Perspective

Received: 9 April 2018 Revised: 9 November 2018 Accepted article published: 18 November 2018 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/ps.5267

Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to herbicides?

Stephen Moss*

Abstract

Implementation of integrated weed management (IWM) has been poor, with little evidence of concomitant reductions in herbicide use. Non-chemical methods are often adopted as a means of compensating for reduced herbicide efficacy, due to increasing resistance, rather than as alternatives to herbicides. Reluctance to adopt non-chemical methods is not due to a lack of research or technology but to a lack of farmer motivation and action. Justifiably, herbicides are often seen as the easier option – their convenience outweighs the increased complexity, costs and management time associated with non-chemical alternatives. Greater use of non-chemical alternatives to herbicides will only occur if the following seven aspects are addressed: (i) better recognition of the reasons why farmers are reluctant to use non-chemical alternatives; (ii) encouraging farmers to adopt a longer-term approach to weed control; (iii) changing farmers' attitudes to pesticides; (iv) paying more attention to the individual farmer's perspective; (v). greater involvement of economists, social scientists and marketing professionals; (vi) re-evaluating research and extension priorities; and (vii) changing the mindset of funders of research and extension. If 'persuasion' fails to deliver greater implementation of IWM, authorities may resort to greater use of financial and other incentives combined with tougher regulations.
© 2018 Society of Chemical Industry

Keywords: IPM; IWM; herbicide resistance; knowledge transfer; social psychology

1 INTRODUCTION

Weeds are a major constraint to agricultural production, causing significant agronomic and economic damage. Herbicides are the major method of weed control in most conventional cropping systems, but numerous cases of herbicide resistance have evolved. By November 2018, resistance had been confirmed in 255 weed species in 70 countries worldwide, involving 23 of the 26 known herbicide sites of action.[1] The increasing number of resistant weed biotypes is a major concern, especially as no new herbicide mode of action has been marketed for over 30 years.[2] The potential adverse effects of pesticides on human health and the environment, combined with increasing resistance and the lack of new modes of action, has resulted in political and regulatory demands for less reliance on pesticides. To achieve this, greater use of integrated pest management (IPM), which includes integrated weed management (IWM), has been encouraged.[3]

However, the implementation of IWM has been challenging and the objective of this paper is to review the reasons why farmers are reluctant to use non-chemical alternatives to herbicides and to suggest approaches that could lead to greater uptake.

2 INTEGRATED WEED MANAGEMENT

The concept of IPM was formulated over 50 years ago to promote the greater use of non-chemical methods of pest control in association with more rational and targeted applications of pesticides.[3] Although there are numerous definitions of IPM, a consistent aim has been to reduce the reliance on pesticides and promote non-chemical alternatives.[3,4] The European Union's Sustainable Use of Pesticides Directive (2009/128/EC) requires all 28 Member States to 'promote low pesticide input pest management, in particular integrated pest management, with priority given wherever possible to non-chemical methods of plant protection'.[5] IWM is a component of IPM and involves the use of cultural, genetic, mechanical and biological weed control measures as well as herbicides.[6] The aim is to diversify weed management strategies through greater use of non-chemical methods of control in order to place less reliance on herbicides.[7]

It is important to stress that herbicides will continue to have an important role in managing weeds within a diversified IWM strategy. Maintaining the same intensity of herbicide use could rightly be considered a successful outcome, especially if less resistance-prone herbicides or those with better environmental or human health risk profiles were used. Ideally, there would also be better targeting of herbicides, through the greater use of weed thresholds and site-specific weed management, although commercial adoption of these techniques remains poor.[8]

Many non-chemical methods of weed control are available, including crop rotation, changes to primary and in-crop cultivations, changes to sowing date, use of cover crops and mulches, growing more competitive crops or cultivars, reducing weed seed

* *Correspondence to: S Moss, Stephen Moss Consulting, 7, Alzey Gardens, Harpenden, AL5 5SZ, UK. E-mail: alopecurus@aol.com*

Stephen Moss Consulting, Harpenden, UK

 © 2018 Society of Chemical Industry

return and introducing rotational grassland or fallowing. A considerable amount of research has been conducted on non-chemical methods of weed control and IWM and this has been summarized in many reviews.[9–11]

3 IMPLEMENTATION OF IWM: SUCCESS OR FAILURE?

Despite a considerable amount of research on the subject, the implementation of IWM strategies by farmers has been poor.[12,13] Considering that this concept was first devised over 50 years ago, how can we explain the paradox of such a considerable amount of research delivering so little?

To counter this view, plenty of evidence can be cited to show a high level of awareness and adoption of IWM. For example, in both Australia and the USA, surveys showed widespread use of IWM practices in a range of crops.[14,15] In a UK survey conducted in 2016, widespread use of non-chemical control methods for grass-weed control was reported (Fig. 1).[16] The increased use, since a previous survey in 2000, of methods known to be particularly effective against grass-weeds such as *Alopecurus myosuroides* Huds. (black-grass), was particularly impressive. *A. myosuroides* is currently the most problematic herbicide-resistant weed in Europe.[17] The proportion of farms using stale seedbeds (shallow post-harvest cultivations) increased from 29% to 78%, delayed autumn sowing from 15% to 69%, and spring cropping from 32% to 81% of farms. So, are the pessimistic views about lack of use of IWM unjustified?

If you accept that one objective of IWM is to reduce reliance on herbicides, it follows that herbicide use could be used as one metric to gauge the success of implementation. Sadly, there is little evidence to support the view that adoption of IWM, or IPM more generally, has resulted in a widespread reduction in pesticide use.[3,18] In the UK, herbicide use, in terms of spray ha (area treated × number of applications) increased from 14.4 to 25.5 million ha between 1990 and 2015, a 1.8-fold increase, with a similar increase (×1.6) for all pesticides.[19] By contrast, the weight of herbicides and pesticides applied reduced substantially, by 33% and 48% respectively, largely due to greater use of more active pesticides, applied at g rather than kg ha^{-1}. During this 25-year period, greater use of IPM (including IWM) and reduced reliance on pesticides has been both a UK government and European Union policy.[5] This highlights one potential problem with assessing the effectiveness of pesticide minimization policies; you can use the same pesticide usage survey data to show either the success (use total weight) or failure (use area treated) of such policies, according to your own agenda. Researchers, politicians and regulators who are required to demonstrate the success of pesticide minimization policies will be only too familiar with this ethical dilemma.

Reliance on herbicides has been perceived by farmers as the easiest and most cost-effective short-term solution to weed control. This perception was not necessarily misplaced prior to the widespread evolution of herbicide resistance and in an era (1950–1980) when a new herbicide mode of action was introduced every 1–2 years.[2] Even where there is widespread and successful adoption of more non-chemical alternatives, it appears to be largely a consequence of the loss of chemical options rather than the success of political or regulatory initiatives to reduce reliance on pesticides. Non-chemical alternatives are often adopted as a means of compensating for reduced herbicide efficacy, due to increasing resistance, rather than as a partial replacement for herbicides. Consequently, herbicide use may remain the same, or even increase, as has happened in the UK and many other European countries.[18] Herbicides are an important component of an integrated weed control strategy, but their ever-increasing use can hardly be considered compatible with 'reducing reliance on herbicides', which is wording that many accept in relation to the concept of IWM as a more sustainable approach to weed control.

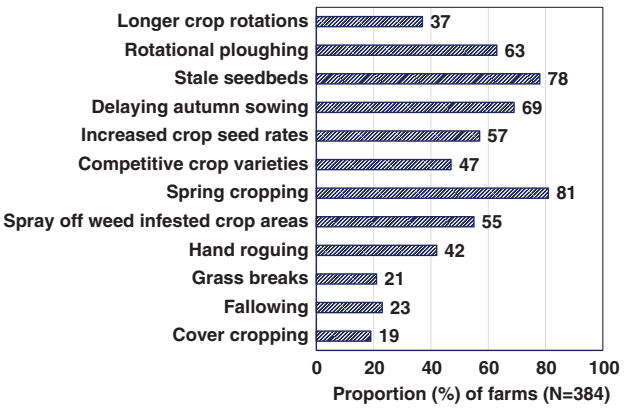

Figure 1. Survey of 384 arable farmers in the UK conducted in 2016. Responses to the question, 'What main cultural control techniques do you use to control grass-weeds?' (Source: Data reproduced with permission of Monsanto UK Ltd.)

4 BARRIERS TO ADOPTION OF NON-CHEMICAL ALTERNATIVES TO HERBICIDES

The reasons why farmers are reluctant to adopt non-chemical methods of weed control are summarized in Box 1. Producing such a long list may appear somewhat negative, but greater uptake of IWM will not happen until there is better recognition of these barriers to adoption.

These 16 reasons are applicable to a wide range of agronomic systems although not all will be relevant to every weed control situation. Most of these reasons are self-explanatory, but the 'little visible evidence of immediate success' needs explanation as it has rarely been mentioned before, although it is, arguably, one of the most important reasons for the lack of uptake of non-chemical methods of weed control. A farmer is unlikely to be able to assess the success of most non-chemical weed control techniques because the farmer has, in effect, used a single unreplicated treatment, without controls, so cannot quantify its efficacy. By contrast, researchers who have compared treatments side by side in field experiments, are much more confident about the relative effectiveness of different techniques. The lack of visual clues with non-chemical techniques such as delaying sowing date or using higher seed rates contrasts with herbicide use, where farmers can either see the response of weeds following spraying or compare the efficacy relative to a small area, intentionally or unintentionally, left untreated. This is generally much easier to arrange with herbicides than with non-chemical control methods. Hence, with many non-chemical weed control strategies, farmers have little idea of the return on their investment of time and money.

The relevance of many of the factors listed in Box 1 can be demonstrated by relating them to control of a specific problem, e.g. *A. myosuroides* in the UK.[17] The control achieved by various

© 2018 Society of Chemical Industry

non-chemical methods, based on a comprehensive review,[23] is summarized in Table 1.

BOX 1 Reasons why farmers are reluctant to use non-chemical methods of weed control as alternatives to herbicides.[3,14,15,20–22]

1 More complex and time-consuming to manage; the 'inconvenience' factor.
2 Increased costs, especially if no reduction in herbicide use is achieved.
3 Risky; control levels more variable and less predictable than with herbicides.
4 Less effective than herbicides.
5 More expensive than herbicides for the level of control achieved.
6 Higher labour requirement; availability and cost implications.
7 Lack of appropriate equipment or trained employees.
8 Little visible evidence of immediate success.
9 Risky for farm agronomist/consultant, so reluctance to recommend.
10 Less return for supplier of herbicides, so reluctance to recommend.
11 No compensation following control failure (more likely with herbicides).
12 May have adverse environmental effects (e.g. soil erosion after intensive cultivations).
13 Harder physical effort compared with spraying (e.g. hoe versus knapsack sprayer).
14 Short term priorities; reluctance to commit to long-term strategies.
15 Complacency; belief that new herbicides will solve existing problems.
16 Dependency on favourable weather (e.g. for alternative crops or delayed sowing).

The review highlights the variability in efficacy of all the non-chemical techniques listed, with negative control being possible, for example, where mouldboard ploughing brings more seeds to the surface than it buries, resulting in higher weed populations. It is instructive to present the mean efficacy results in an alternative way, pretending that the non-chemical methods are actually herbicides. The UK pesticide regulators specify the level of weed control required for effectiveness claims on herbicide product labels.[24] Applying these criteria shows that that each of the non-chemical control methods listed in Table 1 gives, on average, levels of control that are poor in comparison with herbicides. This poorer efficacy is not matched by correspondingly lower costs. Consequently, it is not surprising that trying to convince farmers to use more non-chemical methods within an IWM strategy is such a challenge. For most farmers, herbicides are still seen as the easier option and their convenience outweighs the perceived risk, cost and increased management time associated with non-chemical alternatives.[20]

5 THE IMPORTANCE OF UNDERSTANDING THE FARMER'S PERSPECTIVE

Perversely, despite the poor uptake of IWM, many farmers have a good awareness of alternative, non-chemical methods of weed control, although there is clearly a difference between having the knowledge and putting this into practice.[20] The problem is not so much a lack of knowledge, rather it is a lack of action. It follows that relying on the same approaches to promote IWM, as used in the past, will not lead to greater adoption.[26]

Greater use of non-chemical techniques within an IWM strategy may be achieved by paying more consideration to the farmer's perspective, and by presenting advice in a manner that coincides with the farmer's experiences and attitudes.[20] Changing farmers' weed control 'mindset' from one based primarily on short-term herbicide solutions to one based on longer-term, more diverse management strategies must be the key objective. Hence, a better understanding of the factors influencing farmer behaviour is required, as that fundamentally is what one is trying to change.

The findings from a study into the factors influencing farmer behaviour in relation to the adoption of environmental protection practices are equally relevant to understanding the barriers to adoption of IWM.[27,28] There is a complex relationship between communicating advice and putting it into practice, whether it be environmental protection practices or IWM (Fig. 2).

Advice on IWM is communicated to farmers in many ways but diversity is the key, as farmers use a wide range of sources. These include the farming press, attending indoor and field events, consultants, other farmers, internet, agchem suppliers and, increasingly, social media. Perhaps surprisingly, the printed farming press features highly as a key source of information, not only in older surveys but also in ones conducted more recently.[29] Receptiveness to different forms of communication varies between individual farmers, but the credibility of advice depends partly on the perceived independence and reputation of the source. Farmers evaluate both the messenger and the message.[27]

Past attempts at promoting IWM have tended to concentrate on simply communicating information to farmers with the expectation that farmers will follow that advice[26] However, simply relying on such 'top down' approaches to instruct farmers on the potential of non-chemical alternatives to herbicides within an IWM strategy has not been, and will not be, effective.[30] It is important to recognize that advice will only be implemented successfully if farmers are both willing and have the ability to change existing behaviour. The ability to change is dependent largely on individual farm characteristics ('facts'), which dictate what is feasible practically as well as economically. By contrast, willingness to change is more dependent on individual farmer personality ('beliefs'). This is a complex area encompassing both personal values as well as societal level influences.

Effective implementation of IWM strategies will only be achieved when the trio of factors depicted in Fig. 2 are combined successfully. Knowledge alone is not enough. Critically, all three elements are amenable to change: advice can be better communicated, the ability to change is not insuperable, and farmers' willingness to change is subject to persuasion.

6 THE RELEVANCE OF ECONOMICS, PSYCHOLOGY AND SOCIOLOGY TO IWM IMPLEMENTATION

Short-term economic pressures and increased financial costs are cited commonly by farmers as major barriers to adoption of IWM.[31,32] Input costs could be higher (e.g. more intensive cultivations or higher crop seed rates) or outputs reduced (e.g. growing less profitable crops or lower yields due to later sowing). It is difficult to predict whether any compensatory savings in herbicide

 © 2018 Society of Chemical Industry

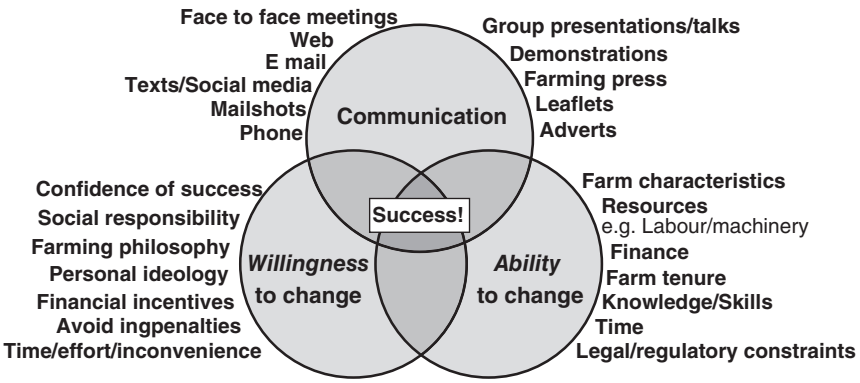

Figure 2. The trio of factors defining the relationship between advice and resulting behaviour (adapted from Dwyer *et al.*[27]).

Table 1. Efficacy of non-chemical methods for control of *Alopecurus myosuroides* in winter wheat crops, and one widely used herbicide option. Based on a review by Lutman *et al.*[23]

Method (number of comparisons)	% Reduction achieved		'Label' rating[a]	Additional cost[b] or loss £/US$/€ ha^{-1}
	Mean	Range		
Ploughing (25)	+69	−82 to +96	MR	35/49/40
Delayed autumn sowing by ~ 3 weeks (19)	+31	−71 to +97	R	0.85 t ha^{-1} yield loss
Higher crop seed rates (6)	+26	+7 to +63	R	29/41/33
More competitive cultivars (8)	+22	+8 to +45	R	Potentially 0
Spring cropping (5)	+88	+78 to +96	MS	2–3 t ha^{-1} yield loss
Mesosulfuron + iodosulfuron	> 95	–	S	38/53/44

[a] The equivalent efficacy rating on a UK herbicide label for the mean levels of control. S = susceptible, MS = moderately susceptible, MR = moderately resistant, R = resistant.[24] See text. Note that 'resistant' in this context refers to the inherent insensitivity of the weed species, not evolved resistance.
[b] Updated from Moss[22] using *John Nix Pocketbook for Farm Management*.[25] Average winter wheat yield in the UK = 8.5 t ha^{-1}.

or other costs will occur so the long-term benefits of adopting an IWM strategy remain uncertain. By contrast, in the absence of resistance, herbicide costs and efficacy are more predictable, at least in the short-term. Hence, it is difficult to present a convincing case to farmers, especially as they tend to be suspicious about the reliability of generalized economic analyses in relation to their specific personal circumstances.

Farmers willingness to adopt IWM is dependent, not just on knowledge about alternatives to herbicides, but on the complex psychological and sociological factors that influence their behaviour, both individually and collectively. Psychology involves the study of mental processes and behaviour in individuals; sociology the collective behaviour of organized groups of human beings. Social psychology is about understanding the behaviour of the individual in a social context so is the most relevant discipline in relation to modifying farmer behaviour.

The importance of these economic, psychological and sociological aspects to motivating farmers to adopt IWM strategies is now being recognized. In 2016, a Special Issue of *Weed Science* (Vol. 64) containing 12 papers on the 'Human dimensions of herbicide resistance' was published. A common theme was the need to reduce dependency on herbicides by using more diverse strategies and, within the 12 papers (115 pages), there were 116 mentions of economics and 100 mentions of sociology and related terms. Perhaps surprisingly, there was only a single mention of psychology, and that was a bit speculative ('Engaging community stakeholders in that process will likely require contributions from the social sciences, including sociology, economics, anthropology and even psychology').[30]

The series of papers highlights the need to place more emphasis on the human component of weed management and, especially, the complex web of social and economic drivers that influence the way farmers make decisions.[33] The need for greater involvement of community-based approaches was advocated, as it is now recognized that weeds are more mobile than previously thought, with seeds moving in various ways between farms and resistance genes dispersed via pollen.[21] However, the movement of weeds should not be overstated and there is much that individual farmers can do to improve weed control on their own farms irrespective of what their neighbours are doing.

7 SEVEN POINT ACTION PLAN TO IMPROVE UPTAKE OF IWM

It is evident that reliance on herbicides alone for weed control is not sustainable and more diversified management strategies (IWM) are required. There is a consensus that implementation of IWM by farmers has been poor or, at the very least, inadequate. There is also little evidence to show concomitant reductions in herbicide use. Hence new approaches are needed. Better and more rapid uptake of IWM is essential and will only occur if the following seven action points are addressed effectively.

7.1 Better recognition of the reasons why farmers are reluctant to use non-chemical methods of weed control

The reasons itemized in Box 1 constitute the most comprehensive list yet produced. Understanding the impact of each of these factors in different agronomic situations is vital if the problem of the

© 2018 Society of Chemical Industry

lack of uptake of non-chemical alternatives to herbicides is to be addressed successfully. The relative importance of each of these factors will vary between farms depending partly on farm characteristics and partly on farmer attitudes. Addressing these factors at the individual farm level should be the first step in reducing the barriers to adoption of IWM.

7.2 Encouraging farmers to adopt a longer-term approach to weed control strategies

Farmers are tempted to delay adoption of IWM as the costs (in terms of time and inconvenience, as well as financial) are immediate, whereas the benefits may take a long time to become apparent.[21] Farmers are accustomed to the rapid response they get from herbicides with effects usually evident within days or weeks. By comparison, non-chemical strategies, such as crop rotation, may take months or years to show evidence of success so are bound to lack credibility. The psychological response of instant gratification achieved by herbicides is very powerful when compared with the lack of visual clues that typify most non-chemical strategies, such as changing crop sowing date or seed rate. Good field demonstrations can be a very powerful weapon in convincing farmers of the success of long-term IWM strategies.

Changing farmer 'mindset' from one based primarily on short-term herbicide solutions to one based on longer-term weed management strategies is difficult, but essential. Success will only be achieved by convincing farmers that over-reliance on herbicides is unsustainable and that more diverse strategies are required throughout the crop rotation. This stands more chance of success if additional benefits, such as improved soil fertility, better pest and disease control, and access to a wider range of herbicides from better crop rotations, can also be demonstrated.

7.3 Change farmer attitude to pesticides as well as behaviour

Behaviour can be changed relatively easily by incentives (e.g. financial subsidies) or regulation (e.g. controlling herbicide use), although these approaches may not be affordable, practicable or acceptable politically. Changing attitudes is more challenging, but this should be the primary long-term aim as changes in behaviour are then likely to be more permanent. Many farmers still have a high expectation that new herbicides will be introduced to replace those which are failing.[34] Farmers must be persuaded that the lack of new modes of action, increasing resistance and widespread public concern about pesticides mean that the continued availability of herbicides should not be taken for granted, but rather herbicides should be treated as a scarce and valuable resource.[35] Other aspects relevant to changing attitudes are moral ('excessive use of herbicides is wrong'), pragmatic ('over-dependence on herbicides will result in more resistance, antagonize the public and lead to stricter regulation') and practical ('herbicides are not delivering what they used to, so I must look for alternatives'). Critically, individual farmers will respond very differently to these concepts, so a multi-faceted approach is required.

Sceptics of this proposition might wish to contemplate the huge change in attitudes to pesticides within the agricultural community since 1962, when Rachel Carson wrote *Silent Spring*.[36] Publication of her book provoked fierce opposition and she was personally vilified, yet few today, even in the agrochemical industry itself, would dismiss her critique as baseless. If they do, they should have no place in today's industry. Attitudes can change.

7.4 Placing more attention to the individual farmer's perspective

There must be greater recognition of what individual farmers are able and willing to 'do'. The trio of factors (Fig. 2) defining the relationship between advice and resulting behaviour provides a good basis for understanding the barriers to uptake of IWM at the individual farmer level. Addressing the multitude of factors that influence both an individual farmer's ability and willingness to change behaviour in relation to weed management strategies is essential. The following aspects are also important, but the response to these will vary greatly among farmers: (i) 'Repetition for retention', patience is needed as gaining acceptance of major changes in agronomic practices is usually a slow process. Regardless of how information is delivered and by whom, the advice must be consistent and sustained over many years.[37] (ii) 'Benefit versus effort', if the perceived benefit is greater than the 'effort' involved farmers will accept the advice, but not if the 'effort' is more than the benefit. This is very dependent on the individual farm characteristics, and farmer's temperament and personal circumstances. 'Effort' in this context has multiple components, some tangible (e.g. farm resources), some more nebulous (e.g. time, inconvenience). (iii) 'Let the farmer make the final decision', 'persuasion' is more effective than 'preaching', which can be counter-productive. If farmers feel under pressure to adopt strategies to which they are not fully committed, long-term success is unlikely. Importantly, farmers will often be more receptive to adopting alternative weed control techniques when they hear about these from other farmers who have implemented them successfully, rather than from researchers.[38]

A useful approach would be to actively involve groups of farmers in multi-site and multi-year experiments or monitoring exercises with the aim of increasing uptake of IWM strategies. Assessments should include: the short and long-term cost–benefits of different approaches, both chemical and non-chemical; detailed recording of herbicide use; and detailed agronomic, weed infestation and management information. Importantly, individual and collective farmer attitude and behaviour in relation to decision-making should be evaluated. The main objective should be determination of the key agronomic and behavioural factors responsible for any positive outcomes that occur during the period of investigation. While the detailed outcomes may be agronomic system specific, the approaches and more general findings should have wider relevance.

7.5 Greater involvement of economists, social scientists and marketing professionals

More emphasis on integrating the human and social dimensions of IWM is required. This requires input from social science disciplines, such as economists and social psychologists.[30,39]

More sophisticated economic analyses would be useful in examining the 'cost relative to efficacy' aspects of different non-chemical control methods compared with herbicides, and how they are integrated most cost-effectively. In the absence of resistance, such analysis is likely to favour herbicide use alone but, as resistance increases and efficacy declines, the outcome is less predictable. This approach has considerable potential in persuading farmers to adopt IWM strategies.

The lack of uptake of IWM is a behavioural issue associated with decision-making, rather than a consequence of lack of knowledge. Social psychology is about understanding the behaviour of the individual within a social context so is directly relevant to modifying farmer behaviour. After all, the aim is to change farmer behaviour away from a 'herbicide only' mindset towards one more

 © 2018 Society of Chemical Industry

accepting of diverse IWM strategies. Farmers may be the individuals making decisions about weed control on their own farm, but their decisions are strongly influenced by many other people (e.g. consultants, company representatives, family members, other farmers, the media), although they may well be unaware of or not wish to acknowledge this. However, it is vital that the involvement of social scientists results in real changes in practice rather than simply more research papers with a different angle.

This review has highlighted the importance of tailoring advice to the individual farmer, but how do you do this when the 'market' for IWM research and extension comprises tens of thousands of farmers or more? How many researchers give much thought to the size of their 'market'? Extension initiatives would benefit from a more professional, market-orientated approach. Research scientists tend to prefer 'evidence and facts', whereas marketing professionals prefer 'concepts and angles'. Agrochemical companies commit substantial resources to marketing pesticides, but many of their most-used tactics, such as adverts in the farming press, are rarely, if ever, used by those wishing to promote alternative strategies. Clearly, lack of financial resources is part of the issue – a one-page advert in a major farming journal in the UK costs about £2000 – but, I suspect, research scientists have an inbuilt disdain for what they perceive as superficial and shallow promotional methods. However, implementation of IWM will only improve if there is a more professional approach to 'marketing' advice to farmers.

7.6 Re-evaluating research and extension priorities

If uptake of IWM strategies by farmers has been inadequate, it follows that research and extension on the subject has failed to deliver meaningful change. Funders may question the value of investing in additional initiatives – surely this would simply be throwing good money after bad? This would be an over-simplistic conclusion because IWM is being used increasingly, even if this is a consequence primarily of increasing resistance and the lack of new chemical solutions. It may be a case of 'better late than never', but at least this means that the research and associated publications have not necessarily been wasted. However, simply conducting ever more research on alternative methods of weed control is not the answer to the lack of uptake of IWM, except where needed to address specific, well-defined issues.

There is a need to reassess the aims and objectives of agricultural weed research.[13,40] Research into IWM must be relevant and practical, and not simply conducted as some sort of 'academic' exercise. It could be argued that there has been too much emphasis on basic research at the expense of applied research and extension; understanding problems rather than solving them. Certainly, it would be informative to assess the relative resource allocation to different types of research and extension, and how this has changed with time. A shift in resources away from research and towards extension may well be warranted, at least in some countries. Compared with research, extension is often considered of lower 'status', attracting less funding and prestige.[41] This attitude must change if implementation of IWM is to improve.

A major problem in many countries is that the focus of research funding and the associated mechanisms of reward and career opportunity are titled heavily towards basic research and away from applied.[42] This can severely compromise the translation of research into a commercial practice. Many would agree with the opinion, 'Perhaps a shift in how researchers are evaluated would advance IWM research as much as anything'.[10] Initiatives to improve how the outputs of scientific research are evaluated, such as DORA, the San Francisco Declaration on Research Assessment (DORA website https://sfdora.org) must be applauded. This aims to reduce the emphasis on journal impact factors by encouraging the use of a broader range of metrics for assessing the quality of research. Sadly, at least in the UK, there is little evidence of success so far.[43]

7.7 Change in mindset of governments and other funders of research and extension

Funders of research and extension should exert more influence to ensure improved uptake of IWM. They have the power to stipulate what is done and the way outputs are delivered. They should put more emphasis on initiatives likely to have an impact at the farm level. They must demand tangible results relevant to their specific funding objectives, whether that be increased adoption of IWM, reduced pesticide use or both. They should also encourage the involvement of social science and other disciplines not traditionally associated with weed research.

If funders consider that the primary aim of IWM is to diversify weed management practices, then would it not be better to state this explicitly as the key objective? Quantifying the adoption of non-chemical techniques, as well as herbicide use patterns, could act as specific metrics to assess success or failure. Alternatively, if IWM is being promoted primarily as a means of reducing the use of herbicides, then trends in herbicide usage could be used as the main metric. One has to accept that IWM, like IPM, is a rather 'malleable' concept subject to different interpretations according to personal agendas.[4] In particular, it must be recognized that conclusions based on pesticide usage can be manipulated as trends based on areas treated can be the opposite to those based on total weight.

If 'persuasion' continues to fail to deliver greater implementation of IWM, authorities may resort to greater use of financial and other incentives and tougher regulations. Farmers don't like others controlling their decision-making,[44] but small incentives ('carrots') combined with the threat of oppressive regulations ('big sticks') might well be the most effective approach.

8 CONCLUSIONS

Over 20 years ago, it was stated that: 'although IPM has had limited success in terms of its adoption by farmers, it does have a very successful history in terms of its adoption by scientists, pressure groups and policy makers'.[41] This seems just as pertinent today in relation to IWM. Too much knowledge, not enough application, is a concise explanation for the lack of uptake of IWM. If this situation is to change during the next 20 years, we must accept that this is not a consequence of lack of knowledge or technical expertise, rather, it is due to a lack of motivation and action. The focus must be on changing farmer behaviour and, if possible, attitudes.

Improvements in the implementation of IWM will require collective input from government agencies, economists, social psychologists and marketing professionals, as well as weed scientists, agronomists, the agrochemical supply industry and farmers themselves.[45] Weed scientists do not have a good track record of interdisciplinary research and action,[13,40] so can they rise to the challenge and address effectively the seven key action points identified in this review?

REFERENCES

1 Heap I, *The International Survey of Herbicide Resistant Weeds*. [Online]. Available: www.weedscience.com [9 November 2018].

 © 2018 Society of Chemical Industry

2 Duke SO, Why have no new herbicide modes of action appeared in recent years? *Pest Manag Sci* **68**:505–512 (2012).
3 Ehler LE, Integrated pest management (IPM): definition, historical development and implementation, and the other IPM. *Pest Manag Sci* **62**:787–789 (2006).
4 Morse S, IPM: ideals and realities in developing countries, in *Integrated Pest Management*, ed. by Radcliffe EB, Hutchinson WD and Cancelado RE. Cambridge University Press, Cambridge, pp. 458–470 (2009).
5 European Union Directive 2009/128/EC establishing a framework for community action to achieve the sustainable use of pesticides. *Off J Eur Union* [Online]. **52**:71–86 (2009) Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2009:309:TOC [9 November 2018].
6 Swanton CJ and Weise SF, Integrated weed management: the rationale and approach. *Weed Technol* **5**:657–663 (1991).
7 Shaner DL, Lessons learned from the history of herbicide resistance. *Weed Sci* **62**:427–431 (2014).
8 Fernandez-Quintanilla C, Pena JM, Andujar D, Dorado J, Ribeiro A and Lopez-Granados F, Is the current state of the art of weed monitoring suitable for site-specific weed management in arable crops? *Weed Res* **58**:259–272 (2018).
9 Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM *et al.*, Reducing the risk of herbicide resistance: best management practices and recommendations. *Weed Sci* **60** (Special Issue):31–62 (2012).
10 Harker KN and O'Donovan T, Recent weed control, weed management, and integrated weed management. *Weed Technol* **27**:1–11 (2013).
11 Melander B, Liebman M, Davis AS, Gallandt ER, Bàrberi P, Moonen AC *et al.*, Non-chemical weed management, in *Weed Research: Expanding Horizons*, ed. by Hatcher PE and Froud-Williams RJ. Wiley, Chichester, pp. 245–270 (2017).
12 Shaner DL and Beckie HJ, The future for weed control and technology. *Pest Manag Sci* **70**:1329–1339 (2014).
13 Neve P, Barney JN, Buckley Y, Cousens RD, Graham S, Jordan NR *et al.*, Reviewing research priorities in weed ecology, evolution and management: a horizon scan. *Weed Res* **58**:250–258 (2018).
14 Llewellyn RS, Lindner RK, Pannell DJ and Powles SB, Grain grower perceptions and use of integrated weed management. *Aust J Exp Agric* **44**:993–1001 (2004).
15 Riar DS, Norsworthy JK, Steckel LE, Stephenson DO, Eubank TW, Bond J *et al.*, Adoption of best management practices for herbicide-resistant weeds in midsouthern United States cotton, rice and soybean. *Weed Technol* **27**:788–797 (2013).
16 Jones R, Tactics shift in blackgrass battle. *Crop Prod Mag* [Online]. **19**:48–53 (2017) Available: www.cpm-magazine.co.uk/back-issues [9 November 2018].
17 Moss SR, Black-grass (*Alopecurus myosuroides*): why has this weed become such a problem in western Europe and what are the solutions? *Outlooks Pest Manag* **28**:207–212 (2017).
18 Nave S, Jacquet F and Jeuffroy M-H, Why wheat farmers could reduce chemical inputs: evidence from social, economic and agronomic analysis. *Agron Sustain Dev* **33**:795–807 (2013).
19 Garthwaite D, Barker I, Ridley L, Mace A, Parrish G, MacArthur R and Lu Y, *Pesticide Usage Survey Report 271: Arable Crops in the United Kingdom 2016* (version 2). [Online]. Available: secure.fera.defra.gov.uk/pusstats/surveys/2016surveys.cfm [9 November 2018].
20 Wilson RS, Hooker N, Tucker M, LeJeune J and Doohan D, Targeting the farmer decision making process: a pathway to increased adoption of integrated weed management. *Crop Prot* **28**:756–764 (2009).
21 Hurley TM and Frisvold G, Economic barriers to herbicide-resistance management. *Weed Sci* **64** (Special Issue):585–594 (2016).
22 Moss SR, Non-chemical methods of weed control: benefits and limitations, in *17th Australasian Weeds Conference*, ed. by Zydenbos SM. New Zealand Plant Protection Society, Auckland, pp. 14–19 (2010).
23 Lutman PJW, Moss SR, Cook S and Welham SJ, A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. *Weed Res* **53**:299–313 (2013).
24 Chemicals Regulation Division of the Health and Safety Executive, *Data Requirements Handbook, Chapter 8: Guidance on Efficacy Requirements*. (2010). [Online]. Available: www.hse.gov.uk/pesticides/resources/D/DRH_v2_2_Chapter8_Efficacy.pdf [9 November 2018].
25 Redman G, *John Nix Pocketbook for Farm Management*, 47th edn. Agro Business Consultants Ltd., Melton Mowbray, UK, 308 pp (2017).
26 Doohan D, Wilson R, Canales E and Parker J, Investigating the human dimension of weed management: new tools of the trade. *Weed Sci* **58**:503–510 (2010).
27 Dwyer J, Mills J, Ingram J, Taylor J, Burton R, Blackstock K *et al.*, *Understanding and Influencing Positive Behaviour Change in Farmers and Land Managers*. Final Report 2007. [Online]. Available: randd.defra.gov.uk/Document.aspx?Document=WU0104_6750_FRP.doc [9 November 2018].
28 Blackstock K, Brown K, Burton R, Dilley R, Slee B, Dwyer J *et al.*, Good practice guide: influencing environmental behaviour using advice. *Principles for Use in Designing and Implementing Advisory Measures/Schemes/Initiatives to Stimulate Positive Environmental Behaviour by Farmers and Land Managers*. Final Report 2007. [Online]. Available: www.programme3.ac.uk/water/P345GoodPracticeGuide.pdf [9 November 2018].
29 Ulber L and Rissel D, Farmers' perspective on herbicide-resistant weeds and application of resistance management strategies: results from a German survey. *Pest Manag Sci* **74**:2335–2345 (2018).
30 Jussaume RA and Ervin D, Understanding weed resistance as a wicked problem to improve weed management decisions. *Weed Sci* **64** (Special Issue):559–569 (2016).
31 Livingston M, Fernandez-Cornejo J and Frisvold GB, Economic returns to herbicide resistance management in the short and long run: the role of neighbour effects. *Weed Sci* **64** (Special Issue):595–608 (2016).
32 Mitchell PD and Hutchison WD, Decision making and economic risk in IPM, in *Integrated Pest Management*, ed. by Radcliffe EB, Hutchinson WD and Cancelado RE. Cambridge University Press, Cambridge, pp. 33–50 (2009).
33 Ward S, Human dimensions of herbicide resistance. *Weed Sci* **64** (Special Issue):551 (2016).
34 Schroeder J, Barrett M, Shaw DR, Asmus AB, Coble H, Ervin D *et al.*, Managing wicked herbicide-resistance: lessons from the field. *Weed Tech* **32**:475–488 (2018).
35 Davis AS and Frisvold GB, Are herbicides a once in a century method of weed control? *Pest Manag Sci* **73**:2209–2220 (2017).
36 Carson R, *Silent Spring*. Houghton Mifflin, Boston, MA, 400 pp (1962).
37 Blackshaw RE, Harker KN, O'Donovan JT, Beckie HJ and Smith EG, Ongoing development of integrated weed management systems on the Canadian prairies. *Weed Sci* **56**:146–150 (2008).
38 Scholz M, Enhancing adoption of integrated weed management – an Australian farmer's perspective. *Outlooks Pest Manag* **29**:66–69 (2018).
39 Asmus A and Schroeder J, Rethinking outreach: collaboration is key for herbicide-resistance management. *Weed Sci* **64** (Special Issue):655–660 (2016).
40 Ward SM, Cousens RD, Bagavathiannan MV, Barney JN, Beckie HJ, Busi R *et al.*, Agricultural weed research: a critique and two proposals. *Weed Sci* **62**:678–678 (2014).
41 Morse S and Buhler DG, IPM in developing countries: the danger of an ideal. *Integr Pest Manag Rev* **2**:175–185 (1997).
42 Agriculture and Horticulture Development Board (AHDB), *Horizon Publication: Driving Productivity Growth Together* (January 2018). [Online]. Available: https://media.ahdb.org.uk/media/Default/Market%20Insight/Horizon_Driving%20Productivity_Jan2018.pdf [9 November 2018].
43 Gaind NF, Few UK universities have adopted rules against impact-factor abuse. *Nature News* (12 February 2018). Available: www.nature.com/articles/d41586-018-01874-w [9 November 2018].
44 Barrett M, Soteres J and Shaw D, Carrots and sticks: incentives and regulation for herbicide resistance management and changing behavior. *Weed Sci* **64** (Special Issue):627–640 (2016).
45 Coble HD and Schroeder J, Call for action on herbicide resistance management. *Weed Sci* **64** (Special Issue):661–666 (2016).

 © 2018 Society of Chemical Industry