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Review/Overview Article

Herbicide resistant crops: History, development and current technologies

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ABSTRACT

Advances in biotechnology have led to development and commercialization of several herbicide-resistant crops (HRCs) in the mid-1990s. HRCs survive herbicide treatment that previously would have killed the crop along with targetted weeds. Both transgenic (created through stable integration of a foreign gene) and non-transgenic (developed through traditional plant breeding) HRCs are commercially available to farmers. Although several HRCs are available, only transgenic HRCs, such as, glyphosate- and glufosinate-resistant crops appear to have greatest impact and dominate the market. HRCs are readily accepted in North and South America and are slowly making inroads into other parts of world. Farmers who have chosen HRCs must have seen some economic and weed control benefits; otherwise, the rapid increase in area planted to HRCs in recent years would not have occurred. There are benefits and risks associated with the use of HRCs as a weed management tool. The benefits of HRCs for weed management outweigh the risks based on current knowledge. HRCs should not be relied on solely to the exclusion of other weed control measures and should be used within integrated weed management programmes.

Key words **:** Herbicide resistance, Herbicide-resistant crops, Transgenic crops

Weeds, variously defined, have been in existence since time immemorial. They continually interfere with human activity and crop production, despite the use of best weed management practices. Prior to the advent of synthetic organic herbicides in the twentieth century, weeds were controlled for thousands of years by mechanical, cultural, and biological means. These methods are still widely practised in developing countries. The developed countries have seen a rapid exodus of population from agriculture to pursue lucrative non agricultural occupations, largely driven by mechanization and use of synthetic pesticides; this is also happening and developing countries such as India. Discovered in the mid 1940s 2,4-dichorophenoxyacetic acid was the first synthetic herbicide used for selective broad-leaves weed control. Since then, several herbicides belonging to different chemical classes and possessing diverse modes of action have been discovered and commercialized around the world. Herbicides have vastly contributed towards increasing world food production in an efficient and economic, and environmentally sustainable manner. Weed management has changed dramatically with the commercial launch of herbicide-resistant crops (HRCs) in the mid-1990s. In 2010, globally 148 million ha were planted to transgenic crops (refer to single or stacked genes for herbicide, insect, drought, salinity resistance, and value added traits), including HRCs, of which 61% was planted to herbicide-resistant crops [soybean (*Glycine max* Merr.), corn (maize) (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), canola (*Brassica napus* L.), sugarbeet (*Beta vulgaris* L.), and alfalfa (*Medicago sativa* L.)] and 22% was planted to stacked herbicide and insect traits reference. This review summarizs the historical background on discovery and development, benefits and consequences of their use, currently available technologies, and future outlook of transgenic HRCs. The review also provides information on nontransgenic HRCs that were developed through traditional plant breeding techniques.

History

Extensive reliance on herbicides for weed control in various cropping systems across the world has resulted in the evolution of resistance to herbicides. Interestingly, this problem of weed resistance to herbicides has provided an invaluable opportunity for visionary scientists to develop crops resistant to previously non-selective herbicides. As a consequence, researchers explored ways to develop crops resistant to herbicides with the goals of improving

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herbicide selectivity, expanding weed control spectrum, as well as minimizing crop injury. HRCs can be classified as non-transgenic (traditional genetic methods of selection of resistance trait) and transgenic (genetically engineered). Non-transgenic HRCs, summarized in Table 1, were developed using conventional breeding techniques. The first such example is triazine-resistant canola that was developed through a breeding programme in 1984. Thereafter, various methods of resistance trait/germplasm selection such as microspore selection, seed mutagenesis, pollen mutagenesis, tissue culture, cell selection, and transfer from a weedy relative have been used for generating nontransgenic HRCs. Agronomic performance of non-transgenic HRCs, often, did not meet the expectations of growers and commodity groups. Scientists therefore began to look at alternative ways to develop HRCs as weed management tools, to manage broad spectrum of weeds.

Transgenic Herbicide Resistant Crops

The initial efforts to develop transgenic HRCs using genetic engineering techniques resulted in the release of bromoxynil-resistant cotton in 1995 and canola in 2000 (Table 2). However, bromoxynil-resistant cotton and canola were discontinued because bromoxynil is not a broad-spectrum herbicide and it failed to provide effective

Table 1. Examples of non-transgenic herbicide-resistant crops, developed by traditional breeding/selection techniques

Selection method	Herbicide family	Crop	Year of disclosure
Whole plant	Triazine	Canola	1984
Microspore selection	Imidazolinone	Canola*	1989
Seed mutagenesis	Sulfonylurea	Soybean*	1987
	Imidazolinone	Wheat*	1991
	Imidazolinone	Rice*	1998
	Triazine	Wheat	2006
Pollen mutagenesis	Imidazolinone	Corn/Maize*	1992
Tissue culture	ACCase inhibitor	Corn/Maize	1992
	Imidazolinone	Corn/Maize*	1991
	Triazine	Soybean	1996
	Sulfonylurea	Canola	2002
Cell selection	Imidazolinone	Sugarbeet	1998
Transfer from weedy relative	ALS inhibitor	Sunflower*	2000
	ALS Inhibitor	Sorghum	2008
	ACCase inhibitor	Sorghum	2008

Adapted from Duke (2005) and Green and Castle (2010).

ACCase, acetyl-CoA carboxylase; ALS, acetolactate synthase.

Crops indicated with * are commercially available with resistance to corresponding herbicide family (in the same row).

Table 2. Current transgenic herbicide-resistant crops and associate trait genes

Crop	Resistance trait	Trait gene	First Sales
Alfalfa	Glyphosate	*cp4 epsps*	2005
Canola	Glyphosate	*cp4 epsps* and *goxv 247*	1996
	Glufosinate	*pat*	1995
	Bromoxynil	*bxn*	2000
Cotton	Bromoxynil	*bxn*	1995
	Glyphosate	*cp4 epsps*	1996
		Two *cp4 epsps*	2006
		zm-2mepsps	2009
	Glufosinate	*bar*	2004
Corn/Maize	Glyphosate	Three modified *cp4 epsps*	1998
		Two *cp4 epsps*	2001
	Glufosinate	*pat*	1997
	Glyphosate + glufosinate	Double stack	Not clear
Soybean	Glyphosate	*cp4 epsps*	1996
		cp4 epsps	2009
	Glufosinate	*pat*	2009
Sugarbeet	Glyphosate	*cp4 epsps*	2007

Partly adapted from Green (2009, 2011) and updated.

and economical weed control beyond a few susceptible weeds. The real turning point occurred in 1996-97 with the commercial release of glyphosate-resistant (GR) canola, soybean, and cotton. These crops allowed the application of glyphosate multiple times in the growing season without the risk of crop injury. Glyphosate was, hitherto, used non-selectively for weed control in vineyards, orchards, rights-of-way, industrial areas, and railroads. It has recently been deemed as “a once-in-a-century herbicide” (Duke and Powles, 2008) for its broad weed spectrum, reasonable cost, favorable environmental properties, and association with the widely popular GR crops. Additional GR crops, alfalfa, corn, and sugarbeet, were released to growers between 1998 and 2007.

Glufosinate-resistant canola, released as early as in 1995, did not catch on as well as GR canola. Glufosinate-resistant cotton was commercially made available in 2004, but was inferior in yield as compared to GR cotton. A new generation of GR cotton was developed in 2006 that had enhanced tolerance to glyphosate while at the same time allowing in-season glyphosate applications during the reproductive phase of the crop. New GR and glufosinate-resistant soybean germplasm was released in 2009. Glufosinate-resistant corn was commercialized for the first time in 1997 and was combined with GR corn varieties as a ‘double stacked trait’ in the mid 2000s. This allowed control of a broader spectrum of weeds with the two unique modes-of-herbicide action. Invariably, most transgenic cotton and corn HRCs on the market also carry insect-resistance traits (*Bt* trait), which will not be discussed here.

Worldwide Use Of Transgenic Crops

According to a 2010 database maintained by a non-profit environmental risk assessment institution, 60% (87 of 144) of all transgenic/biotechnological events reported involved herbicide resistance traits (CERA, 2010). All herbicide resistance traits that had regulatory approval did not result in commercialization and sales. In 2003, 67.7 million ha were planted to transgenic crops (both herbicide and insect resistance) in the world (Dill, 2005) and by 2010, the area planted to transgenic crops increased to 148 million ha (James, 2010) (Table 3). The following section discusses this rapid growth, adoption, and distribution of transgenic crops around the world, based on data from International Service for the Acquisition of Agri-Biotech Applications (James, 2010).

The cumulative area planted to transgenic crops from 1996 to 2010 exceeded 1 billion ha. An unprecedented 87-fold increase in transgenic crop hectarage, from 1.7 million ha in 1996 to 148 million ha in 2010, makes transgenic crop technologies the most widely accepted in crop husbandry. Since 1996, the only year-to-year double digit (10%) growth in transgenic crop area was from 2009 to 2010. While the number of countries that planted transgenic crops increased to 29 in 2010 from 25 in 2009, the top ten countries each grew more than 1 million ha for the first time. Of the 29 countries growing transgenic crops, 19 were developing and 10 were developed. About 40 countries are expected to grow transgenic crops by 2015. In 2010, 90% (14.4 million) of the 15.4 million farmers growing transgenic crops around the world were from developing countries. Developing countries farmed 48% of the world’s transgenic crops in 2010, with a trend towards exceeding developed nations by 2015. The developing countries taking the lead in growing transgenic crops are China, India, Brazil, Argentina and South Africa. Brazil increased its area of transgenic crops by 4 million ha, more than any other country. In India, a spectacular adoption rate of transgenic *Bt* cotton of 86% was recorded in 2010. More than half (59%) of the world’s population lives in the 29 countries where the 148 million ha of transgenic crops were grown in 2010. Also more than half (52% or 775 million ha) of the nearly 1.5 billion ha of cropland in the world is presently in the 29 countries, where approved transgenic crops were grown in 2010. Transgenic crops, for the first time, accounted for at least 10% of the 1.5 billion ha of all cropland in the world, providing a stable base for future growth (James, 2010).

Among the HRCs, soybean was the most dominant transgenic crop in 2010, occupying 73.3 million ha or 50% of global area planted to transgenic crops. Among the traits, herbicide resistance trait remained the most planted trait. In 2010, herbicide resistance crops: soybean, maize, canola, cotton, sugarbeet, and alfalfa accounted for 61% (or 89.3 million ha) of the global transgenic area (148 million ha). Stacked traits, where more than one transgenes occur in a crop variety, are increasingly becoming important for weed control and economic reasons. In 2010, eight of 11 countries planting stacked trait crops were developing nations.

While 29 countries planted commercialized transgenic crops in 2010, an additional 30 countries, totaling 59 have granted regulatory approvals for transgenic crops import for food and feed use and for release into the environment since 1996. It is expected that the total area planted to biotech crops will increase to 200 million ha cultivated by 20 million farmers in 40 countries by 2015. The global value of the transgenic seed market alone was valued at $11.2 billion in 2010 with commercial biotech maize, soybean grain, and cotton valued at an estimated $150 billion for 2010 (James, 2010).

Impact of Herbicide-resistant Crops

Weed control

Presently, glyphosate-resistant and glufosinate-resistant crops are the only two transgenic HRCs grown. Bromoxynil-resistant crops although commercialized were discontinued for economic reasons. The spectacular increase in area planted to HRCs by the farmers would not have happened if there were no economic and weed control benefits from their use. Simple and flexible weed control programmes can be designed, *viz.* post-emergence only (e.g., glyphosate, glufosinate), tank-mixtures, or a pre-emergence followed by post-emergence herbicide applications as needed for each HRC. A broad spectrum of weeds can be controlled with glyphosate in GR crops and glufosinate in glufosinate-resistant crops. HRCs provide greater flexibility in application timing. For example, glyphosate can be applied from emergence to flowering in GR crops. Extensive research in the USA and elsewhere has shown that one to two timely applications of glyphosate or glufosinate following pre-emergence herbicides can provide effective control of a broad spectrum of weeds (Gianessi 2005; Reddy 2001; Reddy and Whiting 2000). Because of efficient and consistent weed control and economic benefits, the farmers have continued to plant more area in the HRCs each year.

Environmental effects

Transgenic crops have positively impacted the environment in several ways. First is the unprecedented change in herbicide use patterns. GR crops have dominated the market share; as a result glyphosate use increased rapidly with

Table 3. Global area of transgenic crops planted in 2003 and 2010 by country

Country	2003		2010		Crops
	Area (million ha)	% of total planted area	Area (million ha)	% of total planted area	
USA	42.8	63	66.8	45	Maize, soybean, cotton, canola, sugarbeet, alfalfa, papaya
Argentina	13.9	21	22.9	15	Soybean, maize, cotton
Canada	4.4	6	8.8	6	Canola, maize, soybean, sugarbeet
Brazil	3.0	4	25.4	17	Soybean, maize, cotton
China	2.8	4	3.5	2	Cotton, papaya, poplar, tomato, sweet pepper
South Africa	0.4	1	2.2	1	Maize, soybean, cotton
Australia	0.1	<1	0.7	<1	Cotton, canola
India	0.1	<1	9.4	6	Cotton
Romania	<0.1	<1	<0.1	<1	Maize
Uruguay	<0.1	<1	1.1	1	Soybean, maize
Spain	<0.1	<1	0.1	<1	Maize
Mexico	<0.1	<1	0.1	<1	Cotton, soybean
Philippines	<0.1	<1	0.5	<1	Maize
Columbia	<0.1	<1	<0.1	<1	Cotton
Bulgaria	<0.1	<1	-	-	-
Honduras	<0.1	<1	<0.1	<1	Maize
Germany	<0.1	<1	<0.1	<1	Potato
Indonesia	<0.1	<1	-	-	-
Paraguay			2.6	2	Soybean
Pakistan			2.4	2	Cotton
Bolivia			0.9	1	Soybean
Myanmar			0.3	<1	Cotton
Burkina Faso			0.3	<1	Cotton
Chile			0.1	<1	Maize, soybean, canola
Portugal			<0.1	<1	Maize
Czech Republic			<0.1	<1	Maize, potato
Poland			<0.1	<1	Maize
Egypt			<0.1	<1	Maize
Slovakia			<0.1	<1	Maize
Costa Rica			<0.1	<1	Cotton, soybean
Sweden			<0.1	<1	Potato
Total	67.7	100	148	100	

Adapted from Dill (2005) and James (2010).

Transgenic crops include herbicide-resistance and other traits including insect resistance, drought/salinity resistance, value added traits such as nutrition, etc.

a concomitant decrease in the use of other herbicides in the USA (Nandula *et al*., 2005; Reddy, 2001; Reddy and Norsworthy, 2010). For example, the total active ingredient of glyphosate use has increased in soybean from 2.9 million kg/year in 1995 (year before GR soybean was commercialized) to 41.7 million kg/year in 2006 (USDA, 2012). This represents a 14-fold increased use of glyphosate in soybean since commercialization of GR technology. Furthermore, the amount of pesticides applied to cropland has been significantly reduced. The cumulative reduction in pesticides for the period 1996 to 2009 was estimated at 393 million kg of active ingredient (James, 2010). This pesticide reduction resulted in saving 8.8% in pesticides, which is equivalent to a 17.1% reduction in the associated environmental impact of pesticide use on these crops. In 2009 alone, a reduction of 39.1 million kg of pesticide active ingredient was achieved (James, 2010). Second, reduced combustion of fossil fuels and resultant decrease in CO_2 emissions has been achieved through zero or less ploughing. In 2009, the reduction in CO_2 emissions into the environment through decreased fossil fuel use and ploughing/tillage totaled 17.6 billion kg of CO_2 or the equivalent of removal of 7.8 million cars off the road (Brookes and Barfoot, 2011). Third, soil and moisture has been conserved by optimization of zero or reduced tillage practices. In the United States alone, cultivation of GR soybean, maize, and cotton combined reduced soil erosion by 1 billion tons annually (Smith, 2010).

Weed shifts

Wide spread adoption and monoculture of HRCs has resulted in the evolution of herbicide resistant weeds as well as shift in weed spectrum towards non-native and non-cropland weeds in agronomic crop environments. A weed species shift can involve a change in density or diversity in weed flora in a crop production system as a consequence of prevailing weed management practices. An integrated weed management programme is needed to prevent and/or delay shifting weed spectrums and sustaining HRCs in the long term (Reddy and Norsworthy, 2010).

Economic issues

Since their introduction in 1996, over 30 million ha of transgenic HRCs have been planted, accounting for 80% of soybean and 70% cotton area in the US by 2003 (Gianessi 2005). It is estimated that the cultivation of HRCs from 1996 to 2003 has saved US farmers $1.2 billion, due to savings in costs from conventional herbicides, application costs, tillage and hand weeding. Adoption of GRCs by US agricultural industry has reduced herbicide use by 16.6 million kg between 1996 and 2003.

Herbicide-resistant crops as weeds

Volunteer HRCs could become an issue if the herbicide resistance trait was the same in the volunteer plants as well as the HRC being grown in the current season. The HRC volunteers could potentially harbour insect pests and diseases acting as alternate hosts or increasing pest population or intensity in the next season when the HRC volunteer is planted as a crop in a rotation. Pollen from volunteer HRCs can move across the landscape and contaminate conventional crops and/or home-garden flora, which is essentially gene flow. For example, pollen movement from HR corn to sweet corn.

Gene flow and biodiversity

Gene flow in plants can occur by pollen, seed, or vegetative propagules. To date, there have not been many concerns regarding the flow of gene(s) encoding for transgenic herbicide-resistant traits except for herbicide-resistant canola (Légère, 2005). The formation of hybrids is possible, given certain conditions as synchronous flowering, successful fertilization, and viable offspring are satisfied (Légère, 2005). Movement of genes and transgenes encoding for herbicide resistance by pollen flow among cultivars has resulted in multiple herbicide resistance to glyphosate, glufosinate, bromoxynil, or imidazolinone in volunteer plants of canola (Beckie *et al*., 2003).

Another example of potential transgene flow has been in the case of GR creeping bentgrass (*Agrostis* spp.) (Mallory-Smith and Zapiola, 2008). Bentgrass can propagate itself vegetatively via stolons and produces extremely high number of seeds (13,500 g^{-1}). While the probability of production of hybrids between transgenic HRCs and their weedy relatives remains low, the potential for widespread inheritance of herbicide resistance genes by weeds from HRCs remains with rapid evolution of herbicide resistant weeds and weed species shifts. For example, gene flow via pollen from transgenic maize to teosinte (*Zea luxurians, Z. perennis*, and *Z. mexicana*) in Mexico and Central America, and from transgenic soybean to wild soybean (*Glycine soja* and *G. gracilis*) in Asia and Australia is possible. Post harvest volunteers and dormant seed from HRCs can act as a reservoir for future gene flow. Consequences of gene flow from HRCs to weeds include costly alternative management options, redesign of crop rotations, increase in organic produce production costs, and hybrid weeds acting as alternate hosts for insects and diseases. Natural resources conservation groups have also voiced their opposition to transgenic HRCs fearing reduction in biodiversity.

Ethical considerations

The commercialization of HRCs has sparked a spirited discussion around the world about the inherent risks and benefits from their use. This debate has been particularly fierce in Europe (Madsen and Sandøe, 2005). Majority of the concerns in the public eye were focused on effects of HRCs on the environment, especially, with regards to involvement of a 'transgene' (foreign gene) and associated use of herbicides. Additionally, it was perceived that the long-term effects of HRCs were relatively unknown. HRCs were considered as a wrong choice for achieving sustaining agriculture when the risks do not offset the advantages. Further, HRCs were thought to be artificial and violate a grower's right to choose production of non transgenic crops.

Lack of new herbicides

The tremendous ease-of-cultivation and environmental advantages brought about by HRCs, led by GR crops, have caused a severe reduction in the resources allocated by agrochemical industries towards the discovery and associated development of herbicides with new and unique modes of action. It was recently stated that there has not been a new mode of action in herbicides in the past 20 years (Duke, 2011). Some of the reasons offered were high development costs (approximately $250 million from discovery of a herbicide molecule to development), consolidation of industry, diversion of research and development efforts towards insecticides and fungicides, and unfavorable toxicological properties of candidate herbicide molecules. Despite the current dearth of new molecules, it is hoped that the current widespread herbicide resistance in weeds as well as potential resistance and multiple resistance cases in the near future will spur the agrochemical industry towards herbicide discovery.

Future Herbicide-resistant Crop Technologies

HRCs and other transgenic crops are here to stay. While the benefits of these crops are plentiful, there are certain inherent consequences, some obvious and a few not quite apparent. The most important issue requiring attention following commercialization of HRCs has been the evolution of resistance to herbicide(s) in weed populations. The agrochemical industry, seed companies, and related entities have invested most of their resources in development of the next generation of HRCs (and other transgenic crops) with the aim of diversifying the growers' crop portfolio as well as combating weed resistance by providing cropping technologies that allow application of more than one mode of action herbicides.

New HRC technologies currently under development are outlined in Table 4. All new traits will be stacked with glyphosate. Several of these new technologies are expected to be commercialized in 2012 and soon thereafter. Due to severe regulatory monitoring and approval required, some of these technologies may be indefinitely put on the shelf for reasons not made public or beyond the scope of this discussion. For example, a new mechanism of resistance to glyphosate was developed (Castle *et al.*, 2004) and stacked with a high resistance trait from a different mechanism of action of herbicides, but was withdrawn a year or two from commercialization. Some of the technologies involving dicamba and 2,4-D resistance have also associated formulations specifically developed for application with these new stacked technologies. An additional technological advancement is the availability of air induction nozzles (to reduce spray drift by producing larger droplets while reducing the percentage of fine droplets) used with the 2,4-D and dicamba resistance traits.

Table 4. Future transgenic herbicide-resistant crops with earliest expected commercialization in 2012

Crop	Stacked multiple herbicide resistance traits	Year to be commercialized (subject to change)
Cotton	Glyphosate + glufosinate	2012
	Glyphosate + glufosinate + dicamba	2014
	Glyphosate + glufosinate + 2,4-D	2016
Corn/Maize	Glyphosate + glufosinate + 2,4-D	2015
	Glyphosate + dicamba	2014/2015
	Glyphosate + ALS inhibitors	2016
Soybean	Glyphosate + glufosinate	2012
	Glyphosate + glufosinate + dicamba	2013
	Glyphosate + ALS inhibitors	2013
	Glyphosate + glufosinate + 2,4-D	2014
	Glyphosate + HPPD	2015
	Glyphosate + glufosinate + HPPD	2015/2016

Data based on Gerwick (2010), personal communications, and press reports.
ALS, acetolactate synthase; HPPD, 4-hydroxyphenylpyruvate dioxygenase; 2,4-D, 2,4-diclorophenoxyacetic acid.

CONCLUSIONS

Introduction of HRCs, particularly GR crops, have revolutionized weed management especially in North and South America. HRCs as weed management tools have allowed farmers to manage weeds more effectively and economically. High levels of adoption of HRCs have dramatically increased the use of herbicides, with a following increase in resistant weeds and weed species shifts. Management of resistant weeds requires alternative strategies that should not rely solely on different herbicide mechanisms of action. Exciting new technologies such as new generation of HRCs are in development or approaching commercialization in the next few years, which will help manage resistant weeds and reduce their spread. The benefits of HRCs are multifold, with savings in fuel costs coupled with inherent positive effects on the environment, and prevention of top soil loss from erosion arising from zero to low requirement of tillage operations topping the list of benefits. HRCs have revolutionized crop production in the developed world, and the benefits are gradually spilling over to the developing world. HRCs that are currently in development, further warrant sustainability and stewardship of already commercialized HRCs.

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