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Review

Glyphosate sustainability in South American cropping systems†

Pedro J Christoffoleti,[1*] Antonio JB Galli,[2] Saul JP Carvalho,[1] Murilo S Moreira,[1] Marcelo Nicolai,[1] Luiz L Foloni,[3] Bianca AB Martins[1] and Daniela N Ribeiro[1]

[1]University of Sao Paulo, ESALQ/USP/LPV, C.Postal 09, 13418-900, Piracicaba, SP, Brazil
[2]Monsanto of Brazil
[3]University of Campinas, Feagri, Campinas, Brazil

Abstract: South America represents about 12% of the global land area, and Brazil roughly corresponds to 47% of that. The major sustainable agricultural system in South America is based on a no-tillage cropping system, which is a worldwide adopted agricultural conservation system. Societal benefits of conservation systems in agriculture include greater use of conservation tillage, which reduces soil erosion and associated loading of pesticides, nutrients and sediments into the environment. However, overreliance on glyphosate and simpler cropping systems has resulted in the selection of tolerant weed species through weed shifts (WSs) and evolution of herbicide-resistant weed (HRW) biotypes to glyphosate. It is a challenge in South America to design herbicide- and non-herbicide-based strategies that effectively delay and/or manage evolution of HRWs and WSs to weeds tolerant to glyphosate in cropping systems based on recurrent glyphosate application, such as those used with glyphosate-resistant soybeans. The objectives of this paper are (i) to provide an overview of some factors that influence WSs and HRWs to glyphosate in South America, especially in Brazil, Argentina and Paraguay soybean cropped areas; (ii) to discuss the viability of using crop rotation and/or cover crops that might be integrated with forage crops in an economically and environmentally sustainable system; and (iii) to summarize the results of a survey of the perceptions of Brazilian farmers to problems with WSs and HRWs to glyphosate, and the level of adoption of good agricultural practices in order to prevent or manage it.

Keywords: glyphosate; herbicide resistance; herbicide tolerance; weed population shifts; herbicide-tolerant crops

1 INTRODUCTION

Weeds are organisms evolving in response to environmental changes, disturbance and/or stress.[1] Therefore, intensive use of herbicides in agriculture, being a major disturbance process, imposes selection pressure in weed communities, resulting in intraspecific biotype weed selection to produce evolved herbicide-resistant weeds (HRWs) and interspecific species selection to cause weed species shifts (WSs) owing to effective and selective control.[2,3] Other important selective forces are herbicide choice, tillage system, crop selection, cultural practice, climate change/weather patterns and the introduction of new weed species.

The repetitive use of the same herbicide, or different herbicides with the same mode of action, year after year, and even the frequent use of long-term, residual herbicides, favours WSs and the evolution of HRWs.[4,5] The literature has many examples of WSs after repetitive use of herbicides in cropping systems,[6] especially where there is little diversity in the herbicide mode of action choice in a monoculture. Such effects are always due to two main factors: high levels of weed control of the susceptible species and frequent use of herbicides with the same mode of action, resulting in selection of plants within the controlled species that have mutations conferring resistance usually without compromising fitness (HRWs) and of species that are naturally tolerant to the herbicide(s) used that were not a problem in the system previously (WSs). Such a cropping system will have less weed diversity in the short term, a situation that is sometimes associated with the indiscriminate use of glyphosate.

Sustained monoculture, as opposed to multicropping systems over time (crop rotation), is frequently associated with WSs and HRWs. Therefore, diversity in cropping systems is a rational way to avoid specialization of weeds with certain crops. Crop rotation affects soil weed seed bank species composition by increasing diversity and, conversely, reducing total density in the area, which works as an antagonistic process for development of WSs and HRWs. Best weed integrated weed management practices in

* Correspondence to: Pedro J Christoffoleti, ESALQ/USP/LPV, C.Postal 09, 13418-900, Piracicaba, SP, Brazil
E-mail: pjchrist@esalq.usp.br
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an integrated pest management (IPM) programme include adequate cultural practices, such as appropriate row width, seeding rate, seeding date, fertilizer placement, etc., which enable the crop to be more competitive, and which reduce weed density and the likelihood of weed specialization in the cropping system[7] and consequently WSs and HRWs. Plant species may adapt and propagate rapidly when alien to an environment, on account of the absence of natural enemies, resulting in high-density populations.[8] This occurs in the case of WSs.

Conservation of natural resources is essential in the South American agricultural areas, especially in Brazil where the tropical and subtropical climates require conservation production systems that maintain the sustainability of the agroecosystem by reduction of soil erosion and maintenance of the soil fertility and moisture.[9] The sustainability of tropical systems is obtained by good agricultural practices, such as crop rotation and no-tillage systems.

To practice no-tillage agriculture, the herbicide glyphosate is a very useful tool to promote soil protection by plant residues that are obtained from natural vegetation or a cover crop cultivated during the intercropping season.[10] This practice has been adopted by most South American farmers aware of natural resources conservation. However, some problems with the intensive and repetitive use of glyphosate have occurred, such as selection of glyphosate-resistant weeds and WSs to species tolerant to glyphosate, which may impose certain limitations on the use of the technology. Therefore, farmers must pay attention to factors that impose this weed selection, and design herbicide and non-herbicide strategies that effectively delay or manage glyphosate-resistant weeds (GRWs) and WSs in the weed community.

Researchers are developing a sufficient understanding of the factors that impose the selection to make recommendations to delay the emergence of HRWs and WSs. Among the approaches proposed is the integration of crop rotation and intercropping with forage crops to make the system more diverse,[11,12] thereby minimizing shifts to glyphosate-tolerant species and evolution of GRW biotypes, and so making glyphosate and glyphosate-resistant crops (GRCs) useful to farmers for a longer time.

There has been great concern worldwide over the extensive use of glyphosate and GRCs and their effects on WSs and especially evolution of GRWs. This concern extends to the impacts on the use of glyphosate outside GRCs. Agricultural consultants and farmers are greatly interested in how evolution of GRWs might affect the stewardship of glyphosate use in agriculture.[13]

2 CROPPING SYSTEM INFLUENCES ON WSs AND GRWs IN COUNTRIES OF SOUTH AMERICA

2.1 Argentina

During the 1980s, soil degradation in Argentina resulted from cattle production rotated with crops. However, more recently, soybean cultivation in rotation, especially with wheat during the summer, has characterized Argentinian agriculture.[14] Direct seeding with adequate plant residue cover and planned crop rotation is the cropping system that enables soybean to occupy two-thirds of the cropped area in the country.[15] Research and extension efforts in the country have led to a considerable increase in the use of conservation tillage systems, resulting in the practice of no-tillage agriculture on about 14 million ha in 2004.[15]

Intensive production systems based on direct seeding in Argentina, Brazil and Paraguay allowed two crops to be cultivated per year in areas where one was formerly cultivated, and 2.5 crops in areas formerly cropped with two sequential cultivations.[16] This scenario has led to increases in crop productivity and reduction in soil fertilizer amendments.

Associated with the expansion of no-tillage and intensive cropping systems, especially with soybean production with glyphosate-resistant soybeans (GRSs), the use of glyphosate has increased considerably, being the most used herbicide in Argentina.[17] During the last 10–12 years, intensive agriculture in the soybean belt has undergone profound technological changes: large-scale adoption of no-tillage systems, introduction and rapid adoption of GRSs, grown in monoculture, and replacement of traditional herbicides with glyphosate.[18] These factors have imposed selection pressures on the weed community by selecting rarely occurring species in the area that are tolerant to field rates of glyphosate as well as resistant biotypes of *Sorghum halepense* (L.) Pers.[18]

The first suspected population of *S. halepense* resistant to glyphosate to be confirmed was a biotype from the Salta region of north-west Argentina in 2006. In this region, 700 000 ha of GRSs are grown, of which 90% is under a no-tillage system. *Sorghum halepense* is the most important weed in that region, causing losses of up to 40% owing to weed interference.[19] Dose–response curves comparing resistant and susceptible biotypes of *S. halepense* have a resistance factor (GR_{50}) of 2.82 at 21 days after glyphosate application.[19]

The intensive use of glyphosate has helped to reduce the density of many weed species while increasing the density of others that were not always previously a part of the plant community. As a result, biodiversity has been maintained or even increased.[20] Some of the new weed species found in the fields sprayed with glyphosate on no-till planted GRSs have shown a higher degree of tolerance to glyphosate.

2.2 Paraguay

The major agricultural areas of Paraguay are under a consistent rainfall distribution, with the soil constantly cultivated crop after crop, so the main crop is followed by another commercial crop or green manure to enrich the soil. The consequences are increased biomass production, lower leaching of soluble nutrients in the soil and, most important, a weed infestation reduction.[16] One of the cropping systems is soybean/green manure/soybean, with the crop rotated with green manure during 6–7 months in the winter time. Another cropping system is a sequence of crops (soybean/green manure/corn or sunflower/soybean). In this system it is possible to grow 2.5 crops in a year, since the management of the green manure is done during only 90 days, before the end of the life cycle of the plant. The third system is characterized as much more intensive, with the green manure cultivated very briefly in between the summer and winter crops, followed by the summer crop. To date, no case of a GRW has been reported in Paraguay.

2.3 Brazil

Natural resource conservation is a key national priority of Brazilian cropping systems, especially in the soybean agricultural areas of the central/southern parts of the country.[9] Society has influenced growers to adopt conservation cropping systems, thereby reducing damage to the agricultural environment (agroecosystem) as a whole. These systems are based on plant residues covering the soil surface (cover crop), with a minimum disturbance of the topsoil layer. These systems, when compared with conventional cropping systems, reduce diurnal soil temperature variation, decrease water evaporation from the soil surface, enhance organic matter content and microorganism activity in the topsoil layer, improve both the physical and chemical soil properties, provide better soil erosion control and reduce weed infestation as well.

One of the inevitable discussions in Brazilian agriculture recently has been related to the potential for evolution of GRWs. This concern extends from the intensive use of glyphosate in areas of no-till cropping systems and areas where it is used for non-selective weed control, such as in fruit crops and forestry, to its use in GRCs.[21] Recently, the first case of a GRW was reported with the weed Italian ryegrass (*Lolium multiflorum* Lam.) in Brazil.[22,23]

Two species of *Conyza* were also reported as resistant to glyphosate in Brazil. Dose–response curves were recently drawn up for *Conyza canadensis* (L.) Cronq. and *C. bonariensis* (L.) Cronq. selected in citrus areas, and experiments to indicate alternative treatments to these biotypes were carried out.[24]

Populations of glyphosate-resistant biotypes of both species were found, each with different levels of resistance.

Adoption of a living mulch system is one of the sustainability practices that have been adopted in Brazil in order to reduce weed infestation and increase weed flora diversity by reducing weed species selection pressure. The system is based on the use of living mulch intercropped in corn or soybean, the living mulch being a forage crop that is used for cattle feed or as soil cover after dessication by a herbicide.[25] The system is very suitable for the south-east and central areas of Brazil, and brings several additional agronomic benefits: (i) input of organic matter in the system, (ii) higher water retention in the soil, (iii) weed suppression and diversification, (iv) sequestration of carbon from the environment, (v) reduction of soil compaction and (vi) yield increase and sustainability of the system.[26]

3 INTERCROPPING AND COVER CROPPING FOR DIVERSIFICATION OF THE SYSTEM: BRAZILIAN EXPERIENCE WITH INTERCROPPING SOYBEAN OR CORN WITH FORAGE GRASS CROPS

Intercropping includes agronomic systems where a second crop is seeded with the first.[27] It is a system where the yield from both crops might or might not be of the same importance for growers, and, although the yield from each crop may be reduced, the overall yield is increased.[28]

A new system has been developed in Brazil that intercrops a forage cover crop after the harvest of a second crop of corn or soybean.[29] Intercropping corn with forage grass crops is the most common example of this system. This system can be used in farms that need renovation of pastures, as well as for the formation of mulching for no-tillage systems. In the Brazilian Cerrados, this technology has been adopted in order to restore pasture associated with annual crops, such as corn. The system restores the pasture mainly through fertilization of the crop (corn or soybean) that is intercropped.[30]

Intercropping and cover crops can significantly reduce weed infestation. Weed biomass was reduced by cover cropping in 47 studies and increased in only four studies, with a variable response in three, while in intercropping systems weed biomass was lower than in all sole crops in 12 cases, intermediate between component sole crops in ten cases and higher in two cases.[28] Weed establishment and growth are reduced by competition with the cover crop for growth resources, changing environmental factors and possibly phytotoxins released from the cover crop.[28,31]

An experiment was conducted with the objective of evaluating the consequences of adopting a living mulch system with forage grasses intercropped in the corn crop on weed infestation.[32,33] The treatments resulted from the combination between four levels of grass forage (*Brachiaria decumbens* Stapf., *Brachiaria brizantha* Stapf., *Panicum maximum* Jacq. and absence of forage) and three levels of three weed species [*Ipomoea grandifolia* (Jacq.) Hall, *Amaranthus hybridus* L. and *Digitaria horizontalis* Willd.]. Leaf area, dry weight and density of weeds living in association with the corn crop and grass forages were evaluated. In general, the production system involving the association of a forage grass with the corn crop reduced infestation and suppressed the growth of weeds in the system; *B. decumbens* was the forage that least reduced weed infestation; *B. brizantha* was the most efficient forage in reducing *I. grandifolia* infestation, but it did

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not suppress *A. hybridus* growth; *P. maximum* was the species that most reduced *A. hybridus* growth and *D. horizontalis* leaf area (Table 1).

Diversification is the major component of the system of intercropping soybean or corn with forage grass crops. Intercropping is a valuable tool to prevent and/or manage WSs and GRWs and to keep the sustainability of glyphosate in cropping systems by increasing weed biodiversity and reducing the weed community specialization and selection.

4 BRAZILIAN SOYBEAN GROWERS' PERCEPTION ABOUT THE INFLUENCE OF GRCs ON THE SUSTAINABILITY OF GLYPHOSATE

The adoption of GRCs by Brazilian growers may increase the potential for selection of tolerant weed species (WSs) and/or populations of GRWs, and therefore it is important to understand how growers are acting and their perceptions about HRWs and weeds naturally tolerant to glyphosate. This is essential to guide future research and actions to inform farmers the best alternatives for weed control in conservation tillage systems. Therefore, a grower survey was conducted during January and February of 2007, based on a questionnaire sent across the states of Mato Grosso do Sul and São Paulo. This survey was based on a similar one conducted by Johnson and Gibson[34] with corn and soybean growers across Indiana (USA) during the winter of 2003/2004 to assess their perceptions about the importance of GRWs and management tactics to prevent development of resistant populations.

A two-page questionnaire was provided to agricultural consultants of two soybean regions in Brazil: Naviraí, MS, located in the central part of the country and the Cerrados area (28 questionnaires completed), and Orlândia, SP, located in the south of Brazil, São Paulo State (96 questionnaires completed). Nine questions dealt with agronomic aspects that would affect selection of GRW and glyphosate-tolerant species, and there were other questions about the cropping system used and perceptions of the general subject of GRCs and GRWs. Results are summarized in the following section.

The majority of the growers reported a high potential risk of selecting GRWs. Responses varied according to soybean cropped area size on the farm (farm size), as did those obtained in the Indiana survey.[34] Growers with soybean cropped areas of <100 ha were not very concerned about the problem of GRWs, but 94% of the farmers with larger areas had at least some level of concern about GRWs (Table 2). From these results it can be inferred that growers with more extensive areas may be more aware of the impact of GRWs, probably owing to the higher level of technology and information that is not available to growers of smaller cropped areas.

Farmers mentioned four major reasons to adopt GRCs: to experience the technology for the first time (21.8%); to manage HRWs (20.2%) to herbicides such as sulfonylureas, imidazolinones and ACCase inhibitors with glyphosate as an alternative herbicide; reduction of costs (36.3%); and higher flexibility and simplicity of the technology compared with conventional tillage (23.4%) (Table 3). A few other reasons were also listed. Another factor that influenced the answers of farmers with smaller cultivated areas of soybean was the percentage of the area in the property that was seeded with GRSs, which was much higher in the case of growers cultivating >1000 ha than in the case of smaller growers (Table 4).

Glyphosate-tolerant weeds selected owing to repetitive use of glyphosate in the area causing WSs was also a big concern to farmers cultivating more extensive areas (Table 5). Cultivated areas of >1000 ha were of

Table 1. Weed density in the interaction among the treatments with forage crops and weed species, intercropped in the corn crop, 60 days after seeding. Adapted from Severino *et al*.[33]

Grass forage crop	Weed density (plants m^{-2})[a]					
	I. grandifolia		*A. hybridus*		*D. horizontalis*	
Brachiaria decumbens	33.5	aA	18.8	bB	5.6	bC
Brachiaria brizantha	3.6	cA	4.3	cA	3.4	bA
Panicum maximum	12.4	bA	3.6	cB	4.3	bB
No intercropping[b]	36.3	aB	72.2	aA	37.3	aB
C.V. (%)[c]			13.08			

[a] Numbers followed by different letters, upper case in the lines and lower case in the columns, differ at the 5% level of significance according to Tukey's test;
[b] Control plot without intercropping and weeded.
[c] Coefficient of variation of the experiment.

Table 2. Level of concern reported about GRWs according to the soybean cropped area size in Brazil

Soybean cropped area size by farm (ha)	Level of concern about HRW to glyphosate (%)			
	High	Moderate	Low	None
<100	18.2	16.1	15.2	50.5
100–200	50.0	27.3	18.2	4.5
201–500	52.6	26.3	10.5	10.6
501–1000	19.3	53.8	23.1	3.8
>1000	54.2	33.3	8.3	4.2

Table 3. Main reasons for farmers to adopt GRC technology, independent of property size, in Brazil

Reason	%[a]
Experiencing the new technology	21.8
HRW management	20.2
Cost reduction	36.3
Higher flexibility	23.4
Other reasons	5.7
Do not cultivate GRCs	27.4

[a] Total of all reasons is more than 100%, as more than one reason was allowed.

Table 4. Cultivated area with GRCs according to the soybean cropped area in Brazil

Soybean cropped area size by farm (ha)	Percentage of soybean area cropped with GRCs						No answer[a]
	0	<10	10–20	20–50	50–70	70–100	
<100	54.5	9.1	9.1	0	0	27.3	0.0
100–200	50.0	9.1	4.6	9.1	9.1	13.7	4.4
201–500	48.7	5.1	12.8	15.4	7.7	10.3	0.0
501–1000	37.1	7.4	14.8	29.7	0.0	11.1	0.0
>1000	4.2	16.7	20.8	25.0	12.5	16.7	4.1

[a] Percentage of farmers not answering the question.

high to moderate concern to all the farmers. Therefore, in Brazil the selection of tolerant weed species by glyphosate is of much higher concern to farmers than GRWs. This is especially common for soybean growers with extensive areas cultivated with soybean. That a greater proportion of small farmers did not answer the question is probably because they are not aware of the problem and misunderstand the difference between evolved GRWs and WSs to naturally tolerant weed species.

Another question asked was about the reasons for not adopting measures for prevention and management for selection of GRW biotypes and/or glyphosate-tolerant weed species (Table 6). Interestingly, 54.6% of smaller farmers answered that they adopt such measures at the whole-farm level. Only 27.3% had constraints because of costs, and 9.1% did not believe that GRWs would occur on their property. None of the bigger farmers responded that they adopted measures of prevention or management at the whole-farm level, high costs being the reason. However, surprisingly, 20.8% of farmers cultivating >1000 ha of soybeans did not believe in the possibility of selecting GRWs on their properties. Thus, there appears to be a problem that requires effective action by the extension service and agricultural consultants to ensure that correct work is carried out on weed management.

5 CONCLUSIONS

The growing adoption of GRCs (mainly soybean) and no-tillage agriculture in South America has widely increased the use of glyphosate as the main tool to control weeds. This particular situation has helped to reduce the density of many weed species, while at the same time increased the density of some others that were previously not always part of the community. As a result, biodiversity has been maintained or even increased. Some of the new weed species found in the fields sprayed with glyphosate on no-till planted GRCs have shown a higher tolerance to glyphosate, and some intraspecific biotype resistance (HRWs) has occurred. Therefore the sustainability of glyphosate in the system should be adequately studied in order to avoid for as long as possible the selection for GRWs and WSs to glyphosate-resistant species.

Table 5. Level of concern reported about naturally glyphosate-tolerant weed species (WSs) according to the soybean cropped area size in Brazil

Soybean cropped area size by farm (ha)	Level of concern about tolerant weeds to glyphosate (%)				No answer[a]
	High	Moderate	Low	None	
<100	27.3	27.7	18.2	0.0	26.8
100–200	68.2	22.7	4.6	0.0	4.6
201–500	64.1	23.1	2.6	5.1	5.1
501–1000	44.4	40.8	11.1	0.0	3.7
>1000	75.0	25.0	0.0	0.0	0.0

[a] Farmers not answering the question mostly because they could not differentiate between HRWs and naturally tolerant weed species (WSs).

Table 6. Reasons for not adopting measures for prevention and management of GRWs according to the soybean cropped area size in Brazil

Soybean cropped area size by farm (ha)	Replies[a] (%)					
	1	**2**	**3**	**4**	**5**	**6**
<100	27.3	9.1	18.2	9.1	54.6	18.2
100–200	22.7	40.9	18.2	0.0	0.0	18.2
201–500	41.0	15.4	0.0	5.1	0.0	38.5
501–1000	51.8	14.8	7.4	3.7	0.0	22.2
>1000	50.0	20.8	8.3	8.3	0.0	12.5

[a] **1** – high cost of adoption; **2** – growers do not believe in the possibility of selecting GRWs in the cropped area; **3** – when GRWs are selected in the area, the industries and extension service will find out a way to solve the problem; **4** – measures already adopted in part of the soybean cropped area; **5** – measures already adopted at the whole-farm level; **6** – marked more than one of the alternatives.

Diversity of the system is a key factor for sustainability of glyphosate in the cropping system in South America. The use of crop rotation and living mulches may increase weed biodiversity and reduce the weed community specialization and selection. Growers are aware of the problems, but most are not proactive in preventing selection for tolerant weed species and GRWs. Therefore, more effective extension education delivery to growers is required in order to make clear the potential for future problems.

The challenge of designing and communicating herbicide and non-herbicide strategies that effectively delay and/or manage GRWs and WSs to glyphosate-tolerant weed species in economically and environmentally sound cropping systems based on recurrent glyphosate application is challenging. The intra- and interspecific weed dynamics in the field must be understood for success in this effort. Growers with lower technology, associated with smaller cultivated areas in Brazil, should be the focus of more extension education programmes. However, broad areas of this problem need research and suitable technology to be developed in order to maintain sustainability of the system.

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