



AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
<http://ageconsearch.umn.edu>
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Social costs of herbicide resistance: the case of resistance to glyphosate

Sally P. Marsh¹, Rick S. Llewellyn^{1,2} and Stephen B. Powles³

¹ School of Agricultural and Resource Economics, University of Western Australia

spmarsh@cyllene.uwa.edu.au

² Present address: CSIRO Sustainable Ecosystems, Urrbrae, South Australia

³ Western Australian Herbicide Resistance Initiative, University of Western Australia

Abstract:

Social costs and externalities associated with herbicide resistance have not generally been considered by economists. The economics of managing herbicide resistance in weeds has focused on cost-effective responses by growers to the development of resistance at the individual farm and field level. In this paper we argue that the increasing possibility of widespread glyphosate resistance presents a case where social costs associated with glyphosate resistance need to be considered when assessing optimal use of this herbicide resource at the farm level. Social costs associated with the loss of glyphosate efficacy include potential failure of herbicide-resistant crop systems, reduced use of conservation tillage techniques, and a potential greater reliance on herbicides with greater health and environmental risks.

Contributed paper presented at the 50th Annual Conference of the
Australian Agricultural and Resource Economics Society, Manly Pacific Sydney,
NSW, 8–10 February 2006

Social costs of herbicide resistance: the case of resistance to glyphosate

Sally P. Marsh, Rick S. Llewellyn and Stephen B. Powles

Introduction

Resistance to herbicides is an increasing problem world-wide, affecting the efficacy of many major herbicides. Herbicide resistance is defined as “*the inherited ability of a weed population to survive a herbicide application that is normally lethal to a vast majority of individuals of that species*” (Powles *et al.*, 1997). Whereas externalities and social costs associated with resistance to pesticides and antibiotics have been considered by economists (e.g. Miranowski and Carlson, 1986; Laxminarayan, 2003a), this has not been the case for resistance to herbicides. This is explainable by the higher mobility of many insects and diseases relative to weeds, and the consequent higher risk of off-site effects (Mullen *et al.*, 2005).

The economic concerns related to pesticide and antibiotic resistance are that individuals may use the products with insufficient concern about the negative impacts of their current use on the future efficacy of the product for others. If externalities are not taken into consideration then individual optimal use may be too high. Economists have suggested the use of economic and regulatory incentives to ensure that individuals and firms act in a manner that is consistent with societal objectives to conserve pest and disease susceptibility. An example of such an approach is the mandatory requirement in the United States for insect refuges in fields planted to genetically modified *Bt* cotton (Secchi and Babcock, 2003). Measures such as this and restrictions placed on the indiscriminate use of pesticides and antibiotics act to slow the development of resistance, although the effectiveness of measures such as insect refuges have been questioned as they rely on the uncertain compliance of individual farmers (Batie, 2003). Noncompliance by individuals is an explainable economic response to a requirement to provide public goods.

In this paper we discuss the case of the evolution in weed species of resistance to glyphosate, a valuable and widely used broad-spectrum non-selective herbicide first developed by Monsanto in the early 1970s. Some authors (e.g. Powles, 2003; Mueller *et al.* 2005) have argued that glyphosate is such a unique chemical that its current and future value to society should be taken into consideration when considering its optimal use by individuals. We explore this idea: discussing the factors affecting the development of glyphosate resistance; outlining the concept of herbicide efficacy as an exhaustible resource; and considering the economic issues associated with the loss of glyphosate as a herbicide resource.

Factors affecting the use of glyphosate and resistance development

The number of crops and situations in which glyphosate can be safely used has increased rapidly, such that it has become the most widely used herbicide worldwide (Baylis, 2000), and a key component of weed control used by farmers. Amongst its many advantages, glyphosate is considered to be an environmentally ‘safe’ herbicide: it has

very low toxicity to animals, including humans, and degrades rapidly (Roy, 2004). However, despite extensive long-term use worldwide, weeds have been slow to develop resistance to glyphosate and evolved resistance is comparatively rare. This is thought to be largely because the natural frequency of occurrence of genes for resistance is much lower for glyphosate than for the in-crop selective herbicides to which resistance has become widespread (Neve *et al.*, 2003a).

Glyphosate has been off-patent in all major use countries since 1995-2000, and the price has fallen steadily since coming off-patent, with generic product now supplied by a number of manufacturers. Figure 1 gives an example of the fall in the price of glyphosate and the concurrent increase in the number of generic products available in Argentina since 1994. Similarly, the price of glyphosate in Western Australia has fallen in nominal terms from around AUD\$19 in 1986 to AUD\$5 in 2003 (Department of Agriculture Western Australia, various years). The fall in glyphosate price and ready availability has contributed to its increased use.

A major factor contributing to increased glyphosate use is the development and rapid adoption of genetically engineered glyphosate-tolerant crop varieties: Roundup Ready® canola, maize, soybean and cotton (Figure 2). In 2005, glyphosate-tolerant crops made up 87 percent of soybean area, 61 percent of cotton area and 26 percent of maize area in the United States (USDA, 2005). In 2003, 98 percent of soybean plantings in Argentina were glyphosate-tolerant (Dill, 2005). Worldwide, more than 58.5 million hectares are planted to glyphosate-tolerant crops, with the majority of this being soybeans (ISAAA, 2004). Additionally, no-till and minimum-till cropping systems are heavily dependent on glyphosate for knock-down weed control (Neve *et al.*, 2003b; D'Emden and Llewellyn, 2004) and the increased use of these conservation tillage techniques has contributed to increased use of glyphosate. The combination of glyphosate used on glyphosate-tolerant crops, often combined with minimum tillage, provides a comparatively reliable and simple-to-implement weed control system for farmers.

Falling glyphosate prices, the adoption of no-till and minimum till systems and the adoption of glyphosate-tolerant crops, have combined to cause an exponential increase in the use of glyphosate (Roy, 2004). Glyphosate has become so cost-effective and dominant in major markets that the development of new herbicides has been discouraged (Mueller *et al.*, 2005; Duke, 2005). There are implications for resistance management from this dependency on glyphosate for weed control, as there has been a loss in diversity in herbicide mode-of-action on cropping weeds. Weed resistance to glyphosate has been and continues to be identified (Heap, 2005; Preston, 2005), and both herbicide-resistant (HR) crops and no-till systems apply a selection pressure for the further development of resistant weeds (Neve *et al.*, 2003b; Owen and Zelaya, 2005; Puricello and Tuesca, 2005). The selection pressure for resistance created by the use of glyphosate in HR crops, where it is applied as a post-emergent herbicide, is much greater than when it is used pre-seeding (Neve *et al.*, 2003b; Powles and Preston, 2005). In Australia, where glyphosate is mainly used pre-seeding, the number of weed populations resistant to glyphosate in broadacre cropping is 24 (Preston, 2005). In the United States where the uptake of HR

crops is widespread, a conservative estimate of the number of resistant populations numbers over 750 (estimate from Heap, 2005).

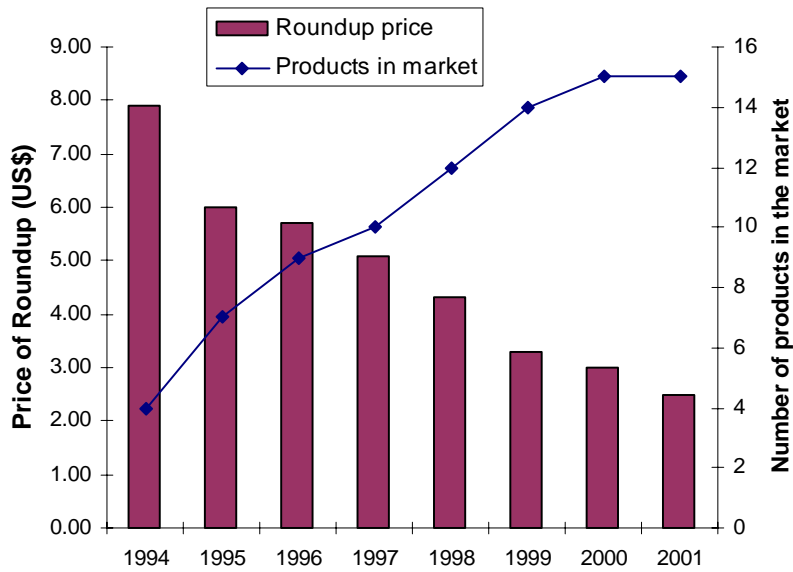


Figure 1. Evolution of the price of glyphosate (in US\$) and number of competing products offered in the Argentine market 1994-2001. Source: Trigo *et al.*, 2003.

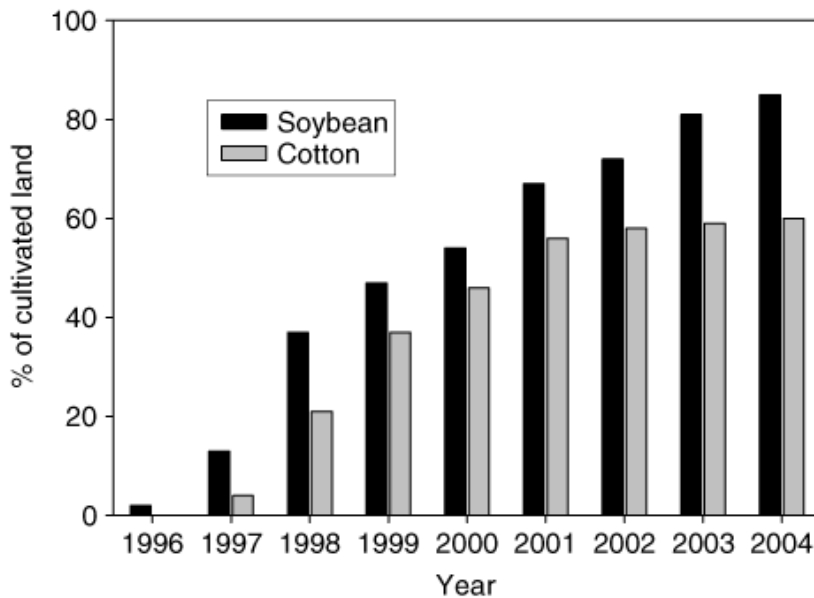


Figure 2. Adoption of glyphosate-resistant soybean and cotton in the USA by year. Source: Duke, 2005.

Herbicide efficacy as an exhaustible resource

Hueth and Regev (1974) first formulated the idea of treating pesticide efficacy as a potentially exhaustible resource. Using this approach, pest susceptibility is viewed as biological capital, a resource stock that can be managed, and pesticide application (i.e. selection for resistance) the analogy for extraction of the resource. Llewellyn *et al.* (2001) extended this exhaustible resource approach to herbicide efficacy, adapting a framework developed by Miranowski and Carlson (1986), to optimise farmer management of the herbicide resource over time. In most situations, the number of herbicide treatments (selection intensity) is approximately linearly related to the development of resistance (Pannell and Zilberman, 2001). The approach used by Llewellyn *et al.* (2001) did not take account of either externalities arising from possible mobility of resistant weeds or genes, or possible social/environmental costs arising from herbicide resistance.

The seriousness of a resource exhaustion problem depends on the likelihood of technical progress and the ease with which other factors of production can be substituted for the resource being exhausted (Solow, 1974). In this case, new herbicides can be developed, but the likelihood of development of a molecule capable of replacing glyphosate is low (Holmburg, 2004) and increasing restrictions on the registration and development of new chemicals are making herbicide R&D more costly (Ollinger and Fernandez-Cornejo, 1998; Laxminarayan, 2003b). With regard to factor substitution, Solow (1974) suggests that there is usually considerable substitutability between exhaustible resources and renewable or reproducible resources. Indeed, other herbicides and techniques can be substituted for a loss of a specific herbicide efficacy, and for example, strategies for glyphosate resistance management in no-till systems in Australia emphasise many of these (e.g. Neve *et al.*, 2003b), but they are generally associated with increased costs.

Miranowski and Carlson (1986) explored circumstances under which different organisational strategies could be implemented to manage the development of resistance. Resistance to herbicides has generally been treated in the literature as falling into the category that Miranowski and Carlson (1986, p. 444) said favoured resistance management by farmers, namely: when there is “*very low pest mobility, with the farmer ‘raising’ and ‘owning’ his pests*”; and “*substitute pesticide and cultural controls are far more costly, and competitive replacement pesticides are not forthcoming.*” This approach is reflected in current real world approaches to managing potential glyphosate resistance, with farmers being urged to take responsibility for minimising practices that will lead to resistance, and herbicide management strategies being encouraged by industry.

In situations such as this, Miranowski and Carlson (1986, p. 446) state that the “*optimal allocation of pest susceptibility over time can be achieved through farmers maximizing their long-term returns.*” They note however that public information may be needed to create awareness and knowledge by farmers of the implications of pesticide resistance development. Maximisation of farmer returns in the long term has been the focus of herbicide use studies (e.g. Pannell and Zilberman, 2001) and two recent studies have used a long term NPV approach to assess whether farmers should manage glyphosate use

preemptively or reactively in the context of developing resistance (Weersink *et al.*, 2005; Meuller *et al.*, 2005). In studies such as these, choice of the discount rate becomes important (Solow, 1974). Additionally, judgments as to whether glyphosate technology will be replaceable, and the costs associated with this or the loss of the resource, are likely to be important. For example, uncertainty exists about the speed with which the evolution of glyphosate-resistant weeds will compromise the use of glyphosate (Duke, 2005). Potential resistance mobility through the movement of pollen, seed or weeds may not be “low” in all situations.

Costs associated with the loss of glyphosate as a herbicide resource

The costs of herbicide resistance usually considered when assessing optimal farmer use of the resource are those associated with the risk of poor weed control and hence loss of crop yield potential, especially in situations where the existence of resistance is not realised; and the extra costs associated with weed control, both in situations where resistant weeds are more expensive to treat or where management to prevent resistance is more expensive, as in the “double-knock” treatment recommended to reduce the probability of the development of herbicide resistance (Diggle *et al.*, 2003). This approach is defensible when externalities (e.g. resistance mobility) are low, or potential social costs are low. In cases where mobility is high, as for insect pests, failure to recognise costs associated with externalities results in behaviour by individual agents that is myopic, and hence overuse of the resource.

The risk of herbicide resistance spread through gene flow and weed mobility has been treated in economic analyses as if it were negligible. In reality, the risk needs to be assessed on a case-by-case basis. Resistance has been shown in many cases to have evolved as multiple events, rather than by spread (Valverde and Itoh, 2001). However, there is also a likelihood of resistance mobility through the spread of seed and pollen (Rieger *et al.*, 2002; Valverde, 2003; Diggle, 2004, pers. comm.). Resistance has been shown to have spread from a single source in irrigation-based agriculture (Fischer *et al.*, 2004); and research in Australia suggests that some separate glyphosate-resistant ryegrass populations in New South Wales are likely to have occurred through seed movement (Stanton *et al.*, 2004). In the U.S., most cases of glyphosate resistance weed populations are reported in horseweed (*Conyza canadensis*), a weed whose seeds are readily dispersed by wind (Owen and Zelaya, 2005), and some resistant populations show a common inheritance of resistance mechanism (Powles and Preston, 2005).

Furthermore, a study in Western Australia shows that farmers perceive that herbicide resistance spreads through seed and pollen movement (Llewellyn and Allen, 2006). Seventy percent of surveyed farmers thought that some herbicide resistance on their farm had come from seed and pollen movement, and nearly all farmers thought that weeds on their farm would become resistant to glyphosate eventually, even if they didn’t apply any more glyphosate themselves. Perceptions such as this may result in farmers using herbicides as if there were weed mobility, and effectively having less incentive to conserve the resource themselves as they believe the benefits in doing so cannot be captured.

The question then becomes focused on how important is conservation of the herbicide resource. This will depend on the herbicide. As previously discussed, some authors consider that glyphosate is a uniquely valuable resource. Glyphosate, especially in combination with HR crop technology, makes a major contribution to world food production (Baylis, 2000; Powles, 2003). In the Americas, glyphosate is closely associated with the use of HR technology for growing soybean, canola, maize and cotton over large areas. Cost savings from growing HR crops in the USA, based on comparisons with conventional crops for costs of herbicide purchases and applications, tillage and handweeding, have been estimated to be US\$1.2 billion per year (Gianessi, 2005). The use of this technology can also significantly reduce the amount of active chemical ingredients used on crops. Gianessi (2005) estimated a reduction of herbicide active ingredient on HR crops, as compared to conventional crops, of 37.5 millions lbs per year. In Canada, where the area of RR canola increased from 10 percent of the total planted canola area in 1996 to 80 percent in 2000, Brimmer *et al.* (2005) estimated that from 1995 to 2000, the amount of herbicide active ingredient applied per hectare of canola declined by 43 percent. In Australia, it has been estimated that the probability of exceeding water run-off quality guidelines under usual cotton growing practices was very much lower when using glyphosate and RR cotton, than when using diuron and trifluralin with conventional cotton (Crossan and Kennedy, undated). The authors conclude that “*The use of glyphosate in combination with other low risk herbicides for weed control with RR cotton provides an opportunity to significantly reduce the risk of off-site herbicide contamination in Australian cotton production*” (p. 11). In developing countries where sprays are often applied without adequate safety precautions, there are direct health benefits to farmers associated with the use of glyphosate in preference to other more toxic alternatives.

Glyphosate is closely associated with the use of conservation tillage techniques (no-till and minimum till) that reduce the probability of wind and water erosion. The cost-effectiveness of glyphosate has been identified as a factor influencing the increased adoption of conservation tillage in Australia (D’Emden *et al.*, 2005), and the increased profitability of no-till in Canada (Gray *et al.*, 1996). The adoption of glyphosate-resistant crops has been a factor in the rapid conversion to minimum tillage agriculture in the U.S. (Duke, 2005). The public cost of wind and water erosion is generally poorly understood and difficult to quantify. One study in Australia estimated the most likely cost, including health effects, of dust from wind erosion caused by agricultural land use in South Australia at AUD\$23 million (Williams and Young, 1999). Costs in this study included estimates of direct market values only, and made no attempt to estimate possible non-market values. However, as noted by Mullen *et al.* (2005), lack of direct evidence about human health and environmental outcomes makes it difficult to assess the public and private benefits and costs that might be associated with policy. They caution that:

“Judging whether society is better off from changes in pest-management technologies requires a subjective balancing of estimated efficiency gains in agriculture against uncertain changes in dimensions of human and environmental health that may be positive or negative.” (pp. 571-72)

There is a further cost associated with herbicide resistance in general, relating to policies or strategies that aim to conserve the herbicide resource. Such strategies, particularly if they restrict or lessen the use of a product during the patent period, have an impact on the manufacturing industry and new product R&D (Laxminarayan, 2003b). Extrapolating from the argument put by Laxminarayan: the issue from society's perspective is to manage the herbicide resource to maximize the value to society derived from their use, and at the same time to encourage the development of new products to replace ineffective ones. The two strategies are linked, as efforts towards managing the resource discourages product development; and the development of resistance may encourage product development, resulting in more product options to achieve management of the resource. These issues have so far largely been ignored in work looking at optimal pesticide use (Alix-García and Zilberman, 2005).

Conclusions

In this paper a case has been put forward suggesting that optimal use of glyphosate by individual farmers should consider not only the direct costs and benefits to farmers, but also other possible social costs associated with the loss of glyphosate efficacy. In economic terms, "social costs" include the impact of resistance development by an individual grower spreading to another farmer through mobility, and the social costs relating to changes to less environmentally-friendly farming systems. Both no-till systems and the use of HR crops have environmental benefits, although the extent of these benefits is not easily quantifiable. The increased use of glyphosate in no-till and HR cropping systems increases the likelihood of the development of glyphosate resistance. Both these systems depend on glyphosate efficacy and have considerable economic value to farmers, and also to society through environmental benefits.

Further studies to determine actual levels of herbicide resistance mobility will help in determining the best policy approach, if any, to achieving socially optimal herbicide use. It remains to investigate models for optimal glyphosate use under different situations of weed mobility, and accounting for social costs associated with loss of glyphosate efficacy. Such analyses ideally would need to account for the effect on herbicide R&D of suggested policies to encourage optimal use from a societal perspective.

Acknowledgements

The authors gratefully acknowledge funding from the Australian Centre for International Agricultural Research for this research work carried out for ACIAR Project ASEM/2003/011 "Herbicide use strategies and weed management options in Filipino and Australian cropping".

References

- Alix-García, J. and Zilberman, D., 2005. The effect of market structure on pest resistance build-up, Working Paper, Department of Agricultural and Resource Economics, Berkeley, California, USA, 23 pp.
- Batie, S.S., 2003. The environmental impacts of genetically modified plants: challenges to decision making, *American Journal of Agricultural Economics* 85 (5): 1107-1111.

- Baylis, A.D., 2000. Why glyphosate is a global herbicide: strengths, weaknesses and prospects, *Pest Management Science* 56: 299-308.
- Brimner, T.A., Gallivan, G.J. and Stephenson, G.R., 2005. Influence of herbicide resistant canola on the environmental impact of weed management, *Pest Management Science* 61: 47-52.
- Crossan, A. and Kennedy, I., Undated. A snapshot of Roundup Ready cotton in Australia: Are there environmental benefits from the rapid adoption of Roundup Ready cotton in Australia?, The University of Sydney, NSW, 13 pp.
- D'Emden F.H. and Llewellyn R.S., 2004. No-till adoption and the weed management challenge, in Sindel, B.M. and Johnson, S.B. *Proceedings of the 14th Australian Weeds Conference. Weed Management: Balancing People, Planet, Profit*, Weed Society of New South Wales, Sydney, pp. 597-600.
- D'Emden, F.H., Llewellyn, R.S. and Burton, M.P., 2005. Adoption of conservation tillage in Australian cropping regions: an application of duration analysis, *Technological Forecasting and Social Change* (in press).
- Department of Agriculture Western Australia, various years. *Farm Budget Guide* (1983-84 to 2002-03), Department of Agriculture Western Australia, Perth, WA.
- Diggle, A.J., Neve, P.B. and Smith, F.P., 2003. Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations, *Weed Research* 43: 371-382.
- Dill, G.M., 2005. Glyphosate-resistant crops: history, status and future, *Pest Management Science* 61: 219-224.
- Duke, S.O., 2005. Taking stock of herbicide-resistant crops ten years after introduction, *Pest Management Science* 61: 211-218.
- Fischer, A.J., Moechnig, M., Hill, J.E. and Mutters, R.G., 2004. Strategic concepts for herbicide resistance in California rice, in Ferrero, A. and Vidotto, F. *Proceedings of the Conference Challenges and Opportunities for Sustainable Rice-based Production Systems*, Torino, Italy, 13-15 September 2004, pp. 69-74.
- Gianessi, L.P., 2005. Economic and herbicide use impacts of glyphosate-resistant crops, *Pest Management Science* 61: 241-245.
- Gray, R.S., Taylor, W.J. and Brown, J.S., 1996. Economic factors contributing to the adoption of reduced tillage technologies in central Saskatchewan, *Canadian Journal of Plant Science* 76: 661-668.
- Heap, I., 2005. The International Survey of Herbicide Resistant Weeds. Online. Internet. Available www.weedscience.com [Accessed 31.10.2005].
- Holmburg, M., 2004. More survivors, *Successful Farming* 102: 41-45.
- Hueth, D. and Regev, U., 1974. Optimal agricultural pest management with increasing pest resistance, *American Journal of Agricultural Economics* 56: 543-551.
- ISAAA (International Service for the Acquisition of Agri-biotech Applications), 2004. Dominant biotech crops, 2004. Online. Available http://www.isaaa.org/kc/CBTNews/press_release/briefs32/figures/dominant_crops.jpg [Accessed 18.10.2005]
- Laxminarayan, R. (Ed), 2003a. *Battling Resistance to Antibiotics and Pesticides: An Economic Approach*, Resources for the Future, Washington, D.C. 375 pp.
- Laxminarayan, R., 2003b. On the economics of resistance, in Laxminarayan, R. (Ed) *Battling Resistance to Antibiotics and Pesticides: An Economic Approach*, Resources for the Future, Washington, D.C. pp. 1-14.
- Llewellyn, R.S. and Allen, D.B., 2006. Expected mobility of herbicide resistance via weed seeds and pollen in a Western Australian cropping region, *Crop Protection* 25 (in press).
- Llewellyn, R.S., Lindner, R.K., Pannell, D.J. and Powles, S.B., 2001. Herbicide resistance and the decision to conserve the herbicide resource: review and framework, *Australian Agribusiness Review*, Vol. 9, Paper 4. Online. Available http://www.agribusiness.asn.au/10pub_rev_vol9_2001.htm

- Miranowski, J.A. and Carlson, G.A., 1986. Economic issues in public and private approaches to preserving pest susceptibility, in Board on Agriculture (Ed) *Pesticide Resistance: Strategies and Tactics for Management*, National Academy Press, Washington D.C., pp. 436-448.
- Mueller, T.C., Mitchell, P.D., Young, B.G. and Culpepper, A.S., 2005. Proactive versus reactive management of glyphosate-resistant or -tolerant weeds, *Weed Technology* (forthcoming).
- Mullen, J.D., Alston, J.M., Sumner, D.A., Kreith, M.T. and Kuminoff, N.V., 2005. The payoff to public investments in pest-management R&D: General issues and a case study emphasizing integrated pest management in California, *Review of Agricultural Economics* 27 (4): 558-573.
- Neve, P.B., Diggle, A.J., Smith F.P. and Powles, S.B., 2003a. Simulating evolution of glyphosate resistance in *Lolium rigidum* I: population biology of a rare resistance trait, *Weed Research* 43: 404-417.
- Neve, P.B., Diggle, A.J., Smith F.P. and Powles, S.B., 2003b. Simulating evolution of glyphosate resistance in *Lolium rigidum* II: past, present and future glyphosate use in Australian cropping, *Weed Research* 43: 418-427.
- Owen, M.D.K. and Zelaya, I.A., 2005. Herbicide-resistant crops and weed resistance to herbicides, *Pest Management Science* 61: 301-311.
- Pannell D.J. and Zilberman, D., 2001. Economic and sociological factors affecting growers' decision making on herbicide resistance, in Powles, S.B. and Shaner, D.L. (Eds) *Herbicide Resistance and World Grains*, CRC Press, Boca Raton, pp. 251-277.
- Powles, S.B., 2003. Will glyphosate continue to aid world food production?, *Weed Science* 51: 471.
- Powles, S.B. and Preston, C., 2005. Evolved glyphosate resistance in plants: biochemical and genetic basis of resistance, *Weed Technology* (forthcoming).
- Powles, S., Preston, C., Bryan, I. and Jutsum, A., 1997. Herbicide resistance. Impact and management, *Advances in Agronomy* 58: 57-93.
- Preston, C. Australian Glyphosate Resistance Register. National Glyphosate Sustainability Working Group. Online. Available www.weeds.crc.org.au/glyphosate [Accessed 17.10.2005]
- Puricello, E. and Tuesca, D., 2005. Weed diversity and density under glyphosate-resistant crop sequences, *Crop Protection* 24: 533-542.
- Rieger, M.A., Lamond, M., Preston, C., Powles, S.B. and Roush, R.T., 2002. Pollen-mediated movement of herbicide resistance between commercial canola fields, *Science* 296: 2386-2388.
- Roy, B.A., 2004. Rounding up the costs and benefits of herbicide use, *Proceedings of the National Academy of Sciences of the United States of America* 101: 13974-75.
- Secchi, S. and Babcock, B.A., 2003. Pest mobility, market share, and the efficacy of refuge requirements for resistance management, in Laxminarayan, R. (Ed) *Battling Resistance to Antibiotics and Pesticides: An Economic Approach*, Resources for the Future, Washington, D.C. pp. 94-116.
- Solow, R.M., 1974. The economics of resources or the resources of economics, *The American Economic Review* 64:1-14.
- Stanton, R., Storrie, A., Urwin, N. and Pratley, J., 2004. Genetic relationship between glyphosate resistant annual ryegrass (*Lolium rigidum* Gaud.) populations from northern New South Wales, in Sindel, B.M. and Johnson, S.B. *Proceedings of the 14th Australian Weeds Conference. Weed Management: Balancing People, Planet, Profit*, Weed Society of New South Wales, Sydney, pp. 445-448.
- Trigo, E., Chudnovsky, D., Cap, E. and López, A., 2003. The Adoption of Transgenic Crops in Argentine Agriculture: An Open Ended Story, International Institute for Sustainable Development, Winnipeg, Canada. Online. Available

- http://www.tradeknowledgenetwork.net/pdf/tkn_transgenic_argentina_sum.pdf [Accessed 17.10.2005]
- USDA, 2005. Adoption of genetically engineered crops in the U.S., Economic Research Service, USDA. Online. Available <http://www.ers.usda.gov/Data/BiotechCrops> [Accessed 17.10.2005]
- Valverde, B.E., 2003. Herbicide-resistance management in developing countries, in Labrada, R. (Ed) Weed management for developing countries, *FAO Plant Protection Paper No. 120 Addendum 1*, FAO, Rome, pp. 223-244.
- Valverde, B.E. and Itoh, K., 2001. World rice and herbicide resistance, in Powles, S.B. and Shaner, D.L. (Eds) *Herbicide Resistance and World Grains*, CRC Press, Boca Raton, pp. 195-249.
- Weersink, A., Llewellyn, R.S. and Pannell D.J., 2005. Economics of pre-emptive management to avoid weed resistance to glyphosate in Australia, *Crop Protection* 24: 659-665.
- Williams, P. and Young, M., 1999. Costing dust: How much does wind erosion cost the people of South Australia?, Policy and Research Unit, CSIRO Land and Water. Online. Available http://www.clw.csiro.au/publications/consultancy/1999/costing_dust.pdf [Accessed 15.08.2005].