SRUC

A desk based review of alternatives to glyphosate to control groundkeepers

Shailesh Shrestha and Fiona Burnett

Table of Contents

Executive summary 2

Introduction 5

Groundkeeper control options 5

Glyphosate 5

Alternatives management options 6

Methodology 7

Consequences of loss of glyphosate 7

Alternatives to glyphosate 11

i. Chemical 13

ii. Non-chemical 15

iii. Integrated methods 18

Cost effectiveness of alternative options 19

Conclusions 25

References 28

Executive summary

Groundkeepers (or volunteer potatoes) represent a substantial economic burden to the potato industry. Groundkeepers negatively impact crops grown in the affected field in subsequent seasons by competing for the resources needed for growth so reducing crop yield. Importantly, they also act as a reservoir for pests and diseases which reduce yield and quality in surrounding and subsequent potato crops.

Groundkeepers are primarily managed in Scotland through the use of the translocated herbicide glyphosate, applied after the groundskeepers start to emerge in the following season. However, there is regulatory uncertainty in the UK (and Europe) around the future use of glyphosate. Its withdrawal would lead to substantial changes to management strategies for potato growers as they move to alternative, potentially more costly or less effective options.

This report provides a review of the alternative treatments for control of groundkeepers available to UK potato farmers. There is, however, a notable lack of detailed economic data on these treatments and this review therefore also presents a qualitative comparison of the cost effectiveness of such treatments.

Using the few published sources on economic impact available, estimates indicate that if glyphosate is withdrawn, the average farm will experience between a 3-20% fall in production. Using the economic report for Scottish agriculture for 2020 the value of the potato crop per annum in Scotland is £250.3 million. This would lead to an estimated loss of £7.5 million - £50 million per year, with mitigating actions included in the lower bounded estimate and without any mitigating control options at the upper estimate. It is important to note that these estimates are based on all aspects of pest, weed and disease control and the losses directly attributable to groundkeeper management within this figure are lower. **An estimated £0.5 million loss per year could be attributable to poorer groundkeeper management**.

The alternative treatments considered in this report are grouped into three categories; namely i. chemical; ii. non-chemical and iii. integrated control methods.

No single alternative option is as effective as glyphosate so there is a risk that groundkeeper problems will increase unless alternative options are stacked. The chemical treatments considered are herbicidal in nature, but their efficacy is lower

than that of glyphosate (glyphosate: 80 – 95% efficacy). Of the herbicides available, the use of sulfonylurea herbicides, often in mix with pyridine herbicides (TMF mix), are the most broadly applicable alternative chemical alternative to glyphosate (TMF mix: 75% efficacy).

Due to higher cost of implementation and lower efficacy, all the alternative chemical, non-chemical and integrated control options are estimated to have lower cost effectiveness ratios (CE) than glyphosate (Figure 1).

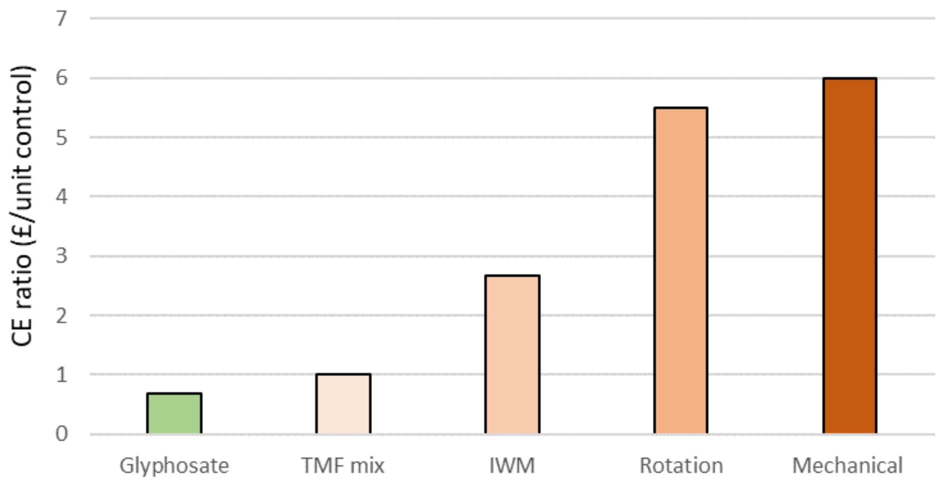

Figure 1: CE ratio of representative treatments used to control groundkeepers. CE ratio represents the cost of application of the treatment to control 1% of groundkeepers in a field. (IWM = Integrated Weed Management; TMF mix = thifensulfuron/ metsulfuron/fluroxypur mix)

Non-chemical alternative treatments include farm management practices that are adopted to minimise groundkeepers in the field. Efficacy ranges from 20% for frost to 40% for extended rotation and mechanical control. Crop rotation requires a strategic selection of suitable crops to follow the potato harvest and a longer interval between crops to achieve some degree of success in controlling groundkeepers. However, crop rotation is estimated to have substantial cost implications compared to glyphosate.

The cost of glyphosate treatment varies by rate and application number £53-£66 /ha and crop rotation is estimated to have a cost of £220/ha per year for extending a typical 6 course rotation by one year. The use of a TMF mix, at approximately £61 / ha, is broadly similar in cost on a per hectare basis to glyphosate but is 33% more expensive on a unit of groundkeeper control basis (Figure 1). Mechanical removal of groundkeepers is the least cost effective due to intensive labour requirements but investment in new and improved harvesters (for reasons other than groundkeeper control) will have knock on benefits with fewer tubers left behind in field at harvest (£240 /ha).

A combination of different alternatives under a properly managed integrated weed management strategy is the best alternative to glyphosate or the TMF mix but (as shown in Figure 1) is still estimated to be more than twice as costly (per unit of groundkeeper control) and will be more complicated to implement, particularly where potato land is rented and some or most aspects of the strategy would fall to the landowner or other renters. This option can be considered as a sustainable alternative to glyphosate but will require support for training and knowledge exchange activities to ensure effective uptake.

This review shows that glyphosate withdrawal would have significant economic impact on the potato industry in Scotland. More research is required to identify effective alternative treatments, both solo and in combination. Since the next most cost-effective alternatives to glyphosate are other herbicides, their use via precision application methods could aid efficacy, reduce cost and reduce unwanted environmental impacts.

Introduction

Groundkeepers, or volunteer potatoes, are potatoes that fail to get lifted during harvesting which survive and emerge during the following spring/summer seasons. There can be as many as 350,000 to 500,000 unharvested tubers per ha of arable land in the UK, and 66% of fields after a potato harvest are estimated to be affected (Davies *et al.*, 1999). Groundkeepers are also a problem for arable farmers in the UK as they compete with arable crops for light and resources and can reduce yields substantially. Less competitive crops such as carrots, cabbage and onions are seriously affected, but even in more competitive crops such as cereals or oilseed rape management costs are incurred using herbicides. There can also be additional costs, for example removing potatoes from a broad bean harvest has been found to cost around £15 - £20 per tonne of beans (Askew, 1998).

For the potato industry, groundkeepers represent a serious biosecurity problem. These provide an on-going host for the persistence and multiplication of potato pests and diseases e.g., potato cyst nematodes, blight and viruses which reduce yield and quality (Rahman, 1980). In terms of potato cyst nematode damage alone, the Scottish potato sector is predicted to suffer economic losses of £125 million by 2040 (Plant Health Centre, 2020).

Groundkeepers therefore represent a substantial economic burden for potato farmers, both in terms of the increased pest and disease burden but also because of additional management costs incurred in managing groundkeepers. There are also potential impacts to the wider industry through actual or reputational damage to the health status of the Scottish seed potato supply chain.

Groundkeeper control options

Glyphosate

The most widely used treatment by UK potato farmers for groundkeepers is glyphosate. Since its introduction by Monsanto in 1974, glyphosate has become a widely used herbicide choice for farmers to control weeds and is the number one control measure adopted globally (Beckie *et al.*, 2020). Due to its broad spectrum of control across many weed species, its higher efficacy and its affordability, the use of glyphosate in the UK has increased by a factor of 45 during the last decade, compared to the earlier decades of its introduction (Beckie *et al.*, 2020). It is the most used herbicide in the UK arable sector with almost one third (2.2 mil ha) of

UK arable land treated with glyphosate in 2014 (Oxford Economics, 2017). Glyphosate is widely used in Scotland for weed management (including groundkeepers) and is also used as a harvest aid in cereal crops where it can ripen the crop evenly. The most recent pesticide surveys carried out in Scotland show that 2,677 ha of vegetable crops were treated with glyphosate in 2021 (Macleod *et al.*, 2021) and 185,000 ha of cereals treated in 2020 (Davies *et al.*, 2020).

Glyphosate is very effective against groundkeepers as it is translocated downwards from the point of contact. Hence, it kills the volunteer plants both above and below ground, preventing resprouting. There have been many studies conducted to determine the effectiveness of glyphosate to control groundkeepers (Lutman and Richardson, 1977; Smid and Hiller, 1981; Mausinas and Weller, 1988; Hutchinson *et al.*, 2014) and they concur that glyphosate is more effective than other available chemical options. In an experiment in England, it was determined that a 2 kg/ha dose can provide 90% success in stopping tubers from sprouting (Lutman and Richardson, 1977).

Since a lawsuit against Monsanto alleging glyphosate to be carcinogenic in 1980, many legal cases have been filed (Centre, 2021). Due to the growing health concerns, countries including within the EU and the UK banned the sale of concentrated forms of glyphosate to amateur users but continued to allow the commercial use of glyphosate (Clapp, 2021). Within the EU, commercial use of glyphosate is under review and political pressures to revoke its use remain strong. Some EU member states such as Germany have decided to phase it out by 2023 (Reuters, 2019). The UK, however, have approved the use of glyphosate until 2025 (VALEUK, 2020). Uncertainty around the future use of glyphosate may lead to a substantial change in management strategies for potato growers. Accordingly, this report aims to review the impact of loss of glyphosate and determine alternate methods of control and their associated cost and practicality.

Alternatives management options

Alternatives to glyphosate as a management tool for groundkeepers include the use of other herbicide actives. The physical removal of groundkeepers is another alternative, as is leaving groundkeepers on the surface of soils to be killed through frost damage. Other more integrated methods of control include extended rotations or combinations of all or some of the above in to integrated control plans.

Some options such as manual removal are prohibitively costly due to higher labour costs, while others may require additional spray passes, higher costs for the alternative herbicide options or they represent lost income through more extended gaps between cash crops in the rotation. Details on available options are set out in the methods section.

Methodology

This report uses a structured literature review based on published sources about the use of glyphosate in the arable sector, its economic impacts on different crops and existing alternative methods. Published reports, however, on the economic assessment of glyphosate and alternative treatments to control groundkeepers in the UK potato sector are very limited. Therefore, in addition to published scientific papers, research reports and the use of reports in the technical press, a selected panel of Scottish industry and academic potato experts were consulted to fill gaps in information through expert opinion.

Consequences of loss of glyphosate

The impacts of glyphosate withdrawal are manifested at farm level through changes in crop production, crop rotation, crop reallocation, yield, production, and income. Since uncertainty on the use of glyphosate emerged in 2015, some studies have been conducted to assess the impact of glyphosate withdrawal on arable farms. This impact differs by crops and regions but also under different methodologies used to determine the impact. However, all these studies show a large negative impact on crop production and farm finances.

In Sri Lanka, a ban on glyphosate use on farms was implemented in 2015. It was estimated that this ban led to an increase in costs of 3.29% in the total cost of paddy production (Marambe and Herath, 2019). Impacts could be much larger in Europe, and in Germany a simulation economic assessment study estimated a reduction in farm gross margin of between 3% and 36% depending on the location of the farm (Kehlenbeck *et al.*, 2016).

Within the EU, a recent analytical review, which collected information from 32 studies across 8 countries and then extrapolating the results to provide an EU-wide perspective, estimated a 30% reduction in wheat and a 20% reduction in vine production if glyphosate was withdrawn from use and other available control options were substituted (Wynn and Webb, 2022).

In the UK, an impact assessment study conducted in 2017 estimated reductions in production of different crops ranging from 14% in oilseed rape to 3% in maize (Figure 2).

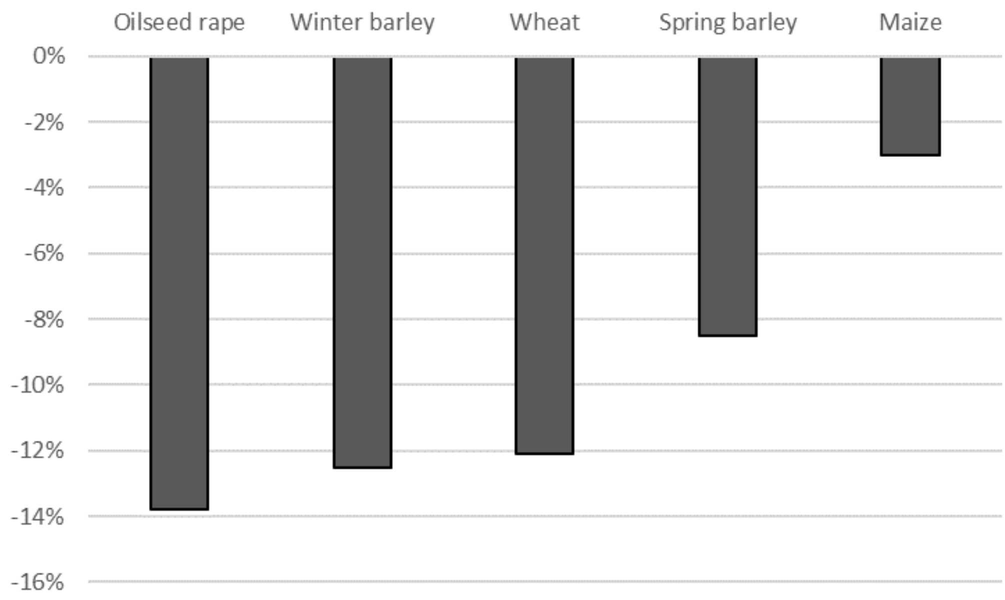

Figure 2: Reduction in some of the crop production in the UK without glyphosate (Source: Oxford Economics, 2017)

Some of the studies examined the impact of glyphosate withdrawal on production economics both at a sector as well as a farm level. A modelled study in Germany estimated a reduction of margins up to 2% on maize farms when farms are not allowed to use glyphosate (Böcker *et al.*, 2020). Across the EU-28 region, estimated cost was around €10.5 billion to the EU wheat sector if glyphosate use is not allowed on farms (Wynn and Webb, 2022).

Some of these studies also estimated impacts of glyphosate withdrawal on the potato sector (Table 1). EU wide potato production is projected to reduce from between 5% and 20% without glyphosate across different regions of the EU (Wynn and Webb, 2022). Wynn and Webb (2022) collected data from 32 socio-economic studies carried out to assess impacts of glyphosate withdrawal across 8 EU countries (including the UK). They estimated that the EU potato sector will face an economic loss of around £1.75 billion per year without glyphosate. In the UK, potato farms are estimated to have a 3% loss in yield without the use of glyphosate (Oxford Economics, 2017(a); Twinning, 2009) which is at the low end of the EU range determined by Wynn and Webb (2022). This is because the UK study includes changes in farm practices to mitigate yield losses. This includes full inversion, extra cultivations, additional spray passes and higher labour use (Oxford Economics 2017 (b)).

These changes in farm practices incur higher farm costs. Specifically, the Oxford Economics model employed costs of changes in farm practices, plus the additional chemical costs as well as losses due to yield reduction to estimate the economic impact of glyphosate withdrawal. This study estimated an average UK arable farmer (including potato producers) would experience reduced annual earnings by 13.9% (Oxford Economics 2017 (b)).

At the extreme, if no mitigating actions or control measures were taken then the UK potato sector is estimated to have an economic loss of £228 million per year (Twinning *et al.*, 2009). This value covers poorer broad-spectrum weed control, within which an estimated economic loss of £1.4 million per year is specifically attributed to groundkeepers. This is the only robust published report on likely impact attributable to groundkeepers should glyphosate be withdrawn.

Using the economic report for Scottish agriculture for 2020 the value of the potato crop per annum in Scotland is £250.3 million. Using the 3% to 20% estimates of losses gathered from the literature sources above this equates to an estimated loss of £7.5 million - £50 million per year in Scotland attributed to poorer broad-spectrum weed control, with mitigation options included in the lower bounded estimate and without any mitigating control options at the upper estimate. The losses directly attributable to groundkeeper management within this figure are much lower. If alternative mitigation actions for weed treatments are deployed, this would lead to an estimated £500K loss per year attributable to poorer groundkeeper management, derived from Twinning *et al.*, 2009s.

Table 1: Impact of glyphosate withdrawal on potato production in the EU and UK.

Impact	Predicted loss	Region	Reference	Comments
Loss in production	-5% to -20%	EU-28	Wynn and Webb, 2022	This prediction range is based on a small number of studies over 8 EU countries
Sectoral impact	-£ 1,750 million / year	EU-28	Wynn and Webb, 2022	This prediction range is based on a small number of studies over 8 EU countries
Loss in production	-3%	UK	Oxford Economics, 2017	The Oxford Economics study included farm practices to mitigate yield loss
	-30%	UK	Twinning et al., 2009	No weed treatments were allowed
Sectoral impact	-£228 million / year	UK	Twinning et al., 2009	Cost of removal of all weed treatments –
Sectoral impact directly attributed to groundkeepers	-1.4 million / year	UK	Twinning et al., 2009	Included within the - £228 million loss per year value above

Alternatives to glyphosate

Alternatives to glyphosate for the control of groundkeepers can be grouped into three different categories; i. chemical; ii. non-chemical and iii. integrated methods. A list of reviewed alternative options with their effectiveness in controlling groundkeepers is presented in Table 2. In Table 4 these are modified to be relevant to Scottish conditions through expert opinion.

Table 2: List of alternatives to glyphosate and their effectiveness against groundkeepers

Category		Effectiveness	Comment	Reference
i. **Chemical**				
	a. glyphosate	>75 -90%	Single pass of 2 to 4 l/ha, with additional control from a second pass.	Lutman and Richardson, 1977; Smid and Hiller, 1981, Mausinas and Weller, 1988, Hutchinson *et al.*, 2014
	b. Maleic Hydrazide	25 -75%	Most effective during sprouting stage. Poor control if timing is wrong. Can only be applied to ware crops.	Buckley *et al.*, 2006; Cunnington, 2019;
	c. Mesotrione	70 - 95%	Most effective during early growth stages. A maize herbicide unlikely to be relevant in Scotland	Sutton *et al.*, 2002; Boydston and Williams, 2005

	d. Thifensulfuron/Metsulfuron (TMF mix)	Up to 60%	Most effective when combined with fluroxypyr	Davies, 2002
ii. Non-chemical				
	a. Crop rotation	Up to 40%	Only a limited number of crops can follow potato crop; long intervals between crops can improve effectiveness	Perombelon, 1975; Lane and Trudgill, 1999; Turley, 2001; Bond *et al.*, 2007; Rahman, 2012;
	b. Frost	Up to 30%	80% effective on near surface tubers, 0% effective against deeply buried tubers	Davies *et al.*, 1997; Bond *et al.*, 2007
	c. Mechanical	Up to 40%	Time consuming, labour intensive. High investment cost for harvester.	Lumkes *et al.*, 1978; Davies, 2002
iii. Integrated methods				
	Integrated methods (including precision management)	Up to 75%	Combines multiple treatments, more sustainable than other treatments but may be complicated for a grower to implement	Chikowo *et al.*, 2009; Merfield, 2019; Harker and O'Donovan, 2013

These options are described in more detail in the following section. The options and findings in Table 2 were presented to our expert group who added comments to reflect experience in practice.

i. **Chemical**

These are registered pesticides which have herbicidal properties and are used to reduce groundkeepers in affected fields. These chemicals work in different ways. Some of these chemicals are enzyme inhibitors (e.g. Mesotrione) and others work as a sprout suppressant (e.g. Maleic hydrazide). They have a success rate ranging around 25% - 75% in eliminating groundkeepers from fields (Davies *et al.*, 1999) and are convenient for a farmer to use on the farm as part of a chemical control strategy. There is an extensive range of herbicides that are used to control weeds on arable farms globally but here we present three of the most used herbicides on UK potato farms for groundkeeper management. Evidence from recent work commissioned from the Plant Health Centre (Burnett *et al.*, 2021) shows that where pesticides are withdrawn from use, the preference amongst farmers is to use an alternative pesticide compared to other available alternative management practices. That preference may apply to glyphosate as well, and substituting an alternative herbicide may be a preferred option.

Glyphosate

As a broad-acting systemic herbicide and crop desiccant, glyphosate sits in a class of its own as a phosphonate (an organophosphorus compound) acting through the inhibition of Enolpyruvyl Shikimate Phosphate Synthase. It can be translocated downwards (in contrast to most hebicides which are only translocated upwards into new growth) and as such can prevent regrowth from below ground parts. There is extensive literature which sets groundkeeper control at up to 95% effectiveness, hence its established position as the benchmark level of control against which alternatives are compared.

Using expert opinion from a selected group with experience of its use in Scotland, the range of control experienced ranged from 75-95% effective. Timing was considered very important, with application during early and rapid growth considered key to good control. The upper range of control (95%) is achieved where two applications are made, with around 80% control achievable from a first application and then 80% control of survivors from a second application leaving just 4% survival (96% control).

The best control is also achieved where the product is used at 4 l/ha as compared to the standard 2 l/ha dose. With poor timing of application, control could be a lot less than 75%.

Glyphosate can be used for other purposes in rotation, and these might have effect on groundkeepers but will not be as effective as a targeted groundkeeper spray (where the higher rate would tend to be used).

Maleic hydrazide

Maleic hydrazide is commonly used in the UK with around 17.6% of potatoes produced being treated with this herbicide (Buckley et al, 2006). Maleic hydrazide kills groundkeepers at the sprouting stage, hence timing of application is very important for an effective result (Mckenzie, 1989). A mistimed application may reduce the yield of the treated potato crop, and late July or early August application (circa 5 weeks before defoliation) is supported for the best results (Cunnington, 2019). Maleic hydrazide has a 75% efficacy when applied five weeks before desiccation (AHDB, 2006) but is less effective when applied during other stages of production. Its application is recommended when the crop is sufficiently mature (Buckley *et al.*, 2006).

Using expert opinion based on experience of using the product in Scotland, 75% was agreed to be a reasonable estimate of efficacy but with a range of 25% control for poorly timed applications and up to 90% control for well-timed applications. This active has a very limited range of crop types on which it is approved for use (onions and potatoes) and many products containing Maleic hydrazide are only approved for use on ground not intended for vegetation so are not relevant in an arable context. In Scotland this active is mainly applied to ware crops in the context of sprout suppression, with groundkeeper control regarded as a bonus. It is not approved for use in seed crops and so will only ever be a partial solution in the Scottish context.

Mesotrione

Mesotrione is an enzyme inhibitor and is approved for use to control weeds in maize (Sutton *et al.*, 2002; Boydston and Williams, 2005). An experimental trial in the USA, applying mesotrione at 0.11 kg/ha in field corn, found tuber numbers were reduced by up to 95% (Boydston and Williams, 2005). Maize, is not widely grown in Scotland and where it is grown (usually as a fodder crop for animals) the overlap with areas where potatoes is grown is limited. As such it is unlikely to be widely used as an option for groundkeeper control in Scotland unless the authorisation for the product is extended to other crops. Given its expense and its efficacy, relative to other options, this is unlikely.

Sulfonylureas, TMF mix (+/- pyridines)

Thifensulfuron and metsulfuron are commonly used sulfonylurea hebicides in Scottish arable systems and are often used in mixture with the pyridine herbicide, fluroxypur.

These actives are used in combination with other herbicides to control groundkeepers and a combination of thifensufuron, metsulfuron and fluroxypyr is reported to reduce groundkeepers by up to 60% (Davies, 2002).

Using expert opinion based on experience of using these actives to manage groundkeepers in Scotland, 50% was considered to be the expected level of control, but with a range of 40 to 60% depending on growth stage, with poorer control for sprays applied before green growth is visible or too late when emerged groundkeepers had passed the early growth stages.

ii. **Non-chemical**

The second category of alternative options are non-chemical treatments, which include exploiting weather conditions or changing farm management practices to prevent or kill groundkeepers in the field. A non-chemical management strategy, if implemented properly, may be more environmentally friendly and hence could be an acceptable and effective alternative to herbicides in the future (Harker and O'Donovan, 2013; AHDB, 2019). The effectiveness of these methods lies in the strategic management of cropping systems. A poor crop management strategy such as using a less competitive crop in a crop rotation, however, could lead to an increase in tuber populations on farms (Turley, 2001). The most common farm management practices that can be used by UK potato growers to control groundkeepers are listed below.

Strategic crop rotation

A strategic crop rotation with competitive crops can reduce groundkeeper numbers. For example, planting winter wheat following potatoes has been shown to reduce groundkeeper numbers due to the competitive nature of winter wheat (Bond *et al.*, 2007; Rahman, 2012). Historically, growing leafy vegetables or fruit crops such as raspberries or leaving the field fallow following potatoes led to substantial reductions in groundkeepers in Scotland (Perombelon, 1975) but some vegetable crops, such as carrots and onions, compete very poorly and planting fruit crops is specialist and unlikely to be practical for much of the arable context where groundkeepers are a problem.

A method used occasionally in New Zealand is to convert the field to pasture after the harvest and then leave it for some years to be grazed by livestock (Rahman, 1980). Increasing the interval between potato crops can be a useful strategy to ensure a reduction in the occurrence of groundkeepers, weed and pests (Lane and Trudgill, 1999). However, this extends the interval between cash crops in affected fields and has a significant adverse impact on farm income. While more grass in arable rotations would reduce the groundkeeper burden in arable systems, it represents a departure for many Scottish specialist arable farms and is more applicable to mixed farming areas. It would have a very significant impact on total agricultural productivity from key Scottish arable / potato areas.

Use of frost

Ground temperatures of less than -2^{o}C are very effective at killing groundkeepers which are on or near the soil surface. It requires at least 50 frost hours at -2^{o}C to kill them successfully (Turley, 2001) and they need to be within the top 50 cm of the soil and ideally on the surface for the frost to be effective (Lutman, 1974). Deeply buried tubers are insulated from the cold temperatures. Hence the use of tillage practices such as using a shallow plough (Bond *et al.*, 2007) or a rotary cultivator

(Davies *et al.*, 1997), which bring groundkeepers closer to the surface, can be up to 80% effective. In an experiment conducted in Japan, researchers achieved 99.5% control by attaining a soil frost depth of 30 cm by ploughing snow over the plots (Yazaki *et al.*, 2013). Snow ploughing is not an option for Scottish growers and with concerns about a warming climate and a significant reduction in ground frost days recorded, the efficacy of surface frosting as a control method is likely to continue to decline.

In the experience of our expert group, frost is most effective when it occurs in the first winter after a potato crop and is clearly very dependent on the severity of the frost. It becomes progressively less effective later into rotation, with an estimate of 50% in year one and then 20% thereafter.

Mechanical

Using better harvesting tools and methods can minimise the number of tubers left behind in fields during the potato harvest (Davies, 2002). Dutch researchers, for instance, have found that small improvements in harvesting tools such as preventing spill overs from the sides reduces the number of tubers left over on fields (Lumkes *et al.*, 1978).

Within Scotland, newer harvesters are much better than older ones in terms of minimising the groundkeepers left behind in fields at harvest. Our expert group pointed out the high purchase costs, with self-propelled harvesters costing in the region of £500K - £700K. However, groundkeepers are not part of the buying decision, and improved efficiency, the ability to harvest in wide range conditions and damage reduction are the key drivers for such a purchase.

Hand picking potatoes left behind at harvest is not likely to be an option, with very limited labour, high costs and limited time being cited as reasons in the expert group.

Since the mechanical options described are primarily carried out for reasons other than groundkeeper control it is not possible to attribute a realistic cost to the element that pertains to groundkeeper management.

iii. Integrated methods

Integrated weed management

A strategic combination of different control options to control groundkeepers has been categorised here separately and designated as an integrated weed management approach. This category is different from the previous two as it includes practices that can include different forms of chemical and non-chemical treatments combined (Figure 3). This approach can be more effective in controlling and less environmentally polluting (Chikowo *et al.*, 2009), and it can also reduce selection pressure for resistance. As such, it has been suggested as the best approach to control groundkeepers by many researchers (Swanton *et al.*, 2008; Chikowo *et al.*, 2009; Harker and O'Donovan, 2013).

Relative to the cost of using glyphosate, integrated weed management will be more expensive, and could incur the penalties to farm income seen where rotations between cash crops are extended. It may need additional machinery and labour costs and may require the integration of the more expensive herbicide options considered above.

Managing groundkeepers using ecological focus areas and buffer zones on a farm may theoretically represent opportunities for control because a wider range of chemicals is approved for use in such fields (Turley, 2001). However, there are strict limitations on the timings of sprays on such areas so that biodiversity benefits are not compromised with the result that this is seldom practical, and in addition the areas involved can be small.

Our expert group considered that an integrated approach that includes the use of chemical alternatives was the most likely way forward if glyphosate was banned. They were unable to give an indicative cost or level of control as the number of options and factors to consider are so broad but they agreed that by stacking options, equal or better control to glyphosate used singly was achievable, albeit at greater cost. In the next section we make estimated costs for some of the key integrated approaches that could be used.

The expert group identified several limitations to the approach so, for example, while the inclusion of grass/ grazing improves groundkeeper control considerably, the use of cover crops can lead to an increase in groundkeepers. Avoiding winter cropping (to enable the use of broad-spectrum herbicides in the spring to manage groundkeepers) has a large cost to farm income after potatoes and so generally can't be justified for groundkeeper control alone.

Precision technology

The use of emerging technologies that allow for automated recognition and spot treatment of groundkeepers could have the advantage of reducing the cost of alternative herbicides. Development costs could be high but are areas of active research and development. Investment costs or the cost of contract services to deliver this option will be higher than the use of a blanket glyphosate spray. This precision option could be used as part of the integrated control strategies described above.

Integrated management options will need to be supported by appropriate knowledge exchange activities. They may be harder to implement where land is rented out as aspects of an integrated strategy will fall to different agents, as would any costs and benefits.

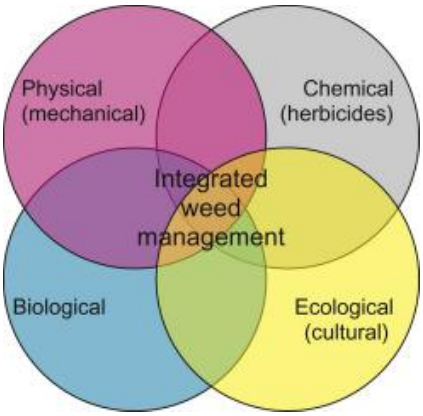

Figure 3: A schematic diagram of an integrated weed management (Source: Merfield, 2019)

Cost effectiveness of alternative options

Cost Effectiveness Analysis (CEA) is a method to compare the effectiveness of different interventions relative to their implementation costs. In agriculture, cost effectiveness analysis has been used to identify optimal strategies of farm management practices (O'Neill and Evans, 1999; Valeeva *et al.*, 2007; Benedictus *et al.*, 2009; Rushton and Jones, 2018; Colmer *et al.*, 2020; McCarty and Sesmero, 2021; Boerlage *et al.*, 2022). CEA uses the Cost-Effectiveness ratio (CE ratio), explained by Equation 1, to determine the effectiveness of an intervention (Rushton *et al.*, 2018).

$$CE\ ratio = \frac{\text{cost of the intervention}}{\text{effectiveness of the intervention}} \qquad \text{(Equation 1)}$$

This method, however, needs extensive data on economics as well as detailed information on effectiveness and cost of implementation. Due to the lack of detailed published information on the economics of alternative options, costs of implementation and effectiveness of options are estimated de novo based on literature and expert opinions in Table 4. The CE ratio in this report is the unitary cost of implementation of alternative options to control groundkeepers in a field.

The estimated cost of implementation under different treatments in Table 4 includes;

i. For chemicals: cost of chemical + cost of spray (1 - 2 sprays for glyphosate and 2 sprays for others). Cost of maximum application rate for chemicals and at the 4 L / ha rate of glyphosate (double what is commonly used where groundkeepers are not the specific target).

ii. For non-chemical:
    a. Crop-rotation: additional cost of specific crop selection or longer intervals between cash crops. The worked example given here extends the interval between potato crops from 6 years to 7 years by inserting an extra spring barley crop at the end of a typical Scottish arable rotation (Table 3). Using medium gross margins for Scotland (Beattie, 2021) in this example, a potato farmer (producing high variety seed potatoes) will have to bear a loss of £1538/ha in gross margin per crop rotation cycle (i.e. £220/ha per year over 7 years crop rotation cycle).

Table 3: A typical Scottish crop rotation vs crop rotation with an additional crop

Years	Typical Scottish crop rotation	Crop rotation with an additional crop to extend the potato rotation
Year 1	Seed potatoes	Seed potatoes
Year 2	Winter wheat	Winter wheat
Year 3	Winter barley	Winter barley
Year 4	Winter oilseed rape	Winter oilseed rape
Year 5	Winter wheat	Winter wheat
Year 6	Spring barely	Spring barely
Year 7	Seed potatoes	Spring barley

b. Frost: cost of shallow ploughing £46/ha (SAC, 2021)
c. Mechanical: cost of manual labour for 20hr/ha at £12/hr (SAC, 2021)

iii. For Integrated Control options:

This covers a huge range of options and some, e.g. precision recognition of groundkeepers and targeted spray technology, are only in development, so any attempt to make detailed estimates of economic costs would be misleading. It would be reasonable to assume that it would incur some of the indicative costs given above in terms of additional costs of application and, very likely, the costs attributed to an extended rotation. Table 4 includes the cost of extending the rotation between potato crops to give an estimate for that as an example of an integrated practice. However, there would likely be many benefits to offset this, e.g. reduced pest, weed and disease burdens and reduced pesticide resistance risk. Since this is the probable direction of travel for agricultural policy in

Scotland it, together with methods in precisions agriculture, should remain an active area of research and knowledge exchange activity.

Table 4 presents the cost and the effectiveness of the identified options for groundkeeper control. So that options can be more directly compared in terms of the cost for any given level of control, we have converted this to a cost effectiveness ratio in Figure 4.

Table 4: Estimated effectiveness and cost of implementation of glyphosate and alternative options

Alternatives	Estimated effectiveness[1] (%)	Estimated cost of implementation[2] (£/ha)
i. Chemical		
a. Glyphosate – 1 spray @ 4 l/ha generic product	80%	£53
b. Glyphosate - 2 sprays @ 2 l/ha generic product	95%	£66
c. Maleic hydrazide	75%	£92
d. Mesotrione	70%	£63
e. Thifensulfuron/ metsulfuron/fluroxypur (TMF mix)	60%	£61
ii. Non-chemical		
a. Crop rotation	40%	£220[3]
b. Frost	20%	£46[4]
c. Mechanical	40%	£240
iii. Integrated and precision management		
a. IWM	80%	£281[5]
b. Precision methods	This method is still at the developing stage and, while existing technologies	

	are expensive to be used on farms, future use if likely to be increasingly affordable both in terms of equipment and reduced chemical application. Estimated cost-effectiveness is not yet available but is expected to be high as available treatment options can be used in more targeted ways, possibly reducing chemical applications by 95%.

[1]based on literature and expert opinions; [2]includes market price of chemical (Source: www.marketplace.farm), labour and spraying costs, (Source: SAC, 2021); [3]cost of loss in income; [4]using a shallow plough; [5]includes cost of rotation and chemicals

Since the range in efficacy of different control options was found to be large, Figure 4 presents the CE ratio of all the treatments listed in this study. The CE ratio represents the cost of application of the treatment to control 1% of groundkeepers in a field. The lower the CE ratio, the more cost effective a treatment becomes.

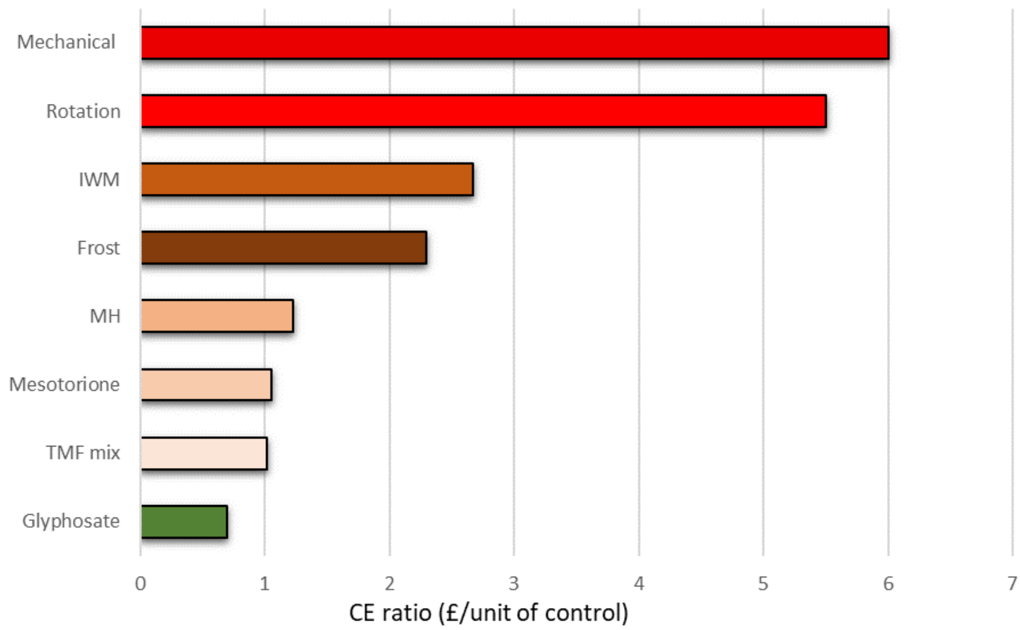

Figure 4: Cost effectiveness of alternative treatments to control groundkeepers (IWM = Integrated Weed Management; MH = Maleic hydrazide; TMF mix = thifensulfuron/ metsulfuron/fluroxypur mix)

As shown in the figure, glyphosate is the most cost-effective treatment to control groundkeepers. Chemical alternatives to glyphosate are more cost effective than any of the non-chemical methods evaluated. The effectiveness of precision methods, in conjunction with the use of chemicals, offers a potential advantage over other methods in terms of achieving cost-effective control. The uptake of precision application technologies could reduce the amount of chemicals applied by up to 95% (from expert opinion) as well as improving control through good targeting of groundkeepers. An integrated weed management approach is the next most effective alternative control option available but is also twice the cost of using any of the chemical treatments, so the CE ratio is high. Integrated management will be more complicated to implement on farms, and options such as extended rotations between crops have implications to farm incomes. The inclusion of precision technologies as part of future integrated weed management options could reduce the need to use more costly options such as more extended rotations.

A well-structured integrated management strategy, particularly if combined with precision technologies that allow spot treatment of groundkeepers, could be highly effective. The cost effectiveness of such a strategy will depend on the complexity of that strategy and the options chosen. Given the desire to integrate more environmental approaches within mainstream agricultural support policy, integrated weed management (including precision technologies) may offer a route to sustainable management of groundkeepers in UK arable farming (AHDB, 2019).

Practicalities

The cost effectiveness of options gives one measure of their feasibility, but there are obvious limitations to several of them, which means they are unlikely to be utilised to any significant degree in Scotland. Of the chemical alternatives to glyphosate the conclusions are:-

- The use of a mix of thifensulfurone / metsulfuron / fluopyram (TMF mix) is currently the most cost-effective treatment option.
- Mesotrione also appears to be cost effective but will have limited applicability in Scotland as it only has approval for use in maize crops. Its potential for use as a future control option therefore seems low.

- Maleic hydrazide has good potential as an alternative active to manage groundkeepers following ware crops, but is not approved for use in seed crops, and is therefore not a suitable alternative for the 50% of Scottish potato crops grown for seed.

This leaves the use of TMF mix (in mix with pyridines or other broad-spectrum herbicides) at the current time as the only practical option for seed crops, and the most cost-effective option also for ware. None of the options give the same level of control as glyphosate so there is some risk that if substitution with other pesticides is the only recourse, then groundkeeper problems in Scotland will increase. The use of TMF mix incorporated into other more integrated weed management programmes in Scotland would, however, add to the level of groundkeeper control achieved under glyphosate and has potential to be even more effective where precision targeting and application is used.

Among these more integrated practices, an extended crop rotation strategy has negative implications to farm income, where the interval between cash crops such as potatoes is increased. The mechanical removal of groundkeepers is costly due to the requirement of intensive labour and is not practical in the Scottish context, but some improvements can be anticipated through the introduction of improved harvesting equipment which leaves fewer tubers behind.

Conclusions

- The presence of groundkeepers is a significant problem for arable farmers. They act as a reservoir for pests and diseases, reduce the yield of subsequent crops and represent a risk to surrounding potato crops. Accordingly, their management is an additional economic burden on the farm.
- Glyphosate has been the most widely used and most effective option to control groundkeepers in the UK. If it is withdrawn from use, alternative options to replace glyphosate in future arable farming will need to be deployed.
- The range of efficacies of alternatives is large, with glyphosate offering up to 95% control and some options, such as frost, as low as 20% control.
- Replacement of glyphosate with current chemical alternatives may be the preferred substitution option for many farmers. Of the chemical options available, maleic hydrazide is effective in ware crops. However, it cannot be used in seed crops, so the use of sulfonylurea herbicides mixed with other

herbicides (e.g. TMF mix) is the most likely current substitution in this scenario.

- The maize herbicide mesotrione is an option in maize crops that follow potatoes, but that scenario is rare in Scotland so is unlikely to apply widely. It is also costly relative to other herbicide options.
- Options such as thifensulfurone / metsulfuron / fluopyram mixes (TMF mix) are already commonly used in cereal crops affected with groundkeepers. However, they are more expensive and less effective than glyphosate. This will lower the cost effectiveness of these alternative treatments, although the differences are not large. In addition, there is uncertainty about the future use of many herbicides, which may ultimately be under regulatory scrutiny similarly to glyphosate, so this approach may be become more restricted in the future.
- Although there is an initial cost in method development and equipment, precision methods that help to target chemical application, are likely in the future to reduce the cost of these chemical applications by as much as 95%. Precision application may also allow for fewer environmental concerns and longer retention.
- There are several non-chemical treatments available to control groundkeepers in the UK. These treatments have varying degrees of practicality and effectiveness. However, individually none are as effective as glyphosate (or combined chemical options) in controlling groundkeepers.
- This review shows that while none of the alternative options can achieve the same degree of cost effectiveness as glyphosate, equivalent control can be achieved by stacking suitable approaches, such as integrated weed management strategies. This, including precision technology, is likely to be the optimal way forward as an alternative to glyphosate (and currently could still include glyphosate).
- It is, however, notable that whilst there is literature on the efficacy of treatments for groundkeeper control, there is limited economic data on their cost-effectiveness and, particularly, on the impact of different combinations of treatments. Accordingly, the estimates presented here require some caution, and further work is required to ensure options are fully costed and assessed in terms of their effectiveness.
- Using the few published sources on economic impact attributable to the loss of glyphosate as a broad-spectrum tool to manage weeds, we assume the loss of glyphosate will be mitigated, and so apply a lower bounded

estimate of 3% yield loss taken from published reviews, i.e. the average potato farm will experience a 3% fall in production.

- An upper range of 20% is possible if none of the mitigating alternative control options are adopted. The economic report for Scottish agriculture states the potato crop is worth £250.3 million per annum and 3-20% of that equates to £7.5 - £50 million.
- Of this, a much lower value would be directly attributable to poorer groundkeeper control with the loss of glyphosate. Using the published £1.4 million estimate for the UK as a whole for the cost of managing groundkeepers, this equates to just £500K when applied to the proportionate value of the Scottish crop.

References

AHDB, 2019. Review of weed control options and future opportunities for UK crops. Research Review No. CP 182/1807258. Agriculture and Horticulture Development Board, Warwickshire, UK

Askew, M.F. 2005. Volunteer potatoes. In Potato in Progress –science meets practice. Ed. Haverkort, A.J. and Struik P.C. Wageningen Academic Publishers, The Netherlands.

Beattie, A. 2021. The Farm Management Handbook 2021/22. Published by SAC Consulting for SRDP Farm Advisory Service October 2021, pp566

Beckie, H.J., Flower, K. C. and Ashworth, M.B. 2020. Farming without glyphosate? Plants, 9 https://doi.org/10.3390/plants9010096

Benedictus, A., Hogeveen, H., Berends, B.R., 2009. The price of the precautionary principle: Cost-effectiveness of BSE intervention strategies in the Netherlands 89, 212–222.

Böcker, T., Britz, W, Möhring, N and Finger R. 2020. An economic and environmental assessment of a glyphosate ban for the example of maize production. European Review of Agricultural Economics. 47: 371-402

Boerlage, A. S., Shrestha, S., Leinonen, I., Dverdal Jansen, M., Revie, C. W., Reeves, A. and Toma, L. 2022. Cost-effectiveness of sea lice management measures for farmed Atlantic salmon (*Samo salar*) in Scotland. Paper in progress)

Boydston, R. A. and Williams II, M. M. 2005. Managing volunteer potato (Solanum tubersum) in field corn with mesotrione and arthropod herbivory. Weed Technology 19: 443-450. https://doi.org/10.1614/WT-04-223R

Bond, W., Davies, G. and Turner, R. 2007. The biology and non-chemical control of volunteer potato (Solanum tuberosum). https://www.gardenorganic.org.uk/sites/www.gardenorganic.org.uk/files/organic-weeds/volunteer-potato.pdf

Buckley, D., Duncan, H. and Anderson, E. 2006. Maleic hydrazide in potato volunteer control. British Potato Council, Oxford, UK.

Burnett, F., Bowser-Gibbs, Mm and Dunbar, D. 2021. Economic impact of pesticide withdrawals to Scotland, with case studies: project summary report. PH2020/09. Scotland's Centre of Expertise for Plant Health (PHC). DOI: 10.5281/zenodo.4581146

Centner, T. J. 2021. Pesticide registration fails to protect human health: damages from exposure to glyphosate-based herbicides. Journal of Environment Law and Litigation, 36: 69-128.

Chikowo, R., Faloya, V., Petit, S. and Nunier-Jolain, N.M. 2009. Integrated weed management systmes allow reduced reliance on herbicides and long-term weed control. Agriculture, Ecosystems and Environment, 132: 237-242

Clapp, J. 2021. Explaining growing glyphosate use: the political economy of herbicide-dependent agriculture. Global Environmental Change, 67: 102239

Colmer, J., O'Neill, C. M., Wells, R., Bostrom, A., Reynolds, D., Websdale, D., Shiralagi, G., Lu, W., Lou, Q., Le Cornu, T., Ball, J., Renema, J., Andaluz, G. F., Benjamins, R., Penfield, S. and Zhou, J. 2020. SeedGerm: a cost-effective phenotyping platform for automated seed imaging and machine-learning based phenotypic analysis of crop seed germination. New Phytologist, 228:778-793

Cunnington, A. J., 2019. Maleic Hydrazide – as a potato sprout suppressant. AHDB, UK.

Davis, C. Wardlaw, J. Monie, C. and MacLeod, C. 2020 Pesticide Usage in Scotland

Arable Crops 2020, [Arable crops and Potato stores 2020 (www.gov.scot)]

Davies, K., Milne, F. and Golden, A. 1999. Potato volunteers and their management. Technical Note T480, SAC, UK

Davies, D. H. K. 2002. Potato volunteers: their biology and management. In Proceedings Crop Protection in Northern Britain. UK

Harker, K. N. and O'Donovan, J.T. 2013. Recent weed control, weed management and integrated weed management. Weed Technology, 27: 1-11

Hutchinson, P. J. S., Felix, J. and Boydston, R. 2014. Glyphosate carryover in seed potato: effects on mother crop and daughter tubers. American Journal of Potato Research, 91: 394-403

Kehlenbeck, H., Sltzmann, J., Schwarz, J., Zwerger, P. and Nordmeyer, H. 2016. Economic assessment of alternatives for glyphosate application in arable farming. Deutsche Arbeitsbesprechung über Fragen der Unkrautbiologie und -bekämpfung, 23.-25. Februar 2016 in Braunschweig. DOI 10.5073/jka.2016.452.038

Lumkes, L. M.; Sijtsma, R. 1972: Mogelijkheden aardappelen als onkruid in volgewassen to voorkomen en/of te bestrijden. Landbouw en Plantenziekten 1: 17-36.

Lurnkes, L. M.; Beukema, H. P. 1973: The effect of cultivation procedure on the liability to freezing of groundkeepers. Potato Research 16: 57-60.

Lumkes, L. M.; Vervaet, H. E. M. M.; Andringa, 1. T. 1978: Modified harvesters to prevent weed potatoes. Proceedings, British Crop Protection Conference - Weeds: 935-41

Lutman, P. J. W. 1974: Factors affecting the overwintering of volunteer potato tubers and the emergence of sprouts in the spring. Proceedings, 12th British Weed Control Conference: 285-92

Lutman, P. J. W. and Richardson, W. G. 1977. The activity of glyphosate and aminotriazole against volunteer potato plants and their daughter tubers. Weed Research, 18: 65-70

MacLeod, C., Wardlaw, J., Davis, C., Robertson, A. and Reay, G. 2021. Pesticide Usage in Scotland, Outdoor Vegetable Crops 2021 Pesticide Usage in Scotland - Outdoor Vegetable Crops 2021 (www.gov.scot)

Marambe, B. and Herath, S. 2019. Banning of herbicides and the impact on agriculture: the case of glyphosate in Sri Lanka. Weed Science, 68: 246-252. doi: 10.1017/ wsc.2019.71

Masiunas, J.B., and S.C. Weller. 1988. Glyphosate activity in potato (Solanum tuberosum) under different temperature regimes and light levels. Weed Sci. 36: 137–140

McCarty, T. and Sesmero, J. 2021. Contracting for perennial energy crops and the cost-effectiveness of the Biomass Crop Assistance Programme. Energy Policy, 149: 112018

Mckenzie, J. 1989. The effects and residues of maleic hydrazide within the potato crop. PhD thesis. University of Glasgow, UK

Merfield, C. N. 2019. Integrated weed management in organic farming. Organic Farming: Global Perspectives and Methods. Woodhead Publishing Series in Food Science, Technology and Nutrition, 117-180

O'Neill, M. and Evans, H.F. 1999. Cost-effectiveness analysis of options within an integrated crop management regime against great spruce bark beetle, Dendroctonus micans, Kug. (Coleoptera: Scolytidae). Agricultural and Forest Entomology, 1:15-156

Oxford Economics, 2017. The impact of a glyphosate ban on the UK economy – summary report. Oxford Economics, London

Perombelon, M. C. M. 1975. Observations on the survival of potato groundkeepers in Scotland. Potato Research, 18: 205-215

Plant Health Centre, 2020. Potato Cyst Nematode (PCN) and the future of potato production in Scotland – report of the Scottish PCN working group. The James Hutton Institute, Dundee, UK

Rahman (1980) Biology and control of volunteer potatoes — a review, New Zealand Journal of Experimental Agriculture, 8:3-4, 313-319

Reuters. 2019. Germany to ban nuse of glyphosate from end of 2023. https://www.reuters.com/article/us-germany-glyphosate/germany-to-ban-use-of-glyphosate-from-end-of-2023-sources-idUSKCN1VP0TY

SAC, 2021. The Farm Management Handbook 2020/21. SAC Consultancy, Edinburgh, UK

Smid, D., and L.K. Hiller. 1981. Phytotoxicity and translocation of glyphosate in the potato (Solanum tuberosum) prior to tuber initiation. Weed Sci. 29: 218–223

Sutton, P., Richards, C., Buren, L. and Glasgow, L. 2002. Activity of mesotrione on resistant weeks in maize. Pest Management Science, 58: 981-984

Swanton, C. J., Mahoney, K. J., Chandler, K. and Guiden, R. H. 2008. Integrated weed management: Knowledge-based weed management systems. Weed Science, 56: 168-172

Rushton, Jonathan, Gilbert, Will, Jones, D., 2018. A guide - Introduction to the use of Cost-Effectiveness Analysis in Animal Health. Rome, Italy.

Turley, D. 2001. Understanding the biology and incidence of potato volunteers. Report Ref: 807/151. British Potato Council, Oxford, UK

Twining, S., Clarke, J., Cook, J., Ellis, S., Gladders, P., Ritchie, F. and Wynn, S. 2009. Pesticide availability for potatoes following revision of Directive 91/414/EEC: Impact assessments and identification of research priorities. Potato Council Ltd., Oxford

Valeeva, N.I., Huirne, R.B.M., Meuwissen, M.P.M., Oude Lansink, A.G.J.M., 2007. Modeling farm-level strategies for improving food safety in the dairy chain. Agricultural Systems 94, 528–540

VALEUK. 2020. Glyphosate is approved for 5 more years – until December, 2025. https://www.valeuk.com/glyphosate/glyphosate-is-approved-for-5-more-years/

Wynn, S. and Webb, E. 2022. Impact assessment of the loss of glyphosate within the EU: a literature review. Environmental Sciences Europe, 34:91. https://doi.org/10.1186/s12302-022-00667-3

Yazaki, T., Hirota, T., Iwata, Y., Inoue, S, Usuki, K., Suzuki, T., Shirahata, M., Iwasaki, A., Kajiyama, T., Araki, K., Takamiya, Y. and Maezuka, K. 2013. Agricultural and Forest Meteorology, 182-183: 91-100

SRUC

At the heart of the natural economy

This and other documents can be made available in other formats such as large print and/or community languages on request. If you would like a translated copy, please contact the author with the details of the format/language required.