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Chemical and cultural management strategies for glyphosate-resistant sourgrass in central Brazil

Abstract – The objective of this work was to evaluate different chemical treatments, associating herbicide combinations with the maintenance of forage species in the off-season, for the management of glyphosate-resistant sourgrass (*Digitaria insularis*) in a soybean crop. The experimental design was a randomized complete block in a 4×5 split-plot arrangement, with four replicates. The treatments consisted of: four combinations of the clethodim, glyphosate, haloxyfop-p-methyl, glufosinate ammonium, and s-metolachlor herbicides in the plots; green covers with the Massai, BRS Tamani, and BRS Zuri cultivars of *Panicum maximum* and with *Urochloa ruziziensis*, as well as fallow, in the subplots; and a control with the isolated application of glyphosate at the desiccation and post-emergence of the soybean crop infested with sourgrass and weeded. The herbicides tested before sowing and at post-emergence of soybean promoted a control above 90% of adult sourgrass plants until grain harvest. After harvest, there was a new emergence of sourgrass, mainly in the plots without green cover in the off-season. Overseeding soybean with forage species allowed of the establishment of these plants, which consequently interfered in sourgrass emergence and growth. The chemical treatments with herbicide combinations associated with the maintenance of forage species in the off-season are effective for the control of adult glyphosate-resistant sourgrass plants.

Index terms: *Digitaria insularis*, *Panicum maximum*, *Urochloa ruziziensis*, chemical control, overseeding.

Estratégias de manejo químico e cultural de capim-amargoso resistente ao glifosato no Brasil Central

Resumo – O objetivo deste trabalho foi avaliar diferentes tratamentos químicos, com a associação de combinações de herbicidas à manutenção de espécies forrageiras no período de entressafra, para o manejo de capim-amargoso (*Digitaria insularis*) resistente ao glifosato em cultura de soja. O delineamento experimental foi de blocos ao acaso, em arranjo de parcela subdividida 4×5, com quatro repetições. Os tratamentos consistiram de: quatro combinações dos herbicidas cletodim, glifosato, haloxifop-p-metil, glufosinato de amônio e s-metolacloro nas parcelas; de coberturas verdes com as cultivares de *Panicum maximum* Massai, BRS Tamani e BRS Zuri e com *Urochloa ruziziensis*, além de pousio, nas subparcelas; e controle com a aplicação isolada de glifosato na dessecação e na pós-emergência da cultura de soja infestada com capim-amargoso e capinada. Os herbicidas testados antes da semeadura e na pós-emergência da soja promoveram um controle acima de 90% de plantas adultas de capim-amargoso até a colheita dos grãos. Após a colheita, houve nova emergência de capim-amargoso, principalmente nas parcelas sem cobertura verde na entressafra. A sobressemeadura da soja com espécies forrageiras permitiu o estabelecimento dessas plantas, que, consequentemente, interferiram na emergência e no crescimento do capim-

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amargoso. Os tratamentos químicos com combinações de herbicidas associados à manutenção de espécies forrageiras no período da entressafra são eficazes para o controle de plantas adultas de capim-amargoso resistente ao glifosato.

Termos para indexação: *Digitaria insularis*, *Panicum maximum*, *Urochloa ruziziensis*, controle químico, sobressemeadura.

Introduction

Some weed species have been selected for resistance due to frequent and exclusive applications of herbicides with the same mechanism of action. Among those, sourgrass [*Digitaria insularis* (L.) Mez ex Ekman] stands out. It is a perennial, herbaceous, and erect species, with striated culms, 50 to 100 cm height, and short rhizomes that form clumps, being reproduced by seeds that are covered by hairs and carried by wind to long distances (Kissmann & Groth, 1997).

In Brazil, glyphosate-resistant sourgrass was first reported in 2008 in the state of Paraná (Heap, 2022). This led to several studies aiming to understand the dynamics of biotypes of the species, focusing on their biology or management (Martins et al., 2017; Pereira et al., 2017; Ferreira et al., 2018; Marochi et al., 2018; Silveira et al., 2018). In agricultural fields, treatments based on ACCase-inhibiting herbicides, such as clethodim and haloxyfop-p-methyl, became the most applied because they were considered effective for the control of adult glyphosate-resistant sourgrass plants when combined or not with other management strategies (Cassol et al., 2019; Mendes et al., 2020; Nunes et al., 2021; Raimondi et al., 2020; Silva at al., 2021). However, chemical control actions for resistant sourgrass should include herbicides from other mechanisms of action and not only ACCase inhibitors, or, at least, a rotation of chemical groups (cyclohexanedione and aryloxyphenoxypropionate, for example) in order to delay the cross-resistance selection that occurs to herbicides from different chemical groups but with the same mechanism of action (Vidal et al., 2006; Nunes et al., 2022).

The increased selection pressure in agricultural areas with the increase of the application of herbicides with the same site of action, therefore, leads to the selection of biotypes with multiple resistance in a population, whose management is difficult and costly, causing great losses for agriculture. In Brazil, the first case of sourgrass showing multiple resistance to glyphosate and ACCase-inhibiting herbicides (aryloxyphenoxypropionate chemical group) was reported in 2020, in the agricultural areas of the states of Mato Grosso and Mato Grosso do Sul (Heap, 2022).

In this scenario, the inclusion of other mechanisms of action in a production system, such as the long-chain fatty acid synthesis inhibitor (s-metolachlor) and glutamine synthetase inhibitor (glufosinate ammonium), is important to improve the diversity of herbicides and minimize the possibility of selection of multiple resistance in agricultural areas. Therefore, residual, broad-spectrum, or grass herbicides, as well as contact herbicides to complement systemic herbicides, should also be used in production systems.

In addition to herbicides, another practice adopted for weed control is off-season crop management, which consists in the maintenance of soil cover plants in the autumn-winter period, occurring from May to August in Brazil. These species can be used for grain production (second crop season), animal feed, green manure, and straw production for the no-tillage system, resulting in improvements in soil chemical, physical, and biological characteristics.

Overseeding with forage species is a technique in which soil cover plants are set up in the off-season by broadcasting forage seeds in the area planted with soybean [*Glycine max* (L.) Merr.] during the physiological maturation stages (R_5 to R_7) of the crop (Pacheco et al., 2013). Although water deficit is one of the factors that limit crop management during autumn-winter in the central region of Brazil, some species, such as those from the genera *Urochloa* and *Panicum*, can develop and produce large amounts of straw on the soil even under such conditions (Pacheco et al., 2008). Currently, *Urochloa ruziziensis* (R.Germ. & C.M.Evrard) Morrone & Zuloaga is the main forage species used in the off-season for straw production in no-tillage systems in the agricultural regions in the Cerrado biome. However, the 'Massai', 'BRS Tamani', and 'BRS Zuri' genotypes of *Panicum maximum* Jacq. are also promising for agriculture-livestock integration systems due to their excellent soil cover, tolerance to drought, and high dry matter yield (Matias et al., 2019; Correia et al., 2021).

Considering the cited literature, it is possible to hypothesize that the combination of chemical and cultural methods can result in a better control of glyphosate-resistant sourgrass and, consequently, in a decrease in a potential reinfestation by the weed.

The objective of this work was to evaluate different chemical treatments, associating herbicide combinations with the maintenance of forage species in the off-season, for the management of glyphosate-resistant sourgrass in a soybean crop.

Materials and Methods

The experiment was carried out from 11/6/2020 to 11/17/2021 in an area used to grow soybean at the experimental station of Embrapa Cerrados, located in the municipality of Planaltina, in Distrito Federal, Brazil (15°36'26.2"S, 47°44'41.2"W, at an altitude of 1.138 m). The climate of the region is Aw, tropical wet with a dry winter, according to Köppen's classification. The total monthly rainfall and mean monthly minimum and maximum temperatures during the experimental period are shown in Figure 1. The soil of the experimental area is representative of the region, being classified as a Latossolo Vermelho-Amarelo (Santos et al., 2018), i.e., a Typic Hapludox, with a clayey texture, with 533 g kg^{-1} clay, 324 g kg^{-1} silt, and 143 g kg^{-1} sand, showing the following chemical characteristics: pH ($CaCl_2$) 5.5; 3.3 dag kg^{-1} organic matter; 9.62 mg dm^{-3} P (Mehlich-1); and 0.20, 3.35, and 1.02 $cmol_c$ dm^{-3} K, Ca, and Mg, respectively.

The experimental design was a randomized complete block, in a 4×5 split-plot arrangement, with four replicates, in which treatments consisted of four herbicide combinations in the plots and of five soil green covers (forage) in the off-season in the subplots. Each plot was 3.0 m wide and 25 m long, whereas the subplots were 3.0 m wide and 5.0 m long, totaling 15 m^2, with an evaluation area of 6.0 m^2 (4.0 m of three rows).

In the plots, the herbicide combinations (chemical treatment) used were: 192 g ha^{-1} clethodim + 1.44 kg a.e. ha^{-1} glyphosate + 0.5% adjuvant for burndown, combined with 120 g ha^{-1} clethodim + 1.44 kg a.e. ha^{-1} glyphosate + 0.5% adjuvant at soybean post-emergence; 151.2 g ha^{-1} haloxyfop-p-methyl + 1.44 kg a.e. ha^{-1}

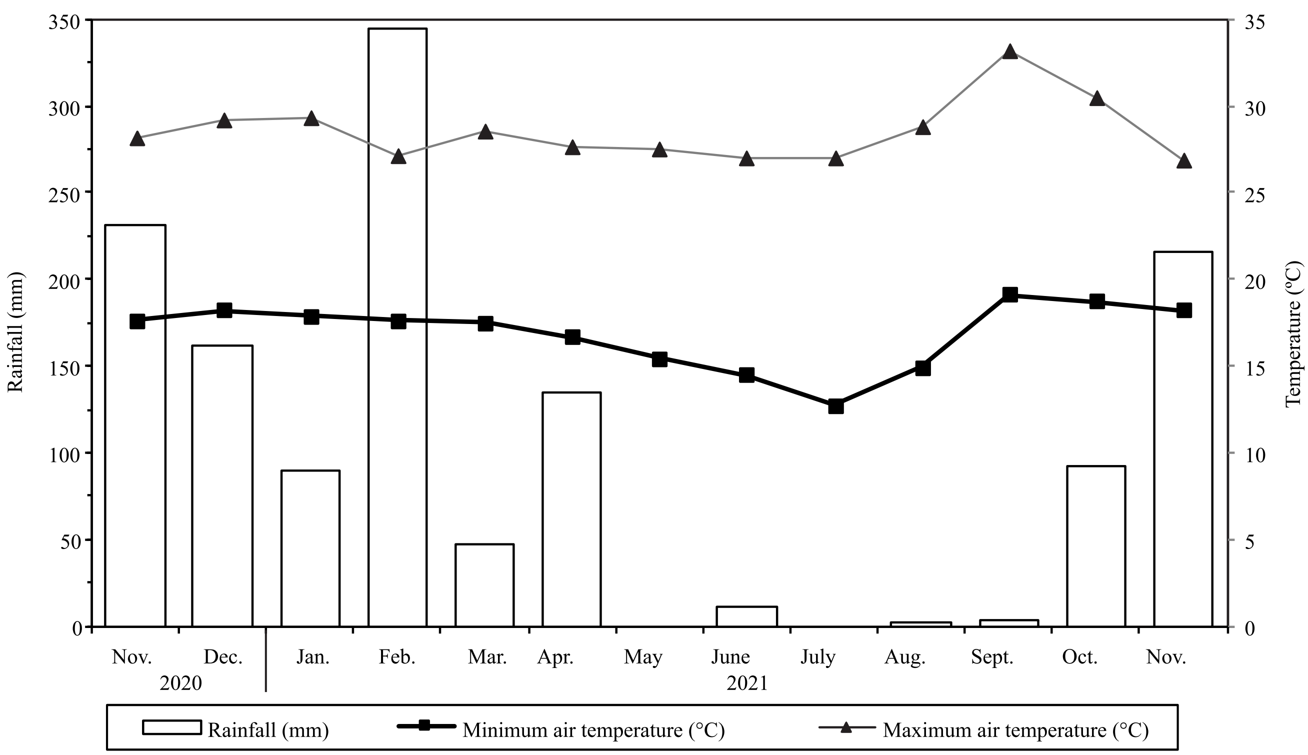

Figure 1. Total monthly rainfall and mean minimum and maximum monthly air temperatures recorded during the experimental period from November 2020 to November 2021 at the climatological station of Embrapa Cerrados, located in the municipality of Planaltina, in Distrito Federal, Brazil.

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glyphosate + 0.5% mineral oil for burndown, combined with the application of the same herbicides and rates at soybean post-emergence; 192 g ha^{-1} clethodim + 1.44 kg a.e. ha^{-1} glyphosate + 0.5% adjuvant for burndown, combined with 151.2 g ha^{-1} haloxyfop-p-methyl + 1.44 kg a.e. ha^{-1} glyphosate + 0.5% mineral oil at soybean post-emergence; and 192 g ha^{-1} clethodim + 1.44 kg a.e. ha^{-1} glyphosate + 0.5% adjuvant and a sequential application after eight days of 0.6 kg ha^{-1} glufosinate ammonium + 1.92 kg ha^{-1} s-metolachlor + 0.2% plant oil for burndown, combined with 1.44 kg a.e. ha^{-1} glyphosate at soybean post-emergence.

In the subplots, overseeding with cover species was carried out at the R_7 soybean stage (beginning of maturation) to determine soil cover after soybean harvest in the off-season. The treatments consisted of: no forage in the off-season, i.e., fallow without weed management to simulate single soybean crops in the two successive crop years; cover with 'Massai' (*P. maximum*); cover with 'BRS Tamani' (*P. maximum*); cover with 'BRS Zuri' (*P. maximum*); and cover with *Urochloa ruziziensis* (common cultivar). The species used for overseeding were manually broadcast when the soybean plants reached the R_7 development stage, on 4/5/2021. A density of 1,200 points for the cultural value of seeds was used, according to the method proposed by Correia & Gomes (2015). The seeds were pelletized, presenting cultural values of 73.39, 74.84, 75.85, and 74.21 for 'Massai', 'BRS Tamani', 'BRS Zuri', and *U. ruziziensis*, respectively. The amounts of seeds used were: 16.35 kg ha^{-1} of 'Massai', 16.02 kg ha^{-1} of 'BRS Tamani', 15.81 kg ha^{-1} of 'BRS Zuri', and 16.17 kg ha^{-1} of *U. ruziziensis*.

Three controls, whose experimental units were the subplots, were also evaluated in the plots: infested, with no management strategy; weeding, with the removal of sourgrass and other weeds using a hoe throughout the soybean cycle; and chemical control, with the isolated application of glyphosate at the rate of 1.44 kg a.e. ha^{-1} for plant burndown and at soybean post-emergence. The control areas were kept fallow after soybean harvest, with no management strategy in the off-season in the autumn-winter period, which corresponds to May–August in Brazil.

The experimental area was predominantly infested with sourgrass at the time of the first application of the herbicide treatments (first, second, third, and fourth) on 11/6/2020 at burndown or soybean pre-sowing, when 65% of the weeds were at the reproduction stage (with panicle, flower, fruit, and seed), with a mean density of 19.2 plants per square meter and a mean height of 91.3 cm. Seven days after the first application, 13 to 14 seeds per meter of the Bônus – 8579 RSF IPRO soybean (Brasmax, Cambé, PR, Brazil) were sown under a no-tillage system at a depth of 5.0 cm, with 0.5 m between rows. The seeds were treated with 0.08 g pyraclostrobin, 0.72 g thiophanate-methyl, and 0.8 g fipronil per kilogram of seeds, also being inoculated with the Semia 5079 and 5080 *Bradyrhizobium japonicum* strains at the rate of 6.0 mL of the commercial product per kilogram of seeds and co-inoculated with *Azospirillum brasilense* at the rate of 2.6 mL of the commercial product per kilogram of seeds. A total of 300 kg ha^{-1} of the formula N-P_2O_5-H_2O (04-30-16) + Zn was applied to the sowing furrow using a five-row pneumatic seeder.

All herbicide treatments were applied the day after sowing. However, at soybean post-emergence, they were applied at two different times due to the size of the weeds in the plot: at 30 days after the first application (DAFA) for the first, second, third, and fifth treatments; and at 37 DAFA for the fourth since the use of a residual herbicide for the second burndown retarded the emergence of new seedlings in the plots.

The herbicides used for burndown and at soybean post-emergence were applied using a CO_2-pressurized backpack sprayer, with a constant pressure of 2.0 kgf cm^{-2}, equipped with a spray boom with six 110015 flat fan spray tips (TeeJet Technologies, Glendale Heights, IL, USA) spaced 0.5 m apart, with a solution consumption of 150 L ha^{-1}. At the time of all applications, the environmental conditions were: wet soil, air temperature of 23.6 to 27.0°C, relative air humidity of 53 to 85%, and wind speed of 1.1 to 8.3 km h^{-1}.

The control of adult sourgrass plants was visually evaluated at 15, 30, 45, and 60 DAFA and at soybean pre-harvest at 130 days after sowing, using a scale of grades from 0 to 100%, corresponding to the absence of visual injuries and plant death, respectively (Velini et al., 1995). The other weed species and new emergences of sourgrass were evaluated from 30 DAFA.

Soybean grain yield (kg ha^{-1}) was determined for each experimental unit, consisting of 4.0 m of the three central rows, which were harvested with an experimental harvester; grain moisture was corrected to 13%. The number of plants in the evaluation area, i.e., 6.0 m^2 subplots, was also evaluated and expressed as plants per hectare. The data of grain yield and population per hectare was used to determine grain production per plant.

The density of forage plants was quantified at 60 days after overseeding, 30 days after soybean harvest. The number of plants in the two sample areas of 0.45 m^2 within the evaluation area of each subplot was counted, and the data were transformed into density (plants per meter).

Soil cover by forage plants was evaluated visually at 240 days after soybean harvest, on 11/17/2021, using a scale of grades from 0 to 100%, where zero represents the absence of plants and 100, total soil cover by the forage.

Also at 240 days after soybean harvest, the shoot of forage plants was collected in a randomly sampled area of 1.0 m^2 within the evaluation area of each subplot in order to determine the shoot dry matter production by the plants (kg ha^{-1}). At this point, the infestation by sourgrass and other weed species was evaluated visually, using a scale of grades from 0 to 100%, considering the soil area covered by the plants. The density of sourgrass plants was obtained by counting the number of plants in the two areas of 0.45 m^2 within the evaluation area of each experimental unit, with the data being transformed into density (plants per square meter). In addition, the grades to determine weed control were estimated considering the infestation in the plots (percentage of plant cover) compared with that by sourgrass plants.

The data were subjected to the analysis of variance by the F-test and, when the interactions were significant ($p<0.01$ or $p<0.05$), they were split and the treatments were compared by Tukey's test, at 5% probability. However, only the data obtained after cover plants were set up (densities, dry matter production, plant cover, and weed infestation) were analyzed as factorial. The results collected until soybean harvest were evaluated as simple treatments (herbicides and controls).

The control with no herbicide application (kept infested) was not included in the statistical analyses for weed control, being only used for the development of the grades. The control treatments (isolated application of glyphosate, infested control, and weeding control) were compared with each other and with the treatments of interest through orthogonal contrasts.

Results and Discussion

After the first application of the herbicide treatments (first, second, third, and fifth) at soybean post-emergence, when soybean had two trifoliate leaves, there was a regrowth of adult sourgrass plants and the emergence of the following weeds: *Portulaca oleracea* L. seedlings with four to six leaves, *Galinsoga parviflora* Cav. with four leaves, *Conyza sumatrensis* (Retz.) E.Walker with two to four leaves, *Amaranthus* sp. with three leaves, *Chamaesyce hirta* (L.) Millsp. with four to six leaves, and *Commelina benghalensis* L. with two to six leaves. Grass species, such as *Digitaria insularis* (L.) Mez ex Ekman with one to three tillers and *Cenchrus echinatus* L. and *Eleusine indica* (L.) Gaertn. with two to five tillers, were also identified. After the second application (only of the fourth treatment) at soybean post-emergence, soybean plants had four to six trifoliate leaves and, as previously observed after the first application, adult sourgrass plants began to regrow and seedlings of other weeds – of similar size and species – to emerge; the exception were sourgrass and *E. indica* seedlings that did not emerge in the area.

The fourth treatment was the most effective for the control of adult sourgrass plants at 15 days after the first herbicide application (Table 1) due to the sequential application 7 days before the evaluation; therefore, this treatment was already complete in the first evaluation. No significant difference was observed between the first, second, third, and fourth treatments at 30 DAFA, which differed from the treatment with the isolated application of glyphosate. Although all herbicide combinations resulted in a weed control higher than 90% at 45 DAFA, the first, second, and third ones – which included ACCase-inhibiting herbicides in both applications – showed the highest control grades. At 60 DAFA and at soybean pre-harvest, however, there was no significant difference between the four herbicide combinations, with a control higher than 90% for all of them. The isolated application of glyphosate resulted in a control lower than 40%, which is considered ineffective, but was already expected. Previous works have shown that the application of only glyphosate, even at high rates and with or without a sequential application, is not enough for controlling adult herbicide-resistant sourgrass plants (Silva et al., 2021).

This finding could be attributed to two changes in the amino acid sequence of the 5-enolpyruvylshikimate-

3-phosphate synthase (EPSP) enzyme observed in resistant biotypes, which result in the replacement of proline by threonine and of tyrosine by cysteine, respectively (Carvalho et al., 2012; Galeano et al., 2016). When compared with susceptible plants, the resistant ones show a lower genetic expression of EPSP, a higher enzymatic activity (Galeano et al., 2016), a lower translocation, and a higher metabolization of glyphosate into aminomethylphosphonic acid, glyoxylate, and sarcosine (Carvalho et al., 2012), with no changes in the absorption of glyphosate (Melo et al., 2019).

The results of the present study are indicative that an effective chemical management of adult sourgrass plants is possible by diversifying the used chemical compound and the herbicide mechanism of action. Moreover, the rotation of chemical groups of ACCase-inhibiting herbicides or the addition of a residual herbicide combined with a second burndown with a contact herbicide were shown to be effective and important not only for the management of glyphosate-resistant weeds, but also for delaying the selection of multiple resistance (Vidal et al., 2006; Nunes et al., 2022).

Regarding the other weed species evaluated, *C. benghalensis* adult plants were not controlled at burndown, and *C. sumatrensis* emerged after soybean sowing. The most effective control was the treatment with the isolated application of glyphosate (Table 2) due to the high competitiveness of sourgrass plants, which disfavored the emergence and growth of other weed species in the plots. The inhibition of other weed species also occurred in the infested control plots due to the high density of sourgrass.

As observed for adult sourgrass plants, the fourth treatment was also the most effective for the control of the other weed species due to its broad control spectrum resulting from the addition of a residual herbicide and the second application of a contact herbicide, which was an effective complementation for the management of several broadleaf species, such as *C. benghalensis*, in the experiment. Moreover, at soybean pre-harvest, the control of weed species was higher than 90%, not hindering harvesting in any way. Although *C. sumatrensis* also showed resistance to glyphosate in the experimental area, the species did not cause any losses in grain yield since it is very sensitive to soybean competitiveness in the Brazilian Cerrado biome, meaning that it is basically controlled by the shading of soybean plants, even with no adequate chemical control (Correia, 2020).

For the soybean crop, the first, second, third, and fourth treatments did not differ from each other and from the weeding control (Table 3), showing the highest means for plant population and for grain production per hectare and per plant due to the sum of effects of the control of sourgrass and other weed species. In the infested control, soybean plants had a mean yield of 39.95 kg ha^{-1}, a value that was only obtained because the plants were manually harvested in the plots and threshed separately. Compared with the weeding control, the grain yield loss was 99% for the plants in the infested control and 34% for those

Table 1. Control of adult sourgrass (*Digitaria insularis*) plants at 15, 30, 45, and 60 days after the first herbicide application (DAFA) and at soybean (*Glycine max*) pre-harvest at 137 DAFA as affected by herbicide treatments at soybean pre-sowing and post-emergence[(1)].

Id.	Treatment/Control		Control of adult sourgrass (%)				
	Pre-sowing	Post-emergence	15	30	45	60	137
1	Clethodim/Glyphosate	Clethodim/Glyphosate	76.25b	85.62a	97.50a	93.75a	95.00a
2	Haloxyfop/Glyphosate	Haloxyfop/Glyphosate	75.62b	86.88a	98.12a	95.62a	96.25a
3	Clethodim/Glyphosate	Haloxyfop/Glyphosate	74.38b	85.00a	96.88a	93.12a	96.25a
4	Clethodim/Glyphosate and Glufosinate/S-metolachlor[(2)]	Glyphosate	91.25a	86.88a	91.88b	93.75a	92.50a
5	Glyphosate	Glyphosate	15.00c	30.00b	42.50c	35.00b	26.25b
	Least significant difference (LSD)		5.21	3.13	4.52	7.44	6.43
	$F_{Treatments}$		653.39**	1,307.59**	579.08**	256.69**	466.54**
	Coefficient of variation (CV, %)		3.48	1.85	2.35	4.01	3.51

[(1)]Means followed by equal letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. [(2)]First application of clethodim + glyphosate and a sequential application of glufosinate ammonium + s-metolachlor after 8 days. **Significant by the F-test, at 1% probability.

under the treatment with the isolated application of glyphosate.

Sourgrass plants from clumps tend to cause higher yield losses than those from seeds because of their established root system, which leads to a fast tiller development and an early competition (Gazziero et al., 2019). These data reinforce the importance of an adequate management of sourgrass plants, mainly at the beginning of their development, due to the high level of losses that these perennial plants can cause to crops (Gazziero et al., 2019; Braz et al., 2021).

The interaction between herbicide treatments and forages was not significant for the characteristics evaluated after soybean harvest, indicating the independence of the studied factors (Tables 4 and 5). The same was observed for the herbicide treatments isolated. However, the forage species differed from each other regarding plant density, soil cover percentage, and shoot dry matter, as well as sourgrass infestation, infestation by other weeds, and sourgrass plant density.

'Massai' presented a higher plant density, but did not interfere with plant growth, not differing significantly

Table 2. Control of seedlings of sourgrass (*Digitaria insularis*) and of other weed species at 30, 45, and 60 days after the first herbicide application (DAFA) and at soybean pre-harvest at 137 DAFA as affected by herbicide treatments at soybean (*Glycine max*) pre-sowing and post-emergence[(1)].

Id.	Treatment/Control		Control of seedlings of sourgrass (%)[(2)]			
	Pre-sowing	Post-emergence	30	45	60	137
1	Clethodim/Glyphosate	Clethodim/Glyphosate	0.00c	85.00cd	79.38c	90.62c
2	Haloxyfop/Glyphosate	Haloxyfop/Glyphosate	0.00c	87.5bc	80.00c	92.50bc
3	Clethodim/Glyphosate	Haloxyfop/Glyphosate	0.00c	81.25d	79.38c	94.38abc
4	Clethodim/Glyphosate and Glufosinate/S-metolachlor[(3)]	Glyphosate	76.25b	91.25b	85.62b	95.62ab
5	Glyphosate	Glyphosate	100.00a	100.00a	100.00a	98.75a
	Least significant difference (LSD)		4.83	4.37	3.13	4.57
	$F_{Treatments}$		2,094.82**	54.50**	162.73**	9.30**
	Coefficient of variation (CV, %)		6.07	2.18	1.64	2.15

[(1)]Means followed by equal letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. [(2)]Control was defined as the percentage of seedlings of the *Cenchrus echinatus*, *Chamaesyce hirta*, *Commelina benghalensis*, *Conyza sumatrensis*, *Eleusine indica*, *Portulaca oleracea* weed species and of sourgrass present in the experimental unit. [(3)]First application of clethodim + glyphosate and a sequential application of glufosinate ammonium + s-metolachlor after 8 days. **Significant by the F-test, at 1% probability.

Table 3. Soybean (*Glycine max*) plant population and grain yield as affected by herbicide treatments applied at pre-sowing and post-emergence[(1)].

Id.	Treatment/Control		Population (1,000 plants per ha)	Grain production	
	Pre-sowing	Post-emergence		(kg ha^{-1})	(g per plant)
1	Clethodim/Glyphosate	Clethodim/Glyphosate	218.75a	3,032.46a	13.96a
2	Haloxyfop/Glyphosate	Haloxyfop/Glyphosate	224.17a	3,165.38a	14.14a
3	Clethodim/Glyphosate	Haloxyfop/Glyphosate	229.17a	3,200.49a	13.97a
4	Clethodim/Glyphosate and Glufosinate/S-metolachlor[(2)]	Glyphosate	229.58a	3,362.43a	13.65a
5	Glyphosate	Glyphosate	146.67b	2,170.82b	14.67a
6	Control – infested		14.17c	39.95c	3.23b
7	Control – weeding		218.33a	3,305.76a	15.12a
	Least significant difference (LSD)		25.39	660.41	3.68
	$F_{Treatments}$		216.65**	72.52**	29.13**
	Coefficient of variation (CV, %)		5.94	10.82	12.29

[(1)]Means followed by equal letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. [(2)]First application of clethodim + glyphosate and a sequential application of glufosinate ammonium + s-metolachlor after 8 days. **Significant by the F-test, at 1% probability.

from the other forages since 'BRS Tamani' and 'BRS Zuri' showed a higher soil cover and shoot dry matter production. The ability of a species to cover the soil and occupy an area, inhibiting the emergence and growth of weed species, is the most important characteristic for weed control in the off-season. Therefore, as the soil cover generated by 'BRS Tamani' and 'BRS Zuri' was higher than 70%, they were considered the most competitive and effective species for the occupation of space even in comparison with *U. ruziziensis*, which is the reference species in studies on weed management in the off-season (Marochi et al., 2018; Timossi et al., 2021).

Considering the infestation by sourgrass, the infestation by other weed species, and the density of sourgrass at 240 days after soybean harvest, i.e., at

Table 4. Forage plant density at 30 days after soybean (*Glycine max*) harvest (DAH), soil cover by forage, and shoot dry matter production at 240 DAH as affected by the species established in the area after soybean harvest in the off-season[(1)].

Forage	Density (plants per m^{-2})	Soil cover (%)	Dry matter (kg ha^{-1})
With no forage (fallow)	-	-	-
'Massai' (*Panicum maximum*)	7.78a	58.12b	3,872.96ab
'BRS Tamani' (*P. maximum*)	3.12bc	76.88a	4,968.59a
'BRS Zuri' (*P. maximum*)	4.03b	72.50a	4,780.53a
Urochloa ruziziensis	1.18c	51.25b	2,767.96b
Least significant difference (LSD)	2.69	11.16	1,265.36
Herbicide	0.14	5.25	0.64
Forage	15.13**	16.50**	9.02**
Herbicide x Forage	0.38	0.61	1.48
Coefficient of variation (CV, %)	40.70	18.29	32.73

[(1)]Means followed by equal letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. **Significant by the F-test, at 1% probability.

Table 5. Infestation by sourgrass (*Digitaria insularis*) and other weed species, as well as sourgrass density (plants per square meter), at 240 days after soybean (*Glycine max*) harvest as affected by herbicide treatments for the control of sourgrass in the soybean crop, combined with the maintenance or not (fallow) of forage species in the off-season[(1)].

Treatment during the crop cycle[(3)]	Treatment in the off-season	Infestation (%)[(2)]		Sourgrass density
		Sourgrass	Other species	(plants per m^2)
Herbicide	With no forage (fallow)	49.06b	47.50d	10.50b
	'Massai' (*Panicum maximum*)	17.50a	24.38bc	3.75a
	'BRS Tamani' (*P. maximum*)	8.75a	13.75a	2.00a
	'BRS Zuri' (*P. maximum*)	6.25a	20.00ab	1.50a
	Urochloa ruziziensis	16.88a	30.94c	3.75a
Least significant difference (LSD)		12.35	9.89	2.64
Glyphosate	Fallow	93.75	5.00	24.50
Control infested	Fallow	93.75	6.25	25.25
Control weeding	Fallow	88.75	11.25	20.00
Herbicide		3.33	0.98	5.33
Forage		30.59**	27.06**	36.58**
Herbicide x forage		1.30	2.54	1.30
Coefficient of variation (CV, %)		42.98	36.35	52.97

[(1)]Means followed by equal letters, in the columns, do not differ from each other by Tukey's test, at 5% probability. [(2)]Infestation was defined according to the weed species present in the experimental unit, which were: *Bidens subalternans*, *Chamaesyce hirta*, *Cenchrus echinatus*, *Commelina benghalensis*, *Conyza sumatrensis*, *Eleusine indica*, *Emilia sonchifolia*, *Euphorbia heterophylla*, *Galinsoga parviflora*, *Nicandra physalodes*, *Portulaca oleracea*, *Richardia brasiliensis*, *Rhynchelytrum repens*, *Sida rhombifolia*, *Solanum americanum*, and *Tridax procumbens*. [(3)]The control treatments (isolated application of glyphosate, infested control, and weeding control) were compared with each other and with the treatments of interest (factorial) through orthogonal contrasts.. **Significant by the F-test, at 1% probability.

the beginning of the subsequent crop season, 'BRS Zuri', 'BRS Tamani', 'Massai', and *U. ruziziensis* caused decreases of 92, 90, 80, and 80% in weed population density when compared with the initial sourgrass density of 19.2 plants per square meter in the experimental area. This result is related to the effective chemical control applied to the soybean crop and to the maintenance of soil cover using forage plants in the autumn-winter period. Contrastingly, the treatment without soil cover plants in the off-season resulted in a decrease of only 45% in weed density, with 10.5 sourgrass plants per square meter remaining in the area.

To maintain the high control of sourgrass observed during the soybean cycle until the next crop season, the use of forage species was required. Although seeds from the soil seed bank germinated and reinfested the plots in the off-season, this reinfestation was more pronounced in the plots without soil cover plants. The competition of forage species with a fast and vigorous growth prevented or inhibited the establishment of the sourgrass plants. Marochi et al. (2018) found that rotating between herbicides and mixes, combined with the intercrop of corn (*Zea mays* L.) and *U. ruziziensis* or with only *U. ruziziensis*, kept sourgrass infestation at very low levels. This is indicative that chemical control alone, even when effective, is ineffective for the management of herbicide-resistant sourgrass in the medium- and long-terms. Therefore, the management of herbicide-resistant sourgrass should be done using herbicide rotation and mixes and also soil cover crops to mitigate weed resistance and prevent the selection of multiple-resistance biotypes (Marochi et al., 2018).

The control treatments (isolated application of glyphosate, weeding control, and infested control) did not differ significantly regarding the infestation by sourgrass, the infestation by other weed species, and the density of sourgrass, but differed from all management treatments, including the one without soil cover plants in the off-season. It should be noted that all these treatments were kept fallow in the off-season, without weed management in the autumn-winter period. Consequently, there were relative increases in plant density of 30% for the infested control plots, 28% for the treatment with the isolated application of glyphosate, and 4% for weeding control when compared with the initial sourgrass density in the experimental area. Furthermore, the mechanical management of sourgrass and other weeds throughout the soybean cycle in the weeding control treatment probably affected the overcoming of dormancy or benefited the germination and emergence of weeds due to soil turning, favoring an increased infestation in the plots.

Conclusion

The chemical treatments with herbicide combinations associated with the maintenance of forage species in the off-season are effective for the control of adult glyphosate-resistant sourgrass (*Digitaria insularis*) plants.

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