop	*Future action*
All crops	Evaluate camera or RTK guided inter and intra-row mechanical weeding combined with and without band spraying
All crops	Continue research into precision herbicide application, particularly in conjunction with weed mapping technologies
All crops	Continue the development of satellite and within field detection technology to distinguish between grass weeds and cereals

Future funding: Much research has been done in this area, existing information available, but continual technological developments require further evaluation. The subject area would benefit from KE and non-biased comparisons of technology.

Constraints – Commercial confidentiality

Timescale	MT	Scale of impact	M	Likelihood of progress	M

8.17. Keeping a watching brief on incoming technologies and demonstration of incoming technologies to the industry.

Crop	*Future action*
All crops	Keep a watching brief on developing technologies, liaise and interact with industry and research establishments.
Legumes	Keep a watching brief on incoming technologies, liaise and interact with industry and research establishments
Horticulture	Evaluate and then demonstrate the use of new mechanical weeding machinery such as the Garford Robocrop In-row weeder
Horticulture	Examine the potential of dock twirler' in horticulture, as the appearance of remaining plants would not be effected, however impact on rooting systems would need to be accessed.

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Grassland	Investigate the commercial availability of the Binch & Fox automated precision sprayer for docks in the UK.

Future funding: New introductions of technology will require further evaluation. Most information will be generated through commercial sources but non-biased evaluations and farmer testing would be beneficial.

Constraints – commercial confidentiality

Timescale	LT	Scale of impact	H	Likelihood of progress	H

8.18. Digital tools – Decision support systems, Apps and internet tools

Whilst some systems are available, uptake can be low. With technological improvement access is becoming easier. User friendliness is key.

Crop	*Future action*
All crops	Simplify the weed identification apps to make them more user-friendly and ensure growers are aware of it and able to use the technology
Cereals Oilseeds	Integrate of existing IWM Decision support systems from countries outside UK for UK conditions and use in UK
All crops	Develop decision support systems and prediction modelling for weed control in different crops other than cereals and oilseeds

Future funding: This is likely to be from commercial sources.

Constraints - none

Timescale	MT	Scale of impact	M	Likelihood of progress	H

8.19. Genetic tools

Crop	*Future action*
All crops	Identify weed UK species of priority for weed genome sequencing and uses of the technology
All crops	Develop herbicide tolerant crops using CRISPR technology
All crops	Investigate the potential for the use of CRISPR technology for use in removing target site herbicide resistant mechanisms in weeds
All crops	Examine the weed species shifts that could be associated with the introduction of genetically modified crops and CRIPSR herbicide tolerant crops, herbicide resistance prevention and IWM strategies
All crops	Keep a watching brief on genetic tools, liaise and interact with industry and research establishments. Particularly for horticulture, potatoes, legumes, and maize

Future funding: Research in this area is likely to be fundamental, or commercially funded. Discoveries are most likely to be patented and commercially sensitive.

Constraints - Legislation

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Timescale	LT	Scale of impact	M	Likelihood of progress	L

8.20. Herbicide tolerant crops

Crop	*Future action*
Sugar beet	Control of ALS resistant grass weeds such as black-grass and broad-leaved weed such as fat hen in Conviso® Smart sugar beet will pose major risks weed populations will be exposed to post-emergence applications of Group B herbicides. Mixtures with chemistry from other herbicide groups is necessary to minimise potential across rotation resistance issues to ALS chemistry. ALS herbicides are widely used in most other crops in the rotation including Clearfield® OSR. The proposed stewardship programme may include both mandatory and recommended practices but additional support for growers is necessary. This will include: • Education programs to maintain and improve knowledge of weeds and their management describing implementation and integration of weed management practices, which may include diversification of crop systems, cultivations, use of cover crops, stubble management and stale seed beds, zero tolerance for weed escapes in some crops, and herbicide resistant weed management strategies. • Development of the stewardship programme with Bayer including development of best management practices, on-farm demonstrations, grower and advisor education and awareness of longer term risks where herbicide resistant weeds are most likely to evolve. This should cover all available herbicides.
Sugar beet	There is a lack of information in UK conditions of the efficacy of Conviso® One, the following questions need to be answered: • How robust are two applications for season long weed control across all soil types for all weed species? • What will happen on soils which continually produce weed flushes late into the season, or where summers are wet? • How robust is volunteer potato control especially control of daughter tubers?
Oilseed rape	Examine weed species shifts in association with the cultivation of herbicide tolerant crops, monitor for herbicide resistance evolution, monitor the use of IWM strategies
Horticulture	Investigate the possibilities of developing ALS tolerant vegetable brassica varieties
Cereals	Assess the potential for the use of herbicide tolerant wheat in the UK, including cost-benefit analysis and potential herbicide resistance

Future funding: Research in this area is likely to be commercially funded. Discoveries are most likely to be patented and commercially sensitive.

Constraints – Commercial confidentiality

Timescale	MT	Scale of impact	H	Likelihood of progress	H

8.21. Preventative weed control

Crop	*Future action*

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All crops	Inform growers of all potential routes through which weeds can infest a farm and issue guidance on preventative measures.
All crops	Quantify the effects of different types of organic manure on weed seed survival and spread.
Cereals Oilseeds	Continue to investigate of the use and potential efficacy of harvest weed seed control options in the UK

Future funding: Much information is available in this area and would benefit from extensive KE and on-farm demonstrations.

Constraints - none

Timescale	ST	Scale of impact	H	Likelihood of progress	H

8.22. Legislation limiting development

Outside of legislation surrounding pesticide registration, two areas that may be restricting progress in agriculture are:

Crop	*Future action*
All crops	Development of health and safety and legislation frameworks for drone usage.
All crops	Review the ethics and regulation surrounding the use of CRISPR technology in the UK

Timescale	LT	Scale of impact	M	Likelihood of progress	M

8.23. Summary

Control method	**Timescale**	**Scale of impact**	**Likelihood of progress**
Altering row widths and seed rates to improve competitiveness	ST	H	H
Improving the competitive ability of grassland against weeds through soil management	LT	L	L
Non inversion tillage, strip tilling and direct drilling – establishment of crops by non-traditional methods	MT	H	H
Physical alternatives to herbicides for in-crop weed control including between crop rows, spot treatment and patch spraying	ST	H	M
Biological control	LT	L	L
Use of cover crops	ST	H	M
Intercropping and companion cropping	ST	H	H
Physical mulches	MT	M	L
Competitive cultivars	ST	H	M
Specific problems created by loss of active substances	MT	M	L
Improving herbicide performance – water conditioning products and adjuvants	ST	H	M

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Chemical alternatives to glyphosate and diquat	ST	H	H
Precision application of herbicides	MT	L	L
Retaining current herbicides, evaluating new herbicides and assessing the potential of new herbicides for use in minor crops.	ST	H	H
Monitoring of changes in weed species and herbicide resistance development	LT	M	H
Sensing and predicting the need for weed control	MT	M	M
Keeping a watching brief on incoming technologies and demonstration of incoming technologies to the industry.	LT	H	H
Digital tools – Decision support systems, Apps and internet tools	MT	M	H
Genetic tools	LT	M	L
Herbicide tolerant crops	MT	H	H
Preventative weed control	ST	H	H
Legislation limiting development	LT	M	M

Timescale: *ST= Short term, MT = Medium term, LT = Long term;*

Scale of impact: *L = Low, M = Medium, H = High*

Likelihood of progress: *L = Low, M = Medium, H = High*

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