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Herbicide Resistance and the Decision to Conserve the Herbicide Resource: Review and Framework

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Abstract

The demonstrated ability of major cropping weeds to evolve resistance to most major herbicides threatens the sustainability of herbicide-dependent weed management systems. In Australia, the rapidly increasing herbicide resistance problem now presents a need to reassess herbicide use as a resource management problem. Although resistance to some herbicides is already widespread, most grain growers have several herbicide options still available to control weed infestations in crops. These growers are being encouraged to adopt practices that place less reliance on herbicides to delay, if not prevent, the emergence of further herbicide resistance. It is argued that this requires a form of resource conservation decision, the resource being herbicide susceptibility. To maximise the net present value of returns, growers need to select the optimal use of herbicide susceptibility and the more costly alternative practices over time. This paper integrates concepts of resource economics and the literature on the adoption of innovations to contribute to a framework for weed management decisions where herbicide resistance is developing. Implications for achieving rapid and high level adoption of integrated weed management practices by growers are discussed, given the requirement for perceived profitability in a complex adoption context where high uncertainty is present.

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Introduction

Since the early 1980s Australian grain growers have had a range of herbicide options available to them that have allowed selective control of weeds in crops. This herbicide technology has facilitated major changes in farming practices. Trends associated with increased use of herbicides include more frequent cropping, the ability to grow less competitive crops such as pulses, reduced cultivation and reduced burning of crop residues. The latter two trends form part of the shift to what has been referred to as ‘conservation farming', one aim of which is to reduce soil erosion risks. The resulting farming system is one that relies heavily on herbicidal weed control for both productivity and sustainable land management. In Western Australia, the average grain grower spends over $40 on herbicides per hectare of crop (Australian Bureau of Agricultural and Resource Economics, 1998).

The evolution of herbicide resistance threatens the sustainability of this farming system. The major weed in Australian cropping, annual ryegrass (Lolium rigidum) (Alemseged et al., 1999), has a demonstrated ability to evolve resistance to most of the major herbicide chemistries used for its control (Heap, 1997) and is recognised as the most resistance-prone weed species world-wide (Powles et al., 1998).

Growers are being encouraged to delay, if not prevent, further herbicide resistance development by adopting extra weed management practices that reduce the reliance on herbicides. The use of a more diverse range of weed control practices is often referred to as integrated weed management (IWM). In this paper, practices that allow selection pressure for herbicide resistance to be reduced are referred to as ‘IWM practices'. Since most growers still have several effective selective herbicide options available, it is argued that adoption of IWM practices will generally involve a decision on the optimal use of the herbicide resource. That is, growers face a question of how much of the stock of herbicide susceptibility to use now and how much should be conserved for the future.

Improved understanding of the socio-economic factors contributing to farmer decision making on resistance management should allow for more effective extension and information strategies to be developed. In this paper, literature on the adoption of agricultural innovations, concepts of resource economics, and modeling of optimal herbicide resistant weed management are integrated to produce a framework for understanding growers' weed management decisions. The focus here is on the optimal use of herbicides where herbicide resistance is developing.

The herbicide resource

The close relationship between the economics of pest resistance and resource economics was demonstrated by Hueth & Regev (1974) in a paper referring to insect management. They argued that whilst the pests themselves have been viewed (by economists at least) as a renewable resource, the effectiveness of pesticide control is a potentially exhaustible resource that also requires management.

Using this approach, pest susceptibility is viewed as biological capital, a resource stock that can be managed similar to resource stocks in other extractive industries. Application of the pesticide, and the consequent selection for pest resistance, is then the form of extraction.

Even at this basic level, adapting this framework to herbicides and weed management requires some justification. Firstly, can herbicides be considered a potentially exhaustible resource? That is, is it possible that the rate of renewal of the herbicide resource will be exceeded by the rate of depletion?

Herbicide resistance development – the rate of depletion

The potential for depletion of the stock of herbicide susceptibility is well documented in Australia. The weed that is the focus of this paper, annual ryegrass (Lolium rigidum), is ubiquitous throughout major grain growing regions of Australia and is recognised as the most important weed of Australian cropping (Alemseged et al., 1999) . The combination of a large number of plants being treated and a high initial frequency of genes conferring resistance to the major selective herbicides, result in relatively rapid selection for resistance (Maxwell and Mortimer, 1994; Powles et al, 1997). High initial gene frequencies make extinction of resistant genes in a paddock unlikely and difficult to achieve. In several cropping areas, the majority of paddocks contain a ryegrass population resistant to one or more of the herbicides used for selective in-crop control of grass weeds (Llewellyn and Powles, 2000) . A study of Western Australian ryegrass populations showed that resistance to such herbicides is likely after approximately 6 field applications (Gill, 1995).

Previous studies of pesticide management as a resource management problem have focused on insects and insecticides. One reason for this is that, in the US at least, herbicide resistance development has been less significant than insecticide resistance development (Clark and Carlson, 1990) . The rapidly increasing herbicide resistance problem in Australia now presents a need to reassess herbicide use as a resource management problem.

New herbicide development – the rate of renewal

New herbicides: The development of effective new herbicide products is one avenue for renewal of herbicide susceptibility. Recent history and the trends outlined below suggest that the availability of new selective herbicide groups to control ryegrass should not be relied upon. All herbicides introduced to the Australian broadacre cropping market since the early 1980's have belonged to an existing herbicide group and, as such, have not had novel modes of action (Table 1). Selection for resistance using a particular herbicide from one of the major mode of action groups (e.g. A and B in Table 1) commonly results in resistance to several, if not all, of the other herbicides that utilize the same mode of action. Similarly, many ryegrass populations are already resistant to previously unused herbicide products that belong to these mode-of-action groups. Therefore, herbicides with a new mode of action are required if farmers are to replace the existing in-crop selective herbicides to which ryegrass may already be resistant. World trends in the pesticide industry appear likely to result in fewer new herbicide developments. Increasing pesticide regulation costs result in fewer new pesticide registrations, particularly for minor crops (Ollinger et al., 1998 ; Ollinger and Fernandez-Cornejo, 1998) . From a world perspective, many crops in southern Australian rotations, and the Australian herbicide market in general, are considered minor.

Resistance regression: Another factor that can lead to renewal of herbicide susceptibility is regression of herbicide resistance. This is where the proportion of resistant plants in the weed population declines once the herbicide selection pressure is removed. One mechanism by which this might occur is through the resistant plants suffering a fitness penalty, as is the case with weeds resistant to triazine herbicides (Gressel and Segel, 1990) . In Australia, regression of resistance in the major weed, annual ryegrass, has not been observed. Studies investigating ryegrass with common forms of resistance have not found significant fitness penalties (Gill et al., 1993; Holt and Thill, 1994) .

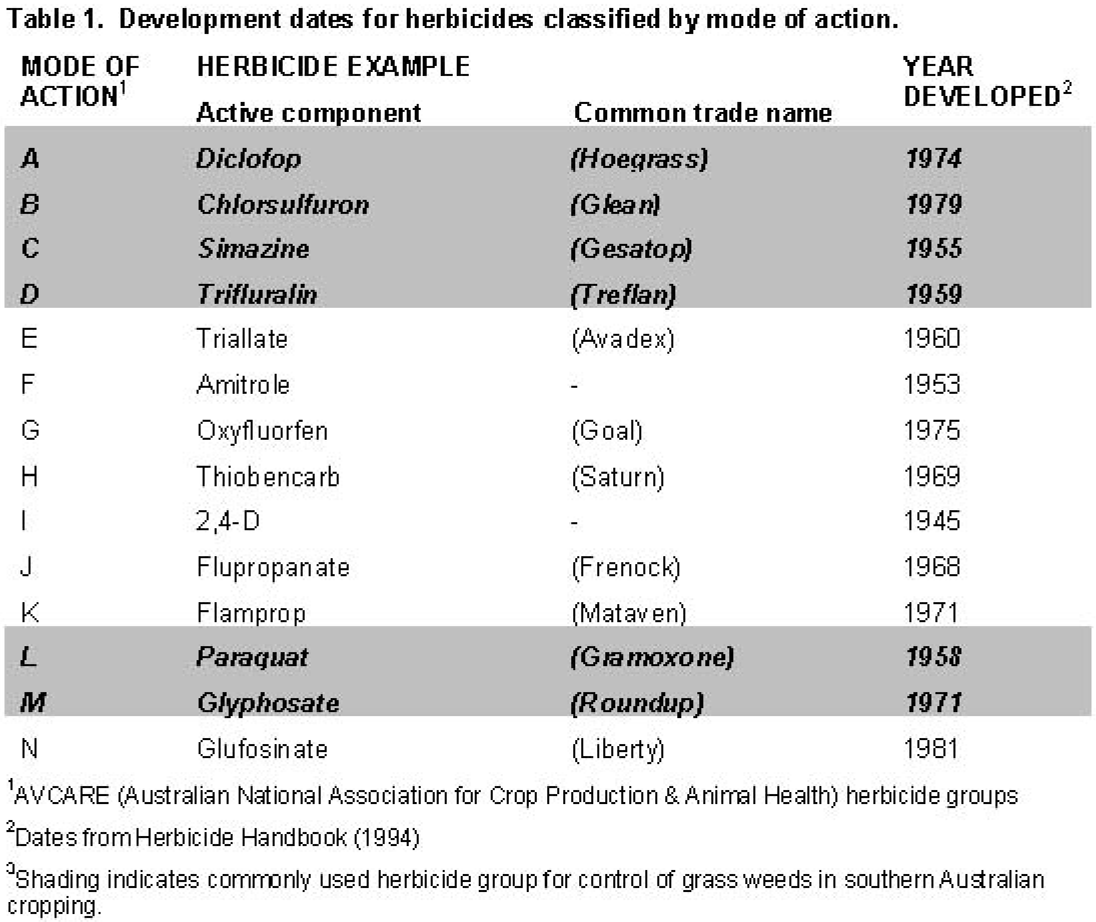


Table 1. Development dates for herbicides classified by mode of action.

MODE OF ACTION[1]	HERBICIDE EXAMPLE Active component	Common trade name	YEAR DEVELOPED[2]
A	***Diclofop***	***(Hoegrass)***	***1974***
B	***Chlorsulfuron***	***(Glean)***	***1979***
C	***Simazine***	***(Gesatop)***	***1955***
D	***Trifluralin***	***(Treflan)***	***1959***
E	Triallate	(Avadex)	1960
F	Amitrole	-	1953
G	Oxyfluorfen	(Goal)	1975
H	Thiobencarb	(Saturn)	1969
I	2,4-D	-	1945
J	Flupropanate	(Frenock)	1968
K	Flamprop	(Mataven)	1971
L	***Paraquat***	***(Gramoxone)***	***1958***
M	***Glyphosate***	***(Roundup)***	***1971***
N	Glufosinate	(Liberty)	1981

[1] AVCARE (Australian National Association for Crop Production & Animal Health) herbicide groups

[2] Dates from Herbicide Handbook (1994)

[3] Shading indicates commonly used herbicide group for control of grass weeds in southern Australian cropping.

This overall combination of rapid development of herbicide resistance in Australian cropping and the uncertain or negative prospects for renewal suggests growers are managing a potentially exhaustible resource. An important factor in how this should be managed by growers is whether or not the benefits from conservative herbicide use can be captured by individual growers.

The herbicide resource as private property versus open access

Much of the research into the economics of resistant pest management has focused on insects. The mobility of major insect pests has meant that insecticide susceptibility is often treated as an open access resource where collective pest-control actions may be required to achieve socially optimal pesticide use. Aggregate US data of insecticide sales has been used to demonstrate the open access characteristics of insect susceptibility (Clark and Carlson, 1990).

Weeds exhibit some mobility through seed import and pollen flow carrying resistant genes. However, it is generally assumed that, in most cases, growers ‘raise and own' their weed problem as a private property resource. If growers see resistance development as an open access resource problem, they would have little incentive to act to prevent resistance developing, as resistance is likely to be introduced from other sources. For this reason, the possibility of growers perceiving significant immigration of resistance genes needs to be considered. As annual ryegrass is known to be an obligate outcrossing species, with resistance commonly a result of a dominant single-gene (Holt et al., 1993), it is plausible that introduced resistant genes can be significant.

In the framework discussed here, herbicide susceptibility is generally considered to be private property. However, in understanding growers' herbicide use patterns the potential for perceived common property characteristics should not be overlooked.

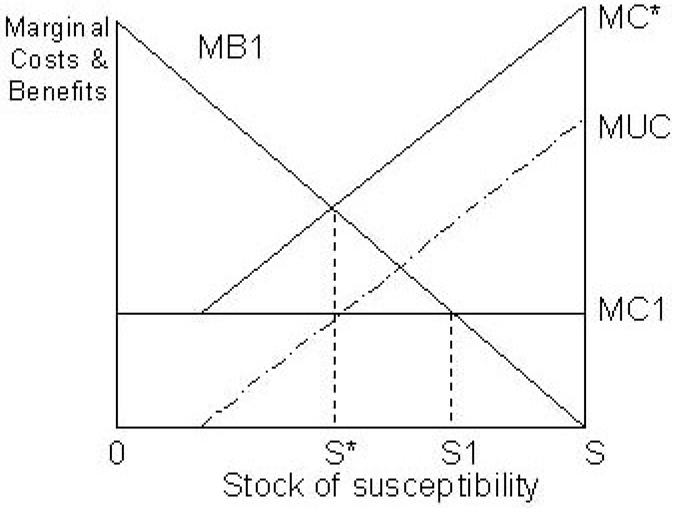
A simple two-period model of optimal herbicide use

As previously discussed, growers are being encouraged by weed scientists and extension agents to pre-emptively reduce their use of herbicides in the short-term to allow the effective life of the available herbicides to be extended. From an economic perspective the primary objective would be to achieve the optimal herbicide use pattern that maximises the net present value of returns over time (see Gorddard et al., 1995; Gorddard et al., 1996; Schmidt and Pannell, 1996).

It should be noted that continued complete reliance on selective herbicides as the only weed control practice is likely to be sub-optimal. Even in the absence of resistance considerations, the optimal weed management strategy is, in practice, always likely to include the use of at least some IWM practices. Reasons for this may include the desirability of even greater weed control than a selective herbicide application can achieve, and issues related to reliability and tactical response discussed later in the paper.

The simple framework that follows (Figure 1) is adapted from the insecticide resource model of Miranowski and Carlson (1986). Herbicide susceptibility is considered to be non-renewable and herbicide resistance is solely a function of the number of herbicide applications. Two periods of unspecified lengths are considered. Period 1 begins with low resistance levels and is long enough that most susceptibility could potentially be used in this first period (e.g. 4-6 years in the case of ryegrass resistance to common selective herbicides (Gill, 1995)). Period 2 (not shown) is in ‘the future' and dependent upon actions in Period 1 (McInerney, 1976). Whilst containing major simplifications, this example illustrates the essential concepts which are investigated in more detail later in this paper.

Figure 1. Optimal use of hericide susceptibility over time showing marginal benefits and costs of herbicide use for the first of two periods.



The total stock of herbicide susceptibility is represented by 0-S along the x-axis. In the absence of Period 2 considerations, the optimal amount of herbicide use in Period 1 would be S1, where the marginal benefit of herbicide use in Period 1, MB1, is equal to the marginal cost of herbicide application, MC1. This would result in only S1-S of the total stock of susceptibility (0-S) remaining available in Period 2.

The cost of foregone future net benefits through the use of herbicide in Period 1 is represented by the marginal user cost, MUC. These user costs are a result of the reduced amount of effective herbicide applications available in Period 2 due to use in Period 1. Given myopic use in Period 1, the amount of herbicide available in Period 2 is likely to be sub-optimal and result in reduced net benefits. The optimal level of herbicide use arises from decisions about the optimal combination of herbicide use and IWM practices. Any shift from this optimal combination results in greater weed control costs and/or greater yield loss as a result of higher weed levels.

When MUC is considered, the marginal cost of herbicide use in Period 1 becomes MC*, the sum of MUC and MC1. This gives the optimal herbicide use in Period 1 of S* where MB1=MC*. This allocation uses 0-S* of the stock of susceptibility in Period 1, leaving S-S* available in Period 2.

We are now able to make use of this simple framework in interpreting some of the factors that may be influencing herbicide use decisions. If, for example, the use of herbicide in Period 1 is not believed to lead to resistance development then the farmer's herbicide use in Period 1 will be S1 as user costs will be zero. Similarly, if the farmer believes that, regardless of his/her own actions, resistance will still be introduced (e.g. through pollen or seed introductions) then the farmer will have no incentive to conserve susceptibility in Period 1 as the MUC would be zero. The cost of resistance build-up will be ignored, and S1 will again be used in Period 1.

Alternatively, if MUC is considered in Period 1 but its value is underestimated then herbicide use in Period 1 will be above optimal levels. This could occur if the rate of resistance development is not understood or the cost of managing a herbicide resistant weed population is underestimated.

The rate of future discounting of Period 2 marginal costs and benefits should also be considered. Higher discount rates reduce MUC and result in greater herbicide use in Period 1 as S* shifts to the right.

Weed management and herbicide resistance in cropping - a bioeconomic model

To further explore the concepts and simplified functional forms represented in the above two-period model it is necessary to examine some of the bioeconomic relationships in more detail. The optimal control model developed by Gorddard et al (1995) provides a relevant basis for this purpose. In the example presented here, a situation where a farmer is continuously cropping and has the option of selective herbicide weed control and a range of IWM weed control practices is assumed. Unlike Gorddard et al (1995), the herbicide dose rate is not considered to be a decision variable. We assume that growers always aim for high weed kill when using a selective herbicide, with use of lower rates reflecting better environmental conditions for herbicide effectiveness.

Let

p_t = profit in year t
P = price per unit yeild
Y = crop yield
C_N = cost of a unit of IWM practice weed control
C_H = cost of herbicide treatement
C_F = costs associated with growing the crop which exclude weed control. These costs include seeding, fertiliser and harvesting costs and are considered fixed
H_t = a binary variable: 1 if you apply the herbicide, 0 if not.
N_t = a number representing intensity of use (number of units) of IWM practicies

$$p_t = P \,.\, Y_t - C_N .\, H_t - C_H \,.\, N_t - C_F \qquad (1)$$

Only the costs of herbicide use and use of IWM practices are considered as decision variables. Yield is then a function of total weed density surviving treatments in the current period (e.g. Auld et al 1987). Weed density is given by:

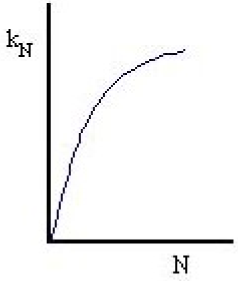
$$W_t = g \,.\, W_{t-1} \,.\, [1 - k_H(H_t)] \,.\, [1 - k_N(N_t)] \qquad (2)$$

Where:

- g is a scalar that accounts for rfactors such as seed production, viability loss and seedling mortality
- k_H gives the proportion of weeds killed by herbicide
- k_H gives the proportion of weeds killed by IWM practices

It is assumed that no individual IWM practice is able to achieve the high proportion of weed kill that herbicides can achieve. As such, multiple IWM practices (i.e. higher N) are required to achieve high levels of k_N (see Figure 2). In an example where there are four IWM practices available and each is able to provide 50% control, the use of one practice ($N = 1$) achieves $k_N = 0.5$, but when all four practices are used ($N = 4$), the overall level of control is 0.9375. This is equivalent to the effectiveness of a single application of some herbicides. Depending on the cost of the IWM practices (C_N), this relationship can result in very high weed control costs when IWM practices alone must be relied upon for high levels of weed control. This relationship would be expected to affect the curve MUC and hence MC* in Figure 1.

Figure 2. A suggested relationship between the number of IWM practices used in a year (N) and the proportion of weeds killed by IWM practices (k_N)

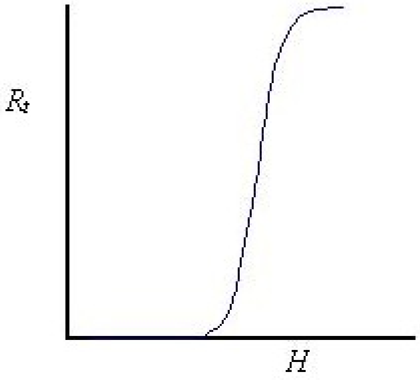


The proportion of weeds killed by the herbicide, k_H , depends on resistance status, R_t , and the proportion of susceptible weeds killed by the herbicide, k_S.

$k_H = k_S (H_t) . (1 - R_t)$ (3)

Resistance status, R_t , is the proportion of weeds not able to be killed by the herbicide due to resistance. This can be modeled using separate state variables for resistant and susceptible weeds, as done by Gorddard et al (1995), or by models with more complex genetics (Maxwell and Mortimer, 1994). In general, the development of resistance in ryegrass populations to the major selective herbicides takes the approximate form shown in Figure 3.

Figure 3. A suggested relationship between the proportionh of herbicide resistant plants, R_t, and cumulative applications of herbicide, H



As shown in Figure 3, increases in the proportion of resistant plants remains low whilst R_t is low. In effect, the first few applications of herbicide usually result in undetectable increases in resistance at the field level. The proportion of resistant plants can then increase rapidly, resulting in the herbicide becoming ineffective in controlling the population within just a few more applications. It is for this reason that herbicide effectiveness is often referred to as being limited to a number of ‘shots', after which the herbicide is no longer worth using on that population. This relationship means that the marginal benefits from herbicide use decreases rapidly once resistance first becomes evident. The pattern of resistance development also makes observation of R_t very difficult during the early stages of resistance development.

Finally,

$$\mathrm{NPV} = S_{t=1\ .\ n}\, p_t\, b_t \qquad (4)$$

The decision problem is to select *H* and *N* in each year of each period to maximise *NPV* from the time 1 to the time horizon n, where ß is the discount factor

$1/(1 + r)^{t-1}$ and r is the discount rate.

Two-Period Example

Referring again to a two-period problem, we can use the model above to help identify the key factors determining the net benefits of choosing the conservative herbicide use pattern, S*, compared to the myopic S1 herbicide use pattern (from Figure 1). In this, the simplest of examples, S* involves not using a herbicide in the first year, Period 1 (i.e. H_1=0), and conserving susceptibility for the second year, Period 2. The S1 herbicide use pattern involves using the herbicide in Period 1 (i.e. H_1=1) leaving reduced susceptibility in Period 2.

First considering the net gain in profit in Period 1 if the herbicide is used (as it would be using the herbicide use pattern S1):

$$p_1|_{H1=1} - p_1|_{H1=0} = P(Y_1|_{H1=1} - Y_1|_{H1=0}) - C_H - C_N(N^*_1|_{H1=1} - N^*_1|_{H1=0}) \qquad (5)$$

where *N** is the optimal level of IWM practice use.

In Period 2 the interest lies in how herbicide use in Period 1 affects profits in Period 2:

$$p_2|_{H1=1} - p_2|_{H1=0} = P(Y_2|_{H1=1} - Y_2|_{H1=0}) - C_H(H^*_2|_{H1=1} - H^*_2|_{H1=0}) - C_N(N^*_2|_{H1=1} - N^*_2|_{H1=0}) \ (6)$$

where H^*_2 is the optimal choice of whether to use or not use herbicide in Period 2.

Over the two periods, the choice of S* ahead of S1 requires that the discounted gains in Period 2 from not using herbicide in Period 1 are greater than the Period 1 losses.

$$(p_2|_{H1=0} - p_2|_{H1=1})b > (p_1|_{H1=1} - p_1|_{H1=0}) \qquad (7)$$

It would be expected that the greater the difference, the more likely it would be that growers adopt the reduced level of herbicide use in Period 1 (S*). This is likely to result in greater pre-emptive use of IWM weed management practices. Relating this to growers' perceptions, adoption of a reduced level of herbicide use in Period 1 would be more likely if:

$p_2|_{H1=0} - p_2|_{H1=1}$ *is perceived to be relatively high*. Thiswould be the cazse if no herbicide use in Period 1 resulted in:

- higher herbicide effectivenes (k_H) because of no increase in resistance (R_t)
- lower non-herbicide weed control costs (C_N N*)
- lower initial weed numbers in Period 2 ($g\ .\ W_{t-1}$) (unlikely)

($p_1|_{H1=1} - p_1|_{H1=0}$) is perceived to be relatively low. This would be the case if non-use of herbicide in Period 1 resulted in:

- no major increase in weed control costs (C_N N*)
- no major yield reduction (Y)

The impact on profit in Period 2 depends on:

- the number of weeds resulting from weeds surviving treatments in Period 1 ($g . W_{t-1}$)
- rate of increase in herbicide resistance status, R_t, from Period 1 to Period 2 if herbicide is used in Period 1
- relative cost and effiacy of H and N
- the rate at which Period 2 profits are discounted (Y) the potential return from crop production in Period 2 (e.g. P.Y)

Comments on the Cost of Control

A factor which appears to have a conflicting interaction with the profitability of conserving herbicide use is the cost of IWM practices (C_N). The issue is that the same IWM practices which allow herbicide use to be conserved, are also the likely methods which allow for control of weeds once resistance has developed. Therefore if C_N is lower, the relative cost of pre-emptive adoption ($p_1|_{H1=1}$ - $p_1|_{H1=0}$)will be reduced if herbicides can be cheaply substituted with IWM practices. However, lower C_N is also likely to reduce the cost of managing a resistant population and hence the relative value of conserved herbicide susceptibility $p_2|_{H1=0}$ - $p_2|_{H1=1}$The overall impact of C_N is likely to require consideration of the relationship shown in Figure 2, where higher levels of weed control using just IWM practices are shown to involve rapidly increasing costs. In practice, not all IWM practices will have the same cost. As a result, the additional IWM practices required to manage weed levels in the absence of selective herbicide use are likely to be those involving higher cost. This would further contribute to the increasing costs shown in Figure 2.

A factor relating to the cost of weed control is the reliability of the weed control practices, or risk. Although not included in the models presented in this paper, it is deserving of some comment. Selective herbicides are generally seen to have relatively high efficacy and reliability. Therefore, full reliance on IWM practices, without retaining the effective and reliable option of selective herbicides, may reduce the ability to tactically respond to unexpected increases in weed numbers that may arise as a result of environmental conditions and/or weed control failures. This would add to the value of preserving at least one ‘shot' of a selective herbicide (or, in other words, increase the cost of having no herbicide shots remaining). There are also likely to be factors associated with risk if there is complete reliance on herbicides alone. Unless other IWM practices are used, it is likely that high weed densities will be regularly treated with selective herbicide. This would increase the risk of costly, large increases in weed numbers should the herbicide treatment fail as a result of environmental reasons for example. When factors such as these are considered, even in the absence of resistance considerations, the optimal weed control combination is likely to include at least some IWM practices. It is not surprising that, in practice, there is very rarely complete reliance on a single form of weed control.

Perceptions of profitability in conserving herbicide susceptibility

The framework allows for some explanation of how adoption may or may not be profitable for individual growers. From the pioneering diffusion studies of Griliches (1957), to more recent literature (Feder and Umali, 1993; Lindner, 1987), it is evident that the profitability of an innovation can explain much of the variation in the adoption decision.

However, given that adoption can essentially be viewed as a process involving uncertainty and learning (Fischer et al., 1996; Hiebert, 1974; Jensen, 1982; Tonks, 1983), it is growers' perceptions of profitability that are likely to be of most relevance. Unless there is complete knowledge about the innovation, which is certainly not the case for herbicide resistance and many IWM weed management practices, growers' perceptions can explain much of the observable differences in adoption (Lindner, 1987).

So what are the difficulties in developing accurate perceptions of the profitability of conserving herbicide susceptibility? The process is made difficult by the fact that it is essentially a conservation, or preventative, ‘innovation'. As demonstrated in the models above, this infers that some short-term profits may need to be foregone to minimise a decline in returns in some future period. Innovations such as these are recognised as having particularly slow rates of adoption (Pannell, 1999; Rogers, 1995). One of the explanations for this is high uncertainty, and that is what will be focused on here.

Factors Contributing to High Uncertainty

The extended time frame for returns from adoption increases uncertainty (Pannell, 1999). Growers are faced with considerable uncertainty regarding factors such as the rate of resistance build-up, the cost of controlling weed populations without the use of herbicides and the future availability of new weed control methods. These add to the standard elements of uncertainty associated with farming such as commodity prices. Recent literature suggests an even more important role for uncertainty. Dong and Saha (1998) argue that even if the returns from adopting are expected to be positive, adoption may still not occur as the returns from waiting for further reductions in uncertainty may be higher.

Appropriate information can reduce some uncertainty. However, for the herbicide resistance problem, attaining high quality information can be difficult, as well as costly. Two major attributes identified by Rogers (1995) as determining the rate of adoption, observability and trialability, are not well satisfied. The development of resistance is not often observable until the effectiveness of the herbicide is almost lost. As a result, the ability to observe the effect of reduced herbicide applications on the stock of weed susceptibility is made difficult. Similarly, this affects trialability. Whilst IWM weed management practices may be able to be trialed and observed to varying degrees, their impact in the context of conserving herbicide susceptibility is not so readily observable.

There is also the potential for considerable uncertainty about the ongoing importance of herbicide resistance development. Due to the competitive commercial nature of pesticide development, little is publicly known about the probability of new herbicide developments. The potential for new herbicide groups that will reduce the impact of current forms of resistance is highly uncertain. Similarly, there is uncertainty regarding the development of new non-herbicide weed control technology or the future profitability of enterprises which rely less on herbicide use (e.g. grazing).

Although not discussed in any detail here, the IWM practices themselves, and IWM as a strategy, present their own set of impediments. The importance of perceptions of not just the ‘problem' but of technology-specific attributes has been recognised in recent studies (Adesina and Baidu-Forson, 1995; Adesina and Zinnah, 1993; Wossink et al., 1997). IWM, by definition, involves a range of practices and therefore a large number of technology-specific attributes. As suggested in this paper, cropping without selective herbicides is likely to require several weed control practices used in conjunction. This complexity adds to the potential for misperceptions and high uncertainty.

The role of information and extension

Even if conserving herbicide susceptibility is profitable, the adoption scenario is clearly complex and, as such, rapid adoption is difficult to achieve. Aside from developing new weed management methods, those with an objective of preventing further herbicide resistance development essentially have the provision of information as the main tool. Where the pest being considered has very low mobility there is little justification for policy other than that which overcomes a lack of information (Miranowski and Carlson, 1986; Pannell, 1994). Improved knowledge and better informed decision making then becomes the objective. Extension of information about herbicide resistance and IWM practices can achieve this by reducing uncertainty and overcoming misperceptions. If the argument that the described adoption scenario is one involving particularly high levels of uncertainty is correct, then it would follow that the potential impact of information is also high.

The framework in this paper is being used as a basis for an empirical study using data from interviews with individual growers in the Western Australian wheatbelt. Survey questions are focused on hypotheses developed here, based on consideration of the variables most likely to be of influence in the decision to conserve or exploit herbicides. A major objective of this work is to test whether grower perceptions and adoption behaviour are consistent with a private property, exhaustible resource model and to identify the important factors influencing the adoption decision. The role of information in influencing perceptions shown to be important in the adoption decision, including possible misperceptions and perceptions of uncertainty, will be examined and tested.

Conclusion

A number of organisations involved with crop production have an objective of reducing the rate of herbicide resistance development by grain growers. What has been presented in this paper suggests that there are major challenges in achieving this. A framework for understanding the important factors determining profitability, together with the likely role of high uncertainty, has been presented. Given the current extent of herbicide resistance in Australian cropping, and the demonstrated potential for this to increase, it is suggested that a framework that considers herbicide susceptibility to be a potentially exhaustible resource may be appropriate. Growers must then choose the optimal levels of herbicide and IWM practice use over time, in an adoption scenario where uncertainty is high. Gaining a greater understanding of the rational economic basis for growers' herbicide resistance management decisions should assist in targeting research and extension.

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