Human dimensions of integrated weed management

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Summary Farmers have always practised Integrated Weed Management (IWM). Throughout the history of agriculture, they have weighed up the available weed control options, and designed systems that they believed would suit their situations. The herbicide revolution of the 1970s and 1980s had a profound impact, particularly in the developed world, but even so, non-herbicide practices retained an important place in many farming systems. The rise of herbicide resistance has seen further pressure on farmers to evolve their weed management systems in new (as well as old) directions, and challenged them to retain the high levels of weed control that seemed relatively easy in the recent past. This paper considers some of those challenges from a socio-economic perspective. The first section provides a brief summary of factors influencing farmers to adopt or reject innovative farming practices, based on findings from an extensive literature. Characteristics of IWM that relate to those findings are spelled out, and then selected results from some recent surveys of farms and farmers are presented. Economics, which can either promote or inhibit change, is then examined, particularly the economics of highly diversified weed management systems. In the final section, weed management is considered briefly in a broader farm management context. Weed control is just one consideration which needs to be meshed with other needs and goals. Thus, integrated weed management should properly be seen as a subset of integrated farm management.

Keywords Integrated weed management, adoption of innovations, economics, herbicide resistance, modelling, sustainability.

INTRODUCTION

Integrated weed management (IWM) implies use of a diversity of weed control methods, including non-chemical methods. Many farmers already profitably combine a range of control methods, more so in some farming systems than others. In any farming system, with the onset of serious, multiple herbicide resistance, it becomes essential to broaden and diversify control methods, and so some farmers are adopting strategies that would satisfy even extreme definitions of IWM. However, changes in farmers' weed management have not been as extensive or as rapid as hoped by some, particularly in relation to the adoption of practices that will delay the onset of resistance.

Research into this issue in Western Australia has helped to clarify the reasons behind this observation. Some of the findings challenge aspects of the conventional wisdom relating to resistance management and some have important implications for the aims and expectations of agricultural research and extension. This paper has three elements: (a) a brief review of general research literature on the adoption by farmers of innovative practices, leading to an assessment of their particular relevance to and implications for integrated weed management, (b) a selection of findings from recent social, economic and biological research focusing on herbicide resistance in Western Australia, and (c) an examination of herbicide resistance in the context of a broader set of farm management problems. The paper concludes with an attempt to apply the findings in these three areas to speculate about possible futures for herbicide resistance research, extension and management in Australia.

ADOPTION OF INNOVATIONS

Pannell and Zilberman (2001) presented a detailed review of past research on the adoption of agricultural innovations and discussed the issues in relation to herbicide resistance and integrated weed management. They identified 11 factors that have been found to be key contributors to actual adoption decisions.

1. **Land quality, soil conditions, soil type** (Caswell and Zilberman 1986, Green 1995, Wu and Babcock 1998). Adoption of herbicides was complementary to the reduced-tillage practices and thus was particularly favoured in situations where soil erosion was a problem and topsoil was shallow.
2. **Prices** Increases in the price of fuel and labour tend to increase the adoption of herbicides (Miranowski and Carlson 1993, Carlson and Wetzstein 1993). Increases in commodity prices tend to increase the intensification of farming and thus increase adoption and use of herbicides (Helms *et al.* 1987, Miranowski *et al.* 1991). Higher product prices also tend to increase the use of land in locations of lower soil quality (de Gorter and Fisher 1993) and this may further increase use of herbicides. These

results highlight the importance of economic incentives as key drivers of adoption.

3. **Government policies** Since there has been an increased emphasis on soil erosion prevention, US governments have required certain environmental practices as conditions for participation in commodity programs that raise product prices. This has led to increases in the area of land with no or minimum tillage, and thus increased the reliance on herbicides (Uri 1998, Wu and Babcock 1998). These programs also include provisions to encourage reductions in the use of some herbicides, such as atrazine. Thus, their overall effect is to increase the use of herbicides but to modify them towards herbicides judged to be more environmentally benign.
4. **Location** For most technologies, the evidence points to higher adoption rates by producers who are closer to the nearest urban centre than by producers who are further away (Rogers 1995). This may be due to a lower transportation cost and/or closer contact with dealers and distributors of the technology or extension agents.
5. **Uncertainty and risk** Most farmers are risk averse (see Bar-Shira *et al.* 1997) meaning that they are willing to give up some average profit in order to reduce fluctuations in, or uncertainty about, profit. In many cases, adoption of new technologies is gradual so that farmers can experiment with them and have more reliable assessments of their impacts. One of the main activities of marketing specialists and extension agents is to reduce farmers' uncertainties about new technologies. This is achieved, for example, by the establishment of demonstration plots, demonstration activities, money back guarantees or warranties.
6. **Observability and trialability** These issues are closely related to the issue of uncertainty. If a technology is highly observable, farmer uptake through imitation of their neighbours is likely to proceed more rapidly. One can well imagine that the high observability of tractors enhanced their rate of spread through farming communities (although it clearly does not over-ride other considerations in a farmer's final decision to adopt or reject an innovation). Perhaps even more important is the potential to trial the innovation on a small scale, so that information can be obtained, uncertainties reduced and skills developed without the risk of large financial costs if the technology turns out to be uneconomic or fails due to inexperience (Pannell 1999). A new herbicide is highly trialable; its impacts on weeds are readily observable, it can be readily compared to existing herbicides, and it can be used effectively on a very small scale.
7. **Adjustment costs** One of the key obstacles to the adoption of some new technologies is that can they require investment of time and effort from the farmers. One reason that the adoption of Integrated Pest Management (IPM) has been slow is the relatively high adjustment cost it entails (Wiebers 1992). Another example is the adoption of tractors, which took about 40 years in the United States to complete (Cochrane 1979). On the other hand, adoption of herbicides was less problematic, especially for farmers who already sprayed against insects and therefore required little up-front investment in machinery. The rapid and high rate of adoption of genetically modified herbicide-resistant crop varieties in North America and South America can partly be explained by the fact that these are technologies that require very little adjustment cost. The farmer simply replaces one seed variety with another and continues to use herbicides with which they are familiar (glyphosate in most cases).
8. **Public acceptance** Adoption of new technologies may be lowered if farmers perceive that they may endanger their capacity to sell their products at high prices, or that they may encounter legal problems or protests (e.g. genetically modified crops).
9. **Education** More educated farmers tend to adopt advanced technology earlier. Education has been shown to be a key factor explaining adoption of various forms of IPM (Wiebers 1992) and soil testing (Wu and Babcock 1998). However, farmers with less education may adopt more sophisticated technologies when they rely on private consultants or public extension. Huffman (1974) found that the impact of extension was higher for farmers who were less educated.
10. **Extension and consulting advice** Empirical evidence that extension and consulting advice can have a measurable impact on farmer adoption of innovative practices is not as common as might be expected, given the large investment in these areas throughout the developed world. Nevertheless, a number of studies have identified a positive relationship between IPM adoption and participation in extension activities (e.g. Napit *et al.* 1988, Thomas *et al.* 1990, Harper *et al.* 1990, McNamara *et al.* 1991, Fernandez-Cornejo and Kackmeister 1996, Maumbe and Swinton 2000).
11. **Marketing** A key to the diffusion of a new technology is providing information about its existence and features. A significant amount of the budget of herbicide manufacturers is dedicated to marketing their products through activities such as advertise-

ments, demonstrations and trade shows, money-back guarantees and warranties, and product stewardship through salespeople (Kotler 1997).

This by no means exhausts the list of factors that have been found or proposed to influence adoption, but it includes the main types of factors of influence mentioned in the literature (although not necessarily with the same language).

ADOPTION OF IWM TO DELAY RESISTANCE

Considering the nature of herbicide resistance and its management, it is possible to make some observations about adoption of resistance prevention strategies based on lessons from the general adoption literature. Herbicide resistance, as a farm management issue is:

- complex;
- potentially expensive or difficult to prevent;
- a source of considerable uncertainty; and
- difficult to observe until herbicide resistance is advanced.

Complexity increases uncertainty, adjustment costs and, possibly, direct costs. Complexity in herbicide resistance management arises from several sources. Firstly, farmers faced with resistance can benefit from understanding the ecological and biochemical theories that explain the occurrence of resistance, but these theories may be difficult to fully understand for non-scientists. Secondly, the weed treatment options that can be used to substitute for herbicides and delay resistance are themselves complex to use relative to herbicides, and normally must be used in combinations in order to achieve adequate weed control. Thirdly, the number of potential combinations of treatments to be considered is vast, especially when the issue is considered as a problem spanning a number of years. In this case, options include not just changes in weed kill methods but also, potentially, changes in land use; for example, pasture may be included in place of a crop to broaden the available range of weed control options.

The cost-effectiveness of herbicides is revealed by their ubiquitous use through cropping systems of agriculture in the developed world. If a farmer is considering changing to a lower intensity of herbicide use in order to delay the development of herbicide resistance, he or she will be very conscious that in most cases such a move will increase costs. Change will therefore be unattractive unless the farmer is convinced that there are sufficient offsetting benefits. There may actually not be sufficient offsetting benefits in some situations.

Even if there are sufficient offsetting benefits to justify early adoption, it may be very difficult for the farmer to determine this with sufficient certainty in time for preventative strategies to be put into place. For some examples of herbicide resistance development, full resistance is apparent within a small number of years (e.g. five years or less in many recorded cases for annual ryegrass, *Lolium rigidum*, in Australia). Even if the innovative technologies are trialable, few years of trialing are available before the potential for preventative action has past.

This problem is worsened by the difficulties of trialing some types of treatment recommended to delay resistance. The difficulties include the following:

(a) Where treatments are implemented in combinations (as they generally must be) it can be very difficult to determine from field observations alone the individual impacts of each element of the combination in order to assess their individual worthiness for inclusion in an integrated management system.

(b) Some treatments have impacts that are relatively difficult to observe even if implemented in isolation. For example, increasing the crop seeding rate affects the seed production of both crops and weeds (in opposite directions), and the latter is rather difficult to observe quantitatively in the field without tedious collection and counting of weed seeds in both standard and high seeding rate plots.

(c) The effectiveness of some alternative weed treatments is very sensitive to weather conditions or the quality of implementation, and so trials give highly variable results from time to time. Even if a treatment is beneficial in the long run, it may not appear so in a short-term trial, or it may take a long time before its value can be determined with adequate confidence.

All of these factors would tend to discourage the rapid adoption of integrated weed management systems, involving combinations of unfamiliar, complex, and expensive treatments that are difficult to trial. On the other hand, the nature of herbicide resistance is that, once it has developed, farmers have no choice but to alter their weed management systems. Thus, following the onset of resistance, most of the problems involved in encouraging farmers to change to some alternative system evaporate. The problem for farmers then becomes, which of the many possible alternative systems should best be adopted?

STUDIES OF FARMS AND FARMERS

Extent of resistance Given the conclusion at the end of the last section, an important question influencing future efforts to promote IWM is the current extent and severity of herbicide resistance. We know that herbicides have been used intensively by most farmers as the primary means of weed control by most Australian crop producers for many years, and that herbicide resistance has been the obvious and inevitable consequence of that, but until the survey of Llewellyn and Powles (2001) we had no unbiased measure of extent and severity in Western Australia. The survey confirms that herbicide resistance is common and widespread in populations of annual ryegrass, but some of the findings may be considered surprising. Here are some results that surprised me.

The extent to which selective herbicides are still effective against ryegrass in many population is surprisingly high. For example, less than half of the randomly selected ryegrass populations exhibited any resistance to diclofop methyl, and only 23 per cent of paddocks had resistance in more than 20 per cent of the population. For chlorsulfuron, 64 per cent of populations exhibited any resistance and only 38 per cent had reasonably severe resistance. The herbicide clethodim remains effective as a selective ryegrass control option in most populations across all surveyed areas.

Llewellyn and Powles (2001) concluded that the opportunity to conserve the effectiveness of at least one ryegrass selective herbicide is available to the vast majority of growers across all surveyed areas. From the perspective of adoption, their findings indicate that even in regions of high cropping intensity, relatively few farmers face a herbicide resistance problem that is so severe as to absolutely require adoption of additional non-herbicide control methods. Furthermore, there are still some areas where the most resistance-prone herbicides are still effective across most of the cropping land.

Another result that would surprise some is that farmers who have weed populations with the common forms of herbicide resistance maintain ryegrass densities that are no higher than in situations where herbicides are still fully effective. This implies that the main cost of herbicide resistance is due to higher control costs rather than higher weed numbers. Interestingly, this is consistent with results from economic (Pannell 2001).

Farmers perceptions and intentions Llewellyn *et al.* (2002) surveyed farmers in Western Australia to ascertain their knowledge and perceptions of herbicide resistance. They found that the majority of growers involved in the study have some experience with resistance development on their property and that most farmers have a reasonably good understanding of resistance and its management. Furthermore, most of their perceptions about quantitative aspects of resistance are reasonably accurate. This was true for issues including:

- the cause of resistance
- the current extent and severity of resistance,
- the number of applications of selective herbicides that is possible before resistance is likely to develop.

Scientists who wish to promote the pre-emptive adoption of IWM in order to delay onset of resistance may be discouraged to learn that farmers with such good knowledge of resistance and personal experience with it, generally choose to maintain their usage of herbicides as their primary weed control method for as long as this is possible. It is particularly interesting that they expect it to be possible for the foreseeable future. Indeed, only 13 per cent of these farmers predict that they will be less reliant on herbicides in ten years time than they are currently.

It is possible that this is partly explained by apparent misperceptions about two issues that Llewellyn *et al.* (2002) identified:

- The likelihood of new herbicides with novel modes of action becoming available for resistant weeds. The vast majority of growers (86 per cent) expected a new ryegrass-effective, wheat-selective herbicide to be available within 10 years, with 52 per cent of growers expecting such a product to be available in less than six years.
- The likelihood of resistant populations of weeds reverting to a state of herbicide susceptibility if use of herbicide is temporarily suspended. Surprisingly, 46 per cent of growers in one region perceive reversion to be likely, almost 14 per cent of all surveyed growers perceive reversion to be very likely.

Both of these views would tend to discourage early adoption of costly preventative strategies (i.e. IWM). Perhaps extension activities to counter these apparent misperceptions could result in more early adoption of IWM. On the other hand, recent economic modelling of the issue, reported in the next section, suggests that changing these perceptions may not be sufficient.

THE ECONOMICS OF IWM

RIM is a multi-period simulation model representing the biology, technology and farm-level financial aspects of integrated weed management in dryland farming systems of southern Australia. Its general features include:

- a 20 year time frame;
- representation of up to seven different crop or pasture based enterprises in a user-specified sequence;
- 35 different weed control options that can be selected in any technically feasible combination and in any technically feasible sequence;
- detailed representation of relevant biological relationships;
- representation of relevant financial details, including input costs, output prices, machinery costs,

- interest rates, yields, and environmental costs for certain treatments;
- ability to specify the herbicide resistance status of the weeds with respect to each herbicide mode-of-action group.

The biological processes, variables and relationships represented include:

- the density of living, ungerminated seeds in or on the soil through each year;
- a germination pattern of weed seeds over time within each year;
- mortality or removal of seeds, seedlings, or adult plants or prevention of seed production through various processes, including both natural and human-applied mechanisms;
- inter and intra-species competition impacts on crop yields, and weed seed production;
- damage to crop production from weed control treatments, including phytotoxic damage from herbicides, and mechanical losses due to treatments such as green manuring;

The original version of RIM (Pannell *et al.* 1999) included ryegrass as the only weed, but more recently, Monjardino *et al.* (2002) have added wild radish. Here I will present a selection of results from RIM that relate to the adoption of IWM by farmers.

Reducing herbicide usage Pannell (2001) presented Table 1, showing results from the ryegrass version of RIM. The scenario is simplified for illustrative purposes. It is based on the assumption that Group A herbicides (fops and dims) are the only selective herbicides available. No constraints are placed on the use of non-selective herbicides or non-chemical treatments, other than those that are required agriculturally. Results are shown for different intensities of use of the selective herbicides, ranging from 10 uses over the 10 years down to two uses. The lupin-wheat cropping rotation is used throughout. Observations and conclusions from these results included the following.

1. A strategy to limit the usage of herbicides in order to preserve their useful life can involve substantial economic costs to farmers. The evidence for annual ryegrass in Australia is that such a strategy does not result in a greater number of uses of a particular herbicide before resistance is evident. Its advantage is purely in maintaining the potential to use the herbicide in subsequent years. The cost of restricting herbicide usage (whether voluntarily or through the necessity of resistance) increases as the restriction is tightened (see the bottom line of Table 1). In this example, if only two uses of selective herbicides are allowed over the 10 years, profit is reduced by 30 per cent relative to one use per year. This is despite the inclusion of an array of non-chemical treatments to replace the herbicide.
2. It is possible to maintain the continuous cropping rotation with reduced herbicide usage and a substantially altered weed management system. The altered system involves a greater diversity of treatment types. Each of these is individually less effective than herbicides, so a greater number of treatments must be employed. The fewer the

Table 1. Consequence of restricting usage of selective herbicides (wheat:lupin rotation, 10 year time frame).

Applications of selective herbicide	2	4	6	8	10
Profitable non-chemical treatments*	High crop seeding rates Paraquat top lupins Seed catching cart, burn dumps Delay seeding 20 days and apply glyphosate (8)	High crop seeding rates Paraquat top lupins Seed catching cart, burn dumps Delay seeding 20 days and apply glyphosate (4)	High crop seeding rates Paraquat top lupins (4) Seed catching cart, burn dumps Delay seeding 20 days and apply glyphosate (2)	High crop seeding rates Paraquat top lupins (3) Seed catching cart, burn dumps (6)	High crop seeding rates Paraquat top lupins (1) Seed catching cart, burn dumps (3)
Total usage of non-chemical treatments	33	29	26	19	14
Weed density surviving to set seed (10 year average m^{-2})	6	8	6	7	7
Equivalent annual profit ($ ha^{-1})	62	69	74	84	89

* The number of years (out of 10) in which this treatment was applied is shown in brackets, if the usage is less than the maximum potential.

number of herbicide applications, the greater the number of non-chemical treatments that are profitable to employ. The third row of Table 1 shows how total usage of non-chemical treatments falls as reliance on selective herbicides is increased.

3. Well-designed, economical strategies involving less reliance on selective herbicides result in almost the same average density of weeds as do herbicide-dominant strategies. This is consistent with survey results of Llewellyn and Powles (2001). Thus the economic difference between the scenarios is not primarily due to differences in weed densities, but to differences in total treatment costs.
4. It is often not possible to generalise about the desirability of a particular practice. Its attractiveness to farmers will depend on the context within which it will be used. That context includes the direct cost of treatment, the weed density at the time of usage, the other treatments being employed, the sale price of outputs, and so on. This is illustrated in Table 1, where delaying seeding is often an economically attractive option in years when a selective herbicide is not used, but is not used at all in the strategies that involve 8 or 10 herbicide uses.
5. When high levels of herbicide resistance develop, the farmer has no choice but to employ an IWM strategy involving diverse chemical and non-chemical practices. The column for two herbicide uses in Table 1 illustrates the kind of strategy that becomes economical in the context of low herbicide availability.

Preserving herbicide susceptibility Just because the cost of losing access to herbicides due to resistance is high (Table 1), it does not necessarily follow that early adoption of IWM is economically preferred. Pannell and Zilberman (2001) noted that factors in favour of early adoption of IWM would include: (a) preserving herbicides would help to avert a major increase in weed numbers late in the planning period, and (b) if the farmer obtains experience and expertise with IWM prior to the onset of resistance, the risk of losing control of the weed population at the time of resistance onset is reduced.

Factors against early adoption include: (a) if the weed population density is low at the time when resistance occurs, it is easier to maintain the weed population at low levels with the use of non-chemical treatments (e.g. increasing the crop seeding rate is more effective if the weed population is low), and (b) farmers can earn more interest from income that is earned sooner rather than later (i.e. the value of later benefits must be discounted relative to early benefits).

Pannell and Zilberman (2001) presented results that allow for all of these considerations, apart from that of gaining early experience with the technologies. Table 2 shows a typical result for one scenario. For this, and many other scenarios that have been examined using both versions of RIM, there appears to be no compelling case for reducing the reliance on herbicides in order to delay the time when they will be lost to resistance. In all cases examined, the long-term economic returns from a strategy that preserves herbicide use is similar to or slightly less that returns from a more 'exploitive' strategy.

Overall, while the economics are not strongly against early adoption of IWM to delay the onset of resistance, they also provide no compelling arguments in favour of it. This result, when combined with the earlier observations about adoption of IWM, means that, most farmers are likely to maintain a more or less traditional, herbicide-based weed management system until forced to change.

BROADER MANAGEMENT ISSUES

Integrated weed management should properly be seen as a subset of integrated farm management. In pursuing objectives of profitability and sustainability, farmers will consider weed management practices in a broad context, and be concerned about their impacts in areas other than weed management. The RIM model, presented above, does include costs or benefits relating to some, but by no means all, of these other areas. I conclude the paper with some comments about a number of existing or emerging broad issues with implications for weed management.

Salinity An overlap between salinity management and herbicide resistance occurs is the case of phase farming with perennial pastures. This system involves the use of occasional phases of two or three years of pasture within a cropping oriented system. Salinity management is achieved because perennial and deep rooted pasture species like lucerne capture and transpire a greater proportion of rainfall, thereby reducing the rate of groundwater recharge. Herbicide resistance management is enhanced by allowing opportunities for a broader range of weed control practices in the pasture phase. It may be that the combination of these issues will encourage uptake of phase farming in situations where it would be not be attractive on the basis of either issue alone.

Erosion Schmidt and Pannell (1996) noted that resistance is likely to encourage farmers to reconsider options such as cultivation and burning, both of which carry a risk of erosion, especially on sandy

Table 2. RIM results with and without early adoption of Integrated Weed Management (wheat:wheat:lupin rotation; 20 year time frame; herbicide applications available: four 'fops' and 'dims', two sulfonyl ureas, four triazines).

	Early adoption	No early adoption
Profit (A$ ha^{-1}, equivalent annual value over 20 years)	$85	$89
Treatment strategy	Available herbicide applications distributed approximately evenly over the 20-year period. Other treatments selected to provide the 'optimal' strategy over the whole period.	Available herbicide applications used up in the first several years of the 20-year period. Other treatments selected to provide the 'optimal' strategy over the whole period.
Weed density (plants m^{-2}, average over 20 years)	3	13

soils. However, given the great progress that has been made in reducing soil erosion on Australian farms, and the greater awareness of erosion by farmers, one would expect a more prudent and sparing use of these techniques than sometimes occurred in the past.

Livestock The attractiveness of a phase farming approach depends in part on the market for livestock products. Therefore the use of phase farming is likely to wax and wane in synchrony with market fluctuations, with implications for compensatory adjustments to other weed management practices.

Risk Apart from the uncertainty inherent in adopting new practices (discussed earlier), different weed management systems are likely to have implications for the long-term riskiness of farming. Livestock enterprises are often seen as less risky than cropping, and so phase farming may be further favoured by this consideration.

The message of this brief discussion is that it can be misleading to consider IWM practices from the narrow perspective of weed management. A number of practices associated with IWM have effects on additional issues that matter to farmers, and these effects need to be weighed up, or at least recognised, when providing information to farmers and/or forming expectations about how farmers may respond.

SOME CONCLUDING SPECULATIONS

The time when most of the innovations in weed management were herbicide-related has probably past. In response to the pressures of herbicide resistance, innovation in other types of weed management will continue and probably accelerate. The innovations will include a diverse range of practical systems developed by farmers, high-technology information-intensive systems, and innovations from biological sciences.

There will be wide adoption by farmers of some of these innovations but not of others, depending on their cost-effectiveness. In considering the cost-effectiveness of practices, complementary benefits to aspects other than weed control will become increasingly important.

Weed science and extension in Australia will continue to broaden their agendas to better address non-chemical weed control. Government extension will continue to de-emphasise herbicides, although farmers will continue to use them to a large extent (indeed, to the largest extent possible). Many advisors in the private-sector will continue to support herbicides, and will not embrace non-herbicide methods except those of high and obvious merit.

If weed resistance to glyphosate reaches high levels, it will precipitate far more radical changes in weed management systems (and indeed of farming systems generally) than we have yet seen. Nevertheless, the fundamental drivers of farmers' decision making, as described in this paper, will remain constant.

ACKNOWLEDGMENTS

I am grateful to Rick Llewellyn, Marta Monjardino, David Zilberman, Steve Powles, and Bob Lindner for their involvement in the collaborative research referred to in this paper, and to Grains Research and Development Corporation for financial support.

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