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Weed management in Roundup Ready® corn and soybean in Southern Brazil: survey of consultants' perception

Aline S. Holkem[a], Anelise L. da Silva[b], Mário A. Bianchi[c], Geomar Corassa[c], André R. Ulguim[d*]

[a] Agronomy, Federal University of Santa Maria, Santa Maria, RS, Brazil.[b] Postgraduate Program In Agronomy, Federal University of Santa Maria, Santa Maria, RS, Brazil.[c] CCGL Technology Unit, Cruz Alta, RS, Brazil. [d] Departament of Crop Protection, Federal University of Santa Maria, Santa Maria, RS, Brazil.

Abstract: **Background:** The presence of weeds in Roundup Ready® (RR) soybean and corn crops compromises yield. Management practices recommended by the consultants and adopted by producers directly interfere in the occurrence of these species.

Objective: To survey management practices used in RR soybean and corn fields in the Rio Grande do Sul.

Methods: Data were gathered via the application of questionnaires during the 2018/19 growing season to consultants working with RR soybean and corn cropping in Rio Grande do Sul state. There were 112 responses, covering about 72 municipalities in the state.

Results: Technical consultants highlighted *Conyza* spp. and *Lolium multiflorum* as the most common weed species and classified resistance to herbicides and advanced stages of weeds at the time of herbicide application as the primary causes of low weed control efficacy. They observed an increase in resistance evolution and a two to three-fold increase in the use of herbicides in glyphosate-tolerant crops. Using a mixture of herbicides was the main recommendation for the management of weeds that escape control, while in areas with proven resistance, crop rotation was the main recommendation.

Conclusions: Crop rotation and herbicide mixtures are the most recommended management practices, with herbicide resistance and advanced stage of development listed as the main reasons for the difficulties of weed control.

Keywords: Glyphosate-tolerant crops; Herbicide resistance; Integrated weed management

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* Corresponding author:
<andre.ulguim@ufsm.br>

1. Introduction

Soybeans [*Glycine max* (L.) Merril.] and corn (*Zea mays* L.) have significant participation in the Brazilian economy. Over the last five years, the mean production of 113.7 million tons of soybeans and 89.64 million tons of corn (Companhia Nacional de Abastecimento, 2020). In the state of Rio Grande do Sul, despite the negative impact due to weather conditions, the 2019/20 growing season reached around 5,768 tons of corn grain and around 19,187 tons of soybean grain (Companhia Nacional de Abastecimento, 2020).

The presence of weeds in cropping systems implies competition with the crop for resources in the environment, such as water, light, and nutrients (Radosevich et al., 2007). The yield reduction by the presence of weeds can reach 52% in soybeans (Soltani et al., 2017) and 57% for corn (Balbinot et al., 2016). The launch of the Roundup Ready® (RR) technology in corn and soybeans allowed advances and flexibility in weed management, enabling the selective in-crop application of glyphosate.

In Brazil, the National Technical Commission on Biosafety (CTNBio) issued a technical opinion in 1998 releasing the use of this technology in soybeans farming. However, a few years after the launch of RR technology in Brazil, there were reports of resistance of weed species to glyphosate, in particular, in ryegrass (*Lolium multiflorum* L.) and fleabane species (*Conyza* spp.) (Heap, 2021). The approval of the first RR corn cultivar in Brazil was in 2007, becoming the third transgenic crop in the country and intensifying the use of glyphosate in grain production areas (Ulguim et al., 2013).

The consecutive use of glyphosate herbicide for weed control in RR crops has selected resistant biotypes of weeds (Vargas et al., 2011), compromising its use. Currently, there are 11 species with recorded resistance to glyphosate in Brazil, these being ryegrass, fleabane [*Conyza bonariensis* (L.) Cronquist], horseweed [*Conyza canadensis* (L.) Cronquist], sumatran fleabane [*Conyza sumatrensis* (Retz.) E. Walker)], sourgrass [*Digitaria insularis* (L.) Fedde.], tall windmill grass (*Chloris elata* Desv.), Palmer amaranth (*Amaranthus palmeri* S. Watson), smooth pigweed (*Amaranthus hybridus* L.), goosegrass [*Eleusine indica* (L.) Gaertn.], wild poinsettia (*Euphorbia heterophylla* L.), and barnyardgrass [*Echinochloa crusgalli* (L.) Beauv.] (Heap, 2021). Among the aforementioned species and that present a great impact on productive systems, fleabane, sourgrass, and ryegrass stand out at a national level (Oliveira et al., 2021). Thus, specific management measures for the control of resistant biotypes should be adopted.

The use of herbicides with different modes of action or their association was reported by 90% of soybean farmers as an important practice in the management of resistant weeds (Ulguim et al., 2017). Furthermore, in about 80% of RR soybean areas, three or more glyphosate applications per year were identified, with approximately 50% of these with the implementation of crop rotation (Vargas et al., 2013). Only 15% of Brazilian farmers use exclusively chemical control for weeds, while 75% use chemical control in addition to alternative methods, such as cover crops, no till, crop rotation/succession. From the farmers that use alternative methods, 61% adopt cover crops to suppress weeds (Oliveira et al., 2021). Thus, it is evident that the recognition and choice of more effective practices are extremely important to obtain better results in weed management.

Surveying of management practices used by farmers (Oliveira et al., 2021) and those recommended by consultants (Fruet et al., 2020) are important because it reflects the true status crop management. Based on these responses, the implementation of measures to improve weed control responses can be carried out. Therefore, the objective of this work was to conduct a survey of weed management practices performed out in the state of Rio Grande do Sul, in particular for RR soybeans and corn cultivation, from the perspective of consultants.

2. 2. Materials and Methods

The study was conducted during the 2018/2019 crop year, through the application of individual questionnaires on weed management to technical consultants working in areas cultivated with soybeans and corn in the Rio Grande do Sul (RS). A total of 72 municipalities participated in this survey, yielding a total of 112 responses, which represent the weed management recommended by the consultants in their respective crops.

The questionnaire was divided into four main sections: (1) general characteristics of the cultivated area, (2) weed species occurrence and resistance cases, (3) weed management and resistance aspects, and (4) consultant perspectives (Table 1). A case of herbicide resistance is considered as a weed species by herbicide site of action that has been confirmed or reported (Heap, 2021). Questions about the occurrence of weeds in crop areas, the possible reasons for low herbicide control efficacy, and the reasons why consultants are called by growers were obtained by sorting a list of pre-defined answers by importance. The remaining questions were multiple-choice, allowing only one answer.

Table 1 - Questionnaire sent to technical consultants of RR soybean and corn in the Rio Grande do Sul during 2018/2019

Section 1: General
1.1 Municipality.
1.2 Geographic coordinates.
1.3 Cultivated area (ha).
Section 2: Weed species occurrence and resistance cases
2.1 Please indicate the most frequent weed species in your field.
2.2 Indicate which of the species listed above has insufficient control. Name the herbicides and their mechanism of action.
2.3 If herbicides are not effective in controlling weeds, indicate the reason.
Section 3: Weed management and resistance aspects
3.1 What is your perception of the weed resistance problem in RR soybean and corn crops today?
3.2 How often is herbicide use increased in areas with resistant weed populations?
3.3 What is the management recommendation for the control of escaped (herbicide survivor) weeds?
3.4 What do you think is the main management practice for resistant weeds?
3.5 According to the management used or recommended, what is your feeling of results for the control of resistant weeds?
Section 4: Consultant perspectives
4.1 Concerning weed management, you are most often contacted by farmers to assist them with which topic(s)?
4.2 In your weed management recommendations, which information is prioritized?

A list of pre-defined answers was used in the importance ranking questions for questions 2.1 and 2.3 in Section 2 as well as questions 4.1 and 4.2 in Section 4. In these questions, the consultants were asked to rank each answer on a scale of 1 to 5, where: 1 = not important, 2 = rarely important, 3 = occasionally important, 4 = important, and 5 = very important (Riar et al., 2013). The analysis of the data obtained was performed by adding the values 5, 4, 3, 2, and 1 to obtain the total number of points for each alternative (Norsworthy et al., 2007). Thus, the alternatives with the highest score value were considered as those with the highest frequency and importance of responses, which was calculated by the weighted average of all points (Equation 1), where Wi represents the individual weights and Xi the value for each consultant. The standard error of the mean (SE) of the importance scale was calculated for each question as a way to evaluate the variation of the consultants' answers.

$$Importance = \frac{\sum_{i=1}^{n} Wi.Xi}{\sum_{i=1}^{n} Wi}, \qquad \text{Equation 1}$$

The remaining results of the multiple-choice questions were converted into percentages, analyzed by descriptive statistics, and presented in graphs.

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3. Results and Discussion

3.1 Problematic weeds

The most important weed were fleabane and horseweed (*Conyza* spp.), with a value on the importance scale of 3.76 (Table 2). The second most important weed was ryegrass, with a total importance of 2.39. *Conyza* spp. are among the main weeds in soybean crops. It occurs in approximately 50% of soybean cultivation areas in Brazil, causing significant losses in grain productivity (Lucio et al., 2019; Agostinetto et al., 2017). These species are characterized by high competitiveness and prolificacy; *C. bonariensis* can produce over 800,000 seeds per plant (Kaspary et al., 2017). Moreover, the greater importance assigned to this weeds may be due to the difficulty of chemical control, since there are reports of *Conyza* spp. biotypes resistant to five herbicide mechanisms of action (Heap, 2021). In turn, ryegrass, despite being cultivated as forage species, is considered a weed in wheat and corn growing areas in Southern Brazil, with high seed dissemination (Pott, 2019).

Other species cited deserve to be highlighted for having resistance to at least one herbicide mechanism of action in Brazil (Heap, 2021). These were, with importance values equal to or greater than 1.0, *Digitaria* spp., Alexandergrass [*Urochloa plantaginea* (L.) Hitch.], and wild poinsettia, as well as the species goosegrass, beggarticks (*Bidens* spp.), tall windmill grass, and pigweed (*Amaranthus* spp.) that presented importance values below 1 (Table 2). The predominant species in all regions of Brazil, except the South Region, was reported to be sourgrass (Oliveira et al., 2021), corroborating the results of this study in which it had a lower value on the scale than the fleabane and ryegrass. This survey however was conducted over two years ago, and the results might have changed since then, especially an increase in sourgrass presence in the region.

Table 2 - Classification of different weed species as to their occurrence in glyphosate-tolerant crop growing areas in the Rio Grande do Sul

Weed species	Points[1]	Importance[2]	(SE)
Conyza spp.[3]	436	3.76	(0.10)
Lolium multiflorum	261	2.39	(0.13)
Digitaria spp.[4]	163	1.60	(0.16)
Urochloa plantaginea	155	1.44	(0.19)
Euphorbia heterophylla	94	1.08	(0.19)
Ipomoea spp.[5]	92	0.90	(0.17)
Richardia brasiliensis	79	0.70	(0.18)
Eleusine indica	76	0.78	(0.22)
Bidens spp.[6]	70	0.70	(0.22)
Schizachirium microstachyum	61	0.72	(0.29)
Commelina spp.[7]	58	0.60	(0.21)
Sida rhombifolia	56	0.55	(0.23)
Chloris sp.[8]	34	0.27	(0.36)
Amaranthus spp.[9]	33	0.37	(0.30)
Solanum americanum	20	0.26	(0.30)
Ambrosia artemisifolia	20	0.26	(0.19)
Cardiospermum halicacabum	14	0.20	(0.38)

[1]Points were calculated from the attribution of values 5, 4, 3, 2 and 1 to the first, second, third, fourth and fifth most important weed for each respondent and resulting from the sum of the values of each weed. [2]The importance was obtained by the weighted average of the score of each weed and the mean standard error (SE) between parentheses. [3]*C. bonariensis, C. sumatrensis, C. canadensis*. [4]*D. insularis, D. ciliaris, D. horizontalis* mainly. [5]*I. triloba, I. indivisa, I. quamoclit, I. nil* mainly. [6]*B. pilosa, B. subalternans*. [7]*C. benghalensis, C. diffusa, C. erecta* mainly. [8]*C. elata, C. distichophylla* maily. [9]*A. hybridus, A. retroflexus, A. deflexus, A. viridis* mainly. n = 108.

3.2 Efficiency of weed control methods

Consultants implicated herbicide resistance, advanced growth stage of weeds at the time of application, and inadequate herbicide application method as the three main reasons for low herbicide efficacy (Table 3). In Brazil, 12 herbicide-resistant species have been recorded in soybeans and seven herbicide-resistant species have been reported in corn (Heap, 2021), confirming the relevance of resistant weeds in hindering control.

The advanced stage of weeds showed a value on the scale of importance similar to herbicide resistance (Table 3). This result shows that although resistance is widespread and present in several places, the implementation of proper management practices at the correct time is important for the effectiveness of weed control. Thus, herbicide applications performed on young plants provide more effective control than in plants at more advanced stages of development (Moreira et al., 2010).

Table 3 - Classification of the main reasons for low weed species control efficiency in glyphosate-tolerant crop areas in the Rio Grande do Sul

Reason	Points[1]	Importance[2]	(SE)
Herbicide resistance	416	3.69	(0.12)
Advanced weed stage	402	3.59	(0.11)
Inadequate herbicide application method	250	2.12	(0.13)
Inadequate environmental conditions	234	2.02	(0.12)
Insufficient dose	155	1.46	(0.17)
Herbicide originally inefficient	142	1.18	(0.15)

[1]Points were calculated from the attribution of values 5, 4, 3, 2 and 1 to the first, second, third, fourth and fifth most important reason for each respondent and resulting from the sum of the values of each reason. [2]The importance was obtained by the weighted average of the score of each reason and the mean standard error (SE) between parentheses. n = 112.

In general, plants in advanced stages of development are less sensitive to herbicides because they have enhanced leaf barriers to herbicide penetration, such as cuticle thickness and wax content. Meanwhile, the smaller leaf area size provides better coverage by the herbicides, being absorbed more easily by the plants (Pereira et al., 2016). The control of weeds at the early stages of development has been reported as one of the main practices for resistance management (Prince et al., 2012), reinforcing the importance of farmers to pay attention to the stage of development of weeds to avoid low control efficiency, as reported in this work (Table 3).

To avoid late management, it is important to monitor and plan during the growing season, to control weeds at the appropriate stage, and provide the sowing and establishment of crops free of their presence, thus reducing competition (Ulguim et al., 2017). In addition, farmers should pay attention to the technologies currently available that can favor management and application of herbicides, this being the third most important factor cited (Table 3). In this sense, different weeds may respond differently to the control measures adopted.

According to consultants, 18 weeds were reported as having insufficient control after herbicide application in Rio Grande do Sul, 11 of which had reported control failure for six mechanisms of action (Table 4). Fleabane and ryegrass were most-cited weeds when it comes to control failures following glyphosate spraying (EPSPs; 5-enolpyruvylshikimate-3-phosphate inhibitors), corroborating the species that were most cited for occurrence in the crop areas of Rio Grande do Sul in glyphosate-tolerant crops (Table 2). In addition, poor control of ryegrass with the application of acetyl coenzyme-A carboxylase inhibitors (ACCase) stands out, which point to the resistance of this species to this mechanism of action (Vargas et al., 2018).

Fleabeane control failures indicated in the questionnaires reaffirm the difficulties of control and confirm the reports of biotypes with multiple resistances to herbicides (Santos et al., 2014). As for bluestem [*Schizachyrium microstachyum* (Desv. Ham) Roseng] and dayflowers (*Commelina* spp.), control failures are related to the phenological development stage and the tolerance of the species, respectively (Maciel et al., 2011).

3.3 Weed resistance to herbicides

Regarding the evolution of herbicide resistance in the surveyed areas, 52% of consultants reported an increase in the number of cases, and 40% reported an increase in area (Figure 1a). As for herbicide use, 88% of consultants reported a two- to three-fold increase in herbicide use because of weed resistance cases in RS (Figure 1b). This shows that the increase in resistance, whether in cases or area, is related to the increase in herbicide use and the lack non-glyphosate herbicides, reinforcing the need to search for other mechanisms of action to solve resistance cases.

It is noteworthy, however, that as soon as glyphosate-tolerant cultivars were adopted in crops, there was a decrease in the use of other herbicides (Givens et al., 2009), a different scenario today. This fact is attributed to the frequently observed problems of resistance to different mechanisms of herbicide action.

3.4 Consultants' work themes and weed management recommendations

When consultants were asked about the main topics that they help farmers with, they pointed out the prescription of herbicide doses as the main one, with a score of 3.22 on the scale of importance (Table 5). One of the measures to

Table 4 - Weeds showing insufficient control by the application of herbicides of different mechanisms of action, according to consultants (%), in glyphosate-tolerant crop areas in the Rio Grande do Sul

Weed species	EPSPS[1]	ALS[2]	PSII[3]	PPO[4]	GS[5]	ACCase[6]
Conyza sp.[7]	90	73	50	42	23	-
Lolium multiflorum	61	5	21	5	10	30
Schyzachirium microstachyum	44	22	35	22	21	29
Commelina sp.[8]	35	14	21	14	10	-
Euphorbia hetefophylla	28	15	5	4	1	-
Eleusine indica	28	5	12	3	6	6
Richardia brasiliensis	27	10	2	7	7	-
Ipomoea sp.[9]	27	11	10	3	2	-
Chloris sp.[10]	15	2	7	2	4	7
Ambrosia artemisifolia	7	3	5	1	2	-
Sida rhombifolia	7	0	5	2	5	-
Amaranthus sp.[11]	6	0	1	1	1	-
Digitaria insularis	4	3	2	1	1	3
Solanum americanum	3	0	2	2	1	-
Echium plantagineum	1	0	2	0	1	-
Digitaria sp.[12]	0	3	4	2	3	3
Urochloa plantaginea	0	2	3	2	3	2
Bidens sp.[13]	0	0	0	2	0	-

[1]5-enolpyruvylshikimate-3-phosphate synthase inhibitors. [2]Acetolactate synthase inhibitors. [3] Photosystem II inhibitors. [4]Protoporphyrinogen oxidase inhibitors. [5]Glutamine synthetase inhibitors. [6]Acetyl-CoA carboxylase inhibitors. [7]*C. bonariensis, C. sumatrensis, C. canadensis*. [8]*C. benghalensis, C. diffusa, C. erecta* mainly. [9]*I. triloba, I. indivisa, I. quamoclit, I. nil* mainly. [10]*C. elata, C. distichophylla* maily. [11]*A. hybridus, A. retroflexus, A. deflexus, A. viridis* mainly. [12]*D. insularis, D. ciliaris, D. horizontalis* mainly. [13]*B. pilosa, B. subalternans*.

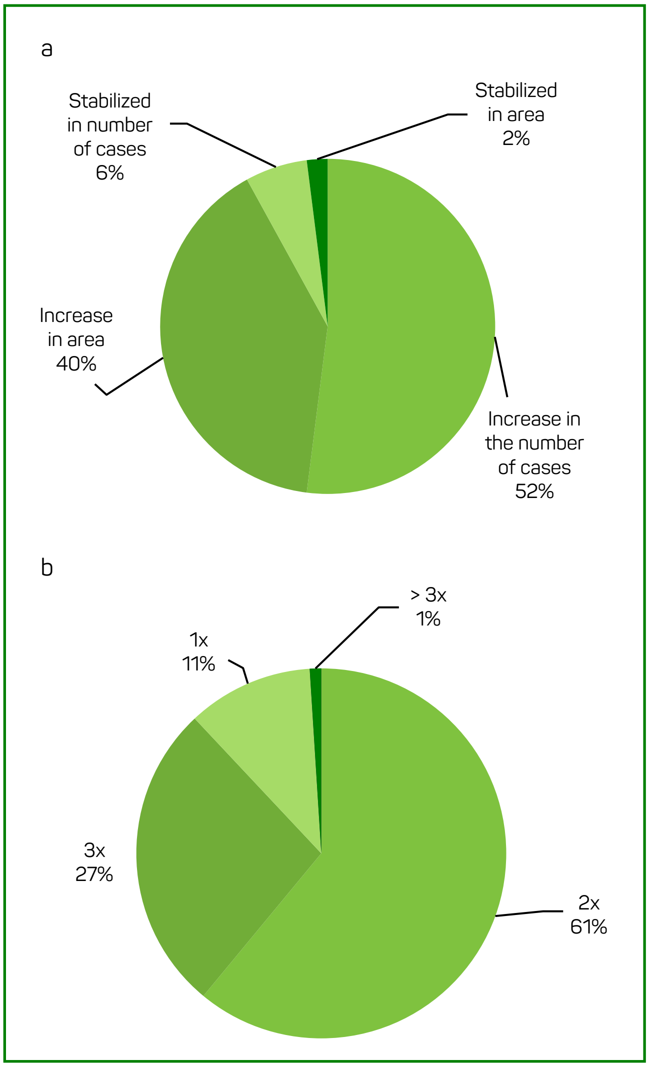

Figure 1 - Consultants' perceptions (%) of resistance evolution (a) and increase in herbicide use (b) in glyphosate-tolerant crops in the Rio Grande do Sul

Table 5 - Classification of the main issues and recommendations prioritized by consultants in glyphosate-tolerant crop areas in the Rio Grande do Sul

Issues	Points[1]	Importance[2]	(SE)
Herbicide dose prescription	376	3.22	(0.12)
Late management recommendation	333	3.00	(0.13)
Management recommendation for resistance	309	2.71	(0.14)
Non-herbicide related management recommendations	169	1.53	(0.17)
Differentiation of herbicide mechanisms of action	153	1.37	(0.14)
Weed species identification	144	1.20	(0.16)
Crop rotation system planning	102	0.96	(0.22)
Management recommendations			
Cultural control	460	3.99	(0.10)
Chemical control	450	3.98	(0.09)
Prevention	311	2.80	(0.09)
Mechanical control	225	1.88	(0.10)
Biological control	165	1.42	(0.11)

[1]Points were calculated from the attribution of values 5, 4, 3, 2 and 1 to the first, second, third, fourth and fifth most important issue or recommendation for each respondent and resulting from the sum of the values of each issue or recommendation. [2]The importance was obtained by the weighted average of the score of each issue or recommendation and the mean standard error (SE) between parentheses. n = 112.

reduce the risk of resistance is to apply the recommended doses of herbicides at the indicated (early) stages of weeds (Norsworthy et al., 2012). The use of overdoses causes increased selection pressure of pre-existing biotypes within populations, increasing the speed to resistance selection (Ulguim et al., 2017), mainly high-level resistance.

Recommending late management (weed survivor management) and resistance management, with values of 3.0 and 2.71, respectively, presented as the second and third main themes of consultants' actions (Table 5). In a similar study, resistance management, herbicide dose prescription, and late management were listed as the three main themes of consultants' actions in irrigated rice areas (Fruet et al., 2020). In this sense, it is evident that consultants are sought by producers mainly to solve already established problems, such as the control of escaped and resistant weeds. This inference is reinforced by the fact that the recommendation of non-chemical management practices and the planning of crop rotation systems had a lower scale of importance than the aforementioned reasons (Table 5).

The methods prioritized by consultants in the management recommendation were cultural and chemical control (Table 5). In addition, based on the scale of importance, cultural control had a score close to that of chemical control, where both were greater than 3.0. In a study evaluating irrigated rice culture and different integrated production systems, cultural measures promoted changes in the occurrence and predominance of certain weeds (Ulguim et al., 2018), and may contribute to the efficiency in the use of herbicides.

Regarding management recommendations for escaped weeds that survive herbicide applications and are present in glyphosate-tolerant soybean and corn crops, 55% of consultants recommended herbicide mixtures and 38% indicated application of different herbicides as the main practices for management (Figure 2a). The use of more than one herbicide mechanism of action is considered one of the main practices that should be used for weed management (Riar et al., 2013). Practices such as roguing or hand pulling as well as harrowing/grinding require high labor demand and cost, which is attributed to the low percentages of response. In the case of harrowing, the conservation system is not favored, because the soil is more exposed and more prone to erosive effects (Bertol et al., 2004). The proportion of responses to an increase in the herbicide dose was considered low, with 2% of responses.

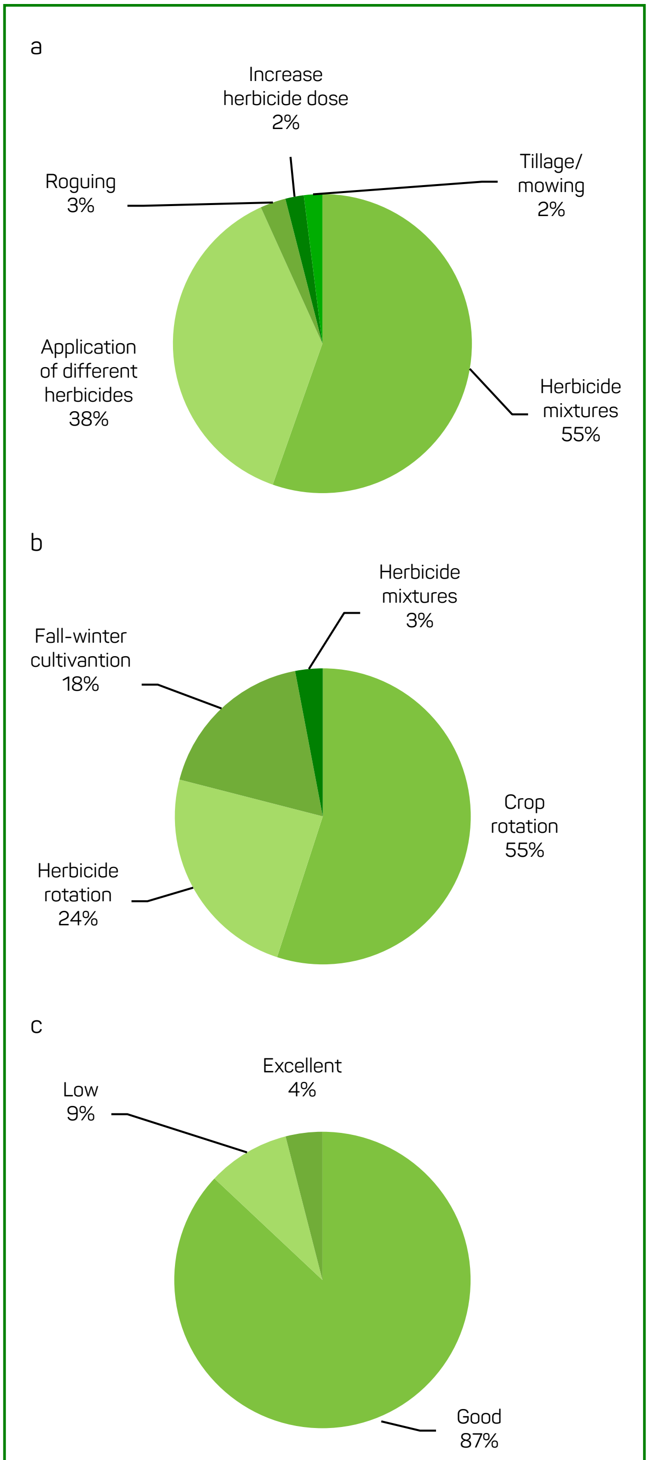

Figure 2 - Recommendations for the management of weeds escaping herbicide control (a), in areas with proven resistance (b) and feeling of results of using these practices (c) according to consultants (%) in glyphosate-tolerant crops in the Rio Grande do Sul

In those areas where the presence of resistant weeds was proven, 55% of consultants recommended crop rotation, followed by herbicide rotation with 24% and fall-winter cultivation with 18% (Figure 2b). One of the main benefits of crop rotation is nutrient cycling, which consists of using different species that have distinct root characteristics, nutritional requirements, and nutrient uptake abilities (Franchini et al., 2011). Although the recommendation to grow cover crops was less reported, it is an important practice and adopted by 61% of respondents in a similar survey (Oliveira et al., 2021). The presence of plant residues arranged on the surface or incorporated into the soil negatively interferes with the germination and emergence of several weed species such as *Ipomoea grandifolia* (Dammer) O' Donell, *Urochloa decumbens* Stapf. and *Panicum maximum* Jacq. (Monquero et al., 2009), *Vernonia ferruginea* Less. (Yamashita, Alberguini, 2011), *Murdannia nudiflora* (L.) Brenan. (Luz et al., 2014) and fleabane (Yamashita, Guimarães, 2015).

Regarding the feeling of results by weed control due to the management practices adopted, 87% of consultants rated it as good, 9% as low, and 4% rated it as excellent (Figure 2c). This result indicates that the adoption of the weed management practices adopted by farmers is considered adequate by consultants. However, can not be considered enough for high control efficacy, since the responses for excellent (greater than 95% control) represented only 4% of responses (Figure 2c). This demonstrates that when seeking to solve the difficulties of the producers, technical consultants achieve some success in the difficulties imposed by escaped and resistant weeds.

4. Conclusions

Fleabane and ryegrass are the weeds indicated as most common in the areas of RR soybean and corn cultivation in Southern Brazil, with herbicide resistance and advanced stage of development listed as the main reasons for the difficulties of control. The resistance evolution reported by the consultants was an increase in cases by more than 50% and an increase in area of 40%. Crop rotation and herbicide mixture were the management practices most recommended by consultants.

Author's contributions

All authors read and agreed to the published version of the manuscript. ARU and MAB: conceptualization of the manuscript and development of the methodology. ALS, MAB, and GC: data collection and curation. ASH and ALS: data analysis. ASH, ALS, and ARU: data interpretation. ARU: funding acquisition and resources, project administration. ARU and MAB: supervision. ASH and ALS: writing the original draft of the manuscript. ASH and ARU: writing, review and editing.

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