EVOLUTION IN ACTION: GLYPHOSATE-RESISTANT WEEDS THREATEN WORLD CROPS

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Introduction

Glyphosate is by far the world's most widely used and important herbicide because it is efficacious, economical and environmentally benign (Dill *et al.*, 2008; Duke & Powles, 2008). Glyphosate dominates for non-selective weed control in agricultural ecosystems, especially to remove weeds between rows in established perennial tree, nut, vine crops and before seeding of annual crops. Globally, glyphosate is also the non-selective herbicide of choice in urban and industrial areas, national parks and other amenity areas. In these use patterns, there have been few instances of weeds evolving glyphosate resistance. While there are documented cases of glyphosate-resistant weed evolution in several countries (Table 1, reviewed by Powles, 2008) given the long term glyphosate usage, experience establishes that plants cannot easily evolve resistance to this herbicide.

The common factor in those examples (Table 1) where glyphosate-resistant weeds have evolved is very persistent glyphosate usage with little or no diversity in weed control practices. Unsurprisingly, glyphosate resistance has evolved most often in the resistance-prone genera *Conyza* and *Lolium*. It is important to recognise, however, that glyphosate continues to be effective globally in its traditional use patterns for non-selective weed control where there is sufficient diversity in control practices and not an extreme over-reliance on glyphosate. However, as discussed below, this situation has dramatically changed now that glyphosate has become a selective herbicide in transgenic crops.

Table 1. Global reports of evolved glyphosate-resistant weeds resulting from use of glyphosate as a non-selective herbicide (see Heap 2008, Powles 2008).

Species	Countries
Conyza spp.	Brazil, China, Spain, Israel, South Africa, USA
Lolium spp.	Australia, Brazil, Chile, France, South Africa, Spain, USA
Echinochloa colona	Australia
Eleusine indica	Malaysia, Taiwan
Parthenium hysterophorus	Colombia
Plantago lanceolata	South Africa

Glyphosate as a selective herbicide in transgenic glyphosate resistant crops

From 1996 onwards, a landmark development occurred with the commercialisation of transgenic (genetic modification obtained through gene manipulation using recombinant DNA technology) crops. By far the most important development has been crops endowed with a bacterial gene conferring resistance to glyphosate (Dill *et al.*, 2008). In transgenic glyphosate-resistant crops (hereinafter referred to as GR crops), glyphosate is used as a selective herbicide to remove weeds without crop damage, providing easy, economical, efficient weed control along with other agronomic advantages such as earlier seeding and reduced or zero tillage. GR crops are a spectacular commercial success (in those countries in which GM crops can be grown) with 95% of the more than 100 million hectares of currently grown transgenic crops being GR crops (Figure 1; James, 2006). In the Americas, the speed and extent of GR crop adoption has been phenomenal. GR soybean, cotton and maize dominate USA cropping. In 2006 GR soybean comprised 90%, cotton 91% and maize 60% of the entire USA plantings of these crops (Figure 2, Dill *et al.*, 2008). In southern USA cropping regions, GR soybean, cotton and maize are rotated on the same fields. In central and northern USA cropping regions, GR soybeans are almost universal and are often in rotation with GR maize.

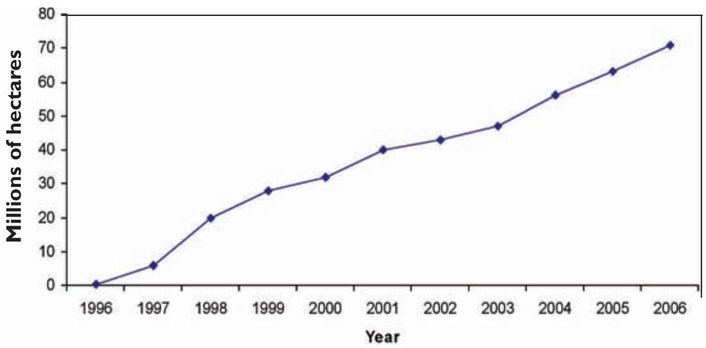

Figure 1: **Global glyphosate resistant crops.**

In Argentina, the adoption of GR crops is even more complete with almost the entire soybean crop being GR (Figure 3). GR crops are also being rapidly adopted in Brazil. The widespread adoption of GR crops and consequent high glyphosate usage (Figures 1-3) is understandable, as glyphosate is easy to use, economical and provides excellent weed control. GR crops all contribute to

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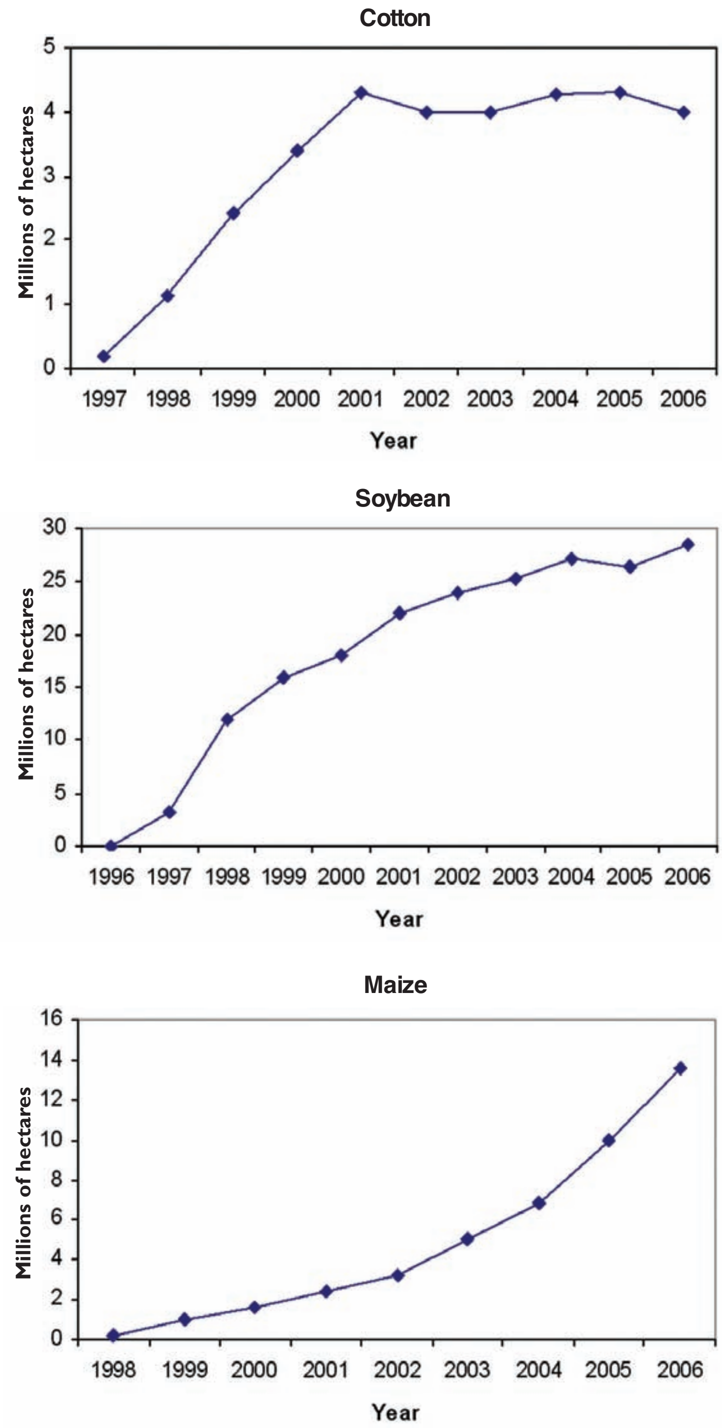

Figure 2: **Adoption of glyphosate-resistant crops in USA.**

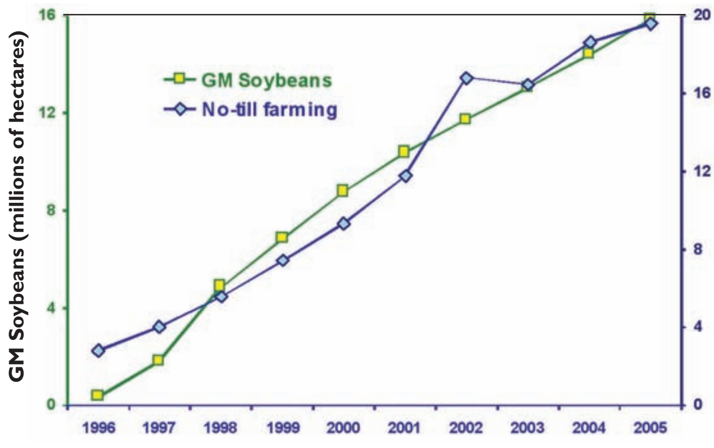

Figure 3: **Adoption of GR soybean and no-till seeding in Argentina.**

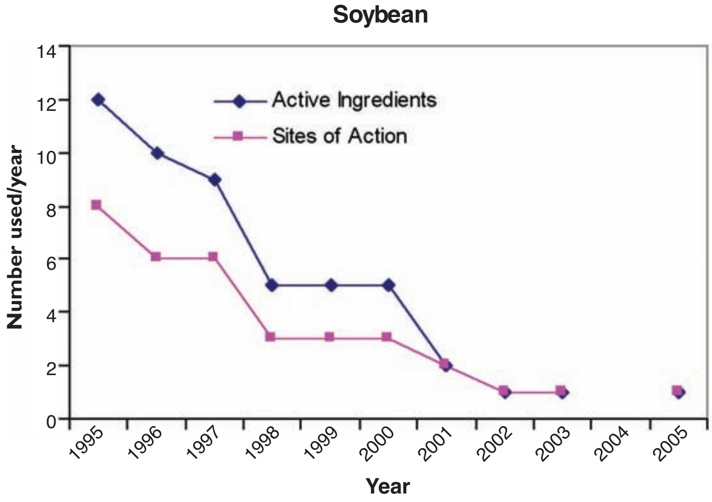

Figure 4: **Number of different herbicide active ingredients and herbicide sites of action used on at least 10% of hectares from 1995 to 2005 in soybean in the USA.**

widespread, high level adoption and therefore unprecedented, often exclusive, use of glyphosate over very large areas. While economically rational for growers and industry (Gianessi, 2005), from an evolutionary perspective the "glyphosate landscape" is an ideal environment in which any weedy plants that can survive glyphosate can thrive. This is especially so because the adoption of GR crops and intensive glyphosate usage often results in the cessation of use of alternative herbicides (Shaner, 2000) and/or tillage, and, therefore, there is no diversity in weed control practices. This further adds to the selection pressure for plants that can survive glyphosate. The adoption of GR soybean and glyphosate in the USA removed alternative herbicide diversity, resulting in almost complete reliance on glyphosate (Figure 4). This is also the case in Argentina and Brazil.

It must be emphasised that glyphosate used repeatedly and persistently post-emergent in GR crops across vast areas is a more intense evolutionary selection pressure for resistance than that which prevails for most traditional glyphosate uses (outlined in the Introduction). In a GR crop, any weed plants that survive glyphosate are likely to flower, pollinate and produce seed. Thus, in GR crops grown on the same fields for several years those weed species that have some level of natural tolerance to glyphosate can come to prominence in GR cropping systems (comprehensively reviewed by Owen, 2008). As well as these widely-occurring weed spectrum shifts, intense glyphosate use in GR crops grown persistently in the same fields/landscapes is a strong selection for resistance to evolve in previously glyphosate susceptible weed species (Powles, 2003). Evolved glyphosate-resistant weeds are a major risk for the continued success of GR crops.

Table 2. Evolved glyphosate-resistant weeds in transgenic glyphosate-resistant crops (see Heap 2008, Powles 2008)

Species	Country
Ambrosia artemisiifolia	USA
Ambrosia trifida	USA
Amaranthus palmeri	USA
Amaranthus tuberculatus	USA
Amaranthus rudis	USA
Conyza spp.	Brazil, USA
Lolium spp.	Brazil, USA
Sorghum halepense	Argentina, USA
Euphorbia heterophylla	Brazil

Table 2 lists the currently documented cases of evolved glyphosate-resistant weeds from usage of glyphosate as a selective herbicide in GR crops.

It is in GR crop areas in the USA and Argentina that glyphosate-resistant weed evolution is most threatening. Since the first report of glyphosate-resistant *Conyza canadensis* in a US GR soybean field in 2001, there are now at least three million hectares of USA GR crops infested with glyphosate-resistant *Conyza*. Even more worrisome are glyphosate-resistant populations of far more economically damaging weed species (Table 2). In some mid-western USA states there are now several known glyphosate-resistant populations of the very vigorous, highly competitive and economically damaging weeds *Ambrosia artemisiifolia* and *Ambrosia trifida*, as well as *Amaranthus rudis* and *Amaranthus tuberculatus*. In the southern cotton-growing states, there are many reports of glyphosate-resistant populations of *Amaranthus palmeri*, a very damaging weed of cotton crops. Evolution of glyphosate resistance in *Ambrosia* and *Amaranthus* populations is a looming threat to GR crop productivity and sustainability in the USA.

As in the USA, GR soybean has been massively adopted in Argentina. Almost the entire 16 million hectare Argentine soybean crop is GR, and nearly all of this is in no-till production systems with little diversity in weed control, and almost exclusive reliance on glyphosate. Additionally, GR maize is being adopted at a rapid rate. Therefore, the selection pressure is intense for evolution of glyphosate-resistant weeds. So far, the very damaging weed *Sorghum halepense* has evolved glyphosate resistance across a significant area of the GR soybean crop in the Salta province (Vila-Aiub *et al*., 2008). Brazil did not commercialise GR crops until well after Argentina, the USA and Canada, with GR crop adoption occurring mainly since 2005. However, rapid adoption of GR soybean, maize and cotton is now underway. Thus far, glyphosate-resistant populations of *Conyza* and *Euphorbia heterophylla* have evolved in Brazilian GR soybean areas (Table 2). Paraguay and Uruguay are also adopting GR crops. Given the dominance of GR crops in soybean, cotton and maize agro-ecosystems in major cropping regions of North and South America, more species will inevitably evolve glyphosate resistance.

Canada: One example of sustainable use of a GR crop

It is instructive to contrast the situation in Canada with that in the USA and Argentina. In the western Canadian grainbelt provinces (Alberta, Manitoba, Saskatchewan), canola is the only GR crop present. In this agro-ecosystem, non-GR wheat and barley dominate, with canola as an important rotational crop. Additionally, not all the canola grown is GR: in 2007, of the six million hectares of canola in Canada, only 70% was GR. Canadian growers also have transgenic glufosinate-resistant canola, and mutagenesis-derived imidazolinone herbicide resistant canola. Therefore, there is the option for diversity in canola type and herbicide use. Also, it is important to recognise that as canola is a rotational crop, it is grown on a particular cropping field only every third or fourth year. As the rotational cereal and any other crops are not GR, it is thus likely that a GR crop is grown on a particular field only infrequently. Clearly, the glyphosate selection intensity on weed species in this Canadian canola-cereal cropping agro-ecosystem is much less than with GR crops in the USA or Argentina. Unsurprisingly, there are currently no known cases of evolved glyphosate-resistant weeds in Canada. This is undoubtedly due to the diversity (as it refers to herbicide use) evident in the Canadian cropping system, relative to that in the GR soybean-maize-cotton agro-ecosystems of the USA. Thus, GR canola should remain sustainable in Canada if this diversity is maintained. There are important lessons to be learnt for other parts of the world, from this sustainable use of a GR crop in Canada.

Conclusion

A major lesson evident from more than three decades of non-selective glyphosate use to control billions of plants worldwide is that where diversity in weed management systems is maintained, then weed control by glyphosate can be sustainable. Glyphosate is a remarkably robust herbicide from a resistance evolution viewpoint. However, as reviewed above, it is clear that where there is very intense glyphosate selection without diversity, glyphosate-resistant weed populations will evolve. Particularly, the evolution of glyphosate-resistant weed populations is a major threat in areas where transgenic glyphosate-resistant crops dominate the landscape, and in which glyphosate selection is intense and without diversity. As glyphosate usage continues to be intensive in these areas (Foresman & Glasgow, 2008), it is likely that glyphosate-resistant weeds will become a major problem. There is a strong likelihood that resistance evolution will eliminate glyphosate as a weed management option in these important crop regions. This being so, the re-introduction and/or maintenance of diversity in these agro-ecosystems is essential. What specifically constitutes "diversity" will vary according to region, ecosystem, enterprises, economics and many other factors. However, diversity will involve herbicide rotations/sequences, mixtures of robust rates of herbicides with different modes of action, and use of non-herbicide weed control tools. Such diversity must be introduced now in the GR cropping areas of the USA, Argentina and Brazil. Mixtures of glyphosate with effective doses of different herbicides are already being adopted, and transgenic crops with additional herbicide-resistance genes are in development (Behrens *et al*., 2007, Green *et al*., 2008, Sammons *et al*., 2007). Alternative herbicides and integration with non-herbicidal weed control tools will be required.

For those regions of the world that have not yet adopted GR crops and/or intensive glyphosate usage, there are lessons to be learnt from the GR crop experience in the Americas. By avoiding intense glyphosate reliance and through maintenance of diversity, the longevity of this precious herbicide resource and of excellent GR crop technologies can be sustained for future harvests. Glyphosate is essential for present and future world food production, and action to secure its sustainability should be a global imperative.

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