Crop and weed resistance to glyphosate: A global overview.

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Abstract

The goal of weed management is to protect crop yield and the use of glyphosate in glyphosate-resistant crops is a cost effective method to control weeds. Glyphosate's high efficacy and other benefits to growers fueled the global adoption of glyphosate-resistance crops, which has exceeded 80 million hectares in 12 years. Glyphosate-resistant weeds did not evolve resistance during the first 22 years that glyphosate was used, but 13 weeds have subsequently become glyphosate-resistant in conventional and glyphosate-resistant cropping systems because of the scale and intensity of glyphosate use. Glyphosate-resistant weeds may reduce the value of glyphosate or glyphosate-resistant crops in many scenarios, especially when individual species are resistant to multiple modes of action or when multiple glyphosate-resistant species exist in the same field. To preserve the benefits of glyphosate-based technologies, growers need to improve their stewardship of glyphosate by maintaining herbicide diversity. Initially, growers need to be aware of the potential for glyphosate-resistant weeds to evolve. Next, education is needed about practices to lessen the selection intensity. However, a primary barrier to improving glyphosate stewardship is the cost of additional herbicides or management practices. This cost may be lower than the increased cost of controlling glyphosate-resistant weeds in the future or may improve overall weed management and crop yield protection. Industry and growers are encouraged to work collectively to increase glyphosate stewardship.

Keywords: corn, cotton, soybean, stewardship.

INTRODUCTION

The goal and principles of weed management for profitable crop production are simple in concept, but often challenging to implement and sustain over time. The goal of weed management is to protect a crop's yield potential in an environmentally safe and economic manner. To achieve this goal, management practices are employed based on integrated principles such as the knowledge of field-specific weed populations, critical periods of weed control, and economic thresholds. However, it may be challenging to implement and sustain theses concepts when new technologies such as glyphosate-resistant crops are available and perceived to be "simple" and used without regard to these principles.

Glyphosate and glyphosate-resistant crops are one set of the inputs or technologies that have significantly affected weed management. A major benefit of glyphosate's use has been the potential and adoption of no-tillage systems, which protect soil resources

(Cerdeira and Duke, 2006). In contrast, glyphosate-resistant crops do not have an inherent benefit such as increased crop yield potential. Rather, this resistance technology only allows the selective use of glyphosate, which offers excellent broad-spectrum efficacy, excellent crop safety, and no rotational limitations at a favorable price. However, two negative issues that may occur with the use of glyphosate in glyphosate-resistant crops are 1) suboptimal weed management and 2) glyphosate-resistant weeds. The principle cause of suboptimal weed management may occur when postemergence applications of glyphosate are delayed beyond the critical period of weed removal (e.g. Hall et al., 1992; Mulugeta and Boerboom, 2000). Hence, the crop yield's potential is compromised. Suboptimal weed control may also occur with delayed applications because glyphosate's efficacy may be reduced if the weed's size is too large when treated. The second concern with the extensive use of glyphosate is the continued evolution of glyphosate-resistant weeds, which may erode the value of both glyphosate and glyphosate-resistant crops. This article will focus primarily on glyphosate-resistant weeds, but will address suboptimal weed management within this context.

A BRIEF CHRONICLE OF GLYPHOSATE DEVELOPMENTS

The history of glyphosate is traced to 1970 when the herbicidal activity of glyphosate was first discovered (Alibhai and Stallings, 2001). Glyphosate was first marketed in 1974, but its use was limited to spot, selective, and burndown applications for over 2 decades because of its nonselective activity. During this time, the evolution and identification of glyphosate-resistant weeds was limited. Although at least one glyphosate-tolerant biotype (e.g. field bindweed, *Convolvulus arvensis*) was described within a decade of commercial use (DeGennaro and Weller, 1984), the first glyphosate-resistant weed to evolve under field conditions was rigid ryegrass (*Lolium rigidum*) in 1996 in Australia (Powles et al., 1998) followed by goosegrass (*Eleusine indica*) in 1997 in Malaysia (Lee and Ngim, 2000). The development and marketing of glyphosate-resistant soybean in 1996 allowed the first selective use of glyphosate in-crop. Despite the contention that weeds would be unlikely to evolve glyphosate resistance (Bradshaw et al., 1997), glyphosate-resistant horseweed (*Conyza canadensis*) was reported within a glyphosate-based soybean cropping system in 2000 (VanGessel, 2001). Since the commercial introduction of glyphosate, a glyphosate-resistant weed did not evolve resistance for 23 years, which supports the contention that resistance is a rare event. However, horseweed evolved resistance by 5 years after the introduction of glyphosate-resistant soybean, which suggests that increased glyphosate use and reduced use of alternative control practices significantly increased the selection intensity for resistance.

CURRENT STATUS OF GLYPHOSATE TRAITS AND RESISTANCE

The current status of global glyphosate use, glyphosate-resistant crops, and expanding frequency of glyphosate-resistant weeds are interrelated. Estimates of glyphosate-resistant corn, soybean, cotton, and canola for 2007 were projected to total 84 million hectares (Table 1, Monsanto 2007). In the U.S., glyphosate-resistant soybean had previously dominated the percentage of hectares planted, but the adoption of glyphosate-resistant corn has increased rapidly. Consequently, about 52 million hectares of glyphosate-resistant crops were projected to be planted in the U.S. in 2007. A high percentage of soybean in Argentina (approximately 15.8 million ha) are planted with glyphosate-resistant varieties whereas the percentage in Brazil has increased rapidly in the last 4 years and accounts for approximately 9.3 million hectares.

The relationship of glyphosate-resistant crops and glyphosate use is inevitable as nearly all fields planted with glyphosate-resistant crops will be treated with glyphosate and a significant percentage of fields will be treated more than once. The consequence of the wide-scale application of glyphosate greatly increases the selection intensity for glyphosate-resistant weeds. Of course, the ultimate frequency of glyphosate application to a given field will depend on the cropping system. It is obvious that a monoculture of a glyphosate-resistant crop will increase the frequency of glyphosate applications. However, a similar intensity of use can exist within a crop rotation. For instance, growers in the American state of Minnesota planted 92% glyphosate-resistant soybean in 2007 and 60% of the planted corn hybrids had either a single herbicide-resistance trait or a stacked gene trait (USDA-ERS, 2007). As a consequence, it is highly probable that a majority of corn planted in rotation after soybean in 2008 will be a glyphosate-resistant hybrid and will be treated with glyphosate. A similar situation exists in the southern U.S. where cotton and soybean are grown in rotation. The intensity of glyphosate use can be increased further depending on the tillage system such as when glyphosate is used both as a burndown herbicide prior to planting and as a postemergence herbicide in-crop. The intensity of use may also be greater in non-competitive crops like glyphosate-resistant sugar beets where three glyphosate applications have been recommended.

After the initial selection of glyphosate-resistant rigid ryegrass, Powles et al. (1998) stated “It is prudent to accept that resistance can occur to this highly valuable herbicide and to encourage glyphosate use patterns within integrated strategies that do not impose a strong selection pressure for resistance.” Unfortunately, glyphosate use patterns have not been effectively integrated with other management strategies and the number and distribution of glyphosate-resistant weeds have continued to increase. Currently, 13 glyphosate-resistant weed species are reported globally (Table 2, Heap, 2008). Table 2 is arranged to show the number of states in the U.S. with glyphosate-resistant species and glyphosate-resistance in other countries. The intent of this arrangement is to highlight that nearly as many glyphosate-resistant weeds occur in the U.S. (eight) as the total of all other countries (nine). Brazil has the second most glyphosate-resistant species with four. Also, the distribution of glyphosate-resistant weeds is wide spread for some species in the U.S. as indicated by the number of states infested. With certain species like Palmer amaranth (*Amaranthus palmeri*), the number of infested states is under reported based on personnel communications. Overall, it appears that a strong relationship exists between the evolution of glyphosate-resistant weed species and adoption of glyphosate-resistant crops (Figure 1). Although some of these species evolved resistance in cropping systems that were not based on glyphosate-resistant crops, the overall relationship is still apparent.

IMPLICATIONS OF GLYPHOSATE-RESISTANT WEEDS

A legitimate question to ask is whether or not glyphosate-resistant weeds are of concern or if they significantly affect the value and utility of glyphosate and glyphosate-resistant crops. A survey by Scott and VanGessel (2007) reports that a majority soybean growers in the American state of Delaware believe that glyphosate-resistant horseweed reduces the value of glyphosate-resistant soybean and decreases the rental values of infested fields. In some situations, it is argued that the impact is not great because the glyphosate-resistant weed could be easily controlled by mixing a second herbicide with glyphosate (Green, 2007). It is also argued that other herbicides such as atrazine retained their utility after triazine-resistance developed. While both of these contentions are true, some of the benefits of these glyphosate technologies may still be lost. For instance, the cost of control will increase, the risk of crop injury may increase with the second herbicide, and the simplicity of the system is reduced. In general, I would concur that a single species with glyphosate resistance is a situation that can be managed. However, glyphosate-resistance species that develop multiple resistance will be challenging to control in certain cropping systems. Five glyphosate-resistant species are resistant to one or two other modes of action (Heap, 2008). Of these species, waterhemp (*Amaranthus rudis*) with resistance to glyphosate, ALS-inhibitors, and PPO-inhibitors and giant ragweed (*Ambrosia trifida*) with glyphosate and ALS-inhibitor resistance are major threats in U.S. soybean. Another challenging management problem will occur when multiple species with glyphosate resistance develop within the same field. One field in the U.S. has glyphosate-resistant horseweed and giant ragweed and glyphosate “tolerant” common lambsquarters (*Chenopodium album*). Management options in such scenarios will be challenging as mixing one single herbicide with glyphosate may not control all of the different glyphosate-resistant species.

GLYPHOSATE STEWARDSHIP

Globally, the total impact of glyphosate-resistant weeds is still minimal, which is to our collective advantage because time exists to improve glyphosate stewardship. Improved glyphosate stewardship begins with greater grower awareness. Even with awareness, growers may lack sufficient concern. In 2004, a majority (65%) of corn and soybean growers in the American state of Indiana had either a low or moderate concern about the development of glyphosate-resistant weeds despite educational efforts (Johnson and Gibson, 2006). Misconceptions also persist that new herbicides with a different mode of action will be marketed to control resistant weeds (Scott and VanGessel, 2007). Other growers may believe solutions reside in crops with new herbicide-resistant traits (Green, 2007). Although some growers may lack concern, many growers understand that repeated herbicide use selects for resistant weeds (Johnson and Gibson, 2006). One challenge appears to be increasing the grower's level of concern so they consider improving their management practices. A major barrier to increasing the level of stewardship is that the cost of control is frequently increased. However, the cost can be modeled to determine if proactive management more cost efficient than reacting after glyphosate-resistance evolves (Mueller et al., 2005). In a case study of waterhemp, more costly proactive management was profitable in the long-term even if glyphosate-resistance did not evolve in this weed for 20 years.

Although a grower's proactive management may avoid or delay financial penalties associated with a glyphosate-resistant weed, growers are resistant to change to prevent a future, unpredictable problem. The proactive options to reduce selection pressure are no different now than those proposed years ago. Simply, weed management programs should maintain herbicide diversity through rotations, sequential applications, and tank mixtures and should be integrated with other control practices. Many extension weed scientists in the U.S. have promoted the other benefits that proactive or integrated weed management practices offer, which include resistance management as a secondary benefit. A common strategy that is promoted is to use a preemergence, residual herbicide in sequence before a postemergence glyphosate application. This has an excellent fit in corn production. For resistance management, this lessens the selection pressure by introducing a second herbicide with a different mode of action and it reduces the number of individuals that are exposed to selection (Stoltenberg, 2008). A key feature to the success of this strategy is that the preemergence herbicide(s) has an overlapping spectrum of control as glyphosate.

Otherwise, species not controlled by the preemergence herbicide would only be controlled by glyphosate and the selection intensity would not be reduced. The agronomic benefits of sequential herbicide applications are minimizing early-season weed competition, greater glyphosate efficacy because smaller weeds are treated, greater flexibility in timing postemergence glyphosate applications, and reduced risk of crop yield loss. These agronomic benefits become economic benefits that can be promoted to growers.

The U.S. has planted the most hectares of glyphosate-resistant crops in the world and consequently has the unfortunate distinction of having the greatest number and area infested with glyphosate-resistant weed species. I hope that lessons from the U.S. experience are observed and not repeated in other crops or regions of the world as the use of these glyphosate technologies are either introduced, continued, or increased. Industry acknowledgement of the potential and negative impacts of glyphosate-resistant weeds, education of growers on this issue, and grower adoption of glyphosate stewardship practices will extend the value of these glyphosate technologies. A coordinated and collaborative effort is encouraged to achieve this goal.

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Table 1 - Hectares of glyphosate-resistant soybean, corn, cotton, and canola planted in major growing regions from 1996 to 2006 with forecasted hectares for 2007 (Adapted from Monsanto 2007).

	Glyphosate-resistant plantings											
Crop	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
	ha x 10^6											
Soybean												
U.S.	0.5	3.2	11.8	16.4	18.2	22.2	24.3	25.7	27.2	26.9	29.0	25.7
Argentina	-	0.2	1.6	5.5	6.9	9.2	11.0	12.1	12.9	14.0	15.1	15.8
Brazil	-	-	-	-	-	-	-	-	3.0	5.0	7.9	9.3
Other	-	-	-	0.1	0.2	0.2	0.4	0.6	1.0	2.3	2.3	2.8
Corn												
U.S.	-	-	0.4	0.9	1.1	1.9	3.2	4.9	6.9	10.0	13.2	22.5
Other	-	-	-	<0.1	<0.1	0.1	0.1	0.2	0.2	0.2	0.6	1.0
Cotton												
U.S.	-	0.3	1.1	2.5	3.5	4.3	4.0	4.0	4.3	4.4	4.6	4.0
Other	-	-	-	-	-	-	0.1	0.1	0.1	0.2	0.4	0.6
Canola												
Canada	-	0.2	1.1	2.0	1.7	1.6	1.6	2.2	2.3	2.5	2.1	2.0
Other	-	-	-	0.1	0.3	0.4	0.4	0.3	0.2	0.2	0.2	0.2
Total	0.5	3.9	16.0	27.5	31.9	39.9	45.0	50.1	58.1	65.6	75.2	83.7

Table 2 - Summary of glyphosate-resistant weeds confirmed in the United States and in other countries (Adapted from Heap 2008).

Weed species		United States	Other countries
		(no.)	
Dicotyledons			
buckhorn plantain	*Plantago lanceolata*		South Africa
common ragweed	*Ambrosia artemisiifolia*	4	
giant ragweed	*Ambrosia trifida*	3	
hairy fleabane	*Conyza bonariensis*	1	Brazil, Colombia, Spain, South Africa
horseweed	*Conyza canadensis*	16	Brazil, China, Spain, Czech Republic
Palmer amaranth	*Amaranthus palmeri*	4	
waterhemp	*Amaranthus rudis*	3	
wild poinsettia	*Euphorbia heterophylla*		Brazil
Monocotyledons			
goosegrass	*Eleusine indica*		Malayasia
Italian ryegrass	*Lolium multiflorum*	2	Brazil, Chile
Johnsongrass	*Sorghum halepense*		Argentina
junglerice	*Echinochloa colona*		Australia
rigid ryegrass	*Lolium rigidum*	1	Australia, France, South Africa

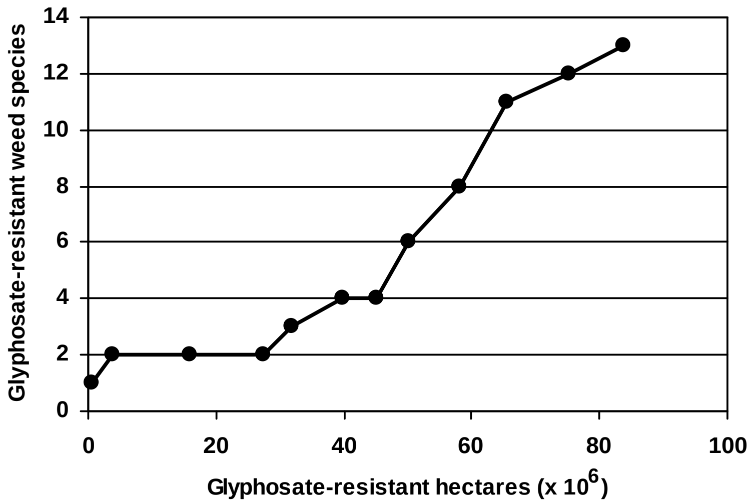

Figure 1 - Relationship of number of hectares planted to glyphosate-resistant crops and the occurrence of glyphosate resistant weed species (not all species evolved resistance in glyphosate-resistant cropping systems).