Herbicide-Resistant Crops — Their Impact on Weed Science*

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Abstract: Crops made resistant to herbicides by biotechnology are being widely adopted in North America and other parts of the world. The major impact will be from crops containing transgenes imparting resistance to post-emergence, non-selective herbicides for which there is only one commercially successful analogue, such as glyphosate and glufosinate. These products allow the farmer to more effectively use reduced- or no-tillage cultural practices, eliminate use of some of the more environmentally suspect herbicides, and use fewer herbicides to manage nearly the entire spectrum of weed species. In some cases, non-selective herbicides used with herbicide-resistant crops even reduce plant pathogen problems because of their toxicity to some microbes. There is concern among weed scientists that eventual over reliance on fewer weed management strategies will result in evolution of resistance to the more useful herbicides and/or weed population shifts to naturally resistant species. Environmentalists are concerned with gene flow from transgenic crops to closely related wild relatives; however, herbicide resistance transgenes alone confer no fitness advantage outside of fields treated

with the herbicide, making it unlikely that they would affect plant populations in natural areas. The next ten years should clarify the eventual impact of these powerful new tools on weed science and weed management.

Key words: Glufosinate, glyphosate, herbicides, herbicide resistance, transgenic crops

Introduction

Weed science became an organized discipline with the introduction of synthetic herbicides in the 1940s. The discipline grew with and focused on an expanding array of new herbicides with increasing efficacy and utility in crop production. The success of this paradigm has generally satisfied farmers and those that control public funding of weed science research. Compared to other pest management disciplines, considerably less effort has been expended on alternative methods of weed management. The proportion of pesticides used in the U. S. that are herbicides continues to grow, and is now close to 75% of the crop protection pesticide market (Fig. 1).

The herbicide market for major crops has been very mature for several decades. Discovery of a new herbicide that provides the farmer with a better and more economical tool than what is already available is now very difficult. Furthermore, the cost of regulatory approval of herbicides has increased significantly. Nevertheless, introduction of new herbicides for major crops continues unabated because of the profit potential of a successful herbicide.

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デューク, ステフェン オスカー: 除草剤抵抗性作物—その雑草科学へのインパクト

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Fig.1. 1997 Crop protection pesticide sales in U. S.³⁾

Biotechnology is now providing an alternative to discovery of new herbicides for particular crops. Crops are being genetically modified by biotechnology to be resistant to existing herbicides, thus widening the potential market and usefulness of these established products. In some cases, this has been achieved by simple selection for resistance in cell or tissue culture, but the most successful approach has been to genetically engineer crops with resistance transgenes.¹⁴⁾ The subject of herbicide-resistant crops (HRCs) has been the focus of several books and reviews.^{e.g., 7,10-14,19,20)} HRCs are also termed herbicide-tolerant crops by some, particularly by those involved in producing them. However, I will use the term preferred by most weed scientists and those who study resistance to pesticides.⁸⁾ The impact of this new technology on the pesticide industry, weed science, and weed management may be profound. This paper attempts to predict some of these impacts.

Driving Forces

Several significant external forces exist that will influence weed science and weed management and, thus, how this new technology for weed management will be utilized.

In Europe and North America, there are rapid and profound changes in the pesticide industry. Companies that relied on new and better pesticides for future profit are investing heavily in plant biotechnology, presumably with the intention of making a significant portion of future profits from transgenic crops. Consolidation of the pesticide and biotechnology industries is dramatic.

There is opposition to two components of modern crop protection technologies. In most of the world, there is a strong sentiment to reduce synthetic pesticide use. As mentioned earlier, most of the pesticides used in developed countries are herbicides (*e. g.*, Fig. 1). Opposition to transgenic crops is variable, with some of the strongest opposition in certain European countries.⁶⁾

Population pressure on land resources will increase dramatically in the near future unless agricultural productivity (yield per unit area) grows concomitantly with population.^{1,24)} New technology will be needed to increase crop productivity in a sustainable fashion, without converting more natural areas to cropland.

Within weed science, there are more specific influences that will affect how HRCs are used. These include the movement towards integrated pest management, which until recently has largely ignored weed management. In the U. S., there is a strong and steady adoption of reduced- and no-tillage agriculture, resulting in greater reliance on post-emergence herbicides for weed management. The occurrence of weeds with evolved herbicide resistance is growing exponentially.⁸⁾ This growing problem has not reached the level of severity of insecticide resistance, but in isolated cases, the impact has been severe. Precision agriculture is being rapidly adopted and will probably reduce herbicide use. Expert decision-making computer pro-

grams have the potential to more accurately determine the most appropriate timing, application rate, and pesticide to apply for maximum economic return. This technology could also reduce herbicide use. Considering the many external and internal forces and changes that are affecting weed science, predictions of the impact of HRCs on weed science can only be made with a significant level of uncertainty.

The Impacts of Herbicide-Resistant Crops

Over the past few years, several HRCs, both transgenic and non-transgenic, have become available in North America (Table 1). Other HRCs will soon be introduced. Of these, glyphosate- and glufosinate-resistant crops appear to have the greatest potential for wide adoption. They are being developed for most major crops. These two herbicides are non-selective, so that the farmer may be able to substitute one herbicide for several. Furthermore, they are foliar-applied herbicides that lend themselves well to the rapid movement toward no- or reduced-tillage agriculture in North America. Finally, they offer the manufacturers of these herbicides the greatest advantage in linking their own

chemical product to the resistant crop, because there are no chemical analogues of either glyphosate or glufosinate that could be used with these crops. The economic advantage for the manufacturer could be lost when the patent rights for production of these herbicides expire. A potential method of circumventing the use of herbicides other than those paired with the HRC by the manufacturer is to formulate the herbicide with a compound that will induce the resistance gene(s) in the HRC.

The herbicide industry appears to be rapidly transforming from a chemistry-based industry into a biotechnology-oriented industry. The larger pesticide producers of the U. S. and Europe have invested heavily in plant biotechnology and in the crop seed industry. The early part of this shift was driven by HRCs. Only a few years ago, most of the field release approvals for transgenic crops in the U. S. were for HRCs. However, as of late 1997, only 29% of the total permits issued and notifications acknowledged for transgenic crops were for herbicide resistance (Fig. 2). Imparting resistance to a successful herbicide in a new crop can be an economical method of expanding the market of a product for which the company has already gained approval, recognition, and manufacturing expertise.

Whether production of crops resistant to broad herbicide classes (*e. g.*, protoporphyrinogen oxidase inhibitors) will be a viable strategy for the agrochemical industry is unclear because of potential problems in linking the crop to only one herbicide from a class in which there are many commercially available analogues. Furthermore, most herbicides, other than glyphosate and glufosinate, do not have the advantages conferred by a broad target spectrum over currently used selective herbicides. An increas-

Table 1. Herbicide-resistant crops that are now available in North America.

Herbicide	Crop	Year available
Bromoxynil	cotton	1995
Cyclohexanediones (sethoxydim)*	maize	1996
Glufosinate	canola	1997
	corn	1997
Glyphosate	soybean	1996
	canola	1996
	cotton	1997
Imidazolinones*	maize	1993
	canola	1997
Sulfonylureas*	soybean	1994
Triazines*	canola	1984

*not transgenic

Field Releases*: Most Frequent Categories
1987 to 1998 (1/31/98)

* Permits Issued and
Notifications Acknowledged

Fig.2. From the USDA, Animal Plant Health Inspection Service web site (<http://www.aphis.usda.gov/biotech/>).

ingly attractive herbicide discovery strategy is to find broad spectrum phytotoxins with few effective analogues and to co-develop them with crops made resistant by biotechnology.

HRCs offer several advantages to the farmer. In most cases, the farmer can design simpler weed management strategies, based on fewer herbicides.²⁰⁾ Glyphosate and glufosinate are ideal herbicides for no-tillage agriculture, allowing the farmer to spray at or near planting and then as needed during crop development. In some cases, HRCs will lower the cost of weed control. As with any new technology, the economic benefits are greatest for those who use it first.²³⁾ The overall environmental impact of managing weeds in HRCs is generally lower than that with selective herbicides combined with tillage. HRCs can be especially useful for eradication of parasitic weeds.¹⁵⁾ Finally, with certain non-selective herbicides, the herbicide may also have activity against plant pathogens. For example, glufosinate inhibits the infection of glufosinate-resistant *Agrostis palustris* with several plant pathogens^{1,8)}

More research needs to be done on the secondary effects of pesticides in order to fully determine their roles in integrated pest management.¹⁾

Although HRCs for most major crops will be available in the near future, the availability of biotechnology-produced herbicide-resistant minor crops will be limited. Slower development and introduction of minor crop HRCs are due to the same reason that companies are reluctant to register their pesticides for small markets - a poor economic return, considering the investment and risk. At this time there is no strong sentiment for public funding for the creation of minor crop HRCs.

A few potential problems exist with HRCs. There is greater risk of herbicide "drift" problems when resistant and susceptible cultivars of the same crop have the same appearance. The risk of over reliance on a single weed management technology gives weeds more opportunity to evolve resistance or for species to shift to fit the ecological vacuum presented by effective control of the weed species now present. Evolved resistance to glyphosate and glufosinate will probably be slower than to many other herbicides.^{5,9)} Nevertheless, glyphosate resistance has already evolved in *Lolium rigidum* in more than one population in Australia.^{21,22)} Most weed scientists agree that, with these herbicides, population shifts to naturally resistant weed species will be a bigger problem than evolution of resistance.²⁰⁾ Where crop rotation is practiced, HRCs can become weeds in the next crop if the second crop is an HRC engineered to be resistant to the same herbicide to which the original crop was resistant.

Introgression of the transgene into weeds is possible with some crops. For example, rice can interbreed with red rice,¹⁷⁾ a feral form of rice that is a serious weed problem in some

areas of the world. The herbicide resistance transgene alone confers no fitness advantage in areas where the herbicide is not sprayed. Thus, if it is transferred to a related plant species, the biggest concern is for the farmer who must cope with the herbicide-resistant weed. A herbicide resistance transgene in a crop can greatly increase the chance of survival of interspecies crosses by eliminating competition of other herbicide-susceptible weeds.¹⁶⁾ If the crop also contains transgenes conferring other survival enhancing traits, such as resistance to insects and/or pathogens, the resulting cross and further backcrosses with the weedy parental species might have enhanced fitness outside the agricultural setting, resulting in ecological disruption.

There is perhaps more potential for unexpected pleiotropic effects of transgenes than with non-transgenes, because these genes have not evolved to function in coordination with the rest of the genome. Furthermore, positional effects in the genome, independent of pleiotropic effects, can be problematic. Lastly, inconsistent expression of the transgene in time or in the proper tissues is a potential problem. Some transgenic, herbicide-resistant varieties have not been evaluated by public sector scientists to the extent that traditional varieties have been tested, causing unresolved questions about yield and quality.^{e.g.,2)}

Despite these potential problems, in most cases, HRCs have been welcomed enthusiastically by North American farmers. The success of HRCs will probably delay the intensive search for non-herbicide-based weed management technology. However, the utility of the most successful HRCs will eventually decrease, resulting in the need for alternative herbicides or weed control methods. There is some concern that the increasing

consolidation of the biotechnology and agrochemical industries may reduce competition in finding new commercial weed management solutions, perhaps increasing the importance of public sector research in this area.

Current trends indicate that within a few years almost all acreage of the major crops grown in North America, except perhaps wheat, will be herbicide resistant. This level of acceptance by farmers strongly indicates that this technology has improved the economics and efficiency of weed management. Weed science research will be strongly impacted by this new technology.

Conclusions and Speculations

Several unpredictable factors can affect how and to what extent HRCs are used the resulting impact of their use. These include international regulation of transgenic crops, unexpected new technologies, the ability of the pesticide/biotechnology industry to protect and recoup their investments, and the speed of weeds in evolving, adapting and shifting in response to new technologies.

Clearly, in most major crops, HRCs are (or soon will be) strongly impacting weed management choices. In many crops their use will decrease the cost of effective weed management in the short to medium term. Their use will speed the adoption of reduced- and no-tillage agriculture, greatly reducing the environmental damage of farming by reducing soil erosion by both wind and water, and by reducing use of herbicides more likely to be found in surface and ground water. Herbicide resistance and new weed species problems that arise as a result of this technology will be dealt with by traditional methods, such as rotating herbicides, mixing herbicides, and rotating crops. Over reliance on HRCs could prematurely reduce their usefulness. However, they offer the farmer a powerful new

tool that, if used wisely, can be incorporated into a integrated pest management strategy that can be used for many years to more economically and effectively manage weeds.

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