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A critical review of integrated grass weed management in Ireland

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Abstract

Grass weeds affect arable crops throughout the world, inflicting yield penalties, reducing crop quality and taking available nutrients away from the growing crop. Recently in Ireland, the presence of herbicide resistance in grass weeds has been noted. In order to preserve the sustainability of crop production in Ireland, an integrated pest management approach must be implemented. How this applies to control grass weeds was the focus of this review. Here we examined the state of current research into grass weed biology and the nature of herbicide resistance, identifying gaps in research in the Irish context. We identified a number of cultural grass weed control techniques, as being relevant to the Irish mode of crop production. Crop rotation, cultivation techniques, manipulation of sowing dates and increased crop competition were recognised as useful strategies. Combining these strategies to provide effective grass weed control may be key to reduce dependence on herbicides.

Keywords

cultural control techniques • grass weeds • herbicide resistance • integrated pest management

Introduction

One of the main challenges that is being faced by the agriculture sector in the 21st century is producing enough food to match the growing needs of our rapidly rising population while safeguarding ecosystem services and protecting the socioeconomic well-being of food producers and rural communities (Godfray *et al*., 2010).

Paramount to meeting this challenge is effective weed control. Weeds inflict damage to crops through competition for light, water and nutrients, leading to significant crop loss and reduction in yields each year (Oerke, 2006). For decades, globally, growers have been increasingly reliant on herbicides for effective weed management. This is unsurprising considering the remarkable success, both economically and in terms of efficacy, of herbicides dating back to their introduction and adoption on a large scale after the Second World War (Shaw, 1964; Gianessi, 2013). Herbicides replaced a range of more laborious weed management techniques, such as hand weeding, resulting in lower labour and time inputs for the growers, reduced energy/fuel costs as well as increased yield potential. This in turn has facilitated the rise of new challenges in weed control, particularly the onset of herbicide resistance (Yuan *et al*., 2007; Délye, 2013).

As current herbicide products lose efficacy due to resistance evolution, chemical control of weeds is proving more difficult, with options for chemical control also shrinking due to legislative restrictions. This is exacerbated by a lack of innovation, with no new mode of action for herbicides having been introduced over 30 years (Duke, 2012). It is thus imperative to recognise that resistance evolution occurs in fields at a rapid ecological timescale, and if this problem is addressed only with additional herbicides, it is likely that evolution will win out (Davis *et al*., 2012).

Irish crop production and grass weed management are not immune to these issues. Although the presence of herbicide-resistant grass weeds has been suspected for a number of years, no research has been carried out to determine the distribution, frequency or levels of resistance until recently. Herbicide resistance to a number of active ingredients in a number of grass weed species has now been confirmed in Irish farms, as seen in Figure 1 (Byrne *et al*., 2017; unpublished data).

Here, we identified recent research into best management practices for grass weeds in arable systems by reviewing research undertaken in other countries and applying it to the Irish tillage industry. Furthermore, we identified a number of areas where work needs to be done if Irish farmers and researchers want to stem the tide of resistance developing in this country. A major challenge of both research and extension services is to uncover effective, sustainable grass weed control measures, suitable to the Irish climate and Irish crop production techniques.

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Herbicide resistance

An effective herbicide has chemical properties that enable it to enter the plant and be transported to its designed target at a lethal dose. The vast majority of herbicides act by inhibiting specific essential enzymes required for various metabolic pathways. This is known as the target site of the herbicides (Powles and Yu, 2010).

Herbicide resistance can be defined as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type". Herbicide resistant grass weed biotypes have been detected across the Irish arable region (see Figure 1). This phenomenon manifests itself in two major ways: target site resistance (TSR) and non-target site resistance (NTSR).

TSR occurs when point mutations endow specific amino acid substitutions in the target site of plant enzymes causing changes to the site, such that the typical lethal dose of a given herbicide does not bind effectively to the target site and kill the targeted plant (Yu and Powles, 2014).

Acetolactate synthase (ALS) and acetyl-coenzyme A carboxylase (ACCase) inhibiting herbicides form an important part of Irish grower's chemical weed control programmes.

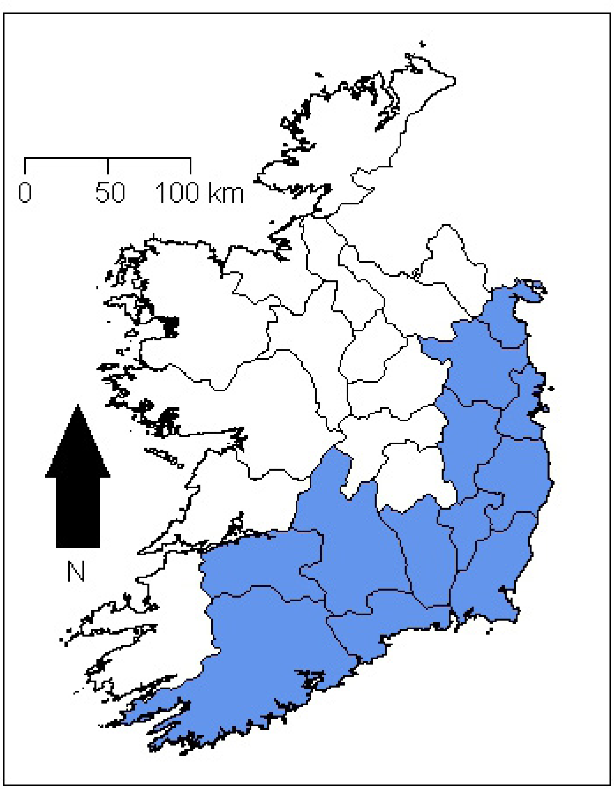

Figure 1. Irish counties with recorded incidences of herbicide-resistant grass weeds (in blue) (Byrne *et al*., 2017; unpublished data).

The genes coding for these enzymes can be mutated at a number of amino acid residues, blocking the binding of the herbicide active ingredients while still retaining, albeit at lower levels in some cases, the activity of the enzymes (Vila-Aiub *et al*., 2009).

Almost 30 different resistance-endowing ALS mutations have been identified globally (Tranel *et al*., 2017). Remarkably, at the Pro-197 residue, 11 separate amino acid substitutions can confer herbicide resistance, with Pro-197-Ser being the most common (Tranel *et al*., 2017). In cross-pollinated species, such as *Alopecurus myosuroides* (black grass), it is not uncommon to find several ALS mutations present in an individual plant (Yu *et al*., 2008).

ACCase inhibitors are extremely useful graminicides due to the presence of the key characteristic of the ACCase protein. Plants have two types of ACCase, cytosolic and plastidic. In grass species, the plastidic ACCase differs from that of dicot species. This plastidic ACCase forms the target site for a number of selective ACCase herbicides (Powles and Yu, 2010).

TSR to ACCase was first discovered by Parker *et al*. (1990). ACCase inhibitors consist of three main groups of chemicals, aryloxyphenoxypropionate, cyclohexanedione and phenylpyrazoline (PPZ), commonly known as the "fops", "dims" and "dens", respectively. Different amino acid substitutions lead to resistance to the various groups, at varying levels of intensity, although some substitutions can endow resistance to all three ACCase herbicide groups (Délye *et al*., 2008; Kaundun, 2010).

NTSR, on the other hand, is where a mutation, or an accumulation of mutations in the plant genome, causes phenotypic changes such that the amount of herbicide reaching the target site is diminished. Genetic control of this mechanism is typically extremely multi-allelic (Délye, 2013). Weed populations in a field display significant levels of heterogeneity, giving rise to natural variance among individuals in the population in terms of their sensitivity to herbicides (Menchari *et al*., 2007). Considering the intensity of selection pressure inflicted by herbicides, any allele endowing even a modicum of resistance will be selected rapidly. Thus, under herbicide selection pressure and given the sheer amount of alleles speculated to be involved in NTSR, these alleles will both increase in frequency within the population and accumulate within individual plants (Jasieniuk *et al*., 1996).

Typically, NTSR is associated with an increased ability of the plant to metabolise a xenobiotic (i.e. herbicide). The resistant plant achieves this through an increase in the activity of a number of enzymes involved in the detoxification of deleterious substances; such enzymes are also upregulated in an analogous way in the case of antibiotic resistance in bacterial diseases and fungicide resistance in fungal diseases (Yuan *et al*., 2007).

NTSR can also be conferred by overexpression of the enzyme targeted by the herbicide, insofar as that the lethal dose of the herbicide is not enough to effectively curtail the action of that enzyme. This may be achieved by gene amplification or by mutations to the gene promoter (Malone *et al*., 2016).

Worryingly, NTSR may pose a greater threat to agriculture due to the unpredictable multiple herbicide resistance it may entail as well as the multi-gene involvement governing the mechanism (Preston *et al*., 1996; Preston, 2004). This multiple resistance may even encompass herbicides not yet discovered (Petit *et al*., 2010). The implication of all of this for the grower is that the gradual evolution of NTSR traits would result in a field population of plants gaining increasingly high levels of resistance to an increasing portfolio of active ingredients of herbicides. This further underpins the necessity to use an integrated weed management (IWM) approach, even in systems where herbicide actives are already rotated regularly to avoid developing TSR.

As with any evolutionary relationship, there are costs, as well as benefits, to adaptation. If a mutation to a plant enzyme causes a change in the wild type function of the enzyme and/or the overall performance and vigour of the plant, then a fitness penalty may be imposed (Vila-Aiub *et al*., 2009).

Herbicide-resistant weeds threaten the sustainability of global crop production, and this requires a well-thought approach as to how to manage this resistance. To achieve this goal, weed management needs to be rooted in a system that is cognisant of the eco-evolutionary relationship between crops and weeds. Such a system reduces the reproductive success of weed populations without putting them under significant selection pressure. IWM may represent a viable solution to this conundrum. Critical to the Irish grower is an understanding of the nature of resistant weeds in this country and developing links between certain behaviours and the onset of the different types of herbicide resistance.

Common grass weeds of arable systems in Ireland

Ireland has a favourable climate for growing cereals, with 750 to 1,250 mm of rain/year (Met Eireann, 2017) and average sunshine hours ranging between 1,100 and 1,600 hours/year (Met Eireann, 2017). This provides enough moisture and solar radiation to ensure that cereal yields in Ireland are consistently high in comparison to the rest of the world (Figure 2).

Strong crop growth provides competition to weeds, and increasingly, Irish tillage farms are affected by a number of pernicious grass weeds. Geographically, the density of the different species is defined by factors such as spring versus winter cropping, commonly grown crops in a given area and soil type/drainage. In the lighter soils found in southeast of the country, spring barley is the most common cereal grown in the region. This lends itself to the demographic success of spring-geminating weeds such *Phalaris minor* (lesser canary grass) and *Avena fatua* (wild oat).

In heavier soil series, where winter wheat is more prominent, species such as the brome grasses (*Bromus* spp.) are more prevalent. In certain cases, one can even find small pockets of *A. myosuroides*, although these cases are quite limited and localised to small populations in comparison to the weed burden this species represents in the UK and continental Europe. These principles are far from dogmatic, and it is common to find any or all the aforementioned species throughout the grain-growing region of Ireland.

Although it exists at quite low levels in Ireland, *A. myosuroides* is considered one of the most economically important grass weeds in Europe due to its propensity to developing herbicide resistance and its strong ability to produce seeds. The majority of *A. myosuroides* in both the UK and the rest of Western Europe is resistant to ACCase-inhibiting herbicides, with varying proportions of TSR and NTSR (Délye *et al*., 2010). Resistance to ALS inhibitors and other active ingredients of herbicides is also commonly observed (Moss *et al*., 2011; Lutman *et al*., 2013).

Currently, the mechanisms and genetic basis for herbicide resistance to *A. myosuroides* in Irish populations are unknown, but it is likely to be similar to other European countries (See Table 1). Furthermore, there is debate as to the origins of the populations of *A. myosuroides* found in the country. Are they indigenous populations that have evolved resistance in a manner analogous to that seen in other countries? Or has there been migration of resistant populations from the UK and elsewhere through seed, machinery, straw bale, etc. followed by dispersal events in Ireland. Uncovering the answer to this question will be important in steering policy

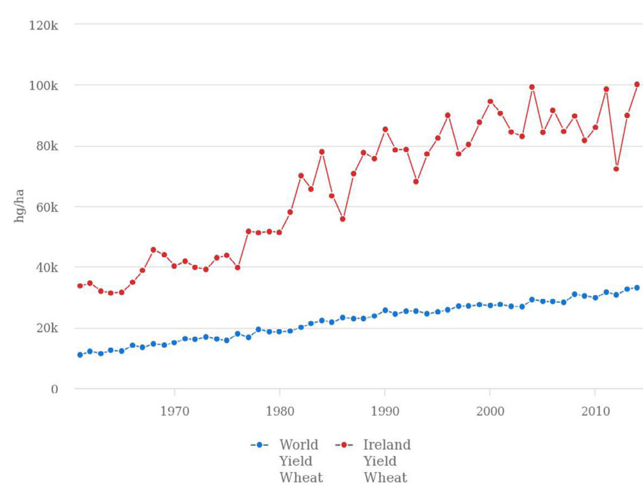

Figure 2. Irish wheat yields per hectare in comparison to the world average for >50 years (FAOSTAT, 2017).

Table 1. A list of incidences of herbicide resistance in weeds common to Ireland

Species	Site of action	Active ingredients
Alopecurus myosuroides	ACCase inhibitors	Clodinafop-propargyl, cycloxydim, pinoxaden
	ALS inhibitors	Mesosulfuron-methyl, pyroxsulam
	PS (Photosystem)II inhibitors	Isoproturon
	Microtubule inhibitors	Pendimethalin
	Long-chain fatty acid inhibitors	Flufenacet
Bromus diandrus	ACCase inhibitors	Clethodim, fluazifop-P-butyl
	ALS inhibitors	Mesosulfuron-methyl, pyroxsulam
	EPSPS inhibitors	Glyphosate
Bromus sterilis	ACCase inhibitors	Cycloxydim, propaquizafop
	ALS inhibitors	Iodosulfuron-methyl-sodium, pyroxsulam
Bromus secalinus	ALS inhibitors	Pyroxsulam, sulfosulfuron
Phalaris minor	ACCase inhibitors	Clodinafop-propargyl, tralkoxydim, pinoxaden
	ALS inhibitors	Mesosulfuron-methyl, pyroxsulam
	PS II inhibitor	Isoproturon
Avena fatua	ACCase inhibitors	Clodinafop-propargyl, tralkoxydim, pinoxaden
	ALS inhibitors	Mesosulfuron-methyl
	Microtubule inhibitors	Propyzamide

These incidences are recorded throughout the world and do not represent Irish samples. Instead, table is displayed to demonstrate a sense of the possible evolutionary events that may occur in these weed species if herbicides are continuously used extensively (Heap, 2017).
ACCase = acetyl-coenzyme A carboxylase; ALS = acetolactate synthase.

that limits the dispersal of resistant weeds and implementing best management practices from other countries that can be tailored to Irelands' own unique crop production industry (Frisvold *et al*., 2010).

More commonly seen in Ireland are the brome grasses, particularly *Bromus sterilis*, *Bromus diandrus*, and *Bromus hordeaceus* and to a lesser extent *Bromus commutatus* and *Bromus secalinus* (sterile brome, great brome, soft brome, meadow brome and rye brome, respectively). These species tend to be found predominantly in winter cereals, especially winter barley due to limited chemical control options within the crop. However, given difficulties with identifying similar species of bromes from one another, little is known about the distribution of these species across Ireland.

Brome grasses are commonly treated with non-selective herbicides post-harvest due to their autumnal germination pattern. Glyphosate resistance has been recorded in *B. diandrus* in Australia; hence perhaps, it would be wise to diversify management strategies in the coming years to mitigate the risk of resistance evolving in Ireland (Malone *et al*., 2016).

P. minor (lesser canary grass) is a predominantly spring-germinating species found most frequently in the southeast of Ireland. *P. minor* is self-pollinated and has high fecundity. *P. minor* is frequently treated with post-emergence herbicides, but resistance to ACCase-inhibiting herbicides has been noted in other countries (Table 1).

A. fatua is another common spring-germinating grass weed affecting Irish tillage farms, with the winter-germinating variety *Avena sterilis* ssp. *ludoviciana* also present, albeit in small numbers. Similar to brome, this species is likely under-recorded due to issues with identification.

Herbicide resistance has been noted in Irish populations of *A. fatua* (Byrne *et al*., 2017; unpublished data). This represents a significant future challenge to growers and researchers as management and disruption of dispersal come to the forefront. A troubling feature of wild oat biology is their ability to survive, dormant in the soil for extended periods of time (Miller and Nalewaja, 1990). This makes management by cultivation more difficult due to the possibility of turning up still-viable seeds. This survival ability represents another knowledge gap in Ireland. It may be useful to carry out long-term studies assessing the viability of buried seed for a variety of grass weed species under Irish weather and soil conditions. This would allow growers to tailor their cultivation practice around estimates of how much viable seed could be brought to the surface by inversion tillage. Conversely, it would also allow growers to estimate how long seed would need to be buried before the viable weed seed bank would be effectively diminished.

Integrated weed management

If the goal of the next generation of weed control is to reduce overall dependence on herbicides, then weed management must be treated as an eco-evolutionary problem. Traditionally, every time a new resistance evolutionary event was noted, new chemical technologies were developed to deal with the issue. Unfortunately, this curative approach did not lead to the development of robust, sustainable weed management policies (Owen *et al*., 2010). Weeds can no longer be seen as a problem that can be treated in a responsive manner; instead, IWM may be seen as a more proactive alternative.

Diverse herbicide-resistant weed management programs incorporating multiple, partially effective approaches to achieve high levels of overall weed mortality have been largely ignored in favour of simpler, herbicide-based approaches. Systems with high dependence on herbicidal control have more frequently given rise to weed populations where resistance has developed, most likely because of the inherently high selection pressure under which they place these populations (Mortensen *et al*., 2000).

The probability of herbicide-resistant mutant plants evolving in a field is proportional to the overall size of the weed population in this field. It has repeatedly been shown that smaller populations of weeds do not require extremely high mortality rates to keep populations under control (Mortensen *et al*., 2000). In the IWM cropping system, numerous partially effective tactics can keep weed populations at manageable levels combined with a reduced reliance on herbicides (Kropff *et al*., 1997). Many studies have demonstrated the efficacy of weed management programs that use combinations of effective cultural practices, commonly referred to as the "many little hammers" approach (Liebman and Gallandt, 1997).

IWM was first described by Walker and Buchanan (1982). It now represents the blueprint for the mitigation of herbicide-resistant weeds through the integration of biochemistry, agronomy, weed ecology and the social sciences (Ervin and Jussaume, 2014).

Gould (1991) remarked that "many of the short-term triumphs of pest control have carried within them the seeds of longer-term failure". This statement seems even more prescient in today's agricultural climate. The challenge of modern research is to develop ways of controlling weeds and protecting crops from yield loss in a sustainable manner. IWM represents a viable system to achieve these goals going forward, particularly in the case of herbicide-resistant grass weeds.

Crop rotation

Crop rotation systems have been used extensively for years to maintain soil fertility, suppress pests and increase yields. Crop rotation and the enhancement of environmentally beneficial farming practices are key objectives of greening direct payments in the most recent European Union (EU) Common Agricultural Policy (Regulation (EU) No 1307/2013). Furthermore, weed populations are demonstrably reduced by rotation of crops; in effect, rotation provides temporal diversity that keeps the weed's life cycle "off balance" (Liebman and Dyck, 1993; Bennett *et al*., 2012).

A rotation between multiple different crops creates changing micro-environments in the field, such as different types of competition for resources, soil disturbance, shade and other elements that create instability in the weed's life cycle (Liebman and Dyck, 1993; Davis *et al*., 2012).

An ideal crop rotation involves crop cultivars with weed suppressive ability, crops with varying growth cycles, a mixture of cereals and broad-leaved crops, as well as winter- and spring-planted crops (Beckie and Harker, 2017). Adding perennial crops, such as a perennial ryegrass, ley to the rotation can also have a deleterious effect on the fitness of annual weed populations, while providing benefits in terms of nitrogen and soil organic carbon cycling (Vertès *et al*., 2007). Moss (1985) determined that the survival of *A. myosuroides* seeds buried in the soil declined to 1% after 4 years. Populations of *A. myosuroides* could conceivably have evolved to have greater survival in the soil, so research tailored to specific soil types and climates representative of the Irish arable sector is required. However, this study suggests that grass leys in arable rotations may provide an option for the control of herbicide-resistant grass weeds.

Davis *et al.* (2012) found that when comparing 4-year crop rotations with more simple 2-year crop rotations, the effects on the weed seed bank and overall weed populations' biomass were largely similar, with reductions in both. However, the more diverse 4-year crop rotations had up to 10-fold lower herbicide inputs, resulting in not only greater profit margin for the growers but also a reduction in the likelihood of resistance evolving in the weed population.

Crop rotation also offers the ability to utilise different modes of action of herbicides each year, further reducing the risk of evolution of resistant plants (Owen *et al*., 2015). However, this tactic can be somewhat limited. Rotating herbicides across seasons or using herbicide mixtures during a single season may only be effective for delaying resistance in the short to medium term as it does not preclude the development of NTSR (Wrubel and Gressel, 1994).

Furthermore, cultivations can be incorporated as part of the rotation (Katsvairo and Cox, 2000); cover crops and forage crops can also disrupt weed populations while adding to ecosystem services (Entz *et al*.,1995; Price and Norsworthy, 2013).

Sowing dates

The sowing date of the crop exerts an influence on the ecological relationship between the crop and weed populations. In this relationship, the emergence of one actor affects the fitness of the other. It has been established that the most important competition for resources takes place early in the growing season when tillering is taking place (Cousens *et al*., 1988).

This knowledge influences and explains all integrated weed control dynamics, such as competitive crop varieties, differences in row spacing and even the timely application of post-emergent herbicides. Knowledge of the emergence pattern of the weed in question allows the growers to tailor the IWM programme to the greatest effect.

The evolutionary success of weed populations depends on seedling survival and plant fecundity, i.e. the number of seeds produced per plant. These factors depend on the rate of emergence, in spring or autumn, depends on the grass weed species in question. Early weed growth is heavily dependent on crop competition during the early stages of growth; thus, adjustments to crop emergence have a bearing on weed fitness and demography (Rice and Dyer, 2001; Conley *et al*., 2002; Gallart *et al*., 2010; García *et al*., 2015).

The influence of delayed sowing is heavily dependent on weather. For example, black grass (*A. myosuroides*) and the brome grasses (*B. sterilis*, *B. hordeaceus*, *B. diandrus*, *B. commutatus* and *B. secalinus*) tend to predominantly germinate in the autumn in Ireland. Damp Irish autumns are inclined to induce relatively early germination of these species compared to the germination patterns observed in continental climates by Swain *et al*. (2006).

These emerged seedlings can be destroyed relatively easily using pre-sowing control methods. During, particularly, dry autumns, delaying sowing may reduce the density and the fitness of weed populations through competition (García *et al*., 2015). Of course, in Ireland, delaying sowing runs the risk of fields becoming difficult to travel as the weather becomes wetter in the late autumn and early winter, while increasing the risk of soil compaction. Research surrounding weed emergence must be established in order for growers to adopt this technique.

The aforementioned weed species are synonymous with winter-sown cereals. Delaying sowing until spring allows the growers to utilise the stale seed bed approach more frequently prior to sowing, and this has a major impact on autumn-germinating weeds. However, for common spring-germinating species such as lesser canary grass (*P. minor*) and wild oats (*A. fatua*), this will have less of an effect. This further highlights the necessity for crop diversity, in terms of not only species but also cropping dates.

Knowledge of the dormancy and emergence of grass weeds is of utmost importance to crop husbandry. That said, the majority of this knowledge comes from research carried out in climates that differ from that of Ireland. These factors may not differ greatly from country to country, but these differences can change the prescribed advice to growers in a given season. The authors would propose a series of long-term experiments to assess the rates and dates of emergence of common Irish grass weeds. This can be calibrated against weather conditions to give accurate predictions to growers as to when may be the optimal time to plan sowing as well as pre- and post-emergent herbicide applications.

Competitive crop cultivars

Crop varieties with increased ability to suppress weed growth may form a valuable part of crop rotations in an IWM system. Improved cultivars present a potentially attractive offer to the growers as they do not incur any additional costs, making them essentially a “free” method of controlling weeds. However, their benefits must be weighed against any yield penalties that increased competitive ability inflicts on the crop if this strategy is to be implemented by growers at large.

Competitive cultivars reduce the fitness of weed populations through a variety of processes, namely, competition for resources, production of allelochemicals that reduce weed growth, or by resisting yield loss in the face of competition from weeds (Christensen, 1995; Wu *et al*., 1999; Vandeleur and Gill, 2004). For the purposes of weed management, suppressive ability is favoured over the latter because it facilitates the build-up of the weed seed bank (Jannink *et al*., 2000).

In general, the competitiveness of a crop variety is governed by a number of simple traits, chief among them rapid emergence (Didon and Hansson, 2002), strong tillering ability (Lemerle *et al*., 1996), increased leaf area index (Huel and Hucl, 1996) as well as the height and architecture of the canopy (planophile versus erectophile leaves) (Christensen, 1995). These factors all exert their influence above the soil level, but there are also below ground parameters that underpin the competitiveness of crop cultivars. Plant density, the rate of root system establishment and relative root growth rate are all essential to reducing the fitness of weeds below the surface of the soil (Gibson *et al*., 2003; Dunbabin, 2007; Ma *et al*., 2008).

Allelopathy is another important and oft-overlooked factor contributing to crop competitiveness. However, research in this area has proven quite difficult as it is challenging to discern the effects of allelopathy from the effects of the other aforementioned traits in field trials (Bertholdsson, 2011). These competitive traits and the suppression of weeds are reviewed in much more detail in Andrew *et al*. (2015).

A further challenge to advancing research into crop competition as a tactic to be utilised in an IWM setting is that these traits are not independent of one another and they do not segregate from other important agronomic traits such as yield and stress tolerance. Modern breeding programmes have understandably selected traits that may run counter to providing increased competition against weeds. For example, increased straw length in winter cereal crops may be undesirable due to its susceptibility to lodging but is a key factor in reducing the fitness of weeds. Of course, the inverse may be true for other traits such as early vigour, which is positively correlated with both weed suppressive ability and increased grain yield (Kumar *et al*., 2009).

The challenge for plant breeders is to identify traits that confer greater suppressive ability without incurring a yield penalty. Unfortunately, there is no reliable index that allows breeders to easily select for increased competition, making a difficult proposition more difficult yet. One of the challenges to future research in this area of IWM will be to develop a simple system of scoring crop traits that contribute to competitive ability (Hansen *et al*., 2008). This score could be provided alongside other traits, such as yield, disease resistance and lodging resistance, in government-recommended variety lists. Only then will competitive crop cultivars become a mainstay of the IWM toolkit.

Row spacing and seeding rates

Seeding configuration can have a similar effect on weed populations as competitive crop varieties. Both of these tactics aim to change the microclimate of crop canopy, which in turn affects available biotic resources available to the weeds (Johnson *et al*., 1998). Establishing a dense, uniform crop will enhance its ability to suppress weed growth. The two parameters most frequently modified are the row width of the crop and the seeding rate, i.e. the density with which it is sown. At times, growers can be reluctant to increase seeding rate as it may run the risk of leading to excessive vegetative growth and increased intra-crop competition for available resources. In general, seeding rates to achieve maximum yields are calculated in weed-free plots. Weighing the benefits of increased seeding rate at varying levels of weed pressure against yield in both herbicide-treated and herbicide-free backgrounds would be both economically and ecologically interesting. This represents a challenge for IWM strategists. Proving that these tactics are economically viable and effective practices for weed control is a critical first step if they are to be implemented in concert with other IWM measures more frequently in the future.

In lower input situations, such as organic farms, this approach is more widely used. Growers have been shown to reduce weed fitness by increasing their seeding rate up to three times the typical levels (Blackshaw *et al*., 2008). This increased adoption may be explained by the fact that growers are less fazed by the prospect of intra-crop competition because weed–crop competition tends to be higher in any case.

That said, O'Donovan *et al*. (2000) showed that increasing seeding rate in conventional farm situations can improve the competitiveness of barley, across a variety of cultivars, resulting in reduced wild oat biomass and seed production. In some cases, yield increases were also recorded in response to higher plant populations.

In addition to increasing seeding rate, utilising narrower row spacing in the crop further serves to decrease light transmittance to the soil and resource availability to weeds. Paynter (2010) found that increasing row spacing in barley may lead to increased *Lolium rigidum* tillering and biomass production. Kirkland (1993) demonstrated that wild oats were significantly suppressed in spring barley by narrowing the space between rows and increasing the seeding rate. Interestingly, no interaction was found between the two measures. Furthermore, both of these practices seem to impact weed fitness and reduce herbicide dependence to a lesser extent than cultivation techniques (Johnson *et al*., 1998).

Cultural changes to seeding configuration still represent an attractive addition to IWM programmes. They incur no additional labour on behalf of the growers and are not knowledge intensive in their application. Targeted trials aimed at finding optimum seeding rates and row spacing relative to expected yield and weed pressure would enhance grower adoption of these simple measures.

Cultivation

Cultivation systems can be split into two broad categories: inversion tillage and non-inversion tillage. Inversion tillage is commonly referred to as conventional tillage and includes systems that involve the complete inversion of the soil and incorporation of the crop residue. This is followed by further cultivation to create a seedbed (Carter *et al*, 2003).

Non-inversion tillage, or conservation tillage, generally requires fewer passes than conventional tillage. This category includes systems that incorporate the crop residue into the soil as well as systems such as direct drilling where the crop residue is left on the soil surface and the seed is placed directly into the soil (Davies and Finney, 2002; Morris *et al*., 2010).

The adoption of conservation tillage systems is largely seen as positive for the environment. Agriculture is a major contributor to increasing the levels of greenhouse gases in the atmosphere; hence, taking steps to curb fossil fuel consumption has been a focus of modern agricultural research.

Reduced tillage significantly reduces the amount of resources required to prepare a field for sowing; one herbicide application replaces numerous passes with tillage equipment. Furthermore, implements used for tilling the soil tend to be considerably heavier than herbicide sprayers, requiring demonstrably more energy to move (Gianessi, 2013). As far as crop production is concerned, the action identified as having the most potential to reduce greenhouse gas emissions was the reduction in tillage (Ortiz-Monasterio and Wassmann, 2010).

In theory, in zero-till systems, mortality of weed seeds would be higher on the soil surface than it would be when left at depth by tillage. This may be due to a number of factors such as degradation by weathering, predation by birds and even inhibition of germination through physical and allelopathic suppression by the crop residue. The drawback with systems of this kind is that their effectiveness relies heavily on the efficacy of the herbicide used on them (Blackshaw *et al*., 2008).

Strict no-till systems remove flexibility from the IWM programme, in that the option to cultivate is removed, depriving the toolbox of a key implement. Furthermore, there is generally an inverse relationship between tillage and herbicide usage, meaning weeds in the reduced tillage system are subject to more intense selection pressure (Owen *et al*., 2015).

Although crop rotation and diversity have been found to be a more important determinant of weed seed banks than cultivation strategy, the effective combination of both of these tactics has been shown to be useful in reducing weed populations (Cardina *et al*., 2002).

A meta-analysis of different agronomic studies regarding the management of *A. myosuroides* by Lutman *et al* (2013) found that inversion tillage reduced weed populations by 69% on average when compared with minimum tillage. That said, the data analysed was not without significant variation. Ploughing may have produced a mean reduction of 69%, but some studies reported up to 82% increases, with others demonstrating 95% reduction in populations of *A. myosuroides.*

The variability in these studies is due to a number of intrinsic factors in the fields being studied. The amount of old seed buried in the soil and the amount of new, freshly shed seed at the soil surface have a huge impact on the efficacy of inversion tillage for weed management. Inversion changes the distribution of both new and old seeds in the soil profile, which effects subsequent populations. Ploughing may have the unwanted effect of turning up old, viable seed.

Research is required to increase understanding of the soil profile and how it relates to weed germination. This knowledge needs to be optimised to provide decision support tools to growers so that they can be flexible in their cultivation strategy as it pertains to weed management.

The benefits of increased weed control, of course, must be weighed against the environmental impact of cultivation. However, improvements made to soil quality and the environment may be hampered if new cultivation technology specifically tailored to addressing herbicide-resistant weeds is not forthcoming. This represents a technological challenge to the agri-engineering sector to innovate in the coming years as the issue of resistant weeds in Ireland is worsening.

Weed dispersal and migration

The severity of a weed infestation is a function of a number of variables such as the density of the weed population, the competitive ability of the weed species and the spatial distribution of the weed patch. This spatial distribution changes over time with response to a number of characteristics of the weed.

Taking *A. fatua* as an example, natural dispersal is quite limited. Seeds reach maturity and are spontaneously shed from the panicle, generally within a radius of 1.5 m of the plant. Tillage is the main driving force behind seed dispersal in the case of *A. fatua*. Inversion tillage can move plants 2–3 m in the direction of the cultivation, with increases in movement observed when tilling downhill (Barroso *et al*., 2006).

Movement due to combine harvesters varies between both weed species and crops. Tall weeds, particularly those that retain a high proportion of their seed through harvest, are subject to much more movement by combine harvesters. It follows that earlier harvested crops such as winter barley would see higher levels of *A. fatua* compared to spring bean crops where most of the weed seeds will have been shed by harvest. This movement is particularly important in *A fatua* as it is a self-pollinating species and mechanical movement represents the simplest way for resistant biotypes to spread throughout the agricultural landscape (Barroso *et al*., 2006).

Knowledge of weed spatial distribution is vital to the growers, especially in scenarios where fresh infestations of weeds are arising in a field. Monitoring and curtailing initial colonisation is by far the most effective means of managing a weed population (Cardina *et al*., 1997). This may be achieved by hand roguing or patch spraying (with a non-selective herbicide) small initial infestations before they have a chance to grow. In the case of herbicide-resistant grass weeds, this approach is perhaps even more important as the curative, selective herbicide-based approach may not be an option for the growers. In terms of research, the tendency is to focus on the individual weed, but perhaps the onus should also be placed on the patch. Ireland represents an attractive research opportunity to investigate this dynamic due to the relatively small populations of resistant weeds and the high possibility of colonisation events.

Models suggest that weeds with lower competitive ability to reduce yield in a crop but with high mobility represent more danger to crops than those with high competitive ability and low mobility (Maxwell and Ghersa, 1992). However, many grass weeds are both highly competitive and highly mobile. This begs the question: Should we be focusing our efforts on reducing weed mobility instead of concentrating on curative approaches? The answer is likely somewhere in the grey area between the two, but the question raises other interesting issues.

Llewellyn and Allen (2006) explored grower's attitudes towards weed mobility and what this meant for management strategies. Herbicide resistance may move from farm to farm via seed, machinery, straw bale, mushroom compost or a variety of other means. This study found that most growers believe that herbicide resistance problems on their farm are caused by immigration of weeds, as opposed to a new evolutionary event.

This would seem to have significant implications for the Irish crop production sector. Currently, the frequency of herbicide-resistant weed populations growing in Ireland is not known. Research has indicated that populations of wild oats and black grass resistant to one or more herbicides are present (Byrne *et al.*, 2017; unpublished data). The mobility of these weeds could be the cause of an increase in resistance nationwide.

The key to limiting weed mobility and seed bank decline could be a change in the paradigm surrounding management. Harvest weed seed control (HWSC) systems target weeds during harvest, acting to minimise additions to the weed seed bank and minimise the availability of weeds for migration via machinery, etc.

Low seed bank levels and low dispersal are crucial to sustainable weed management as part of an IWM programme (Walsh *et al.*, 2013). Shortly after the introduction of the combine harvester, it was realised that they were ideal machines for weed dispersal. Weed seeds enter the front of the harvester and are processed, exiting via the chaff fraction. These "harvested" weed seeds are distributed round the free field to become future weed patches.

In Australia, increased interest has been seen in HWSC systems such as chaff carts (Walsh and Powles, 2007), narrow windrow burning (Walsh and Newman, 2007), direct baling (Walsh and Powles, 2007) and the Harrington seed destructor (Harrington and Powles, 2012). The efficacy of HWSC systems is dependent on the proportion of total weed seeds retained at harvest. Thus, these techniques will work best for late-maturing weed species. The merit of HWSC tactics remains to be evaluated in Ireland.

Social science and weed management

The control of herbicide-resistant weeds is a complex issue and is certainly one that requires a multifactorial approach towards identifying solutions. IWM as a concept is knowledge intensive. By definition, it is a system of guidelines that synergistically work together to manage weed populations. This, of course, is not a readily marketable product in the same manner as agrochemicals.

Ecologists speak of herbicide resistance as being a "tragedy of the commons" insofar as each individual actor acting out of his/her own self-interest may exacerbate the problem (Ervin and Jussaume, 2014). An example could be growing wheat that is heavily infested with herbicide-resistant black grass. The growers might harvest the crop because they are economically incentivised to do so, whereas the most suitable option for avoiding the spread of herbicide-resistant seeds may have been total crop destruction. Thus, not only is it necessary to understand the mechanisms underlying herbicide resistance and strategies to delay and circumvent it but also prudent to gain a deeper insight into the socioeconomic factors that slow integrated management techniques from being adopted.

If agrochemicals have powerful economic mechanisms driving their sale, what are the factors required to implement locally adapted, effective, sustainable weed management techniques in the Irish crop production industry?

Currently, herbicide-resistant weeds are present in Ireland; however, their frequency relative to other grain-growing regions throughout the world is not yet clear (Byrne, 2017; unpublished data). That said, the area within Ireland where crops are typically produced is small. Therefore, the potential for resistant weeds to quickly gain a foothold in the Irish landscape is quite strong. Thus, focus needs to be put on area-wide management plans that work to reduce selection pressure on weeds at a regional level (Mortensen *et al.*, 2012). These plans would aim at bringing about patterns of herbicide and crop rotation in a targeted manner to counteract the migration of resistant weeds throughout the region.

Mortensen *et al.* (2012) recommend that government regulatory agencies should require all new herbicide biotechnologies to clearly address resistant weed management, be it through labelling, advertising, grower outreach events or other educational avenues.

Critical to all of this are growers. Current market forces incentivise the intensification of crop production. Therefore, any policies or guidelines put in place to mitigate the spread of herbicide resistance must align themselves with what is most sustainable for the farmer. Liebman and Staver (2001) suggested that fees connected to the sale of herbicides could be used as negative reinforcement encouraging the adoption of more ecologically friendly approaches to weed management. However, this could be seen as punishing farmers for a problem that may not be entirely their fault.

What is clear from all these studies is that policy needs to be locally adapted and should be region specific to effectively slow the onslaught of resistant weeds. There is no silver bullet technology for this problem. The answer lies at the intersection of research, government, industry and the farm.

Effective management will require effective education, and it is clear that work needs to be done to identify strategies that the Irish crop production sector can implement.

Future directions for sustainable weed control

Stern *et al*. (1959) described the importance of integrating a number of complementary tactics to manage insect pests as means of reducing dependence on chemical pesticides. Six decades on and there are still challenges with over-reliance on chemical control measures. With this in mind, what does the future of weed control hold? Furthermore, how will the past inform the technology of the future?

The efficacy and usefulness of IWM systems should increase as knowledge grows and application specificity increases. However, this will only happen if industry, research and advisory elements of the crop production sector work in concert to innovate and educate growers on the most sustainable, effective practices. One of the main issues plaguing contemporary IWM is that advanced weed management is highly knowledge intensive (Mortensen *et al*., 2012).

Young *et al* (2017) described different levels of IWM as a function of their integration. Low-level IWM refers to single-tactic approaches to control weeds such as simple herbicide application. Low-level IWM is suboptimal because it leads to issues like herbicide resistance. The lack of tactic integration and application specificity in low-level IWM can confer short-term economic benefits, but long-term issues are plentiful, as this review can attest to.

High-level IWM incorporates a number of tactics with high application accuracy in a manner that is field specific. To truly achieve this specificity and to aid decision support, advancements in technology will be required to fully integrate novel tactics into the modern weed management programme (Young *et al*., 2017).

Now we will turn our attention to some of these emergent technologies and the roles they may play in the control of Irish weeds.

Chemical weed control

There is obviously a need for new herbicide sites of action to cope with the evolution of resistant weeds, increasing the efficacy of chemical weed management. That said, no herbicides with novel target sites have been developed in the last 30 years (Duke, 2012). There are known, unused target sites for which inhibitors are available that are highly effective at selectively killing plants. However, these sites have not been commercialised and brought to market for a myriad of reasons, chief among them economic and political. Bringing novel agrochemicals to market is expensive. Coupled with these costs is the political uncertainty surrounding the use of pesticides, particularly in the EU.

A possible avenue towards circumventing this is to improve the efficacy of existing herbicides. This might be achieved through the introduction of synergists to counteract the evolution of NTSR. The main question surrounding these products is the safety of the crop (Shaner and Beckie, 2014). Early studies have shown that various synergists may enhance the activity of a herbicide or restore sensitivity to a resistant plant that has gained NTSR through increased activity of xenobiotics and digesting enzymes such as cytochrome P450 oxidases, glycosyltransferases and ABC transport proteins (Délye, 2013; Lamberth *et al*., 2013).

The rapid advancements in targeted genomic manipulation tools such as RNA interference and CRISPR/Cas 9 will be welcomed by the agrochemical industry, and these tools will likely be used in the ongoing battle against herbicide resistance. Hollomon (2012) reported an RNAi technique being investigated whereby targeted genes in the weed plant's genome can be turned on or off. Guide RNA are utilised to target and subsequently cause the inhibition of the EPSPS (5-enolpyruvylshikimate-3-phosphate synthase) protein in plants. When combined with herbicides, namely glyphosate, this compound can reverse resistance. However, as mentioned earlier in this review, there is panacea for control of weeds. Nature has continuously found a way to circumvent new technology, and this is unlikely (indeed, not) going to slow down any time soon.

The concept of biological herbicides is a desirable alternative to chemical weed management agents. However, these measures will only be adopted by growers if they can provide the same consistent levels of control as conventional herbicides, while being marketed at a similar or indeed lower price point.

Powell and Jutsum (1993) supposed that biocontrol products in earlier stages of development may initially fill niches left behind where weed control can no longer be used, such as resistant weeds or politically unacceptable scenarios like the control of weeds in urban areas.

Very few bioherbicides have been successfully commercialised, but their ongoing development is important to mitigate the possible effects of reduced herbicide options due to legislative influence. Assisting the discovery process by optimising the rapid identification of natural products (Kao-Kniffin *et al*., 2013) and genetic manipulations and/or breeding efforts to enhance their efficacy (Rector, 2008) may aid the commercialisation of biological agents for weed control.

Robotics/mechanical weed control

As mentioned in a previous section, spatial distribution of weed populations and changes within them is an extremely important aspect of IWM programmes. In the future, remote

Table 2. Research on various aspects of integrated grass weed management required in the Irish arable context

Action	Recommendations
Ecological surveying	• Assess the distribution and frequency of black grass and lesser canary grass, as well the various species of brome. • Identify the frequency of herbicide-resistant biotypes of wild oats and the brome species within the wild-type population. • Determine the origin of black grass growing in Ireland.
Weed biology	• Begin a series of long-term experiments looking at the germination of different grass weeds in a number of abiotic contexts (different soil types, temperatures, burial depths). • Understand the nature of herbicide resistance in Irish grass weeds (TSR versus NTSR). • Investigate differences in the reproductive success of grass weeds under a variety of different agronomic conditions.
Chemical control	• Research the feasibility of synergists for improving chemical control. • Identify novel herbicide modes of action.
Non-chemical control	• Assess the efficacy of crop rotation, increased sowing rates, later sowing dates, etc. for reducing grass weed populations. • Develop an accurate score for crop competitiveness that could be incorporated into recommended lists. • Investigate the use of UAVs and tractor-mounted sensors for the detection of grass weeds and how this may influence control measures.
Biological control	• Investigate the potential of bioherbicides for grass weed control. • Determine whether CRISPRs can be deployed to reintroduce sensitivity to herbicides in grass weed species.

TSR = target site resistance; NTSR = non-target site resistance; UAV = unmanned aerial vehicle.

sensing and the use of satellites and unmanned aerial vehicles may offer opportunities to detect and chart populations of weeds at the field level before patch expansions occur (Rew *et al*., 2005; Shaw, 2005).

Currently, spray operators apply herbicides uniformly across whole fields. Inputs and environmental impacts could be decreased if herbicides are sprayed only where they are needed; however, this approach is limited in how it deals with the issue of herbicide resistance (Shaw, 2005). This tactic follows the same principle of variable rate fertiliser spreading, as in "to each according to their need". Recent developments in mounted cameras and sensors to identify weeds mean that spatially specific herbicide application is closer to broad-scale implementation than one might think (Christensen *et al*., 2009; Rasmussen *et al*., 2013).

All of these technological advances will greatly assist the implementation of "true" IWM, taking it from an esoteric ideal to an achievable goal. How quickly this technology comes about depends on socioeconomic factors. Irish crop production is somewhat smaller in scale compared to other countries, so the underlying question may be how little would these emergent technologies have to cost for them to be economically viable at the scale of Irish production.

Care needs to be taken at the policy level to ensure that Irish growers do not get left behind as larger scaled crop production systems invest in advanced methods for weed and pest control. How will we provide incentive for the growers to invest in these technologies while maintaining their already rapidly eroding profit margin? The jury is out.

Conclusions

It can be argued that Irish and even global crop production is at a crossroads. Over the past few decades, advancements have been made in the fields of agronomy and biochemistry that have led to massive improvements in terms of yields and quality of our crops. That said, the onset of herbicide resistance coupled with unpredictable grain prices currently leaves crop production facing an uncertain future.

Research and innovation will be paramount to the Irish crop production sector effectively dealing with the problems caused by herbicide resistance. Using existing research to steer policy towards schemes that take an eco-evolutionary approach to weed control is a major start. Further to that, identifying gaps in our understanding of the biology of these problematic weeds is key to advancing the field into the future (see Table 2).

Without incorporating societal and eco-evolutionary aspects like this into research, one runs the risk of research being "toothless" in a sense. Including all the players involved in the field of sustainable weed management increases the chance of tangible benefits being brought about by this work.

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