Economics of pre-emptive management to avoid weed resistance to glyphosate in Australia

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Abstract

Previous economic analyses of the preemptive use of strategies to delay the onset of herbicide resistance have concluded that they are often not economically attractive for selective herbicides, largely because the only effective delaying strategy is abstinence from use. However, in the case on the important non-selective herbicide glyphosate, the frequency of resistance genes is low enough for their local extinction to be possible. This can be exploited through the joint use of multiple control practices to seek the elimination of any weeds that survive glyphosate application. A particular version of this strategy, known as “double knockdown”, involves a follow-up application of paraquat after glyphosate. Biological modelling of this option has been encouraging. An economic model of the double knockdown strategy is presented, and used to calculate the break-even period before resistance onset. If glyphosate resistance is expected to occur before that break-even period, a farmer would benefit from adoption of the resistance-avoiding strategy, even though it is more expensive in the short term. Surveys of farmers indicate that some, but not all, would currently benefit from such a strategy.

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1. Introduction

As the extent and cost of herbicide-resistant weed populations increases worldwide, farmers are being urged to invest in practices to prevent, or at least delay, further resistance development. Concerns exist among weed scientists and agronomists that the current level of adoption of practices that reduce herbicide reliance is sub-optimal and that farmers may be unaware of the longer term benefits from prevention of herbicide resistance (Dyer, 1997; Roushand Powles, 1996). This concern by weed professionals is partly prompted by the lack of new herbicide products with novel modes of action reaching the market. For example, the most widely used herbicide, glyphosate, was released in the early 1970s. The only other reliable option for non-selective pre-seeding weed control in southern Australian broadacre cropping is paraquat, which was released in the 1960s. No new alternatives are known to be in development.

The rapidly increasing number of cases of glyphosate resistance throughout the world (Heap, 2004) has renewed calls for greater adoption of practices that would conserve the efficacy of glyphosate (e.g., Powles, 2003). Glyphosate is the largest-selling crop-protection chemical in the world and is the most important agricultural herbicide (Baylis, 2000; Woodburn, 2000). Its use as a safe, non-selective herbicide with a broad weed spectrum has facilitated the widespread adoption of reduced-tillage practices in modern cropping systems. In Australia, grain growers value glyphosate more highly than they do other herbicides (Llewellyn et al.,...
However, its continued ability to be a low cost weed management option and the resulting economic impact on farmers is threatened by growing weed resistance. In 2004, there were approximately 40 confirmed *Lolium rigidum* populations that were resistant to glyphosate in Australia, and this number is expected to increase rapidly.

Research into the economics of resistance management began with studies of insecticide resistance (Hueth and Regev, 1974), where insect susceptibility was considered to be a non-renewable resource depleted with each unit of pesticide used (see also Miranowski and Carlson, 1986). Studies of the economics of herbicide resistance management have largely focused on bio-economic modelling of common forms of herbicide resistance, such as annual ryegrass (*Lolium rigidum*) resistance to post-emergence selective herbicides in Australian cropping. In these studies a set number of effective herbicide applications are assumed to be available before resistance develops (e.g., Pannell and Zilberman, 2001; Pannell et al., 2004). The frequency of resistant weeds is always greater than zero in these models, and each application of selective herbicide increases the frequency of resistance genes (Gorddard et al., 1995; Gorddard et al., 1996; Pannell et al., 2004; Schmidt and Pannell, 1996).

In estimating the annual costs of preventing and managing herbicide resistance in *Alopecurus myosuroides* (Blackgrass) in an English cropping scenario, Orson (1999) highlighted the need for the profitability of preventative strategies to be calculated to aid extension and decision making by farmers. Past economic analyses of resistance to selective herbicides by *L. rigidum* in Australia have concluded that there is often no economic advantage from taking pre-emptive action to delay the onset of herbicide resistance (e.g., Powles et al., 2001; Monjardino, 2002; Pannell and Zilberman, 2001). However, the characteristics of *L. rigidum* resistance to glyphosate are different in several respects, so that the previously reported result may not be applicable. Most importantly, there exists a management strategy that may allow glyphosate to be used without increasing the relative frequency of glyphosate-resistant weeds, or that may reduce the existing frequency of resistance genes (Neve et al., 2003b). This strategy, known as “double knock” or “double knock-down”, is explained later.

No comparable strategy exists for the prevention of resistance to in-crop selective herbicides commonly used for controlling *L. rigidum*. After a number of repeated applications, resistance to herbicides such as ALS and ACC-ase inhibiting herbicides becomes almost certain (see Gill, 1995). Contributing to the effectiveness of “double knock” for delaying glyphosate resistance onset is the much lower initial frequency of genes for resistance to glyphosate (Jander et al., 2003) compared to most selective herbicides. This means that local extinction of plants with glyphosate resistance is a realistic possibility (see below).

The objective of this paper is to examine the economics of glyphosate resistance in *L. rigidum* in Australia, with a broader aim of contributing to the understanding of other resistance problems with similar characteristics. The paper begins by providing background on the population dynamics of herbicide resistance in a finite management unit (i.e., a paddock) that allows resistance to be delayed and possibly prevented despite ongoing use of a herbicide. A present-value economic model is then presented and used to calculate the number of resistance-free years at which the farmer is indifferent between two feasible strategies: the double knockdown strategy, and one that involves using glyphosate until resistance develops and then bearing the higher costs for treatment of resistant weeds. This break-even period of freedom from resistance is compared with survey evidence on farmers’ expectations about the period before they expect to suffer glyphosate resistance. Implications for farmers, policy makers and researchers are discussed.

2. Herbicide resistance development and prevention

A combination of a large number of plants being treated and a high initial frequency of genes conferring resistance results in relatively rapid selection for resistance to the major selective herbicides (Jasieniuk et al., 1996; Maxwell and Mortimer, 1994). The most widespread crop weed in Australian agriculture, *L. rigidum* (Alemseged et al., 2001), has been shown to have relatively high initial frequencies of genes that can survive applications of common selective herbicides. A study by Preston and Powles (2002) established that in natural populations of *L. rigidum* the frequency of individuals with a gene endowing resistance to the sulfonylurea herbicide sulfometuron-methyl ranged between $4.6 \times 10^{-5}$ and $1.2 \times 10^{-4}$. This suggests that extinction of these resistant genes in a typical paddock in the southern Australian cropping zone is unlikely to be a practical option. Rather, each application of the herbicide will lead to a higher frequency of resistance genes within the weed population as plants with the resistance genes are likely to survive to set seed. Consequently, the majority of cropping paddocks in some major grain growing regions of Australia contain a *L. rigidum* population with a high proportion of plants resistant to one or more selective herbicides (Llewellyn and Powles, 2001).

Despite more frequent and extensive use of glyphosate relative to these selective herbicides, glyphosate resistance remains rare. One reason is that the natural frequency of weeds with genes for glyphosate resistance is much lower.
Field experience and calibration of population models suggests that the natural frequency of genes endowing glyphosate resistance in *L. rigidum* is likely to be approximately $1 \times 10^{-8}$ (Neve et al., 2003a). This low-gene frequency, combined with the opportunity to use practices that control weeds that survive pre-seeding glyphosate applications (e.g., tillage and selective herbicides) creates the opportunity to greatly reduce the probability that a typical paddock will contain a mature resistant weed. For example, a 100 ha paddock with 100 plants m$^{-2}$ would be expected to have only one glyphosate-resistant plant emerging. In a wheat–canola crop rotation with no-tillage seeding and glyphosate used once pre-seeding each year, resistance was predicted to eventually occur in 90 percent of populations, with resistance becoming apparent after 10–18 years. This result is consistent with observations of glyphosate resistance evolution in the field (Neve et al., 2003b).

Stochastic modeling by Neve et al. (2003b) shows that the addition of key practices, such as tillage, can reduce to low levels the probability of a glyphosate-resistant weed population developing in a 20-year period. All results presented here assume that glyphosate is only used pre-seeding. Glyphosate-resistant grain crops, which would allow in-crop use of glyphosate, have not been introduced to Australia and plans to introduce them have been halted.

A practice shown to delay or prevent resistance to glyphosate in a no-tillage system is the double knockdown. This involves application of a less commonly used alternative non-selective herbicide, paraquat, one to two weeks after the glyphosate application, aimed at killing survivors. On average, seasonal conditions in grain growing regions of Western Australia make this practice feasible in two out of three years (Neve et al., 2003b). Paraquat is more costly per hectare than is glyphosate and it can be less effective on some types of weeds, including more mature weeds. However it has a generally high effectiveness against *L. rigidum*, the subject of this study. Modelling by Neve et al. (2003b) indicates that use of paraquat in a double knockdown strategy can often drive genes for glyphosate resistance to local extinction, so that regular use of double knockdown potentially allows continued use of glyphosate into the indefinite future.

3. Present value model

The profitability of each of the two weed management strategies is evaluated by comparing the annual weed treatment costs ($c$). The present value of costs of initially relying solely on glyphosate ($PV_G$) is given by

$$PV_G = \sum_{t=1}^{F} C_G/(1+i)^t + \sum_{t=F+1}^{T} C_R/(1+i)^t,$$  

where $T$ is the total number of time periods, $F$ is the number of years of freedom from glyphosate-resistance, $C_G$ is the annual weed treatment costs in year $t$ from using only glyphosate ($G$) during the resistance-free period, $C_R$ is the annual cost in year $t$ from the weed management strategy that becomes necessary after glyphosate-resistance has developed, and $i$ is the real discount rate.

The present value of the costs for the double knockdown weed management strategy ($PV_{DK}$) is given by

$$PV_{DK} = \sum_{t=1}^{T} C_{DK}/(1+i)^t,$$  

where $C_{DK}$ is the average annual costs in year $t$ from applying the double knockdown strategy. It is assumed that no resistance to this double knockdown strategy develops.

For this comparison of costs to be sufficient to evaluate the two strategies, we must also assume that the strategies do not differ in terms of weed survival, fitness of any surviving weeds or phytotoxic impacts on crops. We assume that there is no risk of the double knockdown strategy failing to prevent resistance and no risk of importation of already-resistant weeds into the field.

In the next section, results from Eqs. (1) and (2) are compared to identify the value of $F$ at which the present values are the same for both strategies: the breakeven value, $F^*$, if $F$ is less than the calculated value of $F^*$ (i.e., if the period before onset of glyphosate resistance is brief enough), adoption of double knockdown would be beneficial. In all the results presented, the cost of glyphosate ($C_G$) is assumed to be $7.50 per ha per year while the average annual cost of double knockdown ($C_{DK}$) is $15.83 per ha per year (due to an additional $12.50 per ha in 2 years out of 3 for paraquat). All of the above costs incorporate $2.50 per ha herbicide application costs. The cost of the weed management strategy necessary after glyphosate-resistance has developed ($C_R$) is assumed to range from $20 to $45 per ha. This parameter range is based on results from the RIM bioeconomic model (Pannell et al., 2004). Finally, the time period for analysis ($T$) is varied from 20 to 50 years and the real discount rate ($i$) is 5% (or 10% in Table 2). All costs and prices are assumed to remain constant in real terms, and weed-free yields remain constant through the period.

An important assumption is that the farmer makes a once-off decision at the start of the period to either adopt double knockdown for the whole period or not at all. In reality, farmers revisit and revise their management decisions over time, and may reasonably choose to use glyphosate alone for some years before adopting double knockdown prior to the onset of glyphosate resistance. Implications of this are discussed later.
The economic model for one scenario is illustrated in Fig. 1. The discounted cost of glyphosate treatment before resistance develops is represented by area $A$, where $A = \sum_{t=1}^{F} C_G/(1+i)^t$ and the costs after resistance develops is given by area $C+D_1$, where $C + D_1 = \sum_{t=R+1}^{T} C_R/(1+i)^t$. The sum of discounted costs to the double knockdown strategy is shown in Fig. 1 by the area $A+B+C$, which is equal to $PV_{DK}$ given by Eq. (2). While the annual costs for a given practice are constant in nominal terms, their present value declines over time, resulting in the downward sloping cost curves in Fig. 1.

In the scenario illustrated in Fig. 1, short-run cost savings from using glyphosate alone are greater than the long-run extra costs once resistance develops (area $B>D_1$). Thus, using glyphosate until resistance develops at time $F$ (year 10 in this case) and then using an alternative more costly approach thereafter is the lower-cost weed management strategy.

Fig. 2 shows results for a scenario that is the same as Fig. 1 except for having a greater weed control cost after the onset of glyphosate resistance ($$45 per ha per year, rather than $20 in Fig. 1). In this scenario, the double knockdown strategy becomes the cheaper option (area $B<D_2$).

Starting from the scenario in Fig. 2, if the period until resistance onset ($F$) were to be increased, the short term benefit from not using double knockdown (area $B$) would increase and the long-term benefit from using double knockdown (area $D$) would decrease. At some value of $F$, the two would be equal, and the farmer would be indifferent between adoption and non-adoption of double knockdown. This is illustrated in Fig. 3, which shows that the break-even value, $F^*$, is 14 years for this case.

To summarise, if the expected period before resistance onset is less than this break-even value ($F<F^*$), adoption of double knockdown is beneficial. For example, if $F$ was actually 10 years (Fig. 2), this is less than the break-even value of 14 years (Fig. 3), so adoption of double knockdown is beneficial.

Fig. 4 is a different illustration of the identification of the break-even value of $F$. The present value of costs for double knockdown is not affected by the period of freedom from glyphosate resistance, since double knockdown is assumed to be used indefinitely without causing resistance. On the other hand, the present value of costs for the non-double knockdown strategy falls as $F$ increases, as this implies a longer period of use of the
cheaper glyphosate-only strategy. In the example illustrated, the break-even value is approximately 10 years. Thus, double knockdown is the preferred strategy if resistance is expected within the next 10 years. Otherwise, the least cost approach is to continue to use glyphosate until resistance develops after at least year 10.

4. Results and discussion

Table 1 shows values of $F^*$ for various time periods and various weed control costs after the onset of glyphosate resistance. For example, if the time period is 50 years and weed control costs $25 per ha after resistance develops, the farmer should select the double knockdown strategy if resistance would otherwise occur in or before year 13. However, if resistance develops after 14 or more years, then the farmer would be better to exploit the use of glyphosate until that resistance occurs and pay the higher treatment costs to deal with the resistant weeds when that occurs. The short-run costs savings, plus accumulated interest savings on those costs, would exceed the long-term costs from years 14–50.

Reducing the time frame from 50 down to 10 years steadily reduces the break-even value $F^*$, making it less likely that double knockdown will be attractive to farmers. Intuitively, if farmers have a short-term planning horizon, they are less likely to be willing to make short-term financial sacrifices for gain in the longer term. With a shorter planning horizon, the grower will only employ the more expensive double knockdown strategy if resistance is expected to develop earlier.

Increasing the costs of resistance increases the break-even period, meaning that producers are more inclined to avoid resistance if possible. For example, with a 50-year time period, if the cost of dealing with glyphosate-resistant weeds increases from $25 to $45 per ha, the break-even period increases to 26 years (Table 1), making it likely that pre-emptive adoption of double knockdown would be attractive.

Table 2 shows the same set of results for a higher discount rate of 10 percent. A higher discount rate means that short-term benefits and costs weight more heavily on the farmer’s decision making, so that a strategy like double knockdown that is aimed at the long term becomes less attractive. Consequently the break-even values in Table 2 are generally shorter than those in Table 1. The discount rate has a notable impact on the break-even period before resistance onset. Unfortunately, it is not a factor that an extension agent or scientist can easily observe or influence as it depends on each farmer’s attitudes and investment opportunities.

As noted earlier, the analysis is based on a simplifying assumption that the farmer makes a once-off decision at the start of the period to either adopt double knockdown for the whole period or not at all. More realistically, a farmer wishing to minimise costs would delay the adoption of double knockdown until as late as possible without losing its ability to avoid glyphosate resistance. Analysing this aspect of the problem in full detail would require a risk-based model representing the probabilities of different outcomes from different lengths of delay before adoption of double knockdown. This is beyond the scope of the current analysis. However, the results presented here can remain relevant to this dynamic version of the problem if $F$ is reinterpreted as the minimum duration of double knockdown adoption necessary to avoid glyphosate resistance, rather than the total period of freedom from resistance. The farmer would make the decision on adoption or non-adoption once the field reached $F$ years before resistance onset. As before, if $F$ was less than the calculated value of $F^*$, adoption of double knockdown would be beneficial. Under either interpretation of $F$, the break-even results in Tables 1 and 2 provide a decision criterion for whether the period before resistance onset is short enough to warrant adoption of double knockdown.

This raises the question of what are realistic values for $F$. A national survey of 380 Australian grain growers conducted in 2003 found that, on average, grain growers expect that they will get glyphosate resistance in at least one field in 12 years, with 8 percent of growers expecting it in less than 5 years and 31% in less than 10 years (D’Emden and Llewellyn, 2004). If these expectations are accurate, those farmers with expectations for more rapid onset of resistance would be likely to benefit from adoption of double knockdown under many of the scenarios of Tables 1 and 2. Those with average expectations would only benefit if they have a relatively
low discount rate, a relatively long planning horizon, and/or a relatively high expected cost of weed control after resistance onset.

This analysis has important implications for farmers in the modelled farming system. By comparing their own situation with the break-even values calculated here, farmers could evaluate whether adoption of the double knockdown strategy would be financially beneficial. The results demonstrate a need for risk assessment tools that can be used by farmers to estimate the probability and timing of glyphosate resistance development in their paddocks.

Government policy makers may also wish to respond to the knowledge that impending costs from glyphosate resistance are at least partly avoidable. Information provision is one obvious response. There may be a case for information and regulation to restrict the movement of seeds from existing resistant populations. This would reduce the risk that farmers who have invested in prevention still gain glyphosate resistance via external sources.

For researchers, the study highlights the need for good quality information about various parameters, including:

- the time lags to resistance onset under various weed control strategies,
- the cost of weed management after resistance onset, and
- the risk of failure of intended preventative strategies.

We note that the economic modelling approach used here is relatively simple. There is scope for explicit representation of a number of additional bio-physical aspects of the issue (e.g., weed survival of herbicide treatments, phytotoxicity, the importation of resistant weeds to the field, and the risk of double knockdown failing to fully prevent glyphosate resistance). Further, as noted earlier, the model may be enhanced by more sophisticated representation of risk and dynamics in decision making. The dynamics of decisions are relevant because the issue changes for farmers over time. Initially, it may not be economical to act preemptively, but it will become so at some point when the number of years until expected resistance onset is few enough. Analysing this fully would require a more detailed and sophisticated model than applied in the present study.

The results presented here differ from those previously reported for resistance to selective herbicides because of the existence of a strategy, double knock, that apparently can indefinitely delay the onset of glyphosate resistance in weeds like *L. rigidum*. For most selective herbicides it is judged that abstinence is usually the only effective way to prevent resistance development, leading to an unhappy choice between strategies that might be characterised as “just say no” and “accept the inevitable”. For glyphosate resistance it appears that a third option is sometimes optimal: “short-term pain for long-term gain”.

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