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WEED MANAGEMENT: IMPLICATIONS OF HERBICIDE RESISTANT CROPS\textsuperscript{1,2}

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\textbf{ABSTRACT}

Crops made resistant to herbicides by biotechnology are being widely adopted in North America and entering other parts of the world. Those containing transgenes that impart resistance to post-emergence, non-selective herbicides such as glyphosate and glufosinate will have the major impact. 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 reduce plant pathogen problems because of the chemicals’ toxicity to certain microbes. There is concern among weed scientists that over-reliance on fewer weed management strategies will result in evolution of resistance to the more useful herbicides and/or population shifts to naturally resistant weed species. Although environmentalists are concerned with the potential impacts of gene flow from transgenic crops to wild relatives, herbicide resistance transgenes confer no fitness advantage outside of fields treated with the herbicide. Thus it is unlikely that they would affect plant populations in natural areas. The next decade should clarify the eventual impact of these powerful new tools on weed science and weed management.

\textbf{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 US that are herbicides continues to grow and is now close to 75% of the crop protection pesticide market (see Figure 1).

The herbicide market for major crops has been mature for several decades. Discovery of weed control compounds better and more economical than what is already available is very difficult. Furthermore, the cost of regulatory approval has increased significantly. Nevertheless, introduction of new herbicides for major crops continues unabated because of the profit potential of a successful new product. In most of the world, however, there is a strong sentiment to reduce synthetic pesticide use.

Biotechnology is now providing an alternative to the discovery process for new herbicides. Crops are being genetically modified to be resistant to existing herbicides, thus widening the potential market and usefulness of these established products. In some cases, resistance has been achieved by simple selection in cell or tissue culture. The most successful approach has been to introduce resistance genes by genetic engineering. Opposition to transgenic crops is variable, with some of the strongest opposition in certain European countries (Burghardt 1998). 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.

\textsuperscript{2} Modified from: Duke SO. 1998. Herbicide resistant crops—their influence on weed science, \textit{Journal of Weed Science and Technology} (Zasso-Kenkyu, Japan) 43:94-100.}
Figure 1. The chart shows crop protection pesticide sales in US in 1997 (Anonymous 1998b).

DRIVING FORCES

Significant external forces will influence weed science and weed management and thus how biotechnology will be utilized for weed management. In Europe and North America, there are rapid and profound changes in the pesticide industry. Companies that historically 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.

Population pressure on land resources will increase dramatically in the near future unless agricultural productivity (yield per unit area) grows concomitantly with population. 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 herbicide resistant crops (HRCs) are used. These include the movement toward integrated pest management, which until recently has largely ignored weed management. In the US, 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 rapidly. This problem has not yet reached the severity of insecticide resistance, but in isolated cases the impact has been severe. Precision agriculture is being readily adopted and is expected to reduce herbicide use. Expert decision-making computer programs have the potential to more accurately determine the most appropriate timing, application rate, and pesticide to apply for maximum economic return. Considering the many external and internal forces and changes that are affecting weed science, predicting the impact of HRCs on weed science carries 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 (see Table 1); others will soon be introduced. Of these, glyphosate- and glufosinate-resistant crops appear to have the greatest potential for wide adoption. These two herbicides are non-selective, so the farmer may be able to substitute one herbicide for several. Furthermore, they are foliar-applied herbicides that lend themselves well to no- or reduced-tillage agriculture. Finally, they offer manufacturers the significant advantage of linking their own chemical product to the resistant crop, because there are no analogues of either glyphosate or glufosinate that could be used with these crops. The economic advantage for the manufacturer could be lost when the patents on these herbicides expire. At that point, manufacturers could shut out competitors by engineering the HRC with an inducible promoter and formulating the herbicide with a compound that will induce the expression of resistance gene(s) in the HRC.

The herbicide industry appears to be rapidly transforming from a chemistry-based to a biotechnology-oriented industry. The larger pesticide producers of the US and Europe have invested heavily in plant biotechnology and the seed industry. Each year since the first experimental releases in 1987, HRCs have accounted for nearly one-third of field tests conducted under USDA authority. Imparting resistance to a successful herbicide in a new crop can be an economical method of expanding the market for a product for which the company has already gained approval, recognition, and manufacturing expertise.
Table 1. Herbicide resistant crops now available in North America.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Crop</th>
<th>Year Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bromoxynil</td>
<td>cotton</td>
<td>1995</td>
</tr>
<tr>
<td>Cyclohexanediones*</td>
<td>maize</td>
<td>1996</td>
</tr>
<tr>
<td>Glufosinate</td>
<td>canola</td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td>corn</td>
<td>1997</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>soybean</td>
<td>1996</td>
</tr>
<tr>
<td></td>
<td>canola</td>
<td>1996</td>
</tr>
<tr>
<td></td>
<td>cotton</td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td>corn</td>
<td>1999</td>
</tr>
<tr>
<td>Imidazolinones*</td>
<td>maize</td>
<td>1993</td>
</tr>
<tr>
<td></td>
<td>canola</td>
<td>1997</td>
</tr>
<tr>
<td>Sulfonylureas*</td>
<td>soybean</td>
<td>1994</td>
</tr>
<tr>
<td>Triazines*</td>
<td>canola</td>
<td>1984</td>
</tr>
</tbody>
</table>

*not transgenic

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 currently used herbicides are selective and do not have the advantages conferred by a broad target spectrum such as glyphosate and glufosinate. An increasingly 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. 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 many 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. The overall environmental impact of managing weeds in HRCs is generally lower than that of using selective herbicides combined with tillage. HRCs can be especially useful for eradication of parasitic weeds (Joel et al. 1995). Finally, with certain non-selective herbicides, the herbicide may also have activity against plant pathogens. For example, glufosinate inhibits the infection of glufosinate-resistant creeping bentgrass with several plant pathogens (Liu et al. 1998). More research needs to be done on the secondary effects of pesticides in order to fully determine their roles in integrated pest management (Altman 1993).

Although transgenic herbicide resistant varieties of most major crops will be available in the near future, comparable minor crops will lag behind. Companies are slow to develop and introduce minor HRCs for the same reason they 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. Overreliance on a single weed management technology gives existing weeds more opportunity to evolve resistance to that control mechanism. Alternatively, overuse of one management strategy may allow other weed species to become adapted in the ecological vacuum created by effective control of the weed species now present. Resistance will probably be slower to evolve to glyphosate and glufosinate than to many other herbicides (Bradshaw et al. 1997; Devine et al. 1993). Nevertheless, glyphosate resistance has already appeared in more than one population of ryegrass in Australia (Powles et al. 1998; Pratley et al. 1996). Most weed scientists agree that with these herbicides, population shifts to naturally resistant weed species will be a bigger problem than evolution of resistance (Owen 1997). Where crop rotation is practiced, HRCs can become weeds in a crop rotation system if the second crop is an HRC engineered to be resistant to the same herbicide to which the original crop was resistant.

Introgression of crop genes and transgenes into weeds is possible with some crops. For example, rice can interbreed with red rice (Langevin et al. 1990), a feral form that is a serious weed problem in some rice-growing areas of the world.
A herbicide resistance transgene alone confers no fitness advantage in areas where the herbicide is not sprayed. Thus, if it is transferred from the crop to a related weed species, the biggest concern is for the farmer who must cope with the herbicide resistant weed. An herbicide resistance transgene in a crop can greatly increase the chance of survival of interspecies crosses by eliminating competition of other herbicide susceptible weeds (Keeler et al. 1996). 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 confer enhanced fitness outside the agricultural setting, resulting in ecological disruption.

There is perhaps more potential for unexpected pleiotropic effects with transgenes than 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, leaving unresolved questions about yield and quality (e.g., Anonymous 1998a).

Despite these potential problems, in most cases HRCs have largely been welcomed enthusiastically by North American farmers. In fact, 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 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.

**CONCLUSIONS AND SPECULATIONS**

Several unpredictable factors can affect how and to what extent HRCs are used and the resulting impact of their use. These factors include international regulation of transgenic crops, unforeseen new technologies, ability of the pesticide/biotechnology industry to protect and recoup their investments, and the speed with which weeds evolve, adapting 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. Overreliance on HRCs could prematurely reduce their usefulness. However, they offer the farmer a powerful new tool that, if used wisely, can be incorporated into an integrated pest management strategy that can be used for many years to more economically and effectively manage weeds.

**References:**


