Weed Technology

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Assessment of crop and weed management strategies prior to introduction of auxin-resistant crops in Brazil

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Education/Extension

Cite this article: Oliveira MC, Lencina A, Ulguim AR, Werle R (2020) Assessment of crop and weed management strategies prior to introduction of auxin-resistant crops in Brazil. Weed Technol. doi: 10.1017/wet.2020.96

Received: 23 May 2020
Revised: 23 July 2020
Accepted: 22 August 2020

Associate Editor:
Aaron Hager, University of Illinois

Nomenclature:
2, 4-D; dicamba; glyphosate; Asiatic dayflower, *Commelina communis* L.; asthmaweed, *Conyza bonariensis* (L.) Cronquist; Benghal dayflower, *Commelina benghalensis* L.; Canadian horseweed, *Conyza canadensis* (L.) Cronquist; dayflower, *Commelina* spp.; goosegrass, *Eleusine indica* (L.) Gaertn.; horseweed, *Conyza* spp.; morningglory, *Ipomoea* spp.; sourgrass; *Digitaria insularis* (L.) Mez ex Ekman; tall fleabane, *Conyza sumatrensis* Retz. E. Walker; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merril

Keywords:
Cover crops; herbicide weed resistance; no-till; survey; weed control

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Abstract

A stakeholder survey was conducted from April through June of 2018 to understand stakeholders' perceptions and challenges about cropping systems and weed management in Brazil. The dominant crops managed by survey respondents were soybean (73%) and corn (66%). Approximately 75% of survey respondents have grown or managed annual cropping systems with two to three crops per year cultivated in succession. Eighteen percent of respondents manage only irrigated cropping systems, and over 60% of respondents adopt no-till as a standard practice. According to respondents, the top five troublesome weed species in Brazilian cropping systems are horseweed (asthmaweed, Canadian horseweed, and tall fleabane), sourgrass, morningglory, goosegrass, and dayflower (Asiatic dayflower and Benghal dayflower). Among the nine species documented to have evolved resistance to glyphosate in Brazil, horseweed and sourgrass were reported as the most concerning weeds. Other than glyphosate, 31% and 78% of respondents, respectively, manage weeds resistant to acetyl-CoA carboxylase (ACCase) inhibitors and/or acetolactate synthase (ALS) inhibitors. Besides herbicides, 45% of respondents use mechanical, and 75% use cultural (e.g., no-till, crop rotation/succession) weed control strategies. Sixty-one percent of survey respondents adopt cover crops to some extent to suppress weeds and improve soil chemical and physical properties. Nearly 60% of survey respondents intend to adopt the crops that are resistant to dicamba or 2,4-D when available. Results may help practitioners, academics, industry, and policy makers to better understand the bad and the good of current cropping systems and weed management practices adopted in Brazil, and to adjust research, education, technologies priorities, and needs moving forward.

Introduction

Agriculture has undergone major evolution in the past century, leading to a significant increase in crop yields (Warren 1998). From the 1930s to the 2010s, grain corn, cotton (*Gossypium hirsutum* L.), rice (*Oryza sativa* L.), and soybean crop yields have shown increases in the United States of 740%, 390%, 350%, and 290%, respectively (USDA-NASS 2020; Warren 1998). The discovery of synthetic herbicides, including MCPA, and 2,4-D in the 1940s, had a positive impact on crop yields by allowing more effective control of weeds (Troyer 2001). For example, 2,4-D was adopted as an effective (>90%) broadleaf weed control compound used at lower concentrations compared to organic herbicides, such as sodium chlorate and sodium thiocyanate (Marth and Mitchell 1944). The introduction of *S*-triazine (e.g., atrazine) herbicides in the 1950s represents another milestone in terms of weed control and herbicide popularity among growers (LeBaron et al. 2008). The combination of PRE and POST herbicides plus cultural and mechanical methods reduced the need for labor-intensive hand weeding, increased efficacy, and greatly reduced the costs for weed management (Gianessi and Reigner 2007; Holstun et al. 1960).

From the 1940s to the 1980s (herbicide discovery era), novel herbicide chemistries with broad weed control spectra, application window in relation to crop developmental stage, and selectivity were discovered. During that time, on average, a new herbicide site of action (SOA) was introduced every 2 yr (Appleby 2005; Duke and Dayan 2018). Herbicides quickly became synonymous with weed management and through this date represent the most commonly adopted tool for weed control in conventional production systems. In recent years, given the shortage and challenges related to novel herbicide discovery (Duke 2012), industry focus has shifted toward biotechnology and the development of crop hybrids or varieties genetically engineered with herbicide-resistant (HR) genes (Bonny 2011; Owen 2000).

In 1996, glyphosate-resistant (GR) soybean (Roundup Ready®) was the first transgenic HR crop to be introduced, followed by GR corn and GR cotton, which allowed growers to spray glyphosate, a systemic, nonselective, and very effective herbicide POST in GR crops (Padgette et al. 1995). Glyphosate use has risen followed the introduction of GR crops in 1996 (Benbrook 2016). This increase was further accelerated with introduction of GR crops in developing countries such as Brazil and Argentina in the early 2000s. In 2014, glyphosate represented 66% of herbicide applications in Brazil (SIDRA-IBGE 2020). GR crops are documented as the most adopted technology of modern agriculture (Green 2018). However, glyphosate overreliance resulted in weed shifts and evolution of GR weeds (Owen 2008). Thus far, there are 50 confirmed GR weed species worldwide, 9 weed species in Brazil, including sourgrass and horseweed (Heap 2020).

Rapid evolution of GR weeds prompted the development of other HR crops such as glufosinate, 2,4-D, and dicamba-resistant (DR) soybean, cotton, and/or corn. The new synthetic auxin-resistance (AR) technology was introduced in 2017 to the United States and is expected soon to become available in Brazil. The Roundup Ready 2 Xtend® (Bayer Crop Science, St. Louis, MO) allows the use of glyphosate and new dicamba formulations, including diglycolamine salt with VaporGrip®, an acetic acid-acetate buffering system, or a dicamba salt N,N-Bis-3-aminopropyl methylamine in DR crops. Moreover, the 2,4-D–resistant technology, marketed as Enlist E3® (Corteva Agriscience, Wilmington, DE), allows glyphosate, glufosinate, and a new 2,4-D-choline salt formulation application in Enlist® crops (Wright et al. 2010). These new 2,4-D and dicamba formulations are products with reduced volatility compared to their previous formulations. However, in the first year of AR crops in the United States, an estimated nearly 1.4 million hectares of non-DR soybeans were injured by dicamba (Oseland et al. 2020). In Nebraska, 51% of survey respondents noted dicamba injury in their non-DR soybeans in 2017 (Werle et al. 2018). It is still controversial whether the injury on sensitive vegetation is due to dicamba vapor, particle drift, and/or tank contamination. Nonetheless, the upcoming introduction of AR crops in Brazil raises concerns of off-target movement (OTM) and requires research.

The introduction of AR crops increases complexity but represents a new milestone in terms of weed management; thus, it is essential to document current practices prior to their introduction and after nearly 20 yr of GR crops use in Brazil. Surveys are useful tools for documenting agricultural practitioners' knowledge and perceptions regarding specific strategies. For example, a survey with pesticide applicators indicated the need for further education regarding application of synthetic auxin technologies in the US state of Missouri (Bish and Bradley 2017). Also, a survey conducted in Argentina demonstrated that weed control is based on empirical short-term decisions, with >53% using solely herbicides for weed management (Scursoni et al. 2019). A survey documented a concern about protoporphyrinogen oxidase (PPO) inhibitor–resistant Palmer amaranth (*Amaranthus palmeri* S.Watson) in the US Southwest, the need for diversified weed management strategies, and additional cover crop research in that geographic region (Schwartz-Lazaro et al. 2018). Therefore, documenting current weed management practices in different regions of Brazil could improve weed management decisions, policy, education, investments, research priorities, and further needs.

In Brazil, growers rely mainly on crop advisors for crop management decisions, including strategies for weed control (MR dos Reis, personal communication). The use of survey questionnaires in Brazil with agricultural practitioners has been lacking. Therefore, the objective of this survey was to understand from growers and crop advisors (e.g., crop consultants, cooperatives, industry, and university representatives) current agricultural management practices, perceptions, and challenges regarding current cropping systems and weed management in Brazil. The survey specifically focused on crop management, troublesome and HR weeds, and evaluation of interest, value, and potential challenges the new AR technologies may face if deployed/adopted in Brazil.

Table 1. Survey questionnaire available online for agronomist, consultant, grower, industry, and university representatives in the 2018 Cropping Systems Weed Management Survey.

(Q1)	What is your role?
(Q2)	In which Brazilian state(s) do you manage cropping systems?
(Q3)	How many hectares do you manage/influence?
(Q4)	Which crop(s) do you manage/influence?
(Q5)	How many crop(s) in succession in the area do you manage/influence?
(Q6)	Do you manage/influence irrigated systems?
(Q7)	Do you manage/influence no-till systems?
(Q8)	Do you manage/influence cover crops? If Yes, which species?
(Q9)	Do you manage/influence crop–livestock integration systems?
(Q10)	What are the most troublesome weed(s) that you manage/influence?
(Q11)	Do you manage/influence an area with glyphosate-resistant weeds?
(Q12)	Which glyphosate-resistant weeds do you manage/influence?
(Q13)	Do you manage/influence an area with herbicide-resistant weeds (non-glyphosate)?
(Q14)	Which herbicide-resistant weeds do you manage/influence?
(Q15)	Which herbicide program and SOA is used in crops you manage?
(Q16)	Who is responsible for herbicide application in your operation?
(Q17)	Does the herbicide applicator receive pesticide application training?
(Q18)	Do you use nonchemical weed management strategies?
(Q19)	Do you intend to adopt/recommend synthetic auxin crops (2,4-D or dicamba) in the area you manage/influence?
(Q20)	What is your main source of information for weed management?
(Q21)	What is the main weed management limitation in the area you manage/influence?

Materials and Methods

A survey was developed to understand Brazilian stakeholders' perceptions and challenges about cropping systems and weed management strategies (Table 1). To reach a broad representation, the survey was conducted online using Qualtrics (Provo, UT) linked to the University of Wisconsin-Madison and circulated via social media, including Twitter® (San Francisco, CA), Facebook® (Menlo Park, CA), LinkedIn® (Sunnyvale, CA), and Whatsapp® (Menlo Park, CA). The messenger Whatsapp® is popular among agricultural stakeholders in Brazil. Extension agents also assisted with distributing the survey questionnaire to stakeholders through their electronic listservs.

The survey comprised three sections. Questions in the first section focused on respondents' demographics: (Q1) role (e.g., grower or industry representative), (Q2) region, and (Q3) managed area (in hectares). The second section was designed to focus on cropping systems practices: (Q4) crops managed, (Q5) crop succession, (Q6) irrigation, (Q7) tillage, (Q8) cover crops, and (Q9) crop-livestock integration. The third section focused on weed management strategies: (Q10) troublesome weeds, (Q11 through Q14) HR weeds, (Q15) herbicide programs and SOA, (Q16 and Q17) herbicide application information, (Q18) nonchemical weed management, and (Q19) adoption of AR crops. The third section also

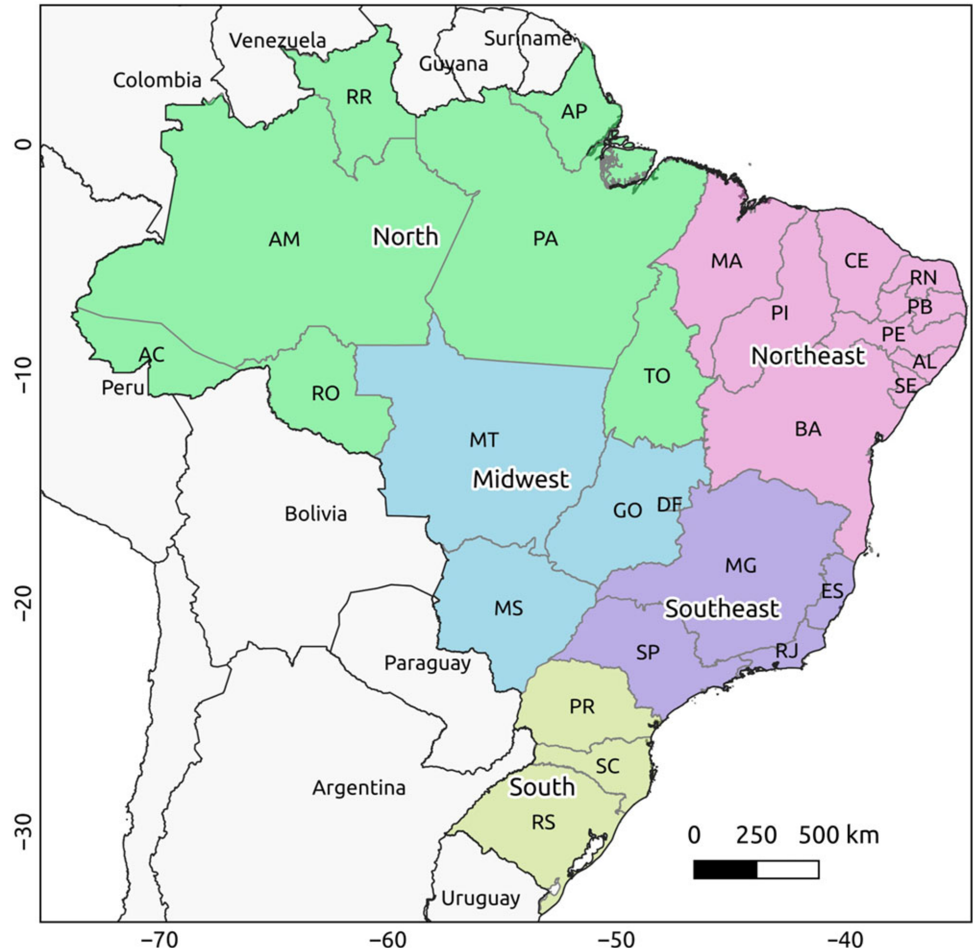

Figure 1. Brazilian map highlighting the five geopolitical macro-regions: North, Northeast, Midwest, Southeast, and South.

incorporated general questions (Q20 and Q21) about cropping systems and weed management challenges (Table 1).

The online survey was available from April 1 through June 30, 2018. Results were exported from Qualtrics as a Microsoft Excel (Microsoft Office, Redmond, WA) file, with the answers to each question in separate columns. Survey data were sorted and analyzed using the *sort*, *filter*, and *count* functions in Microsoft Excel and *summarise*, *filter*, and *pipe* in the package tidyverse (Wickham 2017) of R statistical software (R Core Team 2020). For most questions, results are presented as: (1) percentage of respondents, (2) percentage of answers, and (3) percentage of number of hectares represented. Not every respondent answered every question; for some questions, respondents were allowed to select among multiple choices (e.g., Q15, herbicide programs and SOA). Moreover, survey respondents were grouped according to their region as listed in the demographic geopolitical Brazilian map: North, Northeast, Midwest, Southeast, and South (Figure 1).

Results and Discussion

Crop Management

Demographics

Survey answers were obtained from 343 stakeholders, representing 21 of 27 Brazilian states (including the Federal District, home of Brazil's capital, Brasilia). Most survey respondents were located in the South (43%) and Southeast (38%) regions of Brazil; however, 43% of managed hectares represented in the survey are in the Midwest region (Table 2). The South and Southeast regions encompass small/medium farm sizes (<500 ha), whereas the Midwest, North, and Northeast regions represent the newly expanded agricultural region in Brazil, with farm sizes of >500 ha up to 100,000 ha (Dias et al. 2016). Most survey respondents identified themselves as agronomists (69%), followed by university and industry representatives (22%), growers (21%), and consultants (9%; Table 2). Respondents represent a total of 5.7 million crop hectares, a representative area, as there are 78 million ha of Brazilian territory occupied with crops and planted forest (IBGE 2020).

Cropping Systems

The survey showed that only 16% of respondents manage crops in conventional tillage in Brazil, with highest no-till practice in the Midwest (71%) (Table 3). An average of 6 out of 10 respondents adopt/recommend cover crops to some extent (Table 3), with oats (*Avena sativa* L., 48%), sunn hemp (*Crotalaria juncea* L., 27%), pearl millet [*Pennisetum glaucum* (L.) R.Br., 29%], spreading liverseed grass (*Urochloa* spp., 27%), perennial ryegrass [*Lolium perenne* (L.) ssp. *perenne*, 22%], and field mustard (*Brassica rapa* L., 16%) ranked as the top cover crop species adopted by respondents (Table 3). Moreover, crop–livestock integration is adopted

Table 2. Percentage characteristics of respondents of the 2018 Cropping Systems Weed Management Survey, according to Brazilian region.

Characteristics	Region					
	Brazil	North	Northeast	Midwest	Southeast	South
	—%—					
Respondents[a]		4	8	23	38	43
Hectares managed[b]		9	6	43	41	14
Total hectares	5.7 million					
Role of respondents[c]						
Agronomist	69	68	68	68	73	61
Consultant	9	0	14	16	13	3
Grower	21	18	5	22	24	17
Industry	22	45	36	35	26	13
University	22	18	18	11	26	22
Other	7	7	8	3	4	11

[a]Total number of respondents, *n* = 279.
[b]Number of respondents, *n* = 123.
[c]Number of respondents, *n* = 277.

Table 3. Cropping system management strategies (no-tillage, cover crops, crop–livestock, crop succession, and irrigation) adopted in Brazil according to the 2018 Cropping Systems Weed Management Survey.

Cropping systems	Region					
	Brazil	North	Northeast	Midwest	Southeast	South
	—%—					
No-tillage[a]						
Yes	61	55	50	71	51	67
Partially	22	27	18	18	18	27
No	16	18	32	11	31	6
	n^b = 273	*n* = 11	*n* = 22	*n* = 63	*n* = 99	*n* = 119
Cover crop						
Yes	61	55	55	58	52	68
No	39	45	45	42	48	32
	n = 273	*n* = 11	*n* = 22	*n* = 63	*n* = 99	*n* = 119
Cover crop species						
Field mustard	16	0	5	7	14	17
Oats	48	0	5	7	50	50
Pearl millet	29	27	27	28	68	6
Perennial ryegrass	22	0	0	2	9	27
Spreading liverseed grass	27	27	27	37	68	4
Sunn hemp	27	0	14	28	91	5
Other	3	1	2	1	7	2
	n = 143	*n* = 11	*n* = 22	*n* = 57	*n* = 22	*n* = 113
Crop–livestock integration						
Yes	37	45	14	46	22	48
No	63	55	86	54	78	52
	n = 256	*n* = 11	*n* = 22	*n* = 57	*n* = 93	*n* = 114
Crop succession[c]						
One	29	9	36	7	27	34
Two	41	64	41	74	43	29
Three	30	27	23	20	29	37
	n = 271	*n* = 11	*n* = 22	*n* = 61	*n* = 99	*n* = 119
Irrigation						
Yes	18	9	14	6	17	24
Partially	32	9	41	33	34	29
No	50	82	45	60	48	47
	n = 272	*n* = 11	*n* = 22	*n* = 63	*n* = 99	*n* = 119

[a]Conservation tillage.
[b]Number of respondents.
[c]Number of crops grown within a year.

by 37% of respondents in Brazil (Table 3). Crop–livestock establishment varies within Brazilian regions, plant species selection, and rotation sequence between livestock systems and crop succession/rotation (Moraes et al. 2014).

Survey results show that crop succession (i.e., crop rotation within a year) is a common practice in Brazil, whereas 71% of respondents manage at least two crops on the same land within a year (Table 3). In the South, nearly 40% of respondents grow three crops on the same land within a year but 20% in the Midwest, which strongly rely on two crop succession systems (74%). Soybean is usually planted as the first crop, followed by corn or cotton, and pulse, small grains [barley (*Hordeum vulgare* L.),

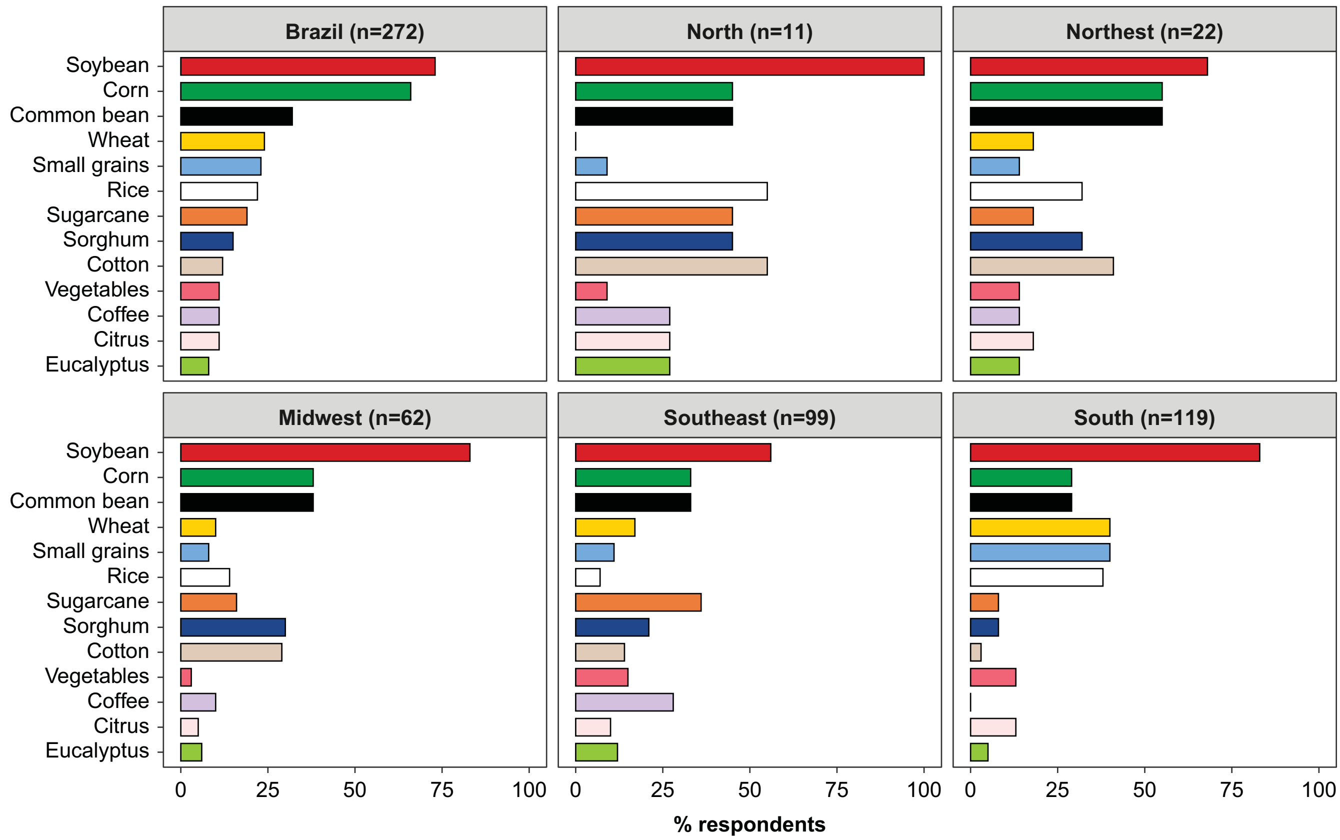

Figure 2. Percentage of respondents managing crops by Brazilian regions according to the 2018 Cropping Systems Weed Management survey (*n* = number of respondents). Citrus [*Citrus* × *sinensis* (L.) Osbeck]; coffee (*Coffea arabica* L., *Coffea canephora* Pierre ex Froehner), eucalyptus (*Eucalyptus* spp.), small grains (barley, cereal rye, oats, triticale), sorghum [*Sorghum bicolor* (L.) Moench], sugarcane (*Saccharum officinarum* L.), vegetables (carrot, *Daucus carota* (L.) var. *sativus* Hoffm.; garlic, *Allium sativum* L.; onion, *Allium cepa* L.).

oats, cereal rye (*Secale cereale* L.), and triticale (*Triticosecale rimpaui* C. Yen & J.L. Yang)], or cover crops across the country (Cerdeira et al. 2011). The number of crops per year is probably a result of moisture availability due to higher and more regular precipitation in southern regions than northern Brazilian states (Alvares et al. 2013). Moreover, 50% and 32% of survey respondents manage rainfed (nonirrigated) and partially irrigated fields, respectively (Table 3). Therefore, according to our survey no-till, crop succession, and cover crops are common practices in Brazil.

No-till strongly contributed to the expansion of annual crops in Brazil, especially in the *Cerrado* (savanna biome) area in the 1980s onwards (Sanders and Bein 1976). The geography of the *Cerrado* biome includes the Midwest and parts of the Southeast, North, and Northeast region of Brazil (Figure 1). The *Cerrado* is characterized by favorable topography for agriculture but low soil fertility (Goedert 1983), which was mainly used for pastures. In the early 2000s, it was estimated that 11% and 41% of the *Cerrado* area was covered with cropland and planted pastures, respectively (Klink and Machado 2005). The cropland in the *Cerrado* expanded 81% from 2000 to 2014, mainly replacing poorly managed pastures (Zalles et al. 2019). No-till, crop succession, cover crops, and crop–livestock integration strategies have resulted in improved soil chemical and physical properties in Brazil, especially in the *Cerrado* biome (Moraes et al. 2014; Yamada 2005).

The current expansion of cropland is occurring to the new *Cerrado* areas within the states of Maranhão, Tocantins, Piauí, Bahia (MA-TO-PI-BA), and in the Northeast and North parts of the Amazonian biome in the state of Pará (North region) (Lucio et al. 2019; Zalles et al. 2019). The steady increase of cropland in Brazil is partially due to the success of no-till and soybean production in the *Cerrado* (Araújo et al. 2019; Fearnside 2001). The importance of soybean for Brazilian agriculture is highlighted in our survey, as it is the most managed crop across the five major regions (Figure 2). Currently, there are 36 million ha of soybean grown with productivity of 119 billion kg of grain, which makes soybean the top agricultural export commodity of Brazil (IBGE 2020).

Weed Management

Herbicide Programs

The wide adoption of no-till soybean systems in Brazil would be less likely without glyphosate. Because glyphosate is a nonselective and systemic herbicide, it provides strong vegetation control (Duke and Powles 2008). Over 80% of respondents spray/manage burndown-type herbicides for management of existing vegetation prior to establishment of annual crops (Table 4). High glyphosate reliance is clearly demonstrated, as this is the main herbicide used for burndown applications to target weed control and cover crop termination in several annual and perennial cropping systems (Figure 3). Additional herbicide options sprayed as part of burndown programs are the synthetic auxin (e.g., 2,4-D), photosystem I (PSI, e.g., paraquat), and PPO (e.g., saflufenacil)–inhibiting herbicides. The survey also showed glyphosate as a foundation for POST weed management in corn, cotton, and soybean (Figure 3). For instance, Ulguim et al. (2017) have documented that

Table 4. Herbicide program (burndown, PRE, POST, and harvest aid) for weed management in multiple crops in Brazil according to the 2018 Cropping Systems Weed Management Survey.

Crops[a]	Weed management program			
	Burndown	PRE	POST	Harvest aid[e]
	——%——			
Corn (n^b= 119)	85	41	92	–
Cotton ($n = 23$)	87	70	87	39
Coffee ($n = 20$)	35	25	85	–
Citrus ($n = 19$)	32	16	68	–
Common bean ($n = 57$)	93	44	81	58
Eucalyptus ($n = 15$)	80	47	67	–
Rice ($n = 45$)	91	76	93	–
Small grains[c] ($n = 30$)	97	20	70	–
Sorghum ($n = 22$)	100	55	68	–
Soybean ($n = 159$)	82	53	81	61
Sugarcane ($n = 31$)	71	87	77	–
Vegetables[d] ($n = 16$)	69	50	69	–
Wheat ($n = 33$)	100	33	94	30

[a]See Figure 2 for Latin binomials and authorities of crops not otherwise mentioned in text.
[b]Number of respondents.
[c]Barley, cereal rye, oats, triticale.
[d]Carrot, garlic, onion.
[e]Herbicide applied at crop maturity to desiccate weed and crop foliage.

within a soybean season, glyphosate is typically sprayed three times in Rio Grande do Sul state (RS, South region).

Our survey suggests that PRE herbicides use are not popular as burndown and POST herbicide programs (Table 4). Not only are PRE herbicides costly, but they are also restricted because of intensive crop succession/rotation (Reis et al. 2018) and are typically not adopted in the absence of HR weeds. In addition, cover crop residue from burndown applications in no-till systems results in a physical barrier that may either prevent germination of early-season weed species (Altieri et al. 2011) or prevent sprayed PRE herbicides from reaching the soil (Christoffoleti et al. 2007), thus reducing either the need for PRE herbicides or the efficacy of PRE herbicides on weeds.

Troublesome and HR weeds

Survey results indicate that the top five problematic weed species in Brazil are either glyphosate tolerant (morningglory and dayflower) or GR (horseweed, sourgrass, and goosegrass) (Figure 4). Distribution of troublesome (Figure 4) and GR weeds (Table 5) varied across regions. Although ranked among the most problematic grass weed because of its high capacity to evolve resistance to herbicides (Preston et al. 2009), Italian ryegrass [*Lolium perenne* subsp. *multiflorum* (Lam.) Husnot], a cool-season grass, is mainly adapted to the South region of Brazil (Table 5 and Figure 4). However, horseweed, an annual species adapted to no-till areas, is reported as the most widespread weed species present in nearly 50% of soybeans cropland of Brazil (Lucio et al. 2019). Because of horseweed's intrinsic biology, its seeds may reach the planetary boundary layer (140 m) achieving seed dispersal of as much as 500 km (Shields et al. 2006) strongly contributing to the spreading of horseweed to adjacent and nonadjacent areas (Dauer et al. 2007). The seed-mediated flow also plays an important role in distribution of other HR weeds. The first reports of GR Palmer amaranth and GR sourgrass in South America were in Brazilian neighboring countries Argentina and Paraguay, respectively (Heap 2020). It is hypothesized that seeds from these two weed species migrated to Brazil through equipment, human traffic, and/or animals. For example, GR sourgrass is widespread across Brazilian regions but was first reported in western Paraná state (PR, in southern Brazil) in 2016 near Paraguay (Ovejero et al. 2017). Genetic similarities within GR sourgrass biotypes from Paraguay and Paraná were found but not with GR sourgrass biotypes from the Southeast and Midwest (Takano et al. 2018), suggesting that evolution of GR sourgrass is occurring through seed-mediated flow and independent selection.

GR weeds have been documented in orchard, cereal, and legume crops (Vila-Aiub et al. 2008) and are on the rise across Brazilian cropping systems. Nine weed species have evolved resistance to glyphosate in Brazil, including four monocots and five dicots (Brunharo et al. 2016; Heap 2020; Küpper et al. 2017; Takano et al. 2019). Recent reports have documented glyphosate failure to control slim amaranth (*Amaranthus hybridus* L.) (HRAC-BR 2019) and jungle rice [*Echinochloa colona* (L.) Link] (Pivetta et al. 2018) in Brazil. Other HR weeds, including those resistant to acetolactate synthase (ALS)–inhibitor herbicides, are widespread in Brazil. For example, our data suggest that 87% of respondents are managing ALS inhibitor–resistant weeds in the South (Table 5), a region where ALS-inhibiting herbicides are a foundation for weed control in rice, wheat (*Triticum aestivum* L.), and soybean (Figure 4). Weed resistance to ACCase-inhibitor herbicides is also a major problem in Brazil (Takano et al. 2019). The weed species plantain signalgrass [*Urochloa plantaginea* (Link) R.D. Webster], southern crabgrass [*Digitaria ciliaris* (Retz.) Koeler], goosegrass, Italian ryegrass, wild oats (*Avena strigosa* Schreb.), barnyardgrass [*Echinochloa crus-galli* (L.) P.Beauv.], and sourgrass have evolved resistance to ACCase-inhibiting herbicides (Heap 2020). The number of biotypes with multiple HR is increasing in Brazil, including goosegrass, barnyardgrass, and sourgrass with resistance to glyphosate and to inhibitors of ACCase and/or ALS. Moreover, a horseweed biotype was reported that is resistant to 2,4-D, glyphosate, and inhibitors of PSI, photosystem II (PSII), and PPO (Heap 2020), which certainly increases the complexity of weed management in cropping systems where such biotypes are present.

New Technologies

Our survey shows respondents willingness to adopt synthetic AR crops (57%) in Brazil (Table 5). Over 90% of growers surveyed in Nebraska reported weed management improve after using DR crops (Werle et al. 2018). Moreover, research has demonstrated effective control of pigweed species with dicamba (Schryver et al. 2017) and horseweed with 2,4-D (Frene et al. 2018). However, if adopted, dicamba or 2,4-D would have to be tank-mixed with another herbicide for control of grass weed species, given that the main weed problems in Brazil are GR grasses, such as sourgrass, goosegrass, and Italian ryegrass (Lucio et al. 2019). Studies have documented that tank-mixing 2,4-D (Li et al. 2020) or dicamba (Hart and Wax 1996; Underwood et al. 2016) can antagonize efficacy of ACCase-inhibitor herbicides

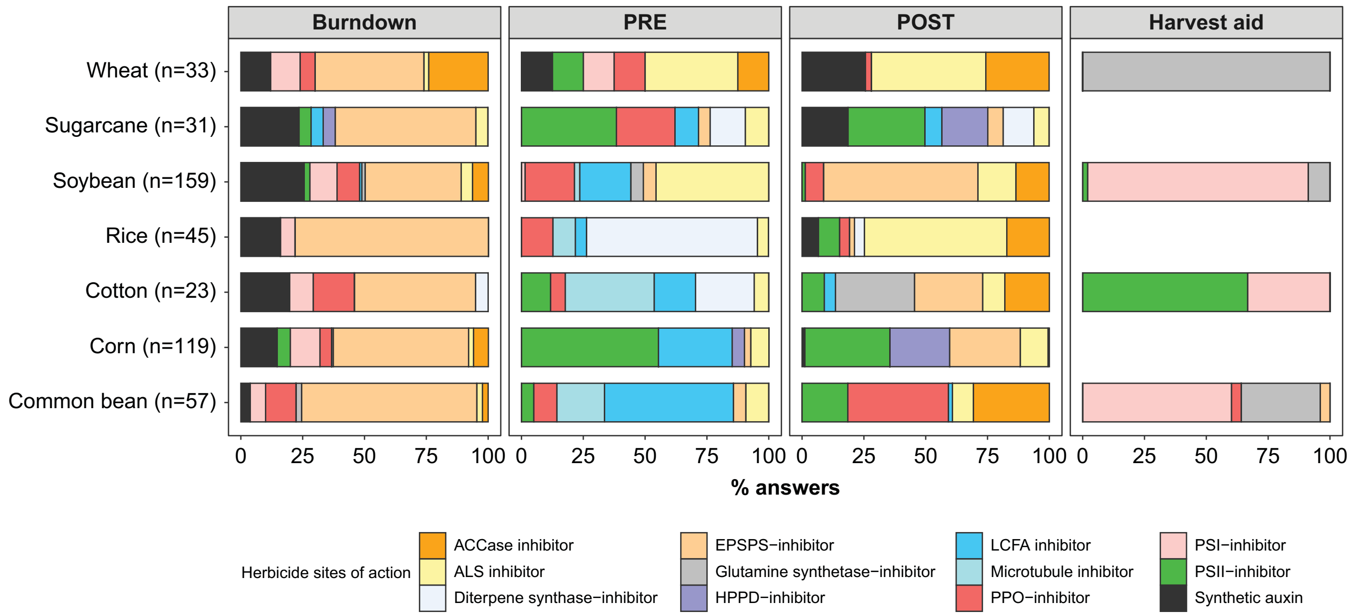

Figure 3. Percentage of answers by survey respondents on herbicide site-of-action use on common bean, corn, cotton, rice, soybean, sugarcane, and wheat in burndown, PRE, POST, and harvest aid programs according to the 2018 cropping systems weed management survey (*n* = number of respondents). Abbreviations: ACCase, acetyl-CoA carboxylase; ALS, acetolactate synthase; HPPD, 4-hydroxyphenylpyruvate dioxygenase; LCFA, long-chain fatty acids; PSI, photosystem I; PSII photosystem II; PPO, protoporphyrinogen oxidase.

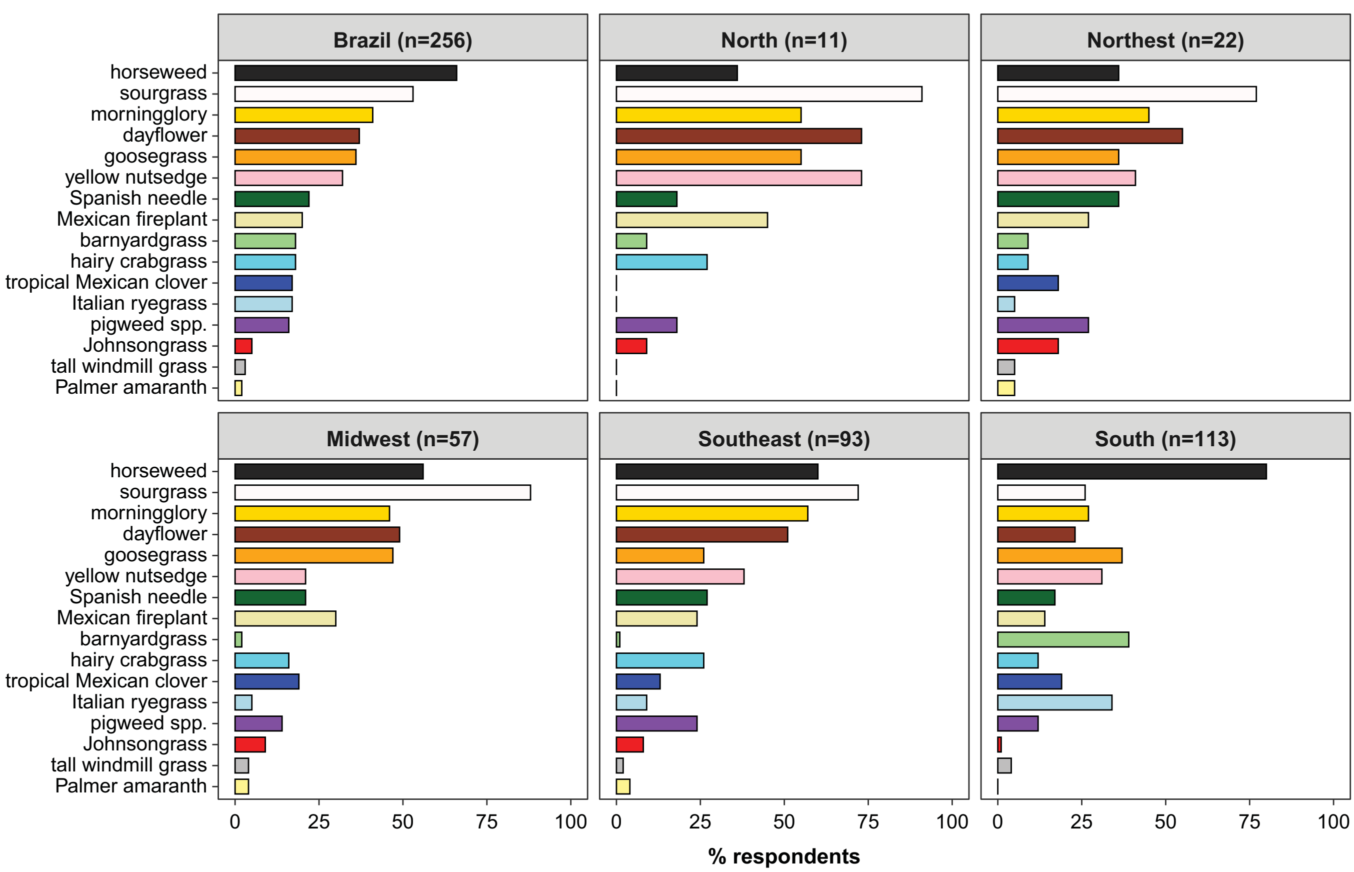

Figure 4. Percentage of respondents managing troublesome weeds by Brazilian regions according to the 2018 cropping systems weed management survey (*n* = number of respondents). Dayflower (Asiatic dayflower and Benghal dayflower), hairy crabgrass (*Digitaria sanguinalis* L. Scop.), horseweed (asthmaweed, Canadian horseweed, and tall fleabane), Johnsongrass (*Sorghum halepense* L. Pers.), Mexican fireplant (*Euphorbia heterophylla* L.), pigweed sp. (*Amaranthus* spp.), Spanish needle (*Bidens* spp.), tall windmill grass (*Chloris elata* Desv.), tropical Mexican clover (*Richardia brasiliensis* Gomes), yellow nutsedge (*Cyperus esculentus* L.).

Table 5. Weed management status (herbicide weed resistance) and strategies (adoption of auxin-resistant crops and nonchemical control) in Brazil according to the 2018 Cropping Systems Weed Management Survey.[a]

	Region					
	Brazil	North	Northeast	Midwest	Southeast	South
	%					
Glyphosate resistance						
Yes	74	73	64	79	73	80
Not sure	12	18	27	12	13	7
No	14	9	9	9	14	13
	$n^b = 258$	$n = 11$	$n = 22$	$n = 57$	$n = 94$	$n = 114$
Glyphosate-resistant weeds						
Goosegrass	31	50	43	44	28	25
Horseweed[c]	82	88	79	71	79	91
Italian ryegrass	28	13	14	9	10	54
Palmer amaranth	2	0	4	4	1	0
Sourgrass	56	75	79	91	82	25
Tall windmill grass[d]	7	13	7	7	6	9
	$n = 190$	$n = 8$	$n = 14$	$n = 45$	$n = 67$	$n = 91$
Other herbicide resistance						
Yes	46	55	50	79	37	54
Not sure	24	36	23	12	29	19
No	30	9	27	9	34	26
	$n = 257$	$n = 11$	$n = 22$	$n = 57$	$n = 94$	$n = 114$
Herbicide resistance SOA						
ALS inhibitor	78	50	63	76	73	87
ACCase inhibitor	31	50	63	44	46	21
HPPD inhibitor	7	25	38	0	12	2
LCFA inhibitor	4	25	13	0	8	2
PSI inhibitor	13	0	38	8	23	10
PSII inhibitor	12	25	38	16	19	6
PPO inhibitor	11	50	13	16	19	10
Synthetic auxin	13	25	13	0	8	2
	$n = 97$	$n = 4$	$n = 8$	$n = 25$	$n = 26$	$n = 52$
Adoption of AR crops						
Yes	57	56	54	60	64	55
Partially	34	33	23	21	20	42
No	9	11	23	19	16	3
	$n = 154$	$n = 9$	$n = 13$	$n = 42$	$n = 44$	$n = 74$
Nonchemical weed control						
Biological	5	0	6	2	3	6
Cultural	71	100	33	77	65	76
Mechanical	45	25	50	33	58	41
Physical	15	13	0	2	12	24
None	15	0	31	14	15	14
	$n = 192$	$n = 8$	$n = 16$	$n = 43$	$n = 66$	$n = 87$

[a]Abbreviations: ACCase, acetyl-CoA carboxylase; ALS, acetolactate synthase; AR, auxin-resistant; HPPD, 4-hydroxyphenylpyruvate dioxygenase; LCFA, long-chain fatty acid; PPO, protoporphyrinogen oxidase; PSI, photosystem I; PSII, photosystem II; SOA, site of action.
[b]Number of respondents.
[c]Asthmaweed, Canadian horseweed, and tall fleabane.
[d]See Figure 4 for Latin binomials and authorities of weeds not otherwise mentioned in text.

such as clethodim for grass weed control, and higher rates of graminicides are needed to overcome antagonism. In addition, dicamba tank-mixed with glyphosate reduces pH, resulting in increased dicamba concentration in the air following application (Mueller and Steckel 2019a, 2019b; Oseland et al. 2020). Therefore, 2,4-D and dicamba offer little benefit and may complicate POST management of troublesome grass weed species besides the OTM concerns in Brazil.

The OTM of dicamba or 2,4-D leading to injury in sensitive vegetation is currently a major issue in the United States (Knezevic et al. 2018; Kniss 2018; Soltani et al. 2020). Studies have documented that dicamba concentration in the air following application increased with temperature (Jones et al. 2019; Mueller and Steckel 2019a). In Brazil, climatic conditions vary from tropical (with or without a dry season) to subtropical, with annual temperatures commonly >30 C during soybean and cotton POST spray season (Alvares et al. 2013). In addition, dicamba- or 2,4-D-sensitive crops such as grape (*Vitis vinifera* L.), vegetables, orchards, soybean, cotton, and common bean (*Phaseolus vulgaris* L.) are commonly grown in Brazil. Micro-rates of dicamba or 2,4-D may cause visible injury on non-AR soybean (Osipitan et al. 2019), grape (Mohseni-Moghadam et al. 2016), and tomato (*Solanum lycopersicum* L.) (Knezevic et al. 2018). With AR crops, 2,4-D and dicamba herbicides are likely to be sprayed in large areas, which increases the chances of OTM onto sensitive vegetation. In Brazil, there are still no published data regarding potential OTM of newly sprayed dicamba and minimal information regarding 2,4-D–choline formulations (Kalsing et al. 2018). Further studies are needed to evaluate the impact of spraying large areas with dicamba and 2,4-D choline under tropical conditions. With the introduction of synthetic AR crops in Brazil, spraying dicamba and 2,4-D may require restrictions and extra herbicide applicator training similar to what has happened in the United States. Although it is not required in the country, nearly 70% of survey respondents indicated that applicators received some form of training (Table 6).

Table 6. Herbicide application information in Brazil according to the 2018 Cropping Systems Weed Management Survey.

	Region					
Herbicide application	Brazil	North	Northeast	Midwest	Southeast	South
Person responsible for application	—————————	—————	—————	–%—	—————	—————
Ag technician	17	22	24	20	20	19
Agronomist	30	67	47	30	40	19
Applicator specialist	21	44	18	32	24	15
Co-op	3	0	0	0	4	4
Grower	50	56	41	32	36	71
Farm employees	50	33	29	68	56	38
	$n^a = 202$	$n = 9$	$n = 17$	$n = 44$	$n = 70$	$n = 91$
Herbicide application training						
Yes	69	89	64	84	81	56
Not sure	16	11	18	7	10	21
No	15	0	18	9	9	23
	$n = 202$	$n = 9$	$n = 17$	$n = 44$	$n = 70$	$n = 91$

[a]*n* is the number of respondents.

Table 7. General questions regarding weed management strategies in Brazil according to the 2018 Cropping Systems Weed Management Survey.

	Region					
General questions	Brazil	North	Northeast	Midwest	Southeast	South
Limitations	—————————	—————	—————	–%—	—————	—————
Costs	53	63	81	32	56	47
Limited herbicide options	38	0	35	21	34	38
Labor	18	0	13	7	15	20
Legislation	30	25	13	13	29	31
Weed resistance	69	75	56	38	59	78
	$n^a = 198$	$n = 8$	$n = 16$	$n = 90$	$n = 68$	$n = 90$
Source of information						
Consultant	30	44	25	38	35	24
EMBRAPA[b]	43	11	31	41	42	49
Industry	54	78	31	55	65	50
University	52	44	56	48	52	56
State entities	43	22	38	48	36	47
	$n = 199$	$n = 9$	$n = 16$	$n = 44$	$n = 69$	$n = 90$

[a]Number of respondents.
[b]Brazilian Agricultural Research Corporation.

Limitations for Weed Management

As highlighted in our survey, HR weeds are a major constraint on crop management in Brazil (Table 7). Although Brazil has fewer documented cases of HR weeds when compared to Australia, Canada, and the United States (Heap 2020), the upcoming AR crop technologies do not address the current HR-grass weed problems in the country. Managing HR weeds in Brazil may require additional adoption of nonchemical strategies or introduction of new herbicide SOAs that are effective on grass species. Brazilian growers already carry out multiple effective nonchemical strategies, such as cover crops, crop diversity, crop succession in season, and no-till (Table 5). A new nonchemical weed control strategy, harvest seed weed control (Walsh et al. 2018), is a valuable tool for minimizing HR weeds, but to our knowledge is still neither available nor evaluated/studied in Brazil. Nonetheless, the evolution of HR-grass weed species and absence of new effective technologies are threatening the sustainability of Brazilian agricultural production.

Survey respondents reported industry as the main source of information for crop and weed management in Brazil (Table 7). Despite being quite valuable, industry information can be biased toward portfolios. In contrast, sources of unbiased information from basic and applied research are public institutions, including universities, state extension agencies, and EMBRAPA (Brazilian Agricultural Research Corporation). Therefore, there is a need for an increase on collaborative work on basic and applied research in Brazil arising from the upcoming weed herbicide resistance challenges and the introduction of technologies that are novel and complex to adopt, which will demand research and education for proper and effective adoption.

The survey results presented herein highlight the current status and the difference in cropping systems and weed management practices adopted across Brazil. Our survey shows the trends in conservation agricultural practices and advances the knowledge regarding current weed management strategies in Brazilian agriculture. Brazilian stakeholders are progressive in the sense of adopting conservation agricultural practices and new technologies. However, introduction of new technologies focused on the United States (e.g., synthetic AR crops) for weed management may not address the major weed problems in Brazil but potentially generate a new challenge, OTM of herbicides into sensitive vegetation. Therefore, we urge that academics, growers, industry, and policy makers (1) expand monitoring of HR weeds, (2) increase research on nonchemical weed management strategies, and (3) increase investments in public databases, surveys, as well as basic and applied research, so as to support decisions regarding the introduction and adoption of novel agricultural technologies.

Acknowledgments. This survey received no specific grant from any funding agency, commercial, or not-for-profit sectors. The authors would like to thank all respondents for participating in the survey and Dr. Dênis Mariano for developing Figure 1. No conflicts of interest have been declared.

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