JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY ARTICLE

J. Agric. Food Chem. **XXXX,** *XXX,* 000–000 **A**
DOI:10.1021/jf102652y

Agricultural Impacts of Glyphosate-Resistant Soybean Cultivation in South America[†]

Antonio L. Cerdeira,*[§] Dionsio L. P. Gazziero,[#] Stephen O. Duke,[⊥] and Marcus B. Matallo[⊗]

[§]Brazilian Department of Agriculture, Agricultural Research Service, EMBRAPA/Environment, Jaguariúna, SP, Brazil, [#]Brazilian Department of Agriculture, Agricultural Research Service, EMBRAPA/Soybean, Londrina, PR, Brazil, [⊥]Natural Products Utilization Research Unit, Agricultural Research Service, U.S. Department of Agriculture, University, Mississippi 38677, and [⊗]Weed Science Laboratory, Biological Institute, IB, Campinas, SP, Brazil

In the 2009/2010 growing season, Brazil was the second largest world soybean producer, followed by Argentina. Glyphosate-resistant soybeans (GRS) are being cultivated in most of the soybean area in South America. Overall, the GRS system is beneficial to the environment when compared to conventional soybean. GRS resulted in a significant shift toward no-tillage practices in Brazil and Argentina, but weed resistance may reduce this trend. Probably the highest agricultural risk in adopting GRS in Brazil and South America is related to weed resistance due to use of glyphosate. Weed species in GRS fields have shifted in Brazil to those that can more successfully withstand glyphosate or to those that avoid the time of its application. Five weed species, in order of importance, *Conyza bonariensis* (L.) Cronquist, *Conyza canadensis* (L.) Cronquist, *Lolium multiflorum* Lam., *Digitaria insularis* (L.) Mez ex Ekman, and *Euphorbia heterophylla* L., have evolved resistance to glyphosate in GRS in Brazil. *Conyza* spp. are the most difficult to control. A glyphosate-resistant biotype of *Sorghum halepense* L. has evolved in GRS in Argentina and one of *D. insularis* in Paraguay. The following actions are proposed to minimize weed resistance problem: (a) rotation of GRS with conventional soybeans in order to rotate herbicide modes of action; (b) avoidance of lower than recommended glyphosate rates; (c) keeping soil covered with a crop or legume at intercrop intervals; (d) keeping machinery free of weed seeds; and (d) use of a preplant nonselective herbicide plus residuals to eliminate early weed interference with the crop and to minimize escapes from later applications of glyphosate due to natural resistance of older weeds and/or incomplete glyphosate coverage.

KEYWORDS: Glyphosate; weed resistance; South America; soybean; transgenic crops

INTRODUCTION

Soybean was introduced in Brazil in the early 1900s, but its commercial importance dates to the 1940s in Rio Grande do Sul State. Soybean varieties introduced from the United States and varieties from early introductions in Brazil were part of the Brazilian soybean-breeding program, which spread the crop from high to low latitudes, allowing production in tropical acidic soils with lime and phosphorus supplements (*1*). In the 2009/2010 growing season, Brazil was the second largest world soybean producer with 67 million metric tons (*2*), with a total area of 23 million hectares (*3*), about 25% of world production, followed by Argentina with 16% (*2*). Other producer countries in South America with less importance are Paraguay, Bolivia, and Uruguay (*2*).

Glyphosate [*N*-(phosphonomethyl)glycine]-resistant crops (GRCs) are the transgenic crops most extensively grown worldwide, with soybean being the major GRC (*4*). Glyphosate-resistant soybeans (GRS) and their environmental impact have been covered in depth in a review on GRC (*5*), but this review had little comment on tropical areas such as in Brazil.

The topic of herbicide-resistant crops has been extensively reviewed (*6*−*14*) and has been the topic of one edited book (*15*). Dill (*16*) briefly covered the current status of GRC products, and a recent book chapter also discussed the subject (*17*). None of these publications have focused solely on an assessment of the potential environmental impacts of GRCs in South America. GRCs have facilitated increases in conservation tillage production practices and simplified weed control in glyphosate-resistant (GR) corn, soybean, canola, sugar beets, and cotton in the United States. However, increased reliance on glyphosate has resulted in

[†]Part of the Comparing Conventional and Biotechnology-Based Pest Management symposium.

*Address correspondence to this author at the Brazilian Department of Agriculture, Agricultural Research Service, EMBRAPA/Environment, C.P. 69, Jaguariuna-SP-13820-000, Brazil (phone 55-19-3311-2671; fax 55-19-3311-2740; e-mail cerdeira@cnpma.embrapa.br).

weed species shifts and the evolution of weed populations resistant to glyphosate in the United States (*18*).

This review will discuss the potential impacts of GRS cultivation in Brazil and the rest of South America, with emphasis on the effects of this relatively new technology as a weed control method. Some data from temperate areas regarding the behavior of pesticides discussed can be extrapolated to tropical soils (*19*).

GLYPHOSATE-RESISTANT SOYBEANS IN SOUTH AMERICA

A gene (*CP4*) encoding a glyphosate-resistant form of EPSPS from *Agrobacterium* sp. was found to effectively bypass glyphosate inhibition of the native enzyme, producing a GRC (*20*). Most commercial GRS varieties have the CP4 EPSPS gene (*21*). This is the transgene in commercially available GRS in South America.

Adoption of GRS has been rapid and substantial in Brazil, Argentina, Paraguay, and Uruguay (*22*). A survey conducted in Brazil showed the main reason for the farmers to adopt GRS was to control sulfonylurea-, imidazolinone-, and ACCase inhibitor-resistant weeds (*23*). GRS was first legally allowed in Brazil in the crop season of 2003/2004, although it was planted illegally on a small scale beginning in 1998 (*24*). In Argentina, GRS was introduced in 1996 (*25*). By 2005, GRS accounted for 93% of total soybean plantings in Paraguay and all of the soybean plantings in Uruguay (*22*). Bolivia is also a GRS producer with 0.6 million hectares in 2008 (*26*). In Brazil, the hectarage planted in the 2011/2012 growing year is estimated to be 80% of the total soybean area (*27*). Before GRS in Argentina, farmers rotated crops with cattle production, but since GRS introduction, soybeans have been rotated with other crops, especially with wheat during the winter (*28*). Also in Argentina, the adoption of GRS was rapid, reaching almost 90% within 4 years of introduction (*29*). In 2009, 14 years after introduction, 95% of the soybeans planted in the United States were GRS (*30*), where rapid adoption has been due to relatively inexpensive, excellent, simplified, and more flexible weed control (*31*, *32*).

Higher temperatures, light intensity, and water stress can decrease the resistance of some GRS varieties to glyphosate (*33*, *34*). However, no adverse effects of glyphosate on GRS have been reported in Brazil. Temperatures during the crop season are not very different from those in the United States, and generally there is no water deficit in Brazil during the soybean cropping season, although it can happen occasionally.

Glyphosate resistance transgenes in soybeans are highly unlikely to be a gene flow problem with wild plant species in Brazil and South America. According to Riches and Valverde (*35*), soybean is a non-native crop without wild relatives in Brazil and South America, making introgression of transgenes into wild relatives impossible. Soybean is a predominantly self-pollinated plant species with an outcrossing rate of about 1%. Thus, a very low rate of gene flow to non-GR soybean varieties might be possible, but this has not been reported in anywhere GRS is grown. Overreliance on glyphosate in GRS cropping systems has resulted in the selection of resistant weed species through weed shifts and evolution of glyphosate-resistant weed biotypes, especially in Brazil, Argentina, and Paraguay (*23*).

EFFECTS ON TROPICAL SOILS AND HERBICIDE USE

In general, most Brazilian soils have characteristics of tropical and humid subtropical climate regions, including high acidity and high exchangeable aluminum content, sometimes associated with low fertility. These constraints to agricultural production have been overcome in part by liming and phosphate fertilizer application (*36*). Glyphosate is rapidly adsorbed and tightly complexed by most soils and is rapidly degraded by soil microbes (*37*−*39*). Brazilian soil contains microbes that degrade glyphosate (*40*). Mobility is increased slightly at high pH and with high levels of inorganic phosphate. One would expect a lower mobility in Brazilian soils because of the lower pH of those soils (*36*). Inactivation of glyphosate through adsorption is of critical importance. Leaching is nearly negligible, and glyphosate is not volatile (*41*). A study conducted with Brazilian soils has shown similar behavior (*42*).

Comparing the fate of pesticides on tropical and temperate conditions, Racke et al. (*19*) found no evidence of unique behavior of the pesticides in the tropics other than a greater rate of pesticide degradation under tropical conditions. A study and review on glyphosate effects in a tropical environment in Colombia also found no evidence of a unique behavior of glyphosate in the tropics (*43*, *44*).

Overall, the amount of herbicide active ingredient (ai) used per hectare in the United States with conventional and glyphosate-resistant soybeans has been fairly stable, with a slightly higher average usage level in GRS than in conventional soybeans, probably because of changes in cultivation practices in favor of no till (*22*). In GRS, the glyphosate amount and number of applications have increased over the years due to increased problems with weed resistance. In Brazil, GRS cost saving from a combination of reduced herbicide use and price, fewer spray trips, and less labor and machinery has occurred. Overall, there has been controversy about whether adoption of GRS increases herbicide use or not (*45*−*49*).

DOUBLE CROP (“SAFRINHA”) AND NO-TILLAGE

The term “safrinha” in Brazil means growing two crops such as soybean and maize sequentially in the same growing season, which extends from late in one calendar year to early in the next. In central-southern Brazil, there are two distinct growing seasons: the regular summer season, which extends from late September until mid January, and the “second” one, from the months of January to June, depending on the region. Safrinha began at the initiative of farmers, especially in the State of Paraná in the 1990s, seeking a crop to grow after soybean sown in the summer. Over the years, the importance of this practice spread to other states, and GRS is helping the system because it allows farmers to save time on soil preparation.

A beneficial impact from the use of GRS in Brazil is that it helped reduced or zero tillage systems, which contribute to reductions in soil erosion from water and wind, fossil fuel use, air pollution from dust, soil moisture loss, and soil compaction (*50*). Reduced tillage also improves soil structure, leading to reduced risk of runoff and pollution of surface waters with sediment, nutrients, and pesticides. Loss of topsoil due to tillage is perhaps the most environmentally destructive effect of row crop agriculture. Adoption of no-till systems in Argentina, Brazil, and Paraguay allowed the cultivation of two crops per year in areas where only one was formerly grown (*23*, *28*).

There has been a rise in no-tillage agriculture in GRS in Argentina (*29*) with dramatic reductions in soil erosion, leading to an acceleration of glyphosate mineralization found in Brazil (*51*). Fields under no-till and conventional management systems in Ponta Grossa, Paraná state, Brazil, in soybean production for 23 years had a reduced glyphosate persistence (*51*). A proposed 5 year study is underway in Brazil to supply information to the Biosafety Committee of the Ministry of Science and Technology (CTNBio) involving eight ecological regions in the states of Mato Grosso, Mato Grosso do Sul, Goiás, Baia, Paraná, and Rio Grande do Sul (*52*). The purpose of this study is to determine effects on physical, chemical, and biological attributes of soil where GRS

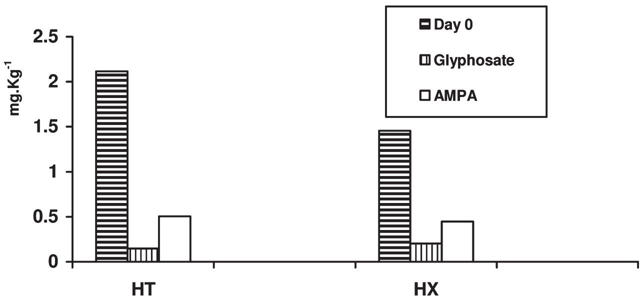

Figure 1. Amounts (mg/kg) of glyphosate and aminomethylphosphonic acid (AMPA) detected in different types of soil in Brazil before (glyphosate, day 0) and after incubation for 32 days: Typical Hapludult (HT) and Typical Hapludox (HX) Brazilian soils with no reported prior application of glyphosate [redrawn from Araujo et al. (*69*)].

is being sown. There are no conclusive data available from this study yet.

Whether no-tillage or reduced tillage agriculture with glyphosate is used, annual use of glyphosate will result in strong selection pressure for weed species shifts and evolution of glyphosate resistance. Some of these problem weeds might be best managed with tillage, resulting in a permanent or occasional return to tillage (*53*, *54*).

Another potential problem are cases of glyphosate drift from GRS to conventional soybeans in Brazil (*55*), and this problem will also occur, regardless of the crop management methods used.

EFFECTS ON SOIL BIOTA AND MICROORGANISMS

The potential direct effects of GRS and its management on soil biota include changes in soil microbial activity due to direct effects of glyphosate, differences due to the amount and composition of root exudates of GRS versus non-GRS, changes in microbial functions resulting from gene transfer from the transgenic crop, and effects of management practices for GRS, such as changes in other herbicide applications and tillage (*56*). Most of the available literature addresses direct effects of glyphosate.

Glyphosate is preferentially translocated from source to sink tissues, such as reproductive tissues and nodules of soybeans (*38*, *57*, *58*), site of the nitrogen-fixing symbiont *Bradyrhizobium japonicum*, which possesses a glyphosate-sensitive EPSPS but, overall, there are no indications that an effect of glyphosate on *B. japonicum* has an impact on soybean yield in the field (*57*, *59*−*63*).

Glyphosate can be toxic to many microorganisms, including plant pathogens found in soybean in Brazil, but not all fungi are susceptible to glyphosate (*64*, *65*). Glyphosate has a half-life in soils with an average value of approximately 47 days, but reaching 174 days in some soils under some environmental conditions (*66*, *67*). Studies conducted in Brazil have shown a half-life of about a month, which is shorter than in some temperate climates (*68*). A study (*69*) has indicated glyphosate degradation by microorganisms in Brazilian soils and some transformation to aminomethylphosphonic acid (AMPA), as shown in **Figure 1**. Those results have shown that after 32 days of incubation, the number of actinomycetes and other fungi had increased, whereas the number of bacteria had been reduced slightly.

In general, there is little or no effect of glyphosate on soil microflora within weeks or months of application. For example, Gomez and Sagardoy (*70*) found no effect of glyphosate on microflora of soils in Argentina at twice the recommended rates of the herbicide and detected AMPA, indicating glyphosate degradation by soil microorganisms. Motavalli et al. (*71*) and Kowalchuk et al. (*72*) found no conclusive evidence that GRS and other transgenic crops which have been used in many cropping situations in many climates and soil types over the past 14 years have had any significant effect on nutrient transformations by microbes. No effects were detected from glyphosate on earthworms (*Eisenia fetida* Savigny) in Brazil (*73*), on other plants from glyphosate exudation from roots of *Brachiaria decumbens* Stapf or drift (*74*, *75*), and on the entomopathogenic fungus *Metarhizium anisopliae* (Metsch.), important in Brazil for insect biocontrol (*76*). However, Andaló et al. (*77*) showed glyphosate to reduce in vitro vegetative growth of the entomopathogenic fungus *Beauveria bassiana* Vuillemin found in Brazil.

Table 1. Reports of Glyphosate Interactions with Soybean Diseases and Nematodes Found in Brazil

disease	effect	ref
Phakopsora pachyrhizi [a]	reduces	Feng et al. (*89*)
Fusarium spp.	increases	Kremer et al. (*90*)
S. schlerotiorum	no effect	Lee et al. (*91*)
F. solani	increases	Sanogo et al. (*93*)
	increases	Njiti et al. (*92*)
Heterodera glycines	no effect	Yang et al. (*94*)

[a] Asian soybean rust.

WATER CONTAMINATION AND EFFECTS ON AQUATIC LIFE

Glyphosate is strongly adsorbed to soil particles, and, even though it is highly water-soluble, it does not leach to groundwater in most soils. Soil and sediments of bodies of water are the main sinks for glyphosate residues from surface water, greatly reducing further transport (*40*). Two extensive reviews about the topic have indicated a relatively low risk of ground and surface water contamination (*5*, *10*).

Inoue et al. (*49*), ranking herbicides according to their leaching potential in Brazil, found that glyphosate leached less than most of the herbicides that it replaced. Glyphosate has little effect on aquatic life (*5*). However, Relyea (*78*) reported that a commercial formulation of glyphosate sprayed directly into aquatic mesocosms caused a reduction in species diversity with particularly severe impacts on amphibians. Their studies did not determine whether the effect was due to glyphosate or formulation ingredients. No studies have been done to confirm whether this happens in the field. There is even an approved formulation of glyphosate for use on aquatic weeds (*67*).

EFFECTS ON OTHER NONTARGET ORGANISMS

Comprehensive reviews have concluded that no significant direct effect of GRS would be expected on birds and wildlife (*5*, *10*). However, indirect effects of glyphosate in GRS could have effects on insects and wildlife. For example, no-tillage agriculture with GRS could result in weed species shifts and more vegetation in the field before and after the period of crop production, with an altered habitat for such organisms. However, any herbicide can indirectly affect arthropod and wildlife populations and species compositions in an area by its effects on vegetation. Changes in cropping systems (e.g., changing from tillage to no-tillage) can drastically influence arthropod populations. Virtually all studies on direct effects of glyphosate on arthropods show no significant effects in Brazil or in the rest of the world (*43*, *52*, *70*, *79*, *80*). At the low doses one might expect with drift to surrounding areas, glyphosate can stimulate plant growth (*81*), something that has not been studied in the field.

The influences of glyphosate on plant diseases in GRS are variable, sometimes reducing and other times increasing disease (**Table 1**). Glyphosate inhibits the biosynthesis of the aromatic amino acids, thereby reducing biosynthesis of proteins, auxins,

Table 2. Weeds in Soybean in Brazil That Have Low Levels of Natural Resistance to Glyphosate (*52*, *55*)

weed	U.S. common name(*98*)	Brazilian common name
Chamaesyce hirta	spurge	erva de santa luzia
Chloris polydacyla	windmillgrass	capim branco
Commelina benghalensis	dayflower	trapoeraba
Ipomoea spp.	morningglory	corda de viola
Richardia brasiliensis	pusley	poaia branca
Spermacoce latifolia	buttonweed	erva quente
Synedrellopsis grisebachii	none	agriãozinho
Tridax procumbens	buttons	erva de touro

pathogen defense compounds, phytoalexins, folic acid, precursors of lignins, flavonoids, plastoquinone, and hundreds of other phenolic and alkaloid compounds (*38*). These effects could, in theory, increase the susceptibility of glyphosate-sensitive plants to pathogens or other stresses (*21*, *38*, *82*−*84*). In non-GRS, glyphosate causes lowered phytoalexin levels and increased susceptibility to plant pathogens (*85*, *86*). Low doses of glyphosate can sometimes make pathogen-resistant cultivars susceptible to plant disease (*87*). Glyphosate was even patented as a synergist for a plant pathogen that controls weeds (*88*). However, reports of both enhanced and reduced disease severity have been reported in GRS (*89*−*93*). The significance of any effects of glyphosate on crop disease in GRS at the field level is unclear.

Recently, glyphosate was reported to have both preventative and curative properties on rust diseases in both glyphosate-resistant wheat and soybean (*89*, *95*). Before the Asian soybean rust (*Phakopsora pachyrhi*) outbreak, about 80% of the area in Brazil was sprayed with fungicides at the end of the growing season mainly for control of diseases such as *Cercospora* spp., *Septoria glycines*, and *Microsphaera diffuse* with fungicides of the inexpensive benzimidazoles group. With the Asian soybean rust outbreak, it is now necessary to use mixtures of triazole and strobirulin fungicide classes with up to seven sprayings, making soybean production in Brazil much more expensive (*96*). Whether glyphosate reduces the need for fungicides in the field has not been determined.

GLYPHOSATE-TOLERANT WEEDS

The following Brazilian weeds are resistant or difficult to control with glyphosate, due to their natural resistance: *Chamaesyce hirta* (L.) Millsp., *Chloris polydacyla* Sw., *Commelina benghalensis* L., *Spermacoce latifolia* Aubl., *Richardia brasiliensis* Gomes, *Synedrellopsis grisebachii* Heiron & Kuntze, *Tridax procumbens* L., and *Ipomoea* spp., among others (*52*, *55*, *96*) (**Table 2**). One would expect an increase of these weed species in GRS in Brazil. The naturally resistant species *Digitaria insularis* is found in Paraguay (*97*).

EVOLVED RESISTANT WEEDS

The first reports of evolved glyphosate resistance in South America included populations of highly diverse taxa (*Lolium multiflorum* Lam., *Conyza bonariensis* L., *Conyza canadensis* L., and *Parthenium hysterophorus* L.) following intense glyphosate use in fruit fields of Chile, Brazil, and Colombia (*54*, *99*, *100*). *L. multiflorum* populations resistant to glyphosate have been found in Chile, and *Eleusine indica* (L.) Gaertn. has evolved resistance in Bolivia (*53*).

In South America, six species have evolved resistance to glyphosate (*101*−*108*). They are *Euphorbia heterophylla* L. (poinsettia, amendoim bravo), *Conyza bonariensis* (L.) Cronquist and *Conyza canadensis* (L.) Cronquist (horseweed, buva), *Digitaria insularis* (L.) Mez ex Ekman (sourgrass, capim amargoso), *Lolium multiflorum* Lam. (ryegrass, azevem), and *Sorghum halepense* L. (Johnsongrass, Sorgo de Alepo) (**Table 3**). *L. multiflorum* was introduced as forage and cover crop in no-till systems, but became a serious weed in wheat and other winter cereals in southern Brazil with a biotype resistant to glyphosate (*100*). In the case of *C. bonariensis* in Brazil, a study with [^{14}C]-glyphosate found that susceptible biotype leaves, stems, and roots showed greater concentration of glyphosate, indicating that the resistance mechanism is related to the differential translocation of this herbicide in the biotypes (*109*). Although not officially listed, resistant *Conyza* spp. are also believed to be found in Paraguay (*110*). *C. canadensis* is also a common weed in no-till crop production systems in the Unites States. It is problematic because of the frequent occurrence of biotypes resistant to glyphosate and acetolactate synthase (ALS)-inhibiting herbicides and the weed's ability to complete its life cycle as a winter or summer annual weed (*111*). Application of glyphosate at planting was more effective in suppressing *C. canadensis* than an in-crop application, and because glyphosate cannot control resistant *C. canadensis*, this biotype should be controlled with a herbicide with an alternate mode of action applied at the most effective timing (*112*, *113*). A study conducted in the United States has shown that *C. canadensis* produces up to 72000 seeds per plant in no-till soybeans (*114*). Also, in terms of management to reduce the presence of *C. canadensis* biotypes, integrated weed management systems should be developed to reduce total populations based on the knowledge that seeds for resistant biotypes are as persistent in the seed bank as glyphosate-sensitive biotypes (*115*). The effect of *Conyza* spp. competition in soybean in Brazil, where it can cause yield losses of up to 70%, is shown in **Figure 2**. *Conyza* spp. competition with soybean also causes a decrease of overall seed quality in terms of increasing the amount of impurity and moisture in the grain (*110*) (**Figure 3**).

A glyphosate-resistant biotype of johnsongrass (*S. halepense* (L.) evolved in Argentina and now covers at least 10000 ha (*116*). Glyphosate-resistant johnsongrass may become a problem in GRS systems in Brazil, Paraguay, and Uruguay because this weed species is found throughout the soybean-growing areas of these countries (*97*, *117*). The first suspected population of

Table 3. Weeds That Evolved Resistance to Glyphosate in GRS in South America (*97*)

weed	country	year first detected
Conyza bonariensis	Brazil	2005
Conyza canadensis	Brazil	2005
Euphorbia heterophylla	Brazil	2006
Digitaria insularis	Brazil, Paraguay	2008, 2006
Lolium multiflorum	Brazil, Argentina	2003, 2007
Sorghum halepense	Argentina	2005

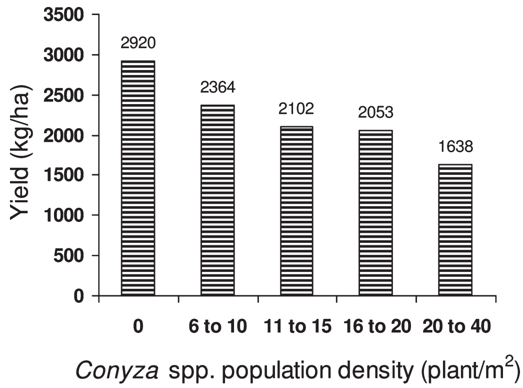

Figure 2. Effects of *Conyza* spp. population density on soybean yield in Brazil (*110*).

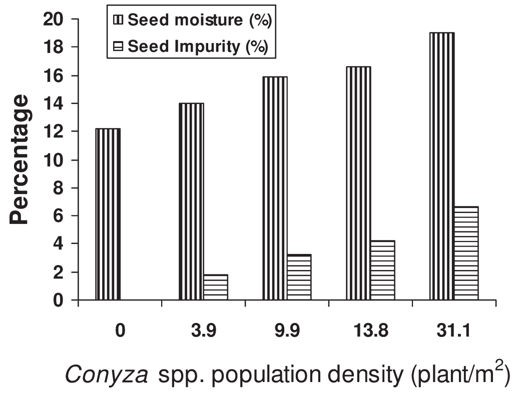

Figure 3. Effects of *Conyza* spp. population density on soybean moisture and impurity in Brazil (*110*).

S. halepense resistant to glyphosate was detected in 2006 in the Salta region of northwestern Argentina, where 700,000 ha of GRS is grown (*23*, *28*). Where glyphosate-resistant *S. halepense* was found, it caused crop losses of up to 40%. Control of *S. halepense* in soybean crops in Argentina requires the use of haloxyfop R methyl plus crop oil with at least two treatments per year, representing an additional cost of U.S.$ 31.20 per ha per year (*118*). The growth stage of *S. halepense* populations at the time of glyphosate treatment has been shown to have a strong effect on the level of glyphosate resistance in Argentina (*119*). At the seedling stage, glyphosate-resistant plants showed a 2-fold level of resistance. However, at the adult stage, the rate of glyphosate required to control 50% of resistant plants increased significantly to a 6-fold level of glyphosate resistance, probably due to reduced glyphosate leaf absorption and translocation (*119*).

The appearance of glyphosate-resistant *L. multiflorum* in GRS required changes in the traditional herbicide treatment in Argentina, adding the mixture of clethodim and haloxyfop each used separately or mixed with 500 g of ae ha^{-1} of glyphosate (*120*) for *L. multiflorum* weed control.

Managing glyphosate-resistant weeds is a new problem for farmers with GRS in South America. The majority of the soybean area in Brazil is very different from that of the United States or Argentina, because there is no cold weather to help suppress weeds (*52*). The following actions are suggested to minimize the problem (*52*, *121*): (a) Rotate GRS with conventional soybeans in order to rotate herbicide modes of action. This is good for weed control but lacks the benefits of using just glyphosate. On the other hand, the reduction in tillage with GRS also could exacerbate certain weed problems, especially perennial weeds with some natural resistance to glyphosate (*52*). (b) Use cover crops at intercrop intervals. This may suppress weeds, but may not be enough to manage and control the resistant weeds. (c) Use a preplant, nonselective herbicide to eliminate early weed interference with the crop and to minimize escapes from later applications of glyphosate due to natural resistance of older weeds and/or incomplete coverage with the postemergence application(s) of glyphosate. (d) Always use the recommended glyphosate rates. This helps weed control but again lacks the benefits of using GRS, and will need less environmental friendly herbicides, including use of residuals that can pollute water and the environment without the benefit of no-till soil management. Which of these options will best improve a particular weed resistance problem will vary, but weed management diversity is the best strategy to mitigate the appearance of glyphosate-resisant weeds, whether due to evolution or species shifts.

Unfortunately, there is a tendency of farmers in Brazil to increase herbicide rates to overcome weed resistance (*52*). Overall, once resistance evolves, herbicide-resistant populations are mostly managed by shifting to herbicides with different modes of action and, in some cases, by slightly modifying agronomic practices (*53*). A study has shown that nonresidual herbicides cannot suppress the rate and density of spring emerging *Conyza* spp. in the United States, and spring-applied saflufenacil provides no-till producers with a preplant herbicide with foliar and residual control of glyphosate- and ALS-resistant horseweed (*111*).

VOLUNTEER CROPS AS WEEDS

Volunteer crops are those left over from the previous crop that grow and compete with a subsequently planted crop such as GRS growing in glyphosate-resistant maize. The popular practice of safrinha, discussed before, which is growing conventional maize or bean just after soybean in the same crop season without tillage, is also affected by using GRS because the farmers rely on glyphosate as a preplant desiccant, which does not work with volunteer GRS in corn, for example (*52*, *55*). The other option, 2,4-D, is not legal in some areas of Brazil (*52*, *55*). GRC have greater potential to become problems as volunteer weeds than do conventional crops.

CONCLUSIONS

GRS is now grown extensively in Brazil, Argentina, Paraguay, Bolivia, and Uruguay. Glyphosate with GRS generally replaces herbicides that are more toxic, with higher persistence in the environment and with much more potential to leach into groundwater. GRS facilitates reduced- or no-tillage systems, which contribute to reductions in soil erosion, soil moisture losses, soil compaction (*9*), and even greenhouse gas emissions (*22*).

The influence of glyphosate on plant diseases in GRC is variable, sometimes reducing and other times increasing disease. Glyphosate resistance transgenes in soybeans are highly unlikely to be a risk due to gene flow to wild plant populations in South America.

The exclusive reliance on glyphosate as the main tool for weed management is leading to agroecosystems biologically more prone to evolution of glyphosate resistance (*54*). *Conyza bonariensis* and *Conyza canadensis*, *Euphorbia heterophylla*, and *Lolium multiflorum* have evolved resistance to glyphosate in GRS in Brazil. Glyphosate-resistant *Sorghum halepense* is also a problem in GRS in Argentina. Those weeds are expected to be a problem in the neighboring areas of Uruguay, Paraguay, and Bolivia. Other weeds such as *Chamaesyce hirta*, *Commelina benghalensis*, *Spermacoce latifolia*, *Richardia brasiliensis*, and *Ipomoea* spp. are naturally resistant to glyphosate and are thus likely to become problems in GRS. A good weed resistance management program can overcome these problems. Such a program would include rotation of GRS with conventional soybeans in order to rotate herbicide modes of action, although it might be more expensive; soil preparation or cultivation to help weed control, using cover crops at intercrop intervals; and using preplant nonselective herbicides. A survey of 400 growers of maize, soybean, and cotton was made in the United States to determine perceptions, experiences, and management practices with glyphosate-resistant weeds, and the key method for managing glyphosate-resistant weeds was to rotate to other herbicides (*122*). Unfortunately, almost all strategies to delay evolution decrease or eliminate one or more of the benefits of the GRS cultivation system in South America. Diversity in weed management methods is a key factor for glyphosate sustainability in cropping systems in South America, and the use of crop rotation and cover crops can certainly increase this diversity. However, the majority of growers are not proactive in using strategies to slow the evolution of glyphosate-resistant weeds (*28*).

The importance of glyphosate-resistant weeds in the United States was recently the subject of an editorial of the *New York Times* (*123*). The editorial stated "*The solution is more diverse crops and cultivation practices, and a wider array of seeds, including non-genetically engineered ones. The unpalatable alternative is the re-introduction of far less benign herbicides*." The same could be said for this emerging problem in South America. However, new discoveries and developments in weed management technology could provide more environmentally benign solutions.

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Received for review July 8, 2010. Revised manuscript received August 11, 2010. Accepted August 12, 2010.