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Herbicide Resistance

Increasing resistance to herbicides, coupled with a lack of new types of herbicides, has the potential to reduce crop yields. The UK Government's commitment to increase yields over the next 25 years[1] will require the development of alternative crop protection methods. This POSTnote outlines the challenges of herbicide resistance and reviews the possible approaches to long-term weed control strategies.

Overview

- Agricultural crop yields are reduced when unwanted plants (weeds) compete with crops. Synthetic herbicides are widely used to control weeds.
- A wide variety of weeds have shown resistance to a range of herbicides, which reduces chemical control options.
- The EU regulates the use of herbicides. Changes to the regulations in 2009 have reduced control options further.
- More diverse management strategies that include non-chemical methods, such as spring cropping, may help conserve the effectiveness of herbicides and contribute to reducing resistant weed numbers.
- Technological advances make it possible to apply herbicides precisely to weeds, reducing off-target environmental damage.

Background

Weeds are unwanted plants that persistently adapt to cropping systems and compete with the intended crop,[2] causing losses in yield.[3] Globally, it is estimated that weeds cause comparable crop losses to those caused by insect pests and crop diseases combined.[4] For agriculture, the control of weeds is integral to achieving 'sustainable intensification', the pursuit of the dual goals of increased yields with decreased environmental damage.[5] For a wider discussion of sustainability, see POSTnote 408.

This POSTnote summarises how herbicides are used to control weeds, what causes herbicide resistance and the various options for weed management that conserve the effectiveness of herbicides.

Herbicides

There are a wide range of herbicides, commonly known as weed killers. The vast majority are manufactured chemicals. Herbicides kill weeds by disrupting specific aspects of plant physiology. While there are 281 different herbicides on the global market, between them they only have 25 different modes of action for disrupting the physiology of weeds.[6] For example, the herbicide glyphosate prevents susceptible weeds from producing certain proteins that are required for growth. Since the 1940s, use of herbicides has allowed cost effective control of weed species, contributing to huge increases in crop yields.[7] Herbicides are most commonly applied via spraying, which is quick and cheap. The control of weeds is now performed almost exclusively through chemical control.[8] The EU National Agrochemical Market (crop protection) was estimated to be £5.3 billion in 2010, with herbicides contributing £2.1 billion (greater than insecticides or fungicides).[9]

Negative Effects of Herbicide Use

However, there are a number of potential disadvantages associated with spraying herbicides. Possible off-target damage includes: leaching or run-off to surface and ground water bodies (POSTnote 478)[10,11] toxicity to organisms living in the soil,[12] damage to wildflower communities[13] (indirectly affecting pollinators[14,15]), and indirect effects on bird populations.[16] There is some disputed evidence that people who work with certain herbicides have a higher risk of Parkinson's disease[17] and various cancers.[18]

Defra's expert committee Pesticide Residues in Food (PRiF) monitors pesticide residues on UK food samples. Herbicide residue has been detected above the maximum permitted levels.[19] However, PRiF advises that the health benefits

from five portions of fruit and vegetables each day outweigh any risks from pesticide residues.[20]

Herbicide Resistance

A small proportion of weeds are able to survive typical herbicide use. When they reproduce they pass this herbicide resistance trait on to the next generation. Repeated applications of the same type of herbicide increases the population of plants resistant to the herbicide. A dramatic increase in the incidence of herbicide-resistant weeds has been documented since the first recorded case in the 1960s. As of 2015, 457 distinct types of resistance across 246 weed species have been detected in 86 crop varieties in 66 countries worldwide.[6] Resistance has evolved to 22 of the 25 different methods that herbicides use to disrupt plant physiology. Some weed species are now resistant to multiple herbicides. As well as limiting herbicide effectiveness and reducing options for weed control, resistance increases agricultural costs.[21]

In the UK, and many other western European countries, black-grass is the most important grass weed of cereal crops. Herbicide resistance in black-grass has been confirmed in 35 counties in England.[22] Wheat yield losses due to black-grass are reported to be 0.4-0.8 tonnes per hectare (T/ha), with losses of over 2 T/ha recorded.[23] In 2014, average UK farm wheat yield was 8.6 T/ha[24] – the Home-Grown Cereals Association expected 22% of total UK wheat crop land (1.9m ha)[24] to suffer a yield loss of 5% in 2014.[25]

Emerging Resistance

Resistance also occurs in wild-oats (detected in 28 UK counties), rye-grass (33 counties) and has recently emerged in poppy (9) and common chickweed (13).[22] These weeds are associated with oilseed rape crops, the UK's third most widely grown crop with 0.67 mha planted in 2014.[24] Other weed species are also likely to develop herbicide resistance and overall resistance levels may increase.

In the US, weeds resistant to the widely used glyphosate are widespread,[26] but this is not so in Europe. The first case of glyphosate resistance in the EU was reported in Italy in 2014; none has been detected in the UK.[27] UK farming practices are currently less likely to lead to resistance, but greater use of glyphosate on oilseed rape crops may increase the risk.[28] There are currently no formal government guidelines to manage resistance to glyphosate. However, the Weed Resistance Action Group (WRAG),[29] a group of government, industry and academic representatives, published guidelines to minimise future resistance in 2015.[30]

Drivers of Herbicide Resistance

Two major factors that affect the likelihood of resistance arising are the lack of new herbicides and how they are currently used on farms.

Lack of New Herbicides

There have been no new herbicides brought to market for over 20 years.[31] Widespread reliance on successful herbicides has limited the incentive to develop new herbicides.[32] Crop protection companies are investigating new methods for controlling plants,[33,34] but the estimated cost of discovery and development of synthetic pesticides has increased substantially from US $184million in 2000 to US $256 million in 2008.[35] This increase in costs is partly due to increased regulatory requirements involving the assessment of toxicological and environmental risks of the chemical,[36] as prescribed by the EU Thematic Strategy for Pesticides (Box 1). Agrochemical companies are changing their R&D investment strategies in the light of these regulations; increasingly, they are turning to non-EU markets.[34] It has been suggested that the UK's role as a major centre for crop protection research may be reduced.[37]

With no new herbicides being brought to market, farmers have increasingly relied on existing herbicides for weed control,[7,8] increasing resistant weed populations.

Use of Herbicides and Farm Practice

The cropping system used can contribute to the growth of herbicide resistance. In 2014, three UK crops (wheat, barley and oilseed rape) accounted for 80.8% of total arable crop land, covering a combined 3.68 m ha.[24] Farmers may opt for the same crop type in successive seasons to maximise financial gains in response to market demands. Growing the same crop for consecutive seasons encourages the growth of the same weed species and applications of the same herbicides selects for resistant-weeds, so the longer such systems are practised, the more likely it is that resistance will develop. Crops genetically modified to be resistant to herbicides may have increased the presence of resistant weeds (Box 2), by increasing reliance on certain herbicides.

Reduced crop rotation has been one of the drivers in the spread of black-grass resistance. It is estimated that

Box 1. EU Thematic Strategy for Pesticides

Adopted in 2009, and as part of the 6th Environmental Action Programme, the strategy sets out three main pieces of legislation that regulate pesticides across the whole life cycle:

- The Plant Protection Products Regulation authorises the introduction and reapproval of plant protection products on the market (EC/1107/2009).
- The Sustainable Use Directive (2009/128/EC) establishes a framework for the sustainable use of approved pesticides.
- The Statistics Regulation (1185/2009/EC) stipulates the provision of data on pesticides used in member states.

The legislation reduces herbicide availability by not re-approving active substances if they are classified as *inherently hazardous*. This differs from the previous risk-based approach,[20] which evaluated the *risks associated with typical use* of the chemical. This hazard-based approach has been criticised by a number of Chief Scientific Advisers.[38] The Sustainable Use Directive promotes the integrated pest management (including the use of non-chemical control methods, see page 3) through each member state's National Action Plan.[39]

Box 2. GM Crops

The problem with herbicides is that they can harm the crops as well as the weeds. Some genetically modified (GM) (POSTnote 482) crop plants have been designed to that they are immune to certain herbicides. This means that farmers can apply those herbicides freely without damaging the crop. GM crops with herbicide resistant genes have been used in the Americas for nearly 20 years.[40] In 2013, 27 countries worldwide grew an area of 175.2 mha of GM crops,[41] with the herbicide-resistant trait accounting for about 84%.[42] In some cases, heavy reliance on a single herbicide (glyphosate),[43] created selection pressure that favoured naturally occurring herbicide-resistant weeds.[44] U.S. farmers now use integrated weed management strategies (see below for details) that were commonly used pre-GM crops, including non-chemical methods.[44] It is not clear if use of GM crops influences overall levels of herbicide use; for example:

- Research suggests for comparable latitudes and crops, farmers in (largely GM-free) Western Europe have achieved similar increases in yields and decreases in pesticide use (including herbicides) compared with farmers in (predominantly GM) North America.[44]
- A meta-analysis of GM crop studies (regardless of presence of herbicide-resistant weeds) suggested GM technology adoption reduced overall herbicide use globally in 1995-2014, but may increase herbicide use in some circumstances.[45]
- Research suggests that the presence of herbicide-resistant weeds in herbicide-resistant GM crop fields increased the volume of herbicides applied in the U.S. in 1996-2011.[46]

resistant black-grass occurs on virtually all of the 20,000 UK farms that spray regularly for weed control.[22] A range of herbicides are now ineffective at controlling this weed species.[47] Approximately 80% of black-grass emergence occurs in autumn,[28,48] which coincides with the growing period of autumn-planted cereal crops. Without the opportunity to remove the weeds prior to the crop growing, farmers are reliant solely on herbicides for weed control, which increases the risk of resistance in black grass.

Options for Weed Management

Strategies that rely on a range of approaches to conserve the effectiveness of herbicides allows resistance in weeds to be managed in some circumstances.

Integrated Weed Management

Integrated Pest Management approaches make use of all available plant protection methods. They integrate-appropriate pest control measures that are both economically and ecologically justified.[49] Integrated Weed Management (IWM) can be considered as one aspect of this. It integrates the application of several weed control measures, including chemical (herbicides) and non-chemical.[50] Examples of non-chemical control include crop rotation, spring cropping, tillage, delayed drilling and competitive cultivars (see below).

Crop Rotation

More diverse crop rotations with longer periods between the same crop type being grown may reduce weed infestation[39,51] and improve soil fertility.[52,53] For example, certified organic farms (Box 3), which employ crop rotations and restrict the use of synthetic fertilisers, report lower incidence of grass weeds.[54]

Spring Cropping

Crops in the UK can either be planted in the autumn or the spring. As explained above, autumn sowing can increase the spread of resistance. By contrast, spring sowing provides a greater time period between the harvest of one crop and planting the next, which allows weeds to be removed before the planting of the next crop. Removing weeds before they seed reduces the number of potentially herbicide resistant weed seeds in the soil. Spring cropping additionally provides nesting opportunities for ground-nesting birds,[55] and also winter foraging for birds (if stubbles are left over winter).[56] However, there are disadvantages to spring cropping such as difficulties in establishing crops on clay soils, particularly in east and central England where most of the UK's arable land is found. Spring is also the last opportunity to plant crops for that growing season. Weather-associated risks such as increased rain could result in crop failure, a large economic risk. Additionally, spring crops typically have lower yields.[57] Autumn sown crops accounted for two-thirds of total arable crop land in 2014,[24] but there was an increased reliance on spring cropping from previous years.[58] This may have been the result of several factors including failure to establish an autumn crop following the bad weather of winter 2013, the recent Common Agricultural Policy reform (Box 4) or increased uptake of IWM measures.

Tillage

Since the 1990s, there has been a trend for no- and reduced tillage (ploughing) practices in cropping systems (POSTnote 486). A reduction in tillage is associated with increases in weed populations, as weed seeds are left near the surface where many grass species germinate readily.[59] In most circumstances, deep tillage buries weed seeds below their germinating depth, reducing subsequent weed populations. However, no- and reduced tillage is considered to have benefits for soil and water conservation,[60] biodiversity[61,62] and reduces costs to farmers.

Delayed Drilling

Most farmers sow autumn crops in September to avoid unpredictable autumn weather.[63] September is when most black-grass emerges, so the crop and weed emerge together.[27,39] Delayed drilling (planting) of crop seed to later in the season allows more weed seedlings to emerge and be controlled before sowing. Furthermore, the chemical activity of some herbicides may be more effective later in the season, for instance when soils hold more moisture.[64]

However, delayed drilling does have disadvantages and can be an economic risk for farmers. For example, heavy rainfall may prevent drilling or spraying because agricultural machinery cannot operate when soils are saturated without severely damaging the soil. Additionally, later cereal sowings may generate bottlenecks in labour (personnel and machinery demands),[57] as the onset of winter weather reduces the time available to sow crops.

Box 3. Organic Farming
Organic farming regulations ban the use of synthetic herbicides. The Soil Association Certification scheme (UK) recommends a minimum rotation of three years in-between crops of certain varieties (onions, brassicas, potatoes). Arable farms are able to benefit from reduced costs by not using crop protection chemicals or manufactured fertiliser.[65] The higher levels of nitrogen in soils arising from the application of synthetic fertilisers in non-organic farming systems (POSTnote 486) also promotes the growth of weeds. However, most organic yields are lower than non-organic (2.6 T/ha less per year for wheat,[67] and similar for legumes).

Box 4. Common Agricultural Policy
Recent Common Agricultural Policy (CAP) reforms included a new 'greening' component, which provides additional payments for the adoption of certain agricultural practices that may benefit the environment and climate.[86,87] For example, crop diversification is where two different crops must be grown on arable land of 10-30 ha (three crops for greater than 30 ha), with the main crop not covering more than 75% of land.[88] From 2015, approximately 30% of payments will depend on meeting these greening rules, with certified organic land qualifying automatically.[89] A CAP mid-term review is planned for 2017, with consultations in 2015 to highlight areas for amendments.

Competitive Cultivars
Cultivars are varieties of crop plant; some cultivars of crops can compete with weed species and limit their growth. Ongoing work at Rothamsted Research aims to identify which wheat varieties are best at suppressing the growth of black-grass,[66] including the effect of crop plant height and different leaf structure on weed growth.[63] The intention is to include a suppression rating on the Home-Grown Cereals Association Recommended List, which would help growers with blackgrass problems choose appropriate varieties of wheat.

Effectiveness and Uptake of IWM

Adoption of IWM practice has the potential to reduce herbicide use while maintaining weed control by:[67]

- reducing the number of weeds exposed to herbicides and the risk of resistance rising
- encouraging the use of a more diverse range of herbicides, which may be more sustainable.

Although IWM has been promoted since the 1970s by crop protection companies, researchers and independent agronomists,[68] it has not been widely adopted (regardless of country or weed species) until recently. [29, 69-76] Recent research suggests that under the most favourable conditions a fully integrated approach with multiple non-chemical measures can reduce weed levels (black-grass).[51] However, control levels of IWM can be highly variable, with decreased control being a possible outcome (i.e. an increase in weed levels).[51] For example, under some circumstances deep tillage can bring more seeds to the surface than it buries. Additionally, IWM is not suitable for every farm situation,[77] as it has an associated cost of increased labour and potentially increased machinery use. Different rental models or ownership of land could alter the uptake and practice of long-term weed management strategies, but there is no evidence on how they affect weed control.

While the disadvantages and costs of IWM may influence the uptake,[66,78] anecdotal evidence[33,63,79,80] suggests that adoption of IWM is dependent upon how well research is communicated to farmers and agronomists to improve weed control.[74,81] Annual events,[82] demonstration farms[83] and working farms[84,85] have been highlighted as important ways of showcasing IWM strategies. However, most countries in the EU no longer have government extension services to provide independent advice to farmers.[77] A House of Lords committee report concluded that agricultural knowledge transfer is complex and requires multiple approaches to be effective.[90]

Technological Advances

Adopting new technologies may enable increased yields while reducing emissions and conserving natural resources.[91] Recent initiatives such as the Agri-Tech Catalyst (which is funded by Innovate UK, DFID and BBSRC),[92] the Sustainable Agriculture and Food Innovation Platform (funded by Innovate UK, BBSRC and Defra)[93] and the BBSRC Global Food Security Programme[94] aim to fund R&D associated with food production. However, much of the research focuses on developing solutions with global potential that may not always be relevant to UK agriculture. Relevant technologies include precision agriculture technology and novel approaches to resistance.

Precision Agriculture Technology
Precision agriculture technology allows the precise application of herbicides to target specific weeds. Imaging equipment attached to a tractor can identify a range of weed species and apply chemicals to the weed leaf only.[95,96] This uses less herbicide and reduces the risk of environmental effects that may occur with less targeted spraying. These technologies may also make possible the use of chemicals that are currently banned from spraying, by limiting their use to specific technologies to minimise risks.

Some machines under development are substantially lighter than traditional tractors, enabling the technology to be operated on all soil types in all weathers.[95] Extending the opportunity for sowing crops later is a key IWM measure.

Novel Approaches to Resistance
The BBSRC/Agriculture and Horticulture Development Board funded Black-grass Resistance Initiative aims to identify solutions to the current UK challenge of resistant black-grass. [97] Part of the project is to identify weed genes associated with resistance, in order to develop diagnostic tools.[98] Mechanisms could potentially be developed to counteract the effects of these genes to restore susceptibilities to herbicides. For example, it has been demonstrated that treating resistant black-grass with an experimental drug for cancer therapy enabled previously ineffective herbicides to kill the treated weeds.[98]

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