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IMPACT OF HERBICIDE TOLERANT CROPS ON WEED MANAGEMENT IN THE ASIA PACIFIC REGION

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ABSTRACT

This paper briefly reviews herbicide tolerance and its impact on weed management regimes, focusing on genetic modification technologies to derive novel herbicide tolerance in various crops worldwide, and how such HT crops may influence weed management strategies in the Asia Pacific region.

Keywords: Genetic modification, herbicide tolerance, weed management, biotechnology, Asia Pacific

INTRODUCTION

Herbicide tolerant crops, contrary to popular belief, are not new. Nor are they restricted to genetically modified (GM) crops, also known as transgenic, genetically engineered, products of recombinant DNA technology (rDNA) or biotechnology. And sometimes they're called "Frankenfoods".

As we know, all crops are tolerant to at least some herbicides. Such tolerance might be entirely natural, or they could be created by humans using various traditional plant breeding methods. However, as 'herbicide tolerance' is so often used synonymously, if incorrectly, with GM technology, let's start by exploring that technology.

What is Genetic Modification (GM) technology?

Recombinant DNA technology is a powerful means to transfer genetic material from one organism of any species to any other. The genetic material is usually a sequence of DNA coding for a particular trait, and the biotech breeder desires to introduce that trait into a host organism that currently lacks the desired trait.

One prominent example of an rDNA product is human insulin, used to treat diabetes. Since the early 20th Century when it was first purified, diabetics injected insulin extracted from dogs, rats and various farm animals, as such animals produce a version of insulin functionally similar to that produced by humans. Half a century later, in 1982, human insulin started being produced by *E. coli* bacteria into which the human DNA coding for insulin had been transferred. This human form of insulin, called Humulin™ rapidly replaced domestic animals as the insulin source, being better for the human diabetics, as

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the insulin was not just functionally similar to human insulin, it was exactly the same as human pancreas biosynthesized insulin. Plus, it saved countless farm animals, and also showed the public at large that human and bacteria DNA are not all that different.

The first example of using rDNA technology in the food realm occurred a few years after insulin (and many other rDNA based pharmaceuticals, which quickly followed), when in 1991 GM bacteria produced chymosin, a coagulating agent used in making cheese. rDNA-derived chymosin is now almost ubiquitous in industrial cheese making, and is popular with vegetarians as, unlike traditional rennet, does not come from animals.

The first GM crops came along a few years later. In 1994 in the USA, Calgene introduced FlavrSavr tomato to the market with great fanfare but was met with great indifference by American shoppers. The FlavrSavr was meant to provide summertime taste to wintertime consumers, as it had an antisense polygalacturonase gene to inhibit over-ripening, which ordinarily occurs between harvest and market when cultivation and consumption venues are distant. The concept was that the GM tomatoes would be grown in winter in southern States like Florida, then shipped ripe to northern markets in winter's deepfreeze grip, like Chicago. Unfortunately, the company suffered a number of setbacks, not least of which was choosing a tasteless tomato cultivar to engineer, and FlavrSavr failed in the marketplace. Other marketing strategies are more successful. In the UK, GM tomato paste in tins was quite successful in groceries, until anti-GM activists decided to threaten the retailers, when the otherwise successful GM paste was removed from market shelves.

Herbicide tolerance as an engineered trait came along soon after, led by Monsanto, who had been developing crop cultivars with rDNA engineered tolerance to Monsanto's glyphosate (the active ingredient in RoundUp™) herbicide. The strategic concept was commercially sound: glyphosate, as a broad spectrum, non-selective herbicide could not be used to control weeds in crops, because the chemical kills (or at least controls) all plants. But a farm field growing a glyphosate tolerant, "Roundup Ready ™ cultivar could withstand the usual dosage without damage to the crop, while controlling all other plants, giving complete weed control in one pass with one chemical.

Plus, RoundUp™ was already in widespread use by farmers as a burndown or complete kill for certain non-selective purposes, so farmers were already familiar with the chemical, the price was competitive and dropping, the chemical had relatively low toxicity to animals and was quickly degraded in the soil.

Other big chemical pesticide companies were active as well, developing GM Herbicide Tolerant (HT) crop cultivars matched to their own chemistries. DuPont, Hoescht, AgrEvo, Syngenta, BASF, Rhone-Poulenc and others all had GM HT R&D programs. And the list of crop species under development grew quickly, and included maize, soybean, canola, cotton, rice, and other major crop species. While HT was not the only GM trait being developed using rDNA in crops, it received a high profile, largely due to HT and big companies being specifically and preferentially targeted by activist groups.

Curiously, the use of GM technology in plants and crops has become controversial worldwide, with charges of "untested technology" and "unknown risks", while the use of the same technology in pharmaceuticals and foods is widely accepted, even though the technology is exactly the same. Logically, because the basis of the anxieties is exactly the same, the same fears and anxieties should apply to pharmaceuticals as they do to foods. But logic is, unfortunately, overwhelmed by emotion and rhetoric in the public discourse of agricultural biotechnology. Since GM crops were introduced in 1994, the numbers of traits, species and regions growing them have all grown substantially (James, 2010).

World Status of GM Crops

James (2010) and colleagues at ISAAA conducted annual surveys of GM crop adoption worldwide and analyse those data.

Figure 1 shows the growth over the years of global area under GM crops, with segments differentiating industrial vs. developing countries (James, 2010).

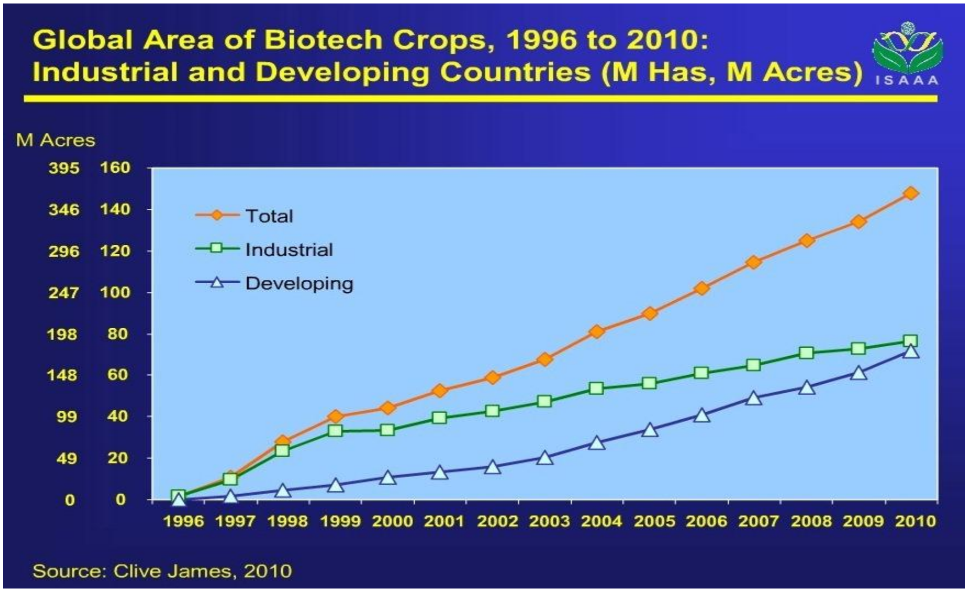

Figure 1.

Figure 2 is a map of the world with GM cropping counties indicated, along with the specific GM crop type and total area under cultivation in each country. In 2010, for example, Australia cultivated 0.7Million Hectares of GM cotton and canola; New Zealand did not (legally) cultivate GM crops at all (James, 2010).

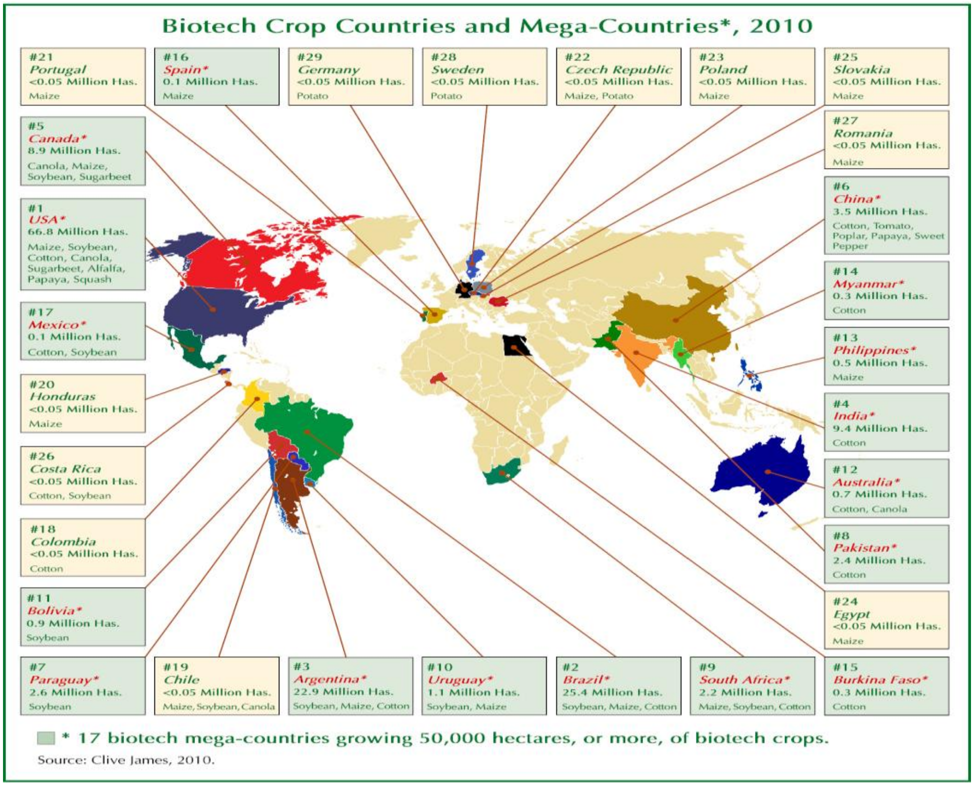

Figure 2.

GM Crops in Asia Pacific

Several countries in the Asia-Pacific area cultivate GM crops. China is by far the most significant grower, with 3.5Million hectares of various GM traits in cotton, tomato, poplar, papaya, and sweet pepper (James, 2010). In addition, China has given regulatory safety certificates to GM cultivars of rice, maize and wheat. These are currently being subjected to mandatory testing in agronomic field trials prior to commercial release (BaoRong Lu, personal communication, 2011).

In the Philippines, GM maize engineered with Bt (for lepidopteran insect control) is the only genetically engineered crop under cultivation (James, 2010). But results have been impressive, with the GM maize cultivars bringing in a 30% increase in yield, due mainly or exclusively to the insect control.

As mentioned, Australian farmers cultivate a substantial area of GM cotton and canola. Australia is also field trialing GM wheat and has a number of other GM species at various pre-commercial testing stages. Australia has a long history of growing triazine tolerant (T) canola, although not technically GM, so Australian scientists and farmers are familiar with management of novel herbicide tolerance traits in crops. This management experience should help in handling GM HT crops as they come more predominant.

New Zealand has been active in agricultural biotechnology research, but remains a "GMO-free" country as far as GM crop cultivation is concerned.

Herbicide Tolerance

Farmers need to control weeds somehow, or else risk losing a substantial portion of the crop to the competing plants, which are usually much more aggressive than the crop plants. Historically, farmers controlled weeds using physical means; tilling, hoeing or rogueing. But such physical methods are problematic in their own right - they are labor intensive, expensive, and environmentally damaging, especially when conducted on commercial sized fields. As a result, most commercial farmers - apart from organic farmers - now use synthetic chemical herbicides to control weeds.

Herbicide tolerance, as a trait of agronomic significance, is not new. Nor is HT exclusive to GM crops. In the 1940s, auxin based chemicals were noted to be more damaging to broadleaf (dicot) plants than grassy (monocot) leaf plants, giving rise to chemical weed control in cereal crops for the predominantly broadleaf weeds. The first and still 'flagship' auxin herbicide, 2,4-D, has been used as a selective herbicide since WWII, mainly to control broadleaf weeds in naturally-tolerant cereal crops.

In the years following, a series of different kinds of synthetic herbicides with different features were developed. Some herbicides are more effective against grassy plants, so are used to control grassy weeds in broadleaf crops. And other chemical families or groups provide different mechanisms of action for more selective weed control properties. In every case, herbicide tolerance within the crop species allows selective herbicide weed control.

And herbicide tolerant weeds have been with us as long as there have been herbicides, either due to the weedy species being naturally tolerant to the chemical, or having acquired tolerance through, for example, spontaneous mutation.

As reported in Hanson *et al.* (2011), no herbicide is completely effective against all weed species and completely benign to the crop plants. There is usually at least some degree of tolerance in weeds, and some degree of susceptibility in the crop plants. Good management means using a herbicide or combination of different herbicides to effectively control the weeds while minimizing the damage to the crop. This management strategy will differ according to crop type, region and spectrum of weeds present in a particular farm. Herbicides kill or retard plant growth by any of several methods; herbicides can be classified based on specific 'mechanism of action'. For example, some herbicides act by interfering with enzymes within the plant, such as the Group 2 herbicides, which bind to (and thus inactivate) acetolactate synthase, ALS. With ALS inactivated, the plant cannot synthesize branched-chain amino acids (valine, leucine, and isoleucine) and so cannot sustain growth; the susceptible plant starves to death. In contrast, Group 4 herbicides (which includes the auxin 2,4-D) work as growth regulators; 2,4-D stimulates rapid uncontrolled growth in susceptible plants and so the plant grows beyond its ability to sustain the growth (Hanson *et al.,* 2011).

Traditional Breeding for Herbicide Tolerance (Not GM)

Eventually, evolution will generate resistance in any plant population exposed to a given herbicide at less than lethal doses. So another approach in conventional breeding for herbicide resistance is to expose the crop plants to sublethal doses of the relevant herbicide and select the best performing survivors over several generations and spray regimes (Hanson *et al.,* 2011).

Also, the crop species germplasm of a given crop species could be surveyed, as some varieties, breeding lines or stock may display a higher degree of resistance than the crop cultivars. Identifying the more resistant lines and introgressing the resistance genes through traditional crossing may be used to move the improved resistance genes into commercial cultivars (Hanson *et al.,* 2011).

In taking a more direct hands-on strategy to acquiring herbicide tolerance in a crop, one successful approach is to alter the herbicide's molecular target. In the case of Group 2 herbicides, for example, changing the structure of the targ*et al*S enzyme such that it has less binding affinity for the herbicide, without unduly sacrificing enzymatic function, will render the previously susceptible plant tolerant to the Group 2 herbicides.

An alternative mechanism to acquire herbicide tolerance is by interfering with the delivery of the chemical herbicide to the target. The mechanism could be physical, such as having a thick cuticle to impede entry of the herbicide into the plant cells, or it could be biochemical, for example by producing an enzyme that binds or metabolizes the herbicide. Using the Group 2 ALS inhibitor example again, the ALS enzyme in linseed flax is susceptible to Group 2 herbicides, but when the herbicide is sprayed on the plant, an enzyme in the linseed plant breaks down the herbicide molecule before it can bind to the ALS target enzyme, rendering the plant tolerant of the herbicide.

In practice, spontaneous mutations generated herbicide resistant commercial cultivars. Australia is very familiar with triazine tolerant (TT) canola, which was first developed from a spontaneous mutant *Brassica rapa* weed growing in a farmer's field in Quebec. The farmer sprayed the field with triazine to kill the various weeds and noticed a weed plant survivor. Plant breeders used that sole surviving plant as a parent in a canola breeding program and derived the entire series of triazine tolerant canolas. Although coming with a severe yield deficit, certain farmers continue to prefer the TT cultivars as they are a good fit with the farmer's management and agronomic practices.

Instead of waiting for fortuitous spontaneous mutations, breeders can also help evolution along by inducing mutations, with treatments of ionizing radiation, EMS or other mutagenic chemicals, etc. The method is simple: start with as large a population of the desired species as you can handle, expose them to the mutagenic agent, grow out a progeny population and spray with the relevant herbicide to which you seek novel tolerance. Survivors may or may not be true genetic mutants, and even mutants may not be suitable for commercial release, as the mutagen likely perturbed other functions of the plant as well, leading to a diminution of some important feature, like reduced yield (as in the triazine tolerant canolas).

Several herbicide resistant commercial crop cultivars were developed using induced mutagenesis. One of the most prominent is the wheat cultivar "Above" which mutated a novel genetic resistance to imidazolinone (Group 2) herbicides.

Pre-GM biotechnology has also been used to creating *de novo* herbicide resistance. In the 1980s, prior to rDNA technologies adapted to transform higher plants, several groups were growing crop plant cells *in vitro*, then adding the active ingredient chemical from various herbicides to the culture medium, and then regenerating whole plants from surviving cell pockets (see e.g. Jordan and McHughen, 1987). In some cases, the progeny of the regenerants also showed enhanced resistance to the herbicide. However, whether any of these lines were commercialized is unclear.

Somaclonal variation is a phenomenon in which plants cells growing *in vitro* are observed to spontaneously mutate (first reported by Australians working with wheat cultures (Larkin and Scowcroft, 1981)). Somaclonal variants with herbicide tolerance have been selected from cell lines growing in vitro which were then regenerated into whole plants. In some rare cases, the variant plant lines founded new herbicide resistant cultivars, mainly crops with resistance to Group 2 herbicides such as BASFs "Clearfield" series of crop cultivars, including canola, sunflower, rice, corn wheat and even lentils (Hanson *et al.,* 2011).

Herbicide Tolerance Using GM

Over the past 20 years, the application of rDNA technologies to agriculture has provided a series of new herbicide tolerant crops, aka HT GMOs. Genes conferring tolerance to several different kinds of herbicides have been isolated, cloned and transferred to various crop plant species, including glyphosate (the active ingredient in RoundUp™), glufosinate (Liberty™), 2,4-D, bromoxynil, sulfonulureas and imidizolinones. The number of genetically engineered crop species is relatively large, but only a small fraction of those are in actual commercial production.

In fact, the majority of those HT GMO crops in commercial production are soybeans, maize, canola and cotton tolerant of either glyphosate or glufosinate. And those four crops and two herbicides account for almost 70% of the world's GM crops (James, 2010). Other crop species genetically engineered for herbicide tolerance include tobacco, alfalfa, sugarbeet, rice, wheat, and linseed flax, and of these, only alfalfa and sugarbeet are currently in legal commercial production.

GM technology is slated to expand rapidly worldwide, with increasing numbers of crop species, GM traits, countries of cultivation and countries of development and release, with an estimated 120 GM crops under cultivation somewhere on the planet by 2015 (Stein and Rodriguez-Cerezo, 2009). Recent analyses of the economic impacts of growing GM crops explains why the expectation for continued growth is so confident: farmers growing GM crops have seen tangible economic gains as well as non-pecuniary benefits. For example, farmers growing HG HT soybeans in 2009 saw an economic benefit of 2.7%, 0.6 % for GM HT maize, 0.13% for GM HT cotton and 7.1% for GM HT canola (Brookes and Barfoot, 2011). However, HT crops, while perhaps expanding their global acreage, are unlikely to expand very much in terms of specific chemistries. That is, as more countries allow GM cropping, the current pool of HT GM crops and chemistries will be primarily utilized, thus expanding the area of HT GM crops cultivated, but the development of new genes conferring tolerance to new herbicides has stalled. We can, however, expect release of HT cultivars of some additional crop species for which GM HT is not currently commercialized, such as GM HT rice and wheat, and these may occupy substantial areas of cultivation.

Impacts of HT GM crops

The number of independent investigations into the various impacts of GM HT crops is accumulating. The reports range from standard small scale academic reports with publication in peer reviewed journals to major studies sponsored by national scientific societies.

Probably the largest of the peer reviewed studies is that from the US National Academy of Sciences. In 2010, they released their opus, two years in the making, on the impact of GM crops on farm sustainability (National Academy of Sciences US 2010). Because HT is the dominant trait in current GM crops in the USA, a primary focus of this study was on the impacts of cultivating those HT GM crops, on farmers, on the environment and on society, with a view to understanding the ultimate effect on farm sustainability.

One of the primary conclusions reached was that GM crops generally have fewer adverse environmental effects than do non-GM crops. A second is that GM HT crops facilitate soil conservation efforts, particularly reduced tillage, which then leads to improved soil and groundwater quality. On this latter point, Carpenter (2010) recorded a 25% drop in pesticide leaching in GM HT cotton fields in North Carolina compared to non GM cotton fields.

Economically, GM crop farmers enjoy higher yields and lower production costs. Among the non-monetary benefits noted are the increased farmworker safety (due to a shift away from more toxic chemicals, a benefit first documented by Fernandez-Cornejo and Caswell, 2006) and greater flexibility in weed control management (National Academy of Sciences US 2010).

There were also concerns recorded for the potential for negative impacts. The main one was the inevitability of weeds evolving resistance to the primary herbicides used in GM HT crop systems, notable glyphosate (National Academy of Sciences US 2010). Glyphosate dominates the herbicide market, capturing 30% of all herbicides sold globally (Bonny 2011). Populations of weeds with novel glyphosate tolerance have already been recorded, and they can present management problems for farmers trying to control those weeds (Nandula *et al.* 2005). Indeed, glyphosate tolerant weed populations have been reported around the world, including ryegrass (*Lolium perenne*) (Pratley *et al.* 1999) and liverseed grass (*Urochloa panicoides*) (Preston and Boutsalis 2008) in Australia, goosegrass (*Eleusine indica*) (Lee and Ngrim 2000) in Malaysia, and horseweed (*Conyza canadensis*) (van Gressel, 2001; Shrestha *et al.* 2007) and pigweed (*Amaranthus palmeri*) (Culpepper *et al.* 2006) in several parts of the USA. A helpful tool is the International Survey of Resistant Weeds, a searchable database online at www.weedscience.org.

It is important to note here that GM HT crops did not give rise to these glyphosate tolerant weeds. But the availability and success of glyphosate tolerant crops will inevitably increase the opportunity for glyphosate overuse, leading to additional populations of weeds with glyphosate tolerance. Bonny (2011) provides several explanations:

- The success of glyphosate tolerant crops inexorably leads to the expansion of the use of glyphosate (there is no advantage to growing glyphosate tolerant cultivars without spraying them with glyphosate);
- with glyphosate being a simple chemical and now being off patent, inexpensive generic versions are readily available in some areas;
- the rise in popularity of conservation tillage encourages glyphosate use;
- the rise in non-agricultural uses of glyphosate, as a non-selective vegetation control for roadsides, power lines, recreational grounds, etc.

The same opportunity to derive weeds with herbicide tolerance is true for all other herbicide tolerant crops, whether GM or traditional.

Also, not all farmers end up reducing the amount of herbicide used as, in certain cases, depending on the type of weeds present, the farmer may use more herbicide than he or she used previously. In such cases, the farmer should consider if he or she is getting value from the new cultivar and consider reverting to prior practice. Of course, simple comparisons of herbicide quantities are not the whole story, as other factors come to bear. It may be that a somewhat larger absolute quantity of glyphosate provides better weed control, is less expensive and is more environmentally benign than the smaller amount of the previously used herbicide.

Another potential problem, not directly related to the agronomic cultivation of GM crops, is the potential negative impact of growing GM crops for export to non-GM markets. This is a difficult topic to discuss scientifically, as it is inherently a non-scientific issue. International political intrigue plays a major role in this, and the rules of international trade seem to shift constantly. Nevertheless, farmers should be aware of their markets and market preferences.

The primary concern raised in the US report was on increasing weed problems arising due to evolution of weeds with resistance to glyphosate, or weed populations with less susceptibility to glyphosate become positively selected in areas where glyphosate is the exclusive herbicide, and then the weeds become established. Of course, as the study notes, these issues are neither new nor exclusive to GM HT crops, but do emphasize the need to strategically manage herbicide usage to assure longterm efficacy of glyphosate as a weed control measure (National Academy of Sciences US 2010).

Other studies of economic impacts of GM cropping may differ in scope, but reach similar conclusions. Brookes and Barfoot (2011) looked at global impacts from 1996 to 2009. They note dramatic benefits for most farmers of GM crops, including both increases in income and reductions in expenditures. Others, particularly in non-peer reviewed publications (e.g. Benbrook, 2009; Gurian-Sherman, 2009) argue that not all GM HT farmers realize such benefits and in fact actually increase the use of herbicides. Unfortunately, such authors fail to explain why farmers would continue to use an herbicide regime inferior to what they practiced before.

In some developing countries, farmers of GM HT soybean will save a portion of their harvested seeds for replanting, thus circumventing the usual expectation that farmers will buy fresh seed each year (Qaim, 2009).

Collectively, these cited studies consistently reached a number of important common findings and conclusions, many or most of which are relevant to weed control with HT crops in the Asia-Pacific realm.

Weed Management and GM Technology: Herbicide Tolerance

As mentioned previously, all crops are tolerant to at least some herbicides, hence farmers, agronomists and weed scientists have a long history of weed control in herbicide tolerant crops using selective herbicides. The problems and challenges are not new with GM HT crops, so the same old management strategies apply.

As noted in various studies, the biggest challenges include evolution or derivation of herbicide tolerant weed populations, thus compromising the utility of the respective herbicide in controlling that weed. Farmers encountering such weed populations have to change practices, to revert to older, more toxic or environmentally damaging chemicals, to re-acquire effective weed control (Lemaux, 2009).

Major issues include evolution of herbicide resistance by weeds, and escape of HT genes from the GM crop, either by seed (and becoming problems as volunteers or feral populations) or by outcrossing to weedy relatives, with the consequence of the hybrid establishing a population of HT weeds. Evolution of resistance in weedy species is well documented and can be expected to occur with the increasing cultivation of GM HT crops. Indeed, such populations are already being documented. And such eventualities are also well known from conventional selective herbicide histories, especially weed populations overcoming Group 2 herbicides in conventional agronomic practice. And there’s no reason to suspect GM HT crops will be any different in this respect: if the use of a specific herbicide is not managed properly, by not overspraying or rotating, then weeds will eventually evolve and overcome that chemical.

Outcrossing of HT genes from GM crops to weedy species presents a slightly more interesting wrinkle with respect to the Asia Pacific region. Of course, this source of herbicide tolerance in weed populations is also well known, and GM HT crops can be expected to behave in the same way as non-GM versions of the same species. That is, outcrossing to weedy relatives is a function of pollen flow, presence of weedy relatives and opportunity for plant sexual trysts. What makes it interesting is that the of the main GM HT crops in cultivation, soy, maize, cotton and canola, only canola has suitably weedy relatives in most regions of cultivation to present the appropriate opportunities for HT gene escape and introgression. There are few or no weedy relatives of soy or maize in areas where they are cultivated, and the threat for cotton is minimal. But canola is grown amid many other interfertile *Brassica* species, some domesticated and some less so. And the experience so far shows GM HT canolas are just as promiscuous as their non-GM relatives (Warwick *et al.* 2003; Beckie *et al.,* 2003).

In the main canola cultivation region of Canada, canola plants with three novel herbicide resistance genes have been identified, a result of multiple outcrossings (Hall *et al.,* 2000; Beckie *et al.,* 2004). Interestingly, such hybrids house glyphosate and glufosinate resistant transgenes, and also a non-transgene HT trait for ALS inhibitors. Not only does this illustrate the need to carefully manage herbicide usage and resistance in highly outcrossing species with weedy relatives in proximity, it shows that outcrossing and trait escape is not limited to GM crops or traits.

Canadian farmers dealing with the multi-HT weeds in their canola crops cannot use either glyphosate, or glufosinate, or imidazoninone to control these ‘superweeds’ with multiple HT gene stacks. But conventional canola farmers cannot use these herbicides either, as a conventional canola crop would succumb as readily as the weeds if they were sprayed with glyphosate, glufosinate or imidazoninones. Instead, these farmers revert to older weed control practices, for example using 2,4-D or bromoxynil, and spray to remove the superweeds when they appear in the rotational crop (typically a cereal).

There are management strategies to delay the onset of weeds with novel tolerance, and there are management strategies to deal with the rise of weedy populations with tolerance to herbicides that previously controlled them (National Academy of Sciences US 2010; Ronald, 2011; Hanson *et al.,* 2011). Crop rotations and herbicide group rotations are clearly crucial. Using appropriate doses and tank mixes are important. Walking the fields with an eye to unusual or unexpected weeds will help identify potential problems and resolve them more easily. When a population of weeds survives a treatment that would ordinarily control them (indicating a possible genetic HT in that weed population), farmers should eradicate the weeds with a different herbicide, or at least combine a different herbicide with the glyphosate or glufosinate, or they should seed that field to a different crop next season and spray with a herbicide appropriate to control that the weed and appropriate for that crop species. None of these are new or limited to GM HT crops or weeds, so the same good management practices that we've advocated for years remain the first line of defence against new or more aggressive weed populations.

CONCLUSIONS

The good news is that GM HT crops, in general, are good news in that they do deliver documented benefits of increased productivity and profitability in an environmentally sustainable manner. But, like any regime involving chemical weed control, they do need proper and attentive management.

The other good news is that the management strategies are the same as they have been for weed control before GM technology came along.

If weed scientists, agronomists and farmers merely continue to apply good science, good stewardship principles and good common sense, GM HT crops can be safely and effectively cultivated, with weed control greatly simplified.

REFERENCES CITED

Beckie, H. J., G. Séguin-Swartz, N. Harikumar, I.W. Suzanne. 2003. Gene flow in commercial fields of herbicide resistant canola (*Brassica napus*). Ecolog. Applicat. 13(5):1276–1294.

Beckie, H. J., G. Séguin-Swartz, N. Harikumar, I.W. Suzanne and J. Eric. 2004. Multiple herbicide–resistant canola can be controlled by alternative herbicides. Weed Sci. 52: 152-157.

Benbrook, C.M. 2009. *Impacts of Genetically Engineered Crops on Pesticide Use in the United States: The First Thirteen Years;* The Organic Center, Boulder, CO, USA.

Bonny, S. 2011. Herbicide-tolerant transgenic crops: impacts on pesticide use, issues, and prospects given weed resistance. *Sustainability* 3: (in press)

Brookes and Barfoot. 2011. *GM crops: global socio-economic and environmental impacts.* PG Economics Ltd., Dorchester UK. http://www.pgeconomics.co.uk/

Carpenter, J.E. 2010. Peer reviewed surveys indicate positive impact of commercialized GM crops. Nature Biotechn. 28:319-321.

Culpepper, A.S., T.L. Grey, W.K. Vencill, J.M. Kichler, T.M. Webster. 2006. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci. 54:620-26.

Fernandez-Cornejo and Caswell. 2006. The first decade of genetically engineered crops in the United States, pp. 1–30. In: *Economic Information Bulletin,* ed. United States Department of Agriculture Economic Research Service. USDA, Washington, DC.

Gurian-Sherman, D. 2009. *Failure to yield*. Union of Concerned Scientists. UCS Publications, Cambridge, MA, USA.

Hall, L., K. Topinka, J. Huffman, L. Davis and A. Good. 2000. Pollen flow between herbicide-resistant *Brassica napus* is the cause of multiple-resistant *B. napus* volunteers. Weed Sci. 48: 688-694.

Hanson, B.D., A. Fischer, A. McHughen, M. Jasieniuk, A. Shrestha and A. Jhala. 2011. Herbicide resistant weeds and crops. In: *Principles of Weed Science, 4th ed*. (in press).

James, C. 2010. Global Status of Commercialized Biotech/GM Crops: 2010. ISAAA Briefs 42-2010. 488 ISAAA (International Service for the Acquisition of Agri-biotech Applications): Ithaca, NY.

Jordan, M.C. and A. McHughen. 1987. Selection for chlorsulfuron resistance in flax *(Linum usitatissimum)* cell cultures. J. Plant Physiol. 131:333-338.

Larkin, P.J. and W.R. Scowcroft. 1981. Somaclonal variation: a novel source of variability from cell cultures for plant improvement. Theoret. and Appl. Genet. 60:197-214.

Lee, L.J. and J. Ngim. 2000. A first report of glyphosate-resistant goosegrass (*Eleusine indica* (L.) Gaertn.) in Malaysia. Pest Manag. Sci. 56:336–39.

Lemaux, P. G. 2009. Genetically Engineered Plants and Foods: A Scientist's Analysis of the Issues (Part II). Annual Rev. Plant Biol. 60: 511-559.

Nandula, V.K., K.N. Reddy, S.O. Duke, and D.H. Poston. 2005. Glyphosate-resistant weeds: current status and future outlook. Outlooks Pest Manag. PP. 183-187.

National Academy of Sciences US. 2010. *Impact of Genetically Engineered Crops on Farm Sustainability in the United States*. National Academies Press, Washington, DC.

Pratley, J., N. Urwin, R. Stanton, P. Baines and J. Broster. 1999. Resistance to glyphosate in *Lolium rigidum*. I. Bioevaluation. Weed Sci. 47:405–11.

Preston, C., and Boutsalis, P. (2008). *Another pesticide resistant weed found.* Weeds CRC. http://www.sciencealert.com.au

Qaim, M. (2009). The Economics of Genetically Modified Crops. Annual Rev. Res. Econom. 1:665–93.

Ronald, P. 2011. Plant Genetics, Sustainable Agriculture and Global Food Security. Genetics 188: 11–20.

Shrestha, A., K.J. Hembree and N. Va. 2007. Growth stage influences level of resistance in glyphosate resistant horseweed. California Agric. 61:67–70.

Stein, A. J. and E. Rodriguez-Cerezo. 2009. The global pipeline of new GM crops: implications of asynchronous approval for international trade, pp. 1–114 in: *JRC Scientific and Technical Reports*, edited by Joint Research Centre European Commission, Institute for Prospective Technological Studies. Joint Research Centre, Institute for Prospective Technological Studies, Seville, Spain.

VanGessel, M.J. 2001. Rapid Publication: Glyphosate-resistant horseweed from Delaware. Weed Sci. 49:703–5

Warwick, S.I., M.J. Simard, A. Légère, H.J. Beckie and L. Braun. 2003. Hybridization between transgenic *Brassica napus* L. and its wild relatives: *Brassica rapa* L., *Raphanus raphanistrum* L., *Sinapis arvensis* L., and *Erucastrum gallicum* (Willd.) O.E. Schulz. Theoret. Appl. Genet. 107:528–39.