Impact of herbicide resistant crops in North America – a northern perspective

Micheal D.K. Owen and Ian A. Zelaya
2104 Agronomy Hall, Ames, IA 50011, USA

Summary A number of questions must be considered when the impact of herbicide resistant crops (HRCs) on agriculture in the North America is considered. Given the number of different HR crops that either have been, or soon will be introduced, each agroecosystem must be considered separately. The general questions include whether or not the HR crop is economically acceptable, compared to non-HR crop. Furthermore, the importance of herbicide resistant weed populations, either through evolution or introgression of the HR trait from the crop, must be considered. Lastly, the socio-economic implications of HRCs must be assessed. Weed scientists have expended significant effort in researching two of these questions. The inevitability of HR weed populations is obvious. Furthermore, while difficult to quantify, the societal implications of HRCs seem to suggest that there is not universal acceptance of the technology. Regardless, HRCs are favoured by growers, particularly maize and soybean, despite the real or perceived problems. The authors submit that the issues of HR weed populations and weed community shifts are not economically important in many HRCs.

Keywords Herbicide resistant crops, herbicide resistant weeds, socio-economic implications, introgression, resistance evolution, maize, soybean.

INTRODUCTION

While herbicide resistant (HR) weeds have been reported for three decades, the evolution of HR weed populations has increased due, in part, to the adoption of HRCs (Zelaya and Owen 2000). The evolution of the HR population may result from the introgression of the HR trait from the crop, if there is genetic compatibility in the weed population, or by increased selection pressure attributable to the elimination of alternative tactics (Massinga and Al-Khatib 2002, Van Gessel 2001). It is largely accepted that HR weeds have a negative impact on agriculture (Volenberg *et al.* 2001). Despite the obvious relationship between HRCs and HR weeds, there has been widespread adoption of the technology. HRCs are being accepted by growers in many of the major grain agroecosystems. Furthermore, the adoption of HRCs has occurred without general societal acceptance (Owen 2000). It is the intent of this manuscript to objectively address the obvious disconnect that has occurred with HRCs and HR weeds.

DISCUSSION

Effort expended by weed scientists A survey of recent activity relating to either HRCs or HR weeds reveals the extent of the scientific effort expended to gain an understanding these apparently important changes in agriculture. The authors tabulated the articles that addressed either HRCs or HR weeds published in 2001 represented 16%, 25% and 22% in *Weed Science*, *Weed Technology*, and *Weed Research* respectively. At the 2001 North Central Weed Science Society annual meeting, 16% of the papers presented, and 21% at the 2002 Weed Science Society of America, addressed these topics. Furthermore, there have been numerous books, book chapters, and symposia on HRCs and HR weeds. Clearly, the weed science community feels that these are significant issues. However, the authors are not aware of any effective economic risk assessment HR weed populations (Owen 2001).

While most scientists agree that HRCs have caused a significant change in production systems, other than the fact that growers are adopting the technology, the actual impact, either economic or environmental is not generally understood (Duffy 2001a). It is interesting that much of the published research for HRCs, particularly for maize (*Zea mays*) and soybean (*Glycine max*), involves efficacy evaluations of herbicides other than the HR-targeted active ingredient. Also, much of the HR weed research is descriptive and typically suggest that ‘knowledge about HR weeds will improve management tactics to avoid the evolution of HR weed populations’, but without providing any specific details.

Acceptance of HRCs A number of crops have been genetically modified, either by ‘traditional’ or by ‘biotechnological’ techniques (Burnside 1996). Several crops (e.g. sugar beets (*Beta vulgaris*) and wheat (*Triticum aestivum*) have HR cultivars that are recently or soon to be introduced for commercial sales and assessment of adoption is not possible. In the southern regions of North America, HR rice (*Oryza sativa*) and HR cotton (*Gossypium hirsutum*) have been widely accepted by growers but a detailed discussion about these crops is not in the scope of this paper.

Maize, soybean and canola (*Brassica napus*) have been widely adopted in the northern regions of North America. Clayton *et al.* (2002) report that an estimated

80% of the canola in Alberta, Canada was HRC. The target herbicides for the HR canola were glufosinate, glyphosate, and imidazolinone herbicides; glyphosate-resistant cultivars was estimated to account for 50% of the HR canola grown in western Canada. HR soybeans are widely planted in North America (Table 1) and represents an incredible success for biotechnology (Owen 2000). Interestingly, HR maize has not met with the same success, in part due to regulatory issues and market acceptance (Miranowksi *et al.* 1999).

An estimated 1000 soybean varieties were available with resistance to glyphosate in 1999 (Lawton 1999). Undoubtedly, many more varieties are now available. Grower acceptance has been driven largely by the simplicity of the 'system' and the aesthetics of the resultant weed control. To date, glufosinate-resistant soybean varieties have not been commercialised.

Maize hybrids that are resistant to glyphosate, glufosinate or imidazolinone herbicides are available commercially. Not all HR maize is certified for human consumption and many hybrids contain other transgenic events such as the gene for *Bacillus thuringiensis* (Bt) toxin. The inability to segregate grain and the lack of registrations resulted in significant economic and political issues as demonstrated by the StarLink contamination of maize in Iowa during 2000 (Fehr 2001). Problems such as this has slowed the acceptance of HR maize and created issues with major markets such as Japan and the European Union (EU) (Miranowski *et al.* 1999)

Economic and environmental concerns with HRCs
A review of current economic assessments of HRCs suggests that there is not a clear consensus opinion for the technology. Duffy (2001a, 2001b) compared the economic returns for 172 soybean and 174 maize fields and found no significant difference between conventional crops and HRCs for return on investment. He suggested that only the seed and herbicide companies gained economically from HRCs. However, there were several non-quantifiable benefits and costs associated with HRCs. Miranowksi *et al*. (1999) suggested a number of economic issues faced the adoption of HRCs including the inability to segregate non-HRC grain from HRC grain, increased demand by processors for non-HRC grain, uncertain markets, and legal requirements.

Hillger *et al.* (2002) found that choice of specific hybrid had more impact on economics than whether or not the hybrid had HR traits. Differences were found comparing glyphosate-resistant and non-resistant soybeans depending on the specific location; HR soybeans were more profitable at Brooksville, MS while at Shelby, MS, non-resistant soybeans were more profitable (Shaw *et al.* 2001). An economic analysis on returns provided by weed management systems in soybeans indicated that the gross returns on investment was impacted by the weed community and the risk variability associated with the number of tactics used in the system (Hoverstad *et al.* 2002).

Table 1. Estimated hectares planted to glyphosate-resistant soybean and maize, 2001 (adapted from Doane Market Research).

State	Soybean (%)	Corn (%)
Illinois	64	1
Indiana	77	3
Iowa	73	4
Michigan	66	8
Minnesota	67	7
Missouri	81	6
Nebraska	80	7
Ohio	65	4
South Dakota	84	23
Wisconsin	69	5

Sugarbeet yields were higher for HRCs when glyphosate was applied three times versus two times despite no difference in weed control (Kniss *et al*. 2001). Wilson *et al*. (2002) reported the HR sugarbeet treated with the glyphosate had 15% greater sucrose yield when compared to alternative herbicides.

In HR wheat (imidazolinone resistant cultivars), economic benefits were expressed in higher yields and less weed seed contamination (Gaffney *et al*. 2001). Control of downy brome (*Bromus tectorum*), jointed goatgrass (*Aegilops cylindrica*) and feral rye (*Secale cereale*) was excellent in imidazolinone-resistant wheat (Stahlman *et al*. 2001, Miller and Alford 2001). Feral rye infestations in wheat causes an annual economic loss of $10 million in Colorado, USA, alone (Miller and Alford 2001).

William *et al*. (2001) likened the controversies, environmentally, socially, and ethically facing HRCs to the public perceptions about pesticide use. They suggested that scientists were making the same 'mistakes' with HRCs that were made when research was conducted with pesticides, and as a result, the public was unlikely to accept the results of the science. However, Fawcett (2002) cited numerous environmental and economic benefits attributable to HRCs. Improved human health, reduced pesticide use, cleaner aquatic ecosystems and lower weed management costs were all due to HRC adoption.

Gene flow from HRCs The movement of HR traits through pollen has been an issue for the adoption of HRCs. It has been demonstrated that resistance to acetolactate synthase (ALS) (EC 4.1.3.18) inhibitor herbicides can be disseminated via pollen in common sunflowers (Marshall *et al*. 2001). Furthermore, *Amaranthus* species are able to hybridise, and ALS resistance will move in the pollen thus contributing to the spread of HR weed populations (Franssen *et al.* 2001). Most weed scientists agree that the transfer of HR traits to weed populations is a problem only if the crop and weed are genetically compatible. This represents a potential problem for wheat (imidazolinone resistant and glyphosate resistant cultivar) and jointed goatgrass.

The gene transfer via pollen has been demonstrated in canola to wild radish (Simard and Legere 2002, Rieger *et al.* 2002) and between rice and red rice (*Oryza sativa*) (Dillon *et al.* 2002). Wild mustard (*Brassica* species) and wild radish are serious problems in canola production and in the latter situation, red rice is described as a devastating economic problem in rice production. Thus, the movement of HR traits to weed populations is clearly a critical issue.

However, another issue related to gene transfer of HR traits relates to corn, where introgression of the trait to related weedy species is not possible. Pollen trespass from HR corn to non-HR corn has evolved as significant economic and environmental issue. For example, in Iowa there is much concern about HR corn pollen contaminating corn grown for human consumption and also organic production is threatened by HR pollen drift (Fehr 2001). The ability to detect the HR trait in grain is quite high, and thus many producers expect an unrealistic zero contamination tolerance. HR corn pollen contamination also threatens seed corn. The HR pollen trespass can also occur as volunteer corn in soybeans. Given the adoption of glyphosate-resistant soybeans, volunteer glyphosate-resistant corn, the result of pollen trespass, has been an issue Iowa (Owen, personal observation).

Weed shifts and HR weeds due to HRCs The evolution of HR weeds has increased in frequency in recent years (Heap 2002). This is attributable to the minimal use of alternative strategies, frequency of applications of herbicides with a specific mechanism of action, and to some degree, the adoption of HRCs. New reports of HR weeds includes common waterhemp (*Amaranthus rudis*) resistance to protoporphyrinogen oxidase inhibiting herbicides (Shoup *et al*. 2002), kochia (*Kochia scoparia*) resistance to dicamba (Cranston *et al.* 2001), annual bluegrass (*Poa annua*) resistance to dinitroaniline herbicides (Isgrigg *et al.* 2002), and giant foxtail (*Setaria faberi*) (Volenberg *et al.* 2001 and shattercane (*Sorghum bicolor*) (Brenly-Bultemeier *et al.* 2001) cross-resistance to ALS inhibitors. The evolution of these HR weed populations is not related to the adoption of HRCs. However, there are clear relationships between the evolution of some HR weed populations and HRCs.

The evolution of glyphosate-resistant horseweed (*Conyza canadensis*) (Van Gessel 2001), creeping bentgrass (*Agrostis stolonifera*) (Loux and Harrison 2002), and common water (Zelaya and Owen 2000) is directly attributable to the adoption of glyphosate-resistant crops and the concomitant use of glyphosate as the primary, if not sole herbicide for weed management. Weeds that have a higher tolerance to glyphosate such as pitted morningglory (*Ipomea lacunose*) are also more prevalent in glyphosate-resistant crops (Norsworthy *et al*. 2001).

Another consideration is the shift in weed communities that have been reported in HRCs. Wicks *et al.* (2001) report significant changes in weed communities attributable to glyphosate-resistant crops. The diversity of the weed community is significantly impacted by the herbicide tactic that is used in the HRC, but also varies with latitude (Scursoni *et al*. 2001). Weed community shifts can occur as a result of natural tolerance to the herbicide used in the HRC, or through an avoidance strategy related to weed emergence timing (Hilgenfeld *et al*. 2001).

The diversity of the weed community increased where one application of glyphosate was used but declined significantly where two applications were used. It is possible that by manipulating the application tactics, either a weed population shift or the evolution of HR weeds can occur.

Stoltenberg (2001) suggests that HRC-based production systems have not greater risk for a weed community shift than conventional production systems. Owen (2002) suggests that the changes attributable to herbicide use and HRCs are inevitable, but are not likely as important in HR maize and soybean systems as in HRCs where alternative herbicides or weed management strategies are less.

CONCLUSIONS

It is apparent the impact of HRCs is different in different agroecosystems and with different HRCs. In situations where the HRC and associated weed populations are genetically compatible, the HR trait is likely to introgress and resultant HR weed population will represent a serious economic problem for growers. However in maize and soybean, the gene flow to weeds does not represent and issue. Weed populations shifts and the evolution of HR weeds are inevitable, but likely less of an economic issue given the alternative tactics and herbicides that are available to maize and soybean producers. An issue of significance is pollen trespass which facilitates gene flow and HR trait transfer into non-HR crops. Furthermore, a serious socio-economic problem exists with regard to the acceptance of HRCs in the world market.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support of Syngenta Crop Protection in the development of this manuscript.

REFERENCES

Brenly-Bultemeier, T.L., Stachler, J.M. and Harrison, S.K. (2001). Cross-resistance and dose response of shattercane to ALS-herbicides. Proc. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent.Weed Sci. Soc., Champaign, IL (Dec. 2001).

Burnside, O.C. (1996). An agriculturalist's viewpoint of risks and benefits of herbicide-resistant cultivars. *In* 'Herbicide resistant crops: Agricultural, environmental, economic, regulatory, and technical aspects', ed. Duke, S.O., pp. 391-340. (Lewis Publishers, Boca Raton).

Clayton, G.W., Harker, K.N., O'Donovan, J.T., Baig, M.N. and Kidnie, M.J. (2002). Glyphosate timing and tillage system effects on glyphosate-resistant canola (*Brassica napus*). *Weed Technology* 16, 124-130.

Cranston, H.J., Kern, A.J., Hackett, J.L., Miller, E.K., Maxwell, B.D. and Dyer, W.E. (2001). Dicamba resistance in kochia. *Weed Science* 49, 164-170.

Dillon, T.L., Bladwin, F.L., Talbert, R.E., Estroninos, L. and Gealy, D.R. (2002). Gene flow from Clearfield rice to red rice. Proc. WSSA 42, 35.

Duffy, M. (2001a). Who benefits from biotechnology? www.ag.iastate.edu/centers/leopold/pubinfo/papersspeeches/biothech.html.

Duffy, M. (2001b). Study shows no economic advantage for Iowa farmers to plant GMO crops. www.ag.iastate.edu/centers/leopold/newsletter/2001-4leoletter/gmo.html.

Fawcett, R.S. (2002). Environmental benefits of transgenic crops. Proc. WSSA 42, 91.

Fehr, W.R. (2001). Strategies for the coexistence of GMO, non-GMO, and organic crop production. www.biotech.iastate.edu/publications/IFAFS/Walt_coexisence.html.

Franssen, A.S., Skinner, D.Z., Al-Khatib, K., Horak, M.J. and Kulakow, P.A. (2001). Interspecific hybridization and gene flow of ALS resistance in *Amaranthus* species. *Weed Science* 49, 598-606.

Gaffney, J.F., Carlson, K.L., Boyles, M.C., Kahlke, B.J., Ogg, P.J. and Fellows, G.M. (2001). Imidazolinone resistant production system – imazamox herbicide for winter wheat. Proc. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent. Weed Sci. Soc., Champaign, IL (Dec. 2001).

Heap, I.M. (2002). The worlds worst herbicide-resistant weeds. Proc. WSSA 42, 64.

Hilgenfeld, K.L., Martin, A.R., Mason, S.C. and Mortensen, D.A. (2001). Mechanisms involved in weed species shifts in a glyphosate tolerant system. Proc. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent.Weed Sci. Soc., Champaign, IL (Dec. 2001).

Hillger, D.E., Bauman, T.T. and White, M.D. (2002). Economic comparison of herbicide resistant corn technologies. *Proc. WSSA* 42, 1.

Hoverstad, T.R., Gunsolus, J.L., King, R.P. and Johnson, G.A. (2002). Risk analysis of soybean weed management systems over time and environment. Proc. WSSA 42, 75.

Isgrigg III, J., Yelverton, F.H., Brownie, C. and Warren Jr., L.S. (2002). Dinitroaniline resistant annual bluegrass in North Carolina. *Weed Science* 50, 86-90.

Kniss, A.R., Wilson, R.G., Feuz, D.M., Burgener, P.A. and Martin, A.R. (2001). Glyphosate resistant sugarbeet: weed control, economics, and environmental impacts. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent. Weed Sci. Soc., Champaign, IL. (Dec. 2001).

Lawton, K. (1999). Roundup of a market. *Farm Industry News*, February, pp. 4-8.

Loux, M.M. and Harrison, S.K. (2002). Survival of glyphosate-tolerant creeping bentgrass in glyphosate-tolerant corn and soybean. Proc. WSSA 42, 19.

Marshall, M.W., Al-Khatib, K. and Loughin, T. (2001). Gene flow, growth, and competitiveness of imazethapyr-resistant common sunflower. *Weed Science* 49, 14-21.

Massinga, R.A. and Al-Khatib, K. (2002). Gene flow of imidazolinone resistance from cultivated sunflower (*Helianthus annuus*) and prairie sunflower (*H. petiolaris*). Proc. WSSA 42, 21.

Miller, S.D. and Alford, C.M. (2001). Feral rye control in imi-tolerant winter wheat. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent. Weed Sci. Soc., Champaign, IL. (Dec. 2001).

Miranowksi, J.A., Giancarlo, M., Babcock, B., Duffy, M., Wisner, R., Beghin, J., Hayes, D., Lence, S., Baumel, C.P. and Harl, N.E. (1999). Economic perspectives on GMO market segregation. Staff Paper No. 298. Iowa State University. 15 p.

Norsworthy, J.K., Burgos, N.R. and Oliver, L.R. (2001). Differences in weed tolerance to glyphosate involve different mechanisms. *Weed Technology* 15, 725-731.

Owen, M.D.K. (2000). Current use of transgenic herbicide-resistant soybean and corn in the USA. *Crop Protection* 19, 765-771.

Owen, M.D.K. (2001). World maize/soybean and herbicide resistance. *In* 'Herbicide resistance and World grains', eds Powles, S.B. and Shaner, D.L., pp. 101-163. (CRC Press, Boca Raton).

Owen, M.D. (2002). Weed population shifts may not represent a problem. Proc. WSSA 42, 63.

Rieger, M.A., Potter, T.D., Preston, C. and Powles, S.B. (2002). Gene movement between *Raphanus raphanistrum* L. and *Brassic napus* L. under Australian farming conditions. Proc. WSSA 42, 39.

Scursoni, J. Peterson, D., Forcella, F., Gunsolus, J., Arnold, R.B., Owen, M., Smeda, R., Oliver, R. and Vidrine, R. (2001). Weed diversity in glyphosate-tolerant soybean from Minnesota to Lousiana. Proc. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent.Weed Sci. Soc., Champaign, IL (Dec. 2001).

Shaw, D.R., Arnold, J.C., Snipes, C.E., Laughlin, D.H. and Mills, J.A. (2001). Comparison of glyphosate-resistant and nontransgenic soybean (*Glycine max*) herbicide systems. *Weed Technology* 15, 676-685.

Shoup, D.E., Al-Khatib, K. and Peterson, D.E. (2002). Common waterhemp (*Amaranthus rudis*) resistance to protoporphyrinogen oxidase (PPO) inhibiting herbicides. Proc. WSSA 42, 28.

Simard, M. and Legere, A. (2002). Synchrony of flowering between canola (*Brassica napus*) and wild radish (*Raphanus raphanistrum*). Proc. WSSA 42, 18.

Stahlman, P.W., Geier, P.W. and Price, T.M. (2001). Winter annual grass control and response of imidazolinone-resistant winter wheat to imazamox. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent. Weed Sci. Soc., Champaign, IL. (Dec. 2001).

Van Gessel, M.J. (2001). Glyphosate-resistant horseweed from Delaware. *Weed Science* 49, 703-5.

Volenberg, D.S., Stoltenberg, D.E. and Boerboom, C.M. (2001). Biochemical mechanism and inheritance of cross-resistance of acetolactate synthase inhibitors in giant foxtail. *Weed Science* 49, 635-641.

Wicks, G.A., Stahlman, P.W., Tichota, J.M. and Price, T.M. (2001). Weed shifts in no-till glyphosate-tolerant crops in semiarid areas of the great plains. Proc. North Cent. Weed Sci. Soc. Abstr. 56. [CD-ROM Computer File]. North Cent.Weed Sci. Soc., Champaign, IL (Dec. 2001).

William, R.D., Ogg, A. and Raab, C. (2001). My view. *Weed Science* 49, 149.

Wilson, R.G., Yonts, C.D. and Smith, J.A. (2002). Influence of glyphosate and glufosinate on weed control and sugarbeet (*Beta vulgaris*) yield in herbicide-tolerant sugarbeet. *Weed Technology* 16, 66-73.

Zelaya, I.A. and Owen, M.D.K. (2000). Differential response of common waterhemp (*Amaranthus rudis*) to glyphosate in Iowa. Proc. WSSA 40, 62.