Biosafety Briefing
August 2008

TWN
Third World Network
www.twnside.org.sg

Special threats to the agroecosystem from the combination of genetically modified crops & glyphosate

By **Jack A. Heinemann and Brigitta Kurenbach**
Centre for Integrated Research in Biosafety and School of Biological Sciences,
University of Canterbury, Christchurch,
New Zealand

Weeds are an important problem in agriculture. The annual cost of weeds has been estimated at US$20 billion in the USA (reported in Basu et al., 2004) and A$3-4 billion in Australia (Sinden et al., 2004). Generally, these costs are incurred by both loss of crop because of the direct influence of weeds and the cost of weed control. In Korea, 5-10% of rice yield is lost to weedy rice (Chen et al., 2004). 'Volunteer wheat and barley, at 7 to 8 plants/m^2 (6 to 7/yd^2) can reduce canola yield by 10 to 13%' (Canola Council, 2007). The DuPont company estimates that without some form of weed control 'the average crop losses for U.S. corn, soybean and cotton growers would be approximately 65%, 74% and 94%, respectively' (DuPont, 2008).

Herbicides are used for weed-control by many kinds of farmers as well as by those who control roadside and urban weeds. The herbicides that are most frequently used include the active ingredient called glyphosate.

All herbicides have their environmental and human health costs and glyphosate-based formulations are no exceptions (e.g. see research by Kremer et al., 2005, Larson et al., 2006, Relyea, 2005, Richard et al., 2005). In this article we will not address the human health or non-target effects of glyphosate or its commercial formulations *per se*. Precisely the 'question that must be addressed is whether or not the most recent major change in agroecosystems, the adoption of herbicide-

TWN THIRD WORLD NETWORK is a network of groups and individuals involved in bringing about a greater articulation of the needs, aspirations and rights of the people in the Third World and in promoting a fair distribution of world resources and forms of development which are humane and are in harmony with nature.

Address: 131, Jalan Macalister, 10400, Penang, MALAYSIA **Tel**: 60-4-2266728/2266159 **Fax**: 60-4-2264505
E-mail: twnet@po.jaring.my **Website**: www.twnside.org.sg

resistant [genetically modified, or GM] crops, represents a different risk than previous changes' (Owen and Zelaya, 2005: p302) in agroecosystems. We will argue that whatever you may feel about glyphosate, it is a tool being lost to the farmers that choose to use it because of the use of GM herbicide-tolerant crops. These 'conventional' farmers and their land are the majority and their tool is being threatened by the practice of a small minority of GM farmers.

Glyphosate's current prominence is linked to the adoption of GM crops that endure otherwise lethal levels of the commercial formulations (Service, 2007). This is referred to as herbicide tolerance (HT) or resistance, a concept defined by the particular concentration of chemical that different plants can withstand. 'The results of this unprecedented change in agriculture have been many, but perhaps most dramatic is the simplification of weed-control tactics; growers can now apply a single herbicide (glyphosate) at elevated rates of active ingredient and at multiple times during the growing season without concern for injury to the crop' (Owen and Zelaya, 2005: p301). For example, 'the use of tank mixtures and sequential applications of more than one herbicide has declined as many growers have elected to rely exclusively on glyphosate for weed control in soybean, which may increase the risk of selecting for glyphosate-resistant weeds. The number of active ingredients used on at least 10% of the treated soybean hectares has declined from 11 in 1995 to only one (glyphosate) in 2002' (Young, 2006: p302).

Like other herbicides, there is a price to pay for using commercial formulations of glyphosate. Glyphosate formulations can have non-target effects. That is, they either can be toxic to non-target animals (e.g. see Relyea, 2005, Relyea et al., 2005, but also challenge by Thompson et al., 2005) and tissues (e.g. Richard et al., 2005), or inhibit non-target enzymes resulting in other unintended effects. An example of the latter is inhibition of ferric reductase resulting in iron deficiencies in some cropping systems (Ozturk et al., 2008). Although glyphosate is claimed to have a lower toxicity to humans than many other alternative herbicides (Alan, 2000), these claims may be oversimplifications of the true impact of glyphosate-based commercial formulations which rely on a number of other chemicals that can be toxic (Richard et al., 2005).

However, the combination of glyphosate's effectiveness on a broad range of plants, and the fact that it is now 'off-patent' make it a convenient and ever-more affordable option (Service, 2007). Accepting that there are downsides of glyphosate (See box "Have GM crops reduced herbicide use?"), it does remain an option for some kinds of farmers that use conventional crops and may have advantages over other herbicides in some contexts.

Whatever the final verdict is on the benefits and harms of glyphosate-based herbicides, and the use of this and other herbicides as a distraction from efforts to develop a more environmentally sustainable form of agriculture (e.g. Badgley et al., 2007, Mancini et al., 2008), in the meantime glyphosate is being used - and in unprecedented amounts - primarily because of GM crops. The amounts and the patterns of glyphosate use made possible by these crops are driving the evolution of glyphosate resistance among weeds (Powles, 2008) and in turn driving up glyphosate use (Young, 2006). That is, as a special result of using HT GM crops, responsible conventional farmers are losing one of their tools.

Importantly, the use of glyphosate for about 20 years before the introduction of glyphosate-tolerant crops did not result in many reports of glyphosate-tolerant weed populations. But its use in the last 10 years has (Powles, 2008, Service, 2007).

Glyphosate use has changed with GM HT cropping

Glyphosate is primarily used as a 'burndown' agent with conventional crops. It is usually applied early in the season before planting or after harvest to purge weeds, or between rows in perennial crops, and it is also used outside of agriculture to control weeds in urban and industrial areas (Powles, 2008, Reddy, 2001). In these applications, glyphosate still has a significant role to play, at least until the world finds a way to feed itself without using herbicides.

While resistance had arisen before the introduction of HT crops, burndown did not create large resistance problems, presumably because this pattern of usage neither exposed as many weeds to glyphosate nor did it stifle a diversity of companion techniques for controlling weeds, such as the use of biocontrol, hand-weeding or rotations with other herbicides, reducing the selection for resistance to any particular herbicide (Graef et al., 2007, Powles, 2008). Resistance arising in burndown applications was most likely to be observed where the use of glyphosate was intensive and usually resulted in replacing other weed-control strategies (Powles, 2008). The most extreme use of glyphosate in conventional applications has become the routine usage in GM cropping. As Zelaya et al. (2007: p669) observed: 'Glyphosate-resistant crop systems are suggested to be simple and without great environmental consequences. However…there are major ecological and economic consequences from these presumed simple systems.'

With the introduction of GM glyphosate-tolerant crops the herbicide can be used throughout the cropping year and at higher concentrations (Owen and Zelaya, 2005, Powles, 2008, Young,

Have GM crops reduced herbicide use?

A consuming debate centres on the claim that overall pesticide use has been reduced in the agricultural systems that have adopted GM crops. GM crops that produce their own insecticide appear to modestly reduce the amount of **other kinds of** insecticides that were previously applied, at least until resistance or secondary pests might emerge and reverse this trend (Pretty, 2001). However, on a weight or volume basis, the amount of herbicide used may have dramatically increased in the USA (FOE, 2008, Pretty, 2001). In contrast, Cerderia and Duke cite research that calculates a net replacement of 3.27 million kg of other herbicides with only 2.45 million kg of glyphosate in USA soybean fields, and other research showing a net 17 million kg reduction across all relevant crops in the USA because of GM crops (Cerdeira and Duke, 2006).

Volume and weight comparisons have their value, but also their limitations. An increase in the weight or volume of glyphosate over some replaced herbicides, such as carfentrazone-ethyl, would be expected in any case because the glyphosate formulations can be 100 times the volume of these alternative herbicides (Cerdeira and Duke, 2006). Thus, glyphosate arguably could increase the volume of herbicide use by about a factor of 100 before more herbicide were actually being used, provided that the glyphosate was replacing these kinds of alternative herbicides.

In the analysis of this paper, the key point is that it is the absolute amount of glyphosate being used, the pattern of its application, and the effective loss of herbicide and alternative weed management diversity that cause the environmental harms, rather than a debate about whether there is more or less herbicide use in general, and the comparative environmental and human health effects of various herbicides.

2006). The amounts of glyphosate usage in the US have increased by 15-fold since 1994, with the period of 1994-2002 being the largest increase in both glyphosate use and herbicide-tolerant crops (FOE, 2008, Young, 2006). Large increases in glyphosate use are also reported in Argentina, one of the four largest GM-crop-producing countries (Pengue, 2005). There especially its potency and spectrum of activity lends it to recruiting what was previously marginal land for large-scale agriculture using herbicide-tolerant GM crops (Pengue, 2005). While these lands may be marginal for agriculture, they are nonetheless important for supplying ecosystem services (GEO-4, 2007). Finally, the use of glyphosate has reduced the diversity of chemical agents used for weed control and this significantly contributes to the selection of glyphosate-tolerant weeds (Powles, 2008, Young, 2006).

Since both crops and some weeds are glyphosate-tolerant, and not fully resistant (despite sometimes being called herbicide resistant), applying more glyphosate can for a while control the weeds (Pengue, 2005, Young, 2006). However, this strategy creates a cycle whereby using even more glyphosate reinforces the evolutionary drive in weeds to achieve ever-higher levels of tolerance, and exposes larger potential weed populations to the herbicide.

Coupled with the large increase in acreage in GM crops and the concentration of this acreage into effectively only four countries (Reddy, 2001, UNEP, 2003), even a rare mutant weed could establish a population of offspring that would persist under the umbrella of repetitive glyphosate applications. Amplification would be fast because each season more glyphosate-tolerant weed seeds would be added to the soil bank. Resistance can spread by weeds hitchhiking on machinery and along with agricultural products that are now globally distributed.

Resistance to glyphosate is a real problem, but the news might get even worse. Herbicides for plants are analogous to antibiotics for bacteria (Service, 2007). Herbicides, like antibiotics, reward resistance by removing susceptible competitors. Many antibiotics work by inhibiting an essential enzymatic activity. Glyphosate does so as well; it inhibits the essential plant enzyme called EPSPS (5-enolpyruvyl-shikimate-3-phosphate synthase), which is required to synthesise certain essential components of proteins. Also like antibiotics, the biochemistry of resistance may simultaneously create resistance to more than one toxic chemical, what is called MDR for multiple drug resistance in the case of antibiotics (Heinemann, 1999). MDR arises when special pumps in the surface of cells selectively remove the toxic chemical and thus prevent it from reaching a lethal concentration inside the cell, wherein the enzyme it targets resides (Heinemann, 1999). MDR pumps are usually mutant versions of already-existing pumps that selectively transport a number of different chemicals. Changes in their substrate range can cause them to recognise several new compounds at once, even if those compounds do not share the same general chemical properties. In this way, the use of one toxin, say glyphosate, could select for weeds resistant to glyphosate and possibly other herbicides all at the same time. While this mechanism of resistance has not been confirmed in *Sorghum halepense* arising in Argentina, for example, it has been suggested as a particularly troubling possibility by government advisers (Valverde and Gressel, 2006).

Weed-shifts and resistance

A high level of glyphosate-tolerance is intrinsic in some plants making them naturally adapted to cropland in which glyphosate is used. Weeds might have other characteristics that adapt them to glyphosate-dominated agroecosystems even if they are susceptible to glyphosate, for example, weeds that can germinate and seed between applications. Given enough time and use, those plants that are adapted to the use of glyphosate by whatever means can move into the agroecosystem, displacing the glyphosate-susceptible weeds that may have previously kept them out. The technical term for this kind of event is a 'weed-shift' (Owen and Zelaya, 2005).

Resistance can also arise through mutation or gene flow, as has happened for example in Canadian canola crops (Heinemann, 2007). For example, HT Canadian canola affects multiple crops because canola volunteers are one of Canada's most serious weeds (Hall et al., 2000). Maize and soybean are weeds in any rotation cropping with one another, and in cotton (Owen and Zelaya, 2005, Reddy, 2001). Volunteers can normally be controlled with other herbicides, but gene flow can create plants simultaneously resistant to several herbicides (Heinemann, 2007). In addition, using other herbicides to control HT volunteers increases the use of these herbicides and thus undermines the claim that glyphosate sustainably replaces other herbicides.

The range and types of resistant weeds are important to note, because they are some of the most important and costly to the cropping systems dominated by GM crops, namely cotton, corn and soybean. Resistant forms of *Sorghum halepense* (or Johnsongrass) are reported in both Argentina (Valverde and Gressel, 2006) and the United States (Monsanto, 2008). Resistant *Ambrosia artemissifolia* and *Ambrosia trifida* (common and giant ragweed, respectively), *Amaranthus palmeri*, *Amaranthus rudis* and *Amaranthus tuberculatus* (waterhemp) have emerged in the US (Powles, 2008). *Lolium spp* (ryegrass) resistance is reported in the US and Australia (Owen and Zelaya, 2005, Powles, 2008). Resistant populations of *Euphorbia heterophylla* are now found in Brazil (Behrens, 2007, Powles, 2008) and populations of *Conyza canadensis* (horseweed) in both Brazil and China (Powles, 2008, Zelaya et al., 2007).

Is genetic engineering a pro-poor technology?

The implications of resistance eat away at both claims for long-term benefits from using these kinds of GM crops and indicate that farmers who use glyphosate are the losers, even if they do not use GM crops. First, the claim of net environmental benefit from substituting glyphosate for more toxic or persistent herbicides is unsustainable because glyphosate failure results in the re-introduction of such herbicides (Pengue, 2005). While new herbicides might also become available (Behrens, 2007), these may not completely substitute for glyphosate and, in the meantime, there are fewer options because alternative herbicides have been driven out of the market (Service, 2007). Second, the claim that glyphosate encourages conservation (or no-) till agriculture (Cerdeira et al., 2007, Raney and Pingali, 2007) is lost as farmers return to tilling to control herbicide-resistant weeds (Valverde and Gressel, 2006). The combination of converting marginal land to glyphosate-controlled crop production and subsequent use of tilling could significantly increase the negative effects of erosion.

With the price of glyphosate herbicides falling (Service, 2007), the utility of this herbicide should be more easily captured by poor farmers, and allow the herbicide to be used in urban settings where other herbicides might be less desirable. However, as resistance spreads, these comparative advantages will be lost. Adoption of other GM crops with tolerance for different herbicides, for example glufosinate or dicamba (Behrens, 2007, Service, 2007), is not an obvious solution to the problem so long as herbicide application patterns remain the same for these GM crops.

It is possible that stacked plants, with tolerance for more than one kind of herbicide simultaneously, might delay the development of resistance because each herbicide could be used in rotation. This again is not a solution and it potentially introduces a bigger risk because gene flow from these crops will accelerate the development of weeds and volunteers resistant to multiple herbicides.

There is great stress on the planet to produce enough food for everyone now and in a sustainable way for future generations; and great stress on nations to maintain indefinitely the capacity to continue to produce nutritious and satisfying food (IAASTD, in press). Current strategies for agriculture were recently criticized in an international review of unprecedented scale (IAASTD, in press). Among the most severe criticisms were reserved for the use of private sector incentives to produce agricultural technologies that were of benefit to the poor and the planet. In the last couple of decades, genetic engineering has been the focus of a large proportion of private sector modern biotechnology (Atkinson et al., 2003, Kennedy, 2003, UNDP, 1999, WHO, 2005). This just does not work to empower the poor and subsistence farmer (IAASTD, in press). As the World Bank recently said, 'the benefits of biotechnology, driven by large, private multinationals interested in commercial agriculture, have yet to be safely harnessed for the needs of the poor' (World Bank, 2007: p158). This is because 'agbiotech, as it currently stands, holds [little] promise for developing countries, where many small-scale, resource-poor farmers rely on the cultivation of minor staple crops on marginal lands for their subsistence' (Spielman, 2007: p190).

The potential loss of another technology, in this case glyphosate, appears to be but one more example of how genetic engineering designed by large corporations for their profit is appropriating a valuable resource from those with the least ability to pay.

Acknowledgements

The authors thank three reviewers for constructive comments. We are grateful to NORAD for support.

About the authors

Jack A Heinemann is a professor of genetics and molecular biology and was a lead author in the International Assessment of Agricultural Science and Technology for Development (IAASTD).

Brigitta Kurenbach is a molecular geneticist and post-doctoral scholar.

References

Alan, D. B. (2000). 'Why glyphosate is a global herbicide: strengths, weaknesses and prospects'. *Pest Manag Sci* 56, 299-308.

Atkinson, R. C., Beachy, R. N., Conway, G., Cordova, F. A., Fox, M. A., Holbrook, K. A., Klessig, D. F., McCormick, R. L., McPherson, P. M., Rawlings Iii, H. R., et al. (2003). 'Intellectual Property Rights: Public Sector Collaboration for Agricultural IP Management'. *Science* 301, 174-175.

Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M. J., Avilés-Vázquez, K., Samulon, A. and Perfecto, I. (2007). 'Organic agriculture and the global food supply'. *Ren. Ag. Food Sys*. 22, 86-108.

Basu, C., Halfhill, M. D., Mueller, T. C. and Stewart, J. C. N. (2004). 'Weed genomics: new tools to understand weed biology'. *Trends Pl. Sci.* 9, 391-398.

Behrens, M. R. (2007). 'Dicamba resistance: enlarging and preserving biotechnology-based weed management strategies'. *Science* 316, 1185-1188.

Canola Council. http://www.canola-council.org/volwheatbarley.aspx Date of Access: 4 March 2007.

Cerdeira, A. L. and Duke, S. O. (2006). 'The Current Status and Environmental Impacts of Glyphosate-Resistant Crops: A Review'. *J Environ Qual* 35, 1633-1658.

Cerdeira, A. L., Gazziero, D. L. P., Duke, S. O., Matallo, M. B. and Spadotto, C. A. (2007). 'Review of potential environmental impacts of transgenic glyphosate-resistant soybean in Brazil'. *J. Env. Sci. Health*, Part B 42, 539 - 549.

Chen, L. J., Lee, D. S., Song, Z. P., Suh, H. S. and Lu, B.-R. (2004). 'Gene Flow from Cultivated Rice (Oryza sativa) to its Weedy and Wild Relatives'. *Ann Bot* 93, 67-73.

DuPont. http://www2.dupont.com/Biotechnology/en_US/science_knowledge/herbicide_resistance/faq.html#one Date of Access: 12 April 2008.

FOE (2008). *Who benefits from GM crops? The rise in pesticide use*. Friends of the Earth. www.foei.org.

GEO-4 (2007). Global Environment Outlook. United Nations Environment Programme. http://www.unep.org/GEO/.

Graef, F., Stachow, U., Werner, A. and Schütte, G. (2007). 'Agricultural practice changes with cultivating genetically modified herbicide-tolerant oilseed rape'. *Ag. Sys.* 94, 111-118.

Hall, L., Topinka, K., Huffman, J., Davis, L. and Good, A. (2000). 'Pollen flow between herbicide-resistant Brassica napus is the cause of multiple-resistant B. napus volunteers'. *Weed Sci*. 48.

Heinemann, J. A. (1999). 'How antibiotics cause antibiotic resistance'. *Drug Discov. Today* 4, 72-79.

Heinemann, J. A. (2007). *A typology of the effects of (trans)gene flow on the conservation and sustainable use of genetic resources.* Bsp35r1. UN FAO.

IAASTD (in press). World Bank, FAO, UNEP.

Kennedy, D. (2003). 'Agriculture and the Developing World'. *Science* 302, 357.

Kremer, R. J., Means, N. E. and Kim, S. (2005). 'Glyphosate affects soybean root exudation and rhizosphere micro-organisms'. *Intern. J. Environ. Anal. Chem*. 85, 1165-1174.

Larson, R. L., Hill, A. L., Fenwick, A., Kniss, A. R., Hanson, L. E. and Miller, S. D. (2006). 'Influence of glyphosate on Rhizoctonia and Fusarium root rot in sugar beet'. *Pest Manag Sci* 62, 1182-1192.

Mancini, F., Termorshuizen, A. J., Jiggins, J. L. S. and van Bruggen, A. H. C. (2008). 'Increasing the environmental and social sustainability of cotton farming through farmer education in Andhra Pradesh, India'. *Ag. Sys.* 96, 16-25.

Monsanto. http://monsanto.mediaroom.com/index.php?s=43&item=580 Date of Access: 9 April 2008.

Owen, M. D. K. and Zelaya, I. A. (2005). 'Herbicide-resistant crops and weed resistance to herbicides'. *Pest Manag Sci* 61, 301-311.

Ozturk, L., Yazici, A., Eker, S., Gokmen, O., Romheld, V. and Cakmak, I. (2008). 'Glyphosate inhibition of ferric reductase activity in iron deficient sunflower roots'. *New Phytol.* 177, 899–906.

Pengue, W. A. (2005). 'Transgenic crops in Argentina: the ecological and social debt'. *Bull. Sci. Technol. Soc.* 25, 314-322.

Powles, S. B. (2008). 'Evolved glyphosate-resistant weeds around the world: lessons to be learnt'. *Pest Manag. Sci.* 64, 360-365.

Pretty, J. (2001). 'The rapid emergence of genetic modification in world agriculture: contested risks and benefits'. *Environ. Conserv.* 28, 248-262.

Raney, T. and Pingali, P. L. (2007). 'Sowing a gene revolution'. *Sci. Am*. September, 104-111.

Reddy, K. N. (2001). 'Glyphosate-resistant soybean as a weed management tool: opportunities and challenges'. *Weed Biol. Manag.* 1, 193-202.

Relyea, R. A. (2005). 'The lethal impact of Roundup on aquatic and terrestrial amphibians'. *Ecol. Appl.* 15, 1118-1124.

Relyea, R. A., Schoeppner, N. M. and Hoverman, J. T. (2005). 'Pesticides and amphibians: the importance of community context'. *Ecol. Appl.* 15, 1125-1134.

Richard, S., Moslemi, S., Sipahutar, H., Benachour, N. and Seralini, G.-E. (2005). 'Differential effects of glyphosate and Roundup on human placental cells and aromatase'. *Environ. Health Perspect.* 113, 716-720.

Service, R. F. (2007). 'A growing threat down on the farm'. *Science* 316, 1114-1117.

Sinden, J., Jones, R., Hester, S., Odom, D., Kalisch, C., James, R. and Cacho, O., eds. (2004). *The economic impact of weeds in Australia: summary* (Adelaide, CRC for Australian Weed Management).

Spielman, D. J. (2007). 'Pro-poor agricultural biotechnology: Can the international research system deliver the goods?' *Food Policy* 32, 189-204.

Thompson, D. G., Solomon, K. R. and Wojtaszek, B. F. (2005). 'The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities'. *Ecol. Appl*. 16, 2022-2027.

UNDP (1999). *Human Development Report 1999: Globalization with a Human Face.* United Nations Development Programme. hdr.undp.org/en/media/hdr_1999_en.pdf.

UNEP (2003). 'Agriculture, trade and sustainable development: an overview of some key issues'. United Nations Environment Programme. http://www.unep.ch/etu/mexico/Overview_Agri.pdf.

Valverde, B. and Gressel, J. (2006). 'Dealing with the evolution and spread of *Sorghum halepense'*. SENASA. www.weedscience.org/paper/Johnsongrass%20Glyphosate%20Report.pdf.

WHO (2005). *Modern food biotechnology, human health and development: an evidence-based study.* Food Safety Department of the World Health Organisation.

World Bank (2007). *World Development Report 2008: Agriculture for Development.* World Bank.

Young, B. G. (2006). 'Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops'. *Weed Technol.* 20, 301-307.

Zelaya, I. A., Owen, M. D. K. and VanGessel, M. J. (2007). 'Transfer of glyphosate resistance: evidence of hybridization in Conyza (asteraceae)'. *Am. J. Bot.* 94, 660-673.