Weed Management Systems in Transgenic Crops in the Western U.S.

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The first demonstration of Buctril (bromoxynil) resistant cotton in the Western U.S. took place near Phoenix, Arizona in 1993 and generated considerable excitement by demonstrating the potential of genetic engineering to provide new weed control technologies to farmers. In recent years, many genetically based examples of herbicide resistance have been found in weeds or have been introduced into crop plants using genetic engineering (Table 1). Agriculture stands on the threshold of an era of widespread availability of crop plants that have been genetically modified using molecular biological techniques to have herbicide and insect tolerance as well as other agronomically desirable yield and quality traits. For example, the Weed Science Society of America recently listed eight transgenic crop species resistant to several herbicides that have been or soon will be commercialized (Table 2). Many other herbicide resistant transgenic crops are currently under development.

With the widespread commercialization of transgenic herbicide resistant crops (HRC), it is relevant to consider the potential economic consequences of HRC. Will HRC reduce the cost of weed control or economic losses caused by weed interference with crops? Clearly, for many farmers the potential reduction in hand weeding costs and reduction in yield losses due to weed interference make the use HRC and associated herbicides economically attractive. However, total seed and weed control costs with HRC and associated herbicides can be more expensive than existing or older chemical control options so that, depending on weed populations in their fields, not all farmers will adopt new weed control technologies based on HRC. The development of HRC has had economic consequences beyond direct impacts on farmer's weed control strategies. The need for coherent crop seed production and marketing of HRC in conjunction with the associated herbicides has led to the consolidation of herbicide manufacturers and crop seed companies. For example, Monsanto now owns or controls most the companies selling cotton seed to American producers. Seed companies producing transgenic crop seed must manage the development of more varieties considering all of the possible combinations of regionally adapted varieties and potential insect and herbicide resistant traits. Will this increased complexity affect the improvement of basic agronomic traits in transgenic crop varieties? Competitive market place pressures from combined chemical/HRC seed companies has also resulted in consolidation and mergers between other chemical companies. The overall increased economic concentration due to the reduction in numbers of independent seed companies, chemical manufactures, and other companies in the portion of the farm economy from which farmers must purchase equipment and inputs may have long-term consequences on the cost of farming.

Do herbicide resistant crops change grower practices? HRC still require that growers use spray rigs or tractor mounted sprayers for ground applications, and airplanes for aerial herbicide applications. Growers must still worry about the calibration and maintenance of spray equipment and the details of herbicide applications such as the selection of nozzle type and size, pressure, spray volume and adjuvant selection. In contrast, transgenic bacillus thuringiensis (Bt) Corn or Bt Cotton produce an insect toxin and thus can eliminate the need for some insecticide applications. This obviously reduces application and insecticide costs and can have desirable secondary effects such as improved management and utilization of beneficial insects in IPM programs for these crops. HRC merely represent another mechanism for providing selective chemical tools to growers and as such supplement more tradition chemical screening and herbicide discovery efforts of the agrochemical industry. As an example, Staple herbicide was developed for selective weed control in cotton by Dupont using traditional methods at about the same time that Buctril and Roundup resistant cotton varieties were developed by Calgene and Monsanto, respectively, allowing the use of the associated herbicides in cotton.

Herbicide resistant crops and new selective herbicides provide many advantages to growers. They may provide new post-emergence weed control options that provide increased flexibility in designing weed management programs. For example, Roundup Ready (RR) Cotton, BXN Cotton, and Staple herbicide all allow cotton growers to control broadleaf weeds in seedling cotton during a time period when they were previously unable to spray post-emergence herbicides. New herbicide technologies often allow easier or better control of previously difficult to control weeds without the disadvantages associated with other herbicides. For example, sequential Roundup Ultra use in RR cotton often results in better control of purple and yellow nutsedge and less injury to cotton than sequential DSMA and MSMA applications. Similarly Roundup Ultra use in RR Corn provides a means to control Johnsongrass without the soil residual effects on rotational crops of Accent (nicosulfuron) or Beacon (primisulfuron).

Herbicide resistant crops and new selective herbicides may also increase the ability of farmers to use non-chemical or mechanical weed control methods. Weed competition with cotton, particularly early season competition, can severely reduce cotton lint yield. Many studies have investigated various levels of herbicide inputs and cultivation for weed control in cotton. In general, both herbicide use and cultivation reduce cotton yield losses caused by weed competition but acceptable control was not obtained with cultivation alone. Poor weed control in the seed row is the major shortcoming of mechanical weed control. Before effective cotton herbicides became available, growers relied on both meticulous cultivation and hand hoeing for weed control. Torsion weeders and spring-hoe weeders were employed on some cultivators to mechanically remove weed seedlings from within the seed row in larger cotton. These devices consist of pairs of spring steel rods which compress and crumble the soil around the base of cotton plants in such a way that small weed seedlings are uprooted. Although effective, the in-row weeders demand careful attention from tractor drivers and slow travel speeds to minimize crop damage. These disadvantages combined with a shrinking agricultural labor pool and the introduction of preemergence herbicides for cotton in the 1960's resulted in the virtual abandonment of mechanical in-row weeding techniques.

The development of precision guidance systems for farm implements has removed many of the impediments to using in-row weeding techniques. Electro-hydraulic guidance systems actively steer the tractor or implement using a sensing device to detect a furrow or crop row. The sensing device sends electrical signals which actuate a hydraulic steering system. Side-shift guidance systems move the implement laterally with respect to the tractor (and crop row) in response to a sensing system mounted on the implement. Side-shift guidance systems have problems moving cultivators laterally with respect to the crop row because cultivators with a lot of steel in the ground have a large amount of lateral stability as they are pulled through the soil. Most side-shift and articulated guidance systems are packaged in a quick-attach hitch configuration. Articulated guidance systems, like side-shift systems, also move the implement relative to the tractor, but rather than shifting laterally, the implement pivots about a king pin, which is a part of the hitch mechanism. As the implement pivots, resistance on the soil engaging tools increases, which in turn causes the implement to move sideways. Because of the convenience of the quick-hitch configuration and the superior steering capability of articulated guidance systems, articulated guidance systems are now gaining popularity for precision cultivation in Arizona cotton fields.

Topical applications of Staple herbicide or Roundup Ultra on RR cotton, or Buctril on BXN cotton followed by sequential post-directed applications now allow growers to chemically control weeds in the cotton seed row. These herbicides complement the use cultivation with in-row weeders by giving growers the means to control weeds in the cotton seed row early in the season when the cotton is not large enough (i.e., generally less than 8 to 10 inches tall) to allow the use of in-row weeders. Electro-hydraulic guidance systems facilitate the use of in-row weeders by keeping the cultivator precisely aligned on the seed row and also allow close cultivation without crop damage early in the season, thereby reducing the amount of herbicide used (i.e., by reducing the width of the spray band). In both research experiments and demonstrations in Arizona, the combination of the early season herbicide sprays and precision guided cultivation with in-row weeding tools made hand weeding of fields unnecessary by nearly eliminating annual morningglory from cotton fields. In-row weeders are effective in removing broadleaf weed seedlings in the crop row but are ineffective on purple and yellow nutsedge. However, close cultivation does reduce nutsedge competition with cotton. In addition to the substantial saving associated with the elimination of hand weeding costs, the reduced operator fatigue and greater tractor speeds attained with precision guidance also increase productivity and reduce cultivation costs.

There are some drawbacks or disadvantages associated with the development and use of HRC. In cases where the genetically engineered tolerance to a herbicide is not complete, careful use of the herbicide may be required. For example, RR cotton exhibits good vegetative tolerance to glyphosate but flower and boll production can be sometimes be affected by “off label” or inappropriate applications when compensation for fruit loss does not occur. For example, over-the-top applications of glyphosate made after the 4 true leaf stage of growth reduced seed cotton yield 60% at the 10 node stage of growth in an Arizona study. However, post-directed glyphosate applications made after the 4 true leaf stage do not cause yield losses. The requirement that a herbicide be used carefully is a relatively trivial disadvantage compared to the potential HRC to increase the occurrence of herbicide resistant weeds.

The greatest risk posed by the widespread adoption of herbicide resistant crops and associated herbicides is the increased risk of developing herbicide resistant weed populations. Herbicide resistance is the ability of a species to withstand substantially higher concentrations of a herbicide than the wild type of the same plant species or, in other words, the inherited ability to not be controlled by a herbicide. Resistance is commonly associated with biochemical and physiological changes due to a single gene that results in a modified site of herbicide action (i.e., a protein) or the detoxification of a herbicide (Table 1). Resistance can arise through a new mutation (genotype) not previously present in a weed population or a resistant genotype present at a very low frequency in the population may become the most common genotype in a particular population. In both situations, a new genotype conferring herbicide resistance becomes common and a species formerly easily controlled by a particular herbicide is no longer controlled. Weed populations can become resistant to more than one type or class of herbicides. Multiple-resistance is the phenomenon of resistance to herbicides from more than one chemical class after exposure of a population to difference herbicides. Cross-resistance is the phenomenon whereby, following exposure to a single herbicide or herbicide class, a weed population evolves resistance to herbicides from different chemical classes to which it has never been exposed.

The era of chemical weed control started after WWII with the spectacular success of 2,4-D in controlling broadleaf weeds in cereal crops. Weed control provided by herbicides is now an integral part of most modern agronomic systems delivering food and fiber. Given the widespread and persistent use of herbicides it was inevitable that there would be biological repercussions from the reliance on a single method of weed control. Herbicide resistance has been found to phenoxyacetic acids such as 2,4-D (1962), to triazines such as simazine and atrazine (1968), to dinitroanilines such as trifluralin (1973), to bipyridiliums such paraquat (1976), to acetyl coenzyme A carboxylase inhibitors such as the aryloxyphenoxpropanoates (e.g., fluazifop-p) and cyclohexanediones (e.g. sethoxydim and clethodim) in 1982, to substitued ureas such as diuron (1983), to organic arsenicals such as MSMA (1984), to acetolactase synthase inhibitors such as the sulfonylureas (e.g., chlorsulfuron) and the imidazolinones (e.g., imazapyr) in 1986, to carbamates in 1988, and to glyphosate (Roundup) in 1997.

Requirements for the development of resistance are that heritable (i.e., genetic) variation for the herbicide resistance trait exists and that natural selection acts upon the weed population. The degree of selection imposed by herbicide use depends on the efficacy of herbicide (i.e., effectiveness of weed control), the frequency of herbicide use, and the duration of the herbicide effect. The widespread use of HRC can greatly increase the frequency of use of a particular herbicide. In addition, if normal crop selectivity and HRC result in the use of the same chemistry or herbicide in several crops in a rotation, the frequency of use further increases and if a chemistry or herbicide has both postemergence and preemergence herbicide activity the duration of the herbicide effect increases. Both phenomenon alone and especially together (e.g., imidazolinone use in IMI-corn, bean, and alfalfa rotations) increase the risk of developing herbicide resistant weeds.

Management to avoid developing herbicide resistant weeds or to manage existing herbicide resistant weeds involves avoiding total reliance on a single herbicide or class of herbicide chemistry. Management strategies include manipulating herbicide rate where appropriate, alternating herbicides with different target sites, and using herbicide mixtures (i.e., using different mechanisms of action simultaneously). Integrated weed management (IWM) practices are also important in minimizing the use of chemicals. In contrast to chemical weed control, mechanical weed control is generally non-selective (i.e., does not discriminate between plant species or genotypes within a species) in that all species contacted by steel are killed. Other IWM practices useful in avoiding the development of herbicide resistant weeds include limiting seed dispersal of suspected small resistant populations (i.e., eradication) and rotating crops and associated cultural practices and herbicides. Most occurrences of herbicide resistant weeds have proven to be manageable using the practices described above. Thus, in the short-term, the advantages associated with HRC appear to out weight the risks of developing more herbicide resistant weeds in many crop production systems. The long-term benefits of HRC are uncertain and will depend on the wise use of chemical technologies within the context of integrated weed management practices.

Table 1. Gene based examples of herbicide resistance in crops and weeds.

Herbicide	Novel gene product	Mechanism
triazines (e.g., prometryn, atrazine)	chloroplast D1 protein	mutated target
substituted ureas (e.g., diuron)	chloroplast D1 protein	mutated target
sulfonylureas (e.g. chlorsulfuron)	acetolactase synthase	mutated target
imidazolinones (e.g., imazapyr)	acetolactase synthase	mutated target
pyrimidyl thiobenzoates (e.g., pyrithiobac)	acetolactase synthase	mutated target
aryloxyphenoxypropanoates (e.g., diclofop)	Acetyl coenzyme A carboxylase	mutated target
cyclohexanediones (e.g., sethoxydim)	Acetyl coenzyme A carboxylase	mutated target
glyphosate (e.g. Roundup, Touchdown)	EPSPS (5-enolpyruvylshikimate--3-phosphate synthase)	over expression
glyphosate (e.g. Roundup, Touchdown)		mutated target
glyphosate (e.g. Roundup, Touchdown)	glyphosate oxidoreductase	detoxification
bromoxynil (e.g., Buctril)	nitrilase	detoxification
2,4-D	monooxygenase	detoxification
glufosinate (e.g., Liberty)	N-acetyl transferase	detoxification

Table 2. Commercialized transgenic crops with herbicide resistance listed by the Weed Science Society of America in 1998[a].

Transgenic Crop	Herbicide Tolerance	Trademark/Company	Estimated Year & Place Commercialized
Canola (*Brassica napus*)	bromoxynil	BXN Canola - Rhone-Poulenc	Europe (1995)
		Liberty Link Canola - AgrEvo	Canada (1995) Europe (1995)
	glyphosate	Roundup Ready Rape - Monsanto	Canada (1997) Europe (1998)
Clover (*Trifolum repens*)	bromoxynil	CSIRO & New Wales Agriculture	Australia (2001)
Corn (*Zea mays*)	glufosinate	Liberty Link Corn - AgrEvo	USA (1997)
	glyphosate	Roundup Ready Corn, Monsanto & DeKALB Genetics	USA (1997) Canada (1998)
	imidazolinones	IMI Corn - American Cyanamid, Pioneer, Ciba Seeds, Asgrow, Northrup King	Australia (1998-99) USA (1997)
	sethoxydim	SR Corn - BASF/DeKalb Genetics	USA (1997) Brazil (1997)
Rice (Oryza sativa)	glufosinate	Liberty Link Rice - AgrEvo	USA (2000-01) Asia (2000-01)
Soybean (*Glycine max*)	glufosinate	Liberty Link Soybean - AgrEvo	USA (1998) Brazil (1998-99)
	glyphosate	Roundup Ready Soybean, Monsanto & Asgrow Seeds	USA (1997) Brazil (1997) Argentina (1997)
	sulfonylureas	STS Soybeans - DuPont	USA (1993)
Sugar Beets (*Beta vulgaris*)	glufosinate	Liberty Link Sugar Beet - AgrEvo	Europe (1999-00)
	glyphosate	Roundup Ready Sugar Beet, Monsanto	Europe (1997-98)
Tobacco (*Nicotiana tabacum*)	bromoxynil	BXN Tobacco - Rhone-Poulenc	Europe (1997-98)
Upland Cotton (*Gossypium hirsutum*)	bromoxynil	BXN Cotton - Rhone-Poulenc	USA (1997)
	glufosinate	Liberty Link Cotton - AgrEvo	USA (2000)
	glyphosate	Roundup Ready Cotton-Monsanto	USA (1997)
	sulfonylureas	19-51a Cotton - DuPont	USA (1997)

[a] Adapted from: Weed Science Society of America. 1998. Herbicide Handbook-Supplement to the 7th ed. Edited by Kriton K. Hatzios. 102 pages.