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How Do Off-Season Cover Crops Affect Soybean Weed Communities?

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Abstract: Weeds compete for environmental resources, leading to reduced soybean yield. In this context, integrated weed management strategies related to cultural control with the use of cover crops are necessary. Our aim was to evaluate weed occurrence in soybean systems with different cover crops. Field studies were conducted at Júlio de Castilhos, Santa Maria, Capão do Leão, Barra do Ribeiro, and Santo Ângelo, Rio Grande do Sul, Brazil. A randomized complete block design with four replications was used. Treatments consisted of black oats (*Avena strigosa* Schreb.), white oats (*Avena sativa* L.), rye (*Secale cereale* L.), hairy vetch (*Vicia sativa* L.), forage turnip (*Raphanus sativus* L.), and white clover (*Trifolium repens* L.) in pure stands or in mixtures. The analyzed variables were relative frequency, density, abundance, and importance value index, similarity index of weeds, dry shoot mass of cover crop, and soybean yield. Cover crops containing white or black oats reduced the relative importance value index of weeds, such as *Lollium multiforum*, *Conyza* spp., and *Bidens pilosa*. Forage turnip, hairy vetch, and white clover showed distinct responses. Black oats and forage turnip did not differ from cover crop mixtures in terms of dry shoot mass and grain yield, being superior to fallow, white clover, and hairy vetch.

Keywords: integrated weed management; winter sow; soybean

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1. Introduction

Cover crops are commonly used to replace fallow in the off season. This strategy is based on the use of living covers, also called secondary crops, and can also be cultivated together with a commercial crop or during part of its development [1]. Cover crops have several functions within agricultural ecosystems, being recognized for their contribution to soil quality and exerting positive effects on the physical, chemical, and biological properties of the soil [1,2]. Furthermore, they suppress weeds, which can vary depending on the environment [3]. However, as the biomass of cover crops increases, there is a tendency for weed biomass to decrease, denoting the suppression capacity exerted by cover crops [4].

Traditionally, cover crops are implemented in monoculture, providing benefits such as weed suppression, nitrogen fixation, carbon sequestration, and increased yield of summer crops. Commonly, this positive effect is proportional to an increase in crop biomass coverage [5]. Currently, several mixes of two or more species of cover crops have emerged, given the recognition that increasing the diversity of the plant community can result in a greater variety of ecological benefits or ecosystem services [5]. Furthermore, increasing species diversity can suppress weeds through biomass production and rapid growth, making them highly competitive [6]. However, studies differ regarding the use of monoculture and intercropping in relation to greater weed suppression capacity [6,7].

To understand the interactions between the weed community and the use of cover crops, phytosociological parameters can be used. Phytosociology is an important tool for weed science and can be simplified as the structure of the association of plant species [8]. The use of ryegrass and forage turnip as cover crops reduced the occurrence of black walleye (*Bidens* spp.), obtaining importance value indices (IVIs) of 105.00 and 45.38, respectively, while the IVI observed during fallow was 140.24 [9]. However, another study evaluating the effect of cover crops and cropping systems observed an IVI of 53.42 for milkweed (*Euphorbia heterophylla*) in black oat and 65.55 in the intercrop of black oat and vetch, while in the conventional soil cultivation system, there was no milkweed presence [10].

The phytosociology of weeds in soybeans varies in relation to other management practices, such as the application of pre-emergent and post-emergent herbicides [11]. Thus, the panorama of infestation in agricultural environments can be estimated, given that changes of any type in the dynamics of agroecosystems can influence phytosociological parameters [12]. Thus, our aim was to quantify, through phytosociological parameters, the occurrence of weeds and soybean yield preceded by different winter cover crops.

2. Materials and Methods

The work was carried out under field conditions in two seasons in the sites of Barra do Ribeiro (30°22′07″ S; 51°20′04″ W), Capão do Leão (31°48′42″ S; 52°28′37″ W), Júlio de Castilhos (29°25′59″ S; 53°32′13″ W), Santa Maria (29°43′31″ S; 53°43′41″ W), and Santo Ângelo (28°15′50″ S; 54°13′25″ W), Rio Grande do Sul, Brazil. The soil in Barra do Ribeiro and Capão do Leão was characterized as Alfisols, while in Santa Maria and Júlio de Castilhos, it was characterized as Ultisols and Oxisols [13] and the climate as humid subtropical. The experimental design used was randomized blocks, with four replications. The experimental units were 7 × 5 m, for a useful area of 35 m^2.

Different cover crop species were evaluated in two experiments. The first study was carried out in the 2020–2021 growing season and the second study was in the 2021–2022 growing season (Table 1). Experiments were conducted in Júlio de Castilhos, Santa Maria, and Capão do Leão in the 2020–2021 period using single cover crops and a mix of commercial cover crops, respecting the sowing density informed by the manufacturing company. In 2021–2022, studies were carried out in Barra do Ribeiro, Santa Maria, and Santo Ângelo, in which single species and a mix of cover crops produced on the farm were used. The weather and rainfall conditions are described in Figure S1.

The experimental areas were soybean in monoculture over the last 5 years and without winter crops in the off-season. Cover crops were sown during fall, in May, in both growing seasons, in a no-till system and with a row spacing of 0.17 m (Table S1). No weed management was carried out during the development of the cover crops. The cover crops burndown were at 30 days before soybean sowing due to glyphosate (1440 g ae. ha^{-1}) spraying. The cover crops were not harvested, and their dry biomass was evaluated before burndown by collecting the green mass on the soil in an area of 0.25 m^2. Weeds were eliminated from the samples, which were left to dry at 60 °C until a consistent mass was obtained; they were then weighed, and the result was expressed in kg ha^{-1}.

Soybean sowing took place between October and December in both seasons, in a no-till system and with a row spacing of 0.45 m (Table S1). Crop emergence was not affected by straw presence in the soil. In the 2020–2021 season, cultivar BMX Zeus IPRO was sown in Júlio de Castilhos and Santa Maria, and cultivar FTR 2155 RR was sown in Capão do Leão. Similarly, in the 2021–2022 season, cultivar BMX Zeus IPRO was sown in Santa Maria and Santo Ângelo, and cultivar BMX Compacta IPRO was sown in Barra do Ribeiro. Soil fertilization was carried out due to NPK application in the soybean sowing furrow, according to soil analysis [14] (Table S1). After soybean sowing, post-emergence weed management occurred at stage V5 [15], with the application of the herbicide glyphosate (1000 g ae. ha^{-1}).

Table 1. Cover crops used in the soybean production system, with their respective sowing rates (DS) and estimated proportion between species in the mix (PE).

Treat.	Species and Their Respective Cultivars (cv)	DS ($kg\ ha^{-1}$)	PE (%) [1]
	2020–2021 season		
PO	Fallow (spontaneous vegetation)	-	-
AP	Black Oat cv Embrapa 139	100	100
ER	Vetch cv Combate	130	100
NF	Forage Turnip cv Pé de Pato	20	100
RX 110®	Rye cv Progresso + White Oat cv IAPAR 61 + Forage Turnip (cv IPR 16 + cv Japonês)	84	42:45:13
RX 210®	Black Oats cv IAPAR 61 + White Oats cv Esmeralda + Rye cv Progresso + Forage Turnip (cv Pé de Pato + cv IPR 16)	60	43:21:22:14
RX 220®	White Oats cv Taura + Black Oats cv BRS139 + Rye cv Serrano + Forage Turnip cv IPR 116	54	8:60:23:9
RX 330®	Rye cv Progresso + Black Oat cv IAPAR 16 + Vetch cv Combate	48	33:58:9
RX 610®	Black Oat cv IAPAR 61 + Vetch cv Combate + Vetch cv Esmeralda + Forage Turnip cv IPR 16	54	65:32:3
	2021–2022 season		
PO	Fallow (spontaneous vegetation)	-	-
AP	Black Oats	70	100
ER	Vetch cv Combate	90	100
NF	Forage Turnip cv Pé de Pato	25	100
TB	White Clover	6	100
Mix 1	Black Oats + Forage Turnip cv IPR 116 + Vetch	60	60:23:17
Mix 2	Black Oats + White Oats + Rye + Forage Turnip cv IPR 116	60	55:12:15

[1] Proportion quantified from the average count of the number of established plants m^{-2} per species (cultivars of each species were not counted individually) being converted into a percentage and presented according to the order in which they are described in the table.

The first phytosociological survey of weeds occurred before the burndown of cover crops, and the second occurred at the V4 stage of soybeans [15]. The survey involved eight samples per experimental unit, using a metal frame with an internal area of 0.25 m^2. In each sample, the number of individuals present and identification at the genus and species levels were determined using specialized literature [16,17].

Variables Analyzed and Statistical Analyses

From the quantitative data recorded in the field, the phytosociological variables were calculated according to the methodology proposed by [18] and described in the following equations:

- Relative frequency (RF):

$$RF = \frac{(number\ of\ samples\ with\ the\ species/total\ number\ of\ samples) \times 100}{total\ frequency\ of\ all\ species\ observed\ in\ the\ treatment} \quad (1)$$

- Relative density (RD):

$$RD = \frac{\left(number\ of\ plants\ of\ the\ same\ species\ in\ the\ sample/0.25\ m^2\right) \times 100}{total\ density\ of\ all\ species\ observed\ in\ the\ treatment} \quad (2)$$

- Relative abundance (RA):

$$RA = \frac{(number\ of\ plants\ of\ the\ same\ species\ in\ the\ sample / total\ number\ of\ samples\ with\ the\ species) \times 100}{total\ abundance\ of\ all\ species\ observed\ in\ the\ treatment} \quad (3)$$

- Relative Importance Value Index (IVIR):

$$IVIR = RF + RD + RA \quad (4)$$

The relative frequency (RF) determines the distribution of species in the samples; relative density (RD) represents the number of plants of each species per unit area; and relative abundance (RA) demonstrates the concentration of species in the area. The relative importance value index (IVIR) determines the most important species present in the survey.

Cover crops were also analyzed using the Simpson (D) and Shannon–Weiner (H′) diversity indices, which express the biodiversity present in the samples [19]. A dendrogram was constructed to compare cover crops and study sites in each season; for this, the Morisita–Horn similarity index [20] was used. This index considers the number of weeds of each species to generate the similarity grouping. The method used to generate the dendrogram was multivariate hierarchical cluster analysis using the unweighted pairs method with arithmetic mean. UPGMA (unweighted pair group method with arithmetic mean) [21] in Past 4.03 software was also used [22]. The critical level for separating groups in the cluster analysis was defined using the arithmetic mean of similarities in the similarity matrix [19].

After soybean maturation in the R8 phenological stage [15], grain yield was evaluated by harvesting 3 m^2 $plot^{-1}$, and grain moisture was adjusted to 13% (Table S1). In Santa Maria and Capão do Leão, in the 2020-2021 harvest, and in Santo Ângelo, in the 2021–2022 harvest, the experiments were not harvested (Table S1). The reasons for this were low rainfall during the soybean reproductive phase and the occurrence of fires that caused the loss of some of the experimental plants. When significant using the F test, the means of both variables were separated using the Scott–Knott test ($p < 0.05$). For statistical analysis, Ref. [23] and the Easyanova statistical package were used [24].

3. Results

3.1. 2020–2021 Season—Júlio de Castilhos

The phytosociological survey at Júlio de Castilhos showed that the families with the highest relative importance value index (IVIR) were Primulaceae (38.81%), Oxalidaceae (19.66%), Asteraceae (16.13%), and Lamiaceae (14.00%). The weed with the highest IVIR in all treatments was *Anagallis arvensis* L., which was not suppressed by cover crops (Figure 1). *Conyza* spp. had the lowest IVIR values in treatments RX 330® (7.47%) and RX 110® (9.96%). *Richardia brasiliensis* was not observed in treatments with NF or RX 220®, but it had the lowest IVIR in treatments RX 110® (7.51%) and RX 610® (6.82%), both with a density of eight plants m^{-2}. The dry mass of the aerial part of the cover crops formed two groups of average statistically significant differences, being higher for the treatments with the mix of cover crops RX 110®, RX 210®, and RX 610®, with an average of 7175.76 kg ha^{-1} of dry mass (Table 2). However, the treatments RX 220®, NF, and RX 330® formed the group with lower averages with a dry mass of 4202.73 kg ha^{-1}.

In the second phytosociological survey at Júlio de Castilho, carried out at stage V4, a lower species diversity was observed than in the first phytosociological survey (Figure 2). The families with the highest IVIR were Brassicaceae (51.15%) and Poaceae (43.55%). Treatments with NF and RX 610® represented the highest IVIR for *Raphanus raphanistrum* L., at 68.61 and 62.00%, respectively, and the lowest IVIR for *Avena* spp., at 19.65 and 26.98%, respectively. Both *R. raphanistrum* and *Avena* spp. may have come from cover crop treatments. Treatments RX 110® and RX 220® did not present *Cyperus* spp., *Urochloa plantaginea*, or *Vicia sativa*. Finally, soybean yield showed the formation of two groupings of means of statistically significant differences in the Scott–Knott test (Table 3). The treatments with RX 210®, RX 330®, and RX 610® comprised the group of higher averages with a yield of

4751.82 kg ha^{-1}, while the treatments with NF, RX 110®, and RX 220® obtained an average of 3279.41 kg ha^{-1}.

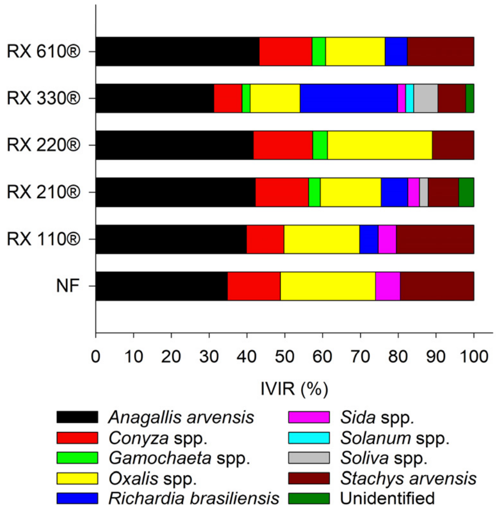

Figure 1. Phytosociological analysis of weeds using the importance value index (IVIR) during cover crop development in Júlio de Castilhos in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Table 2. Dry biomass of cover crop treatments before burndown in Júlio de Castilhos in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Treatment	Dry Biomass (kg ha^{-1})
Forage turnip	4077.07 b [1]
RX 110®	7471.37 a
RX 210®	7322.36 a
RX 220®	4725.07 b
RX 330®	3806.05 b
RX 610®	6732.95 a

[1] Means followed by different letters in the column show statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

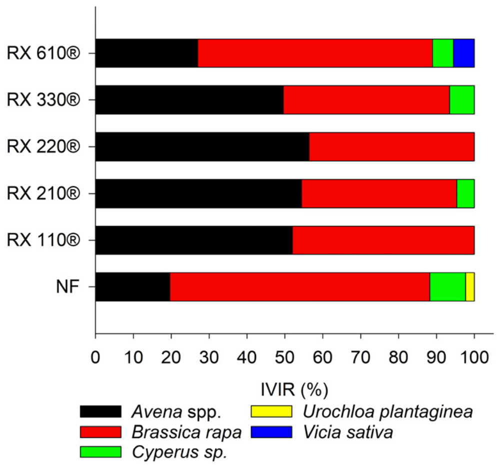

Figure 2. Phytosociological analysis of weeds using the importance value index (IVIR) at the V4 stage of soybeans in Júlio de Castilhos in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Table 3. Soybean yield for the different treatments in Júlio de Castilhos in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Treatments	Yield (kg ha^{-1})
Forage turnip	3064.49 b [1]
RX 110®	3033.74 b
RX 210®	4766.21 a
RX 220®	3740.02 b
RX 330®	4574.07 a
RX 610®	4915.23 a

[1] Means followed by different letters in the column indicate statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

3.2. 2020–2021 Season—Santa Maria

For the Santa Maria site, in the first phytosociological survey, 12 families of weeds were identified, of which the most important according to IVIR were Primulaceae (26.99%) and Asteraceae (25.74%). As observed in Júlio de Castilhos (Figure 1) at the time of evaluation, the most recurrent weed was *Anagallis arvensis* (Figure 3). The presence of *Conyza* spp. was observed in all treatments but with a lower IVIR in the RX 110® treatment, similar to that observed in the first phytosociological survey in Júlio de Castilhos. Likewise, *R. brasiliensis* was observed in all treatments, but had a lower IVIR in PO, RX 210®, and RX 220® treatments. *Lolium multiflorum* was only observed in the ER and NF treatments.

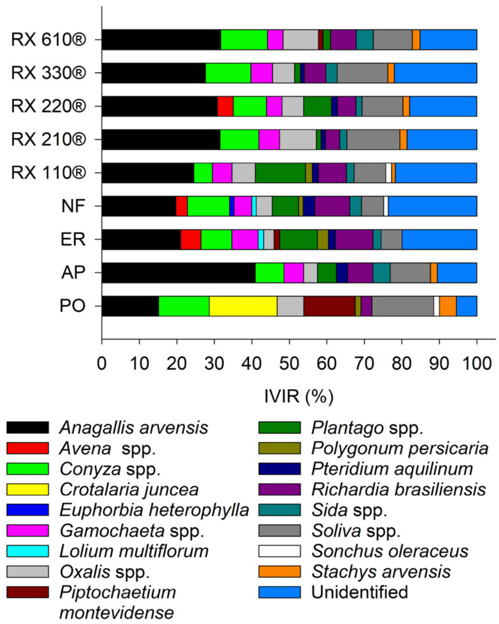

Figure 3. Phytosociological analysis of weeds using the importance value index (IVIR) during cover crop development in Santa Maria in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Regarding the dry cover crop biomass in Santa Maria, the average test showed the formation of three groups of statistically significant differences whose superior treatments were RX 210®, RX 220®, PO, RX 610®, AP, and RX 110® with an average of 5988.82 kg ha^{-1} (Table 4). ER was lower for all treatments, with a dry mass of 1352.13 kg ha^{-1}. However, the biomass of spontaneous vegetation in the treatment without cover crops reached a dry mass of 5935.50 kg ha^{-1}.

Table 4. Dry biomass of cover crop treatments before burndown in Santa Maria in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Treatment	Dry Biomass (kg ha^{-1})
Fallow [1]	5935.50
Black oats	5623.70 a [2]
Vetch	1352.13 c
Forage turnip	4385.47 b
RX 110®	5400.60 a
RX 210®	7213.60 a
RX 220®	5943.90 a
RX 330®	4505.87 b
RX 610®	5815.60 a

[1] Value referring to the total dry mass of spontaneous vegetation present in the fallow treatment not included in the statistical analysis. [2] Means followed by different letters in the column show statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

In the second phytosociological survey the diversity of families was 8, where the highest rates were observed for Convolvulaceae (IVIR of 35.21%), Rubiaceae (29.62%) and Asteraceae (15.56%) (Figure 4). *Ipomoea* sp. remained the same, as it was present in all treatments but obtained the lowest IVIR in the NF treatment (Figure 4). *Richardia brasiliensis* was not observed in the PO treatment and presented a higher IVIR under NF treatment (54.58%). The presence of *Conyza* spp. was observed under ER, NF, RX 220®, RX, 610® and PO treatments, constituting the largest IVIR in the latter treatment. A harvest was not performed (Table S1).

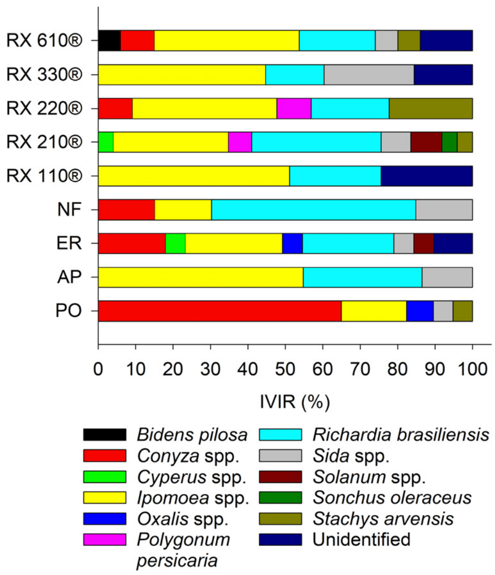

Figure 4. Phytosociological analysis of weeds using the importance value index (IVIR) at the V4 stage of soybeans in Santa Maria in the 2020–2021 season. The composition of the treatments is provided in Table 1.

3.3. 2020–2021 Season—Capão do Leão

A phytosociological survey was carried out during the development of cover crops, and 10 families of weeds were observed, of which the main ones were Poaceae (IVIR of 19.85%), Oxalidaceae (17.89%), and Asteraceae (14.29%) (Figure 5). In the Poaceae family, *Cynodon dactylon* was not found in the NF treatment, and the highest IVIR was evidenced in treatment with RX 220® (Figure 5). *Echinochloa* spp. were not observed in the NF or RX 110® treatments. There was no statistical difference between the average dry mass of the aerial parts of the cover plants, and a harvest was not performed (Table S1).

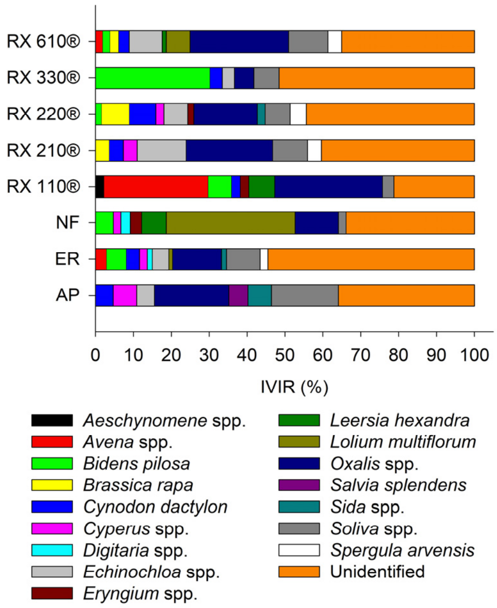

Figure 5. Phytosociological analysis of weeds using the importance value index (IVIR) during cover crop development in Capão do Leão in the 2020–2021 season. The composition of the treatments is provided in Table 1.

3.4. 2020–2021 Season—Similarity Analysis

Considering the data on the flora established in the 2020–2021 season and the response to phytosociological surveys (Figures 1–5), the highest Shannon–Weiner index (H') in Júlio de Castilhos was observed in the treatment with the RX 330® mix in both assessments (Table 5). The greatest diversity was observed with the RX330® mix in ER and NF treatments in Santa Maria and with RX 210® and RX 220® in Capão do Leão (Table 5). The results corroborate the lower dry biomass obtained in these treatments (Tables 2 and 4), and high species richness was evident (Figures 1–5). Equivalent results were observed for the Simpson index (D) (Table 5).

Table 5. Diversity of weed species per cover crop by Simpson (D) and Shannon–Weiner (H') indices in the 2020–2021 season. The composition of the treatments is provided in Table 1.

Treatment	1st Assessment		2nd Assessment		1st Assessment		2nd Assessment		Capão do Leão	
	Júlio de Castilhos				Santa Maria					
	D	H'	D	H'	D	H'	D	H'	D	H'
Fallow	-	-	-	-	0.84	2.82	0.28	0.85	-	-
Black oats	-	-	-	-	0.62	2.21	0.50	1.20	0.81	2.72
Vetch	-	-	-	-	0.85	3.21	0.76	2.35	0.80	2.83
Forage turnip	0.70	1.96	0.26	0.72	0.85	3.15	0.48	1.36	0.70	2.32
RX 110®	0.66	1.85	0.50	1.00	0.80	2.79	0.56	1.37	0.70	2.31
RX 210®	0.60	1.86	0.48	1.01	0.74	2.45	0.65	1.90	0.83	3.04
RX 220®	0.63	1.69	0.48	0.97	0.74	2.52	0.69	1.93	0.83	3.03
RX 330®	0.70	2.12	0.51	1.07	0.75	2.45	0.62	1.66	0.80	2.80
RX 610®	0.63	1.82	0.38	0.95	0.74	2.47	0.66	2.01	0.79	2.87

The dynamics of weed occurrence, as well as the frequency, density, and abundance, varied according to the location and the cover crops used. The similarity index (SI), obtained through the dendrogram (Figure 6), varied from the lowest value (0), indicating that the compared treatments presented low similarity of weed species, while the highest value (1.0) represented high similarity among the weeds present in the treatments at each location. The critical level for separating the groups occurred at an SI of 0.20 in 2020 (Figure 6). Therefore, three groups were formed due to the low similarity between the studied locations and the high similarity between the weeds in the different treatments for the same location.

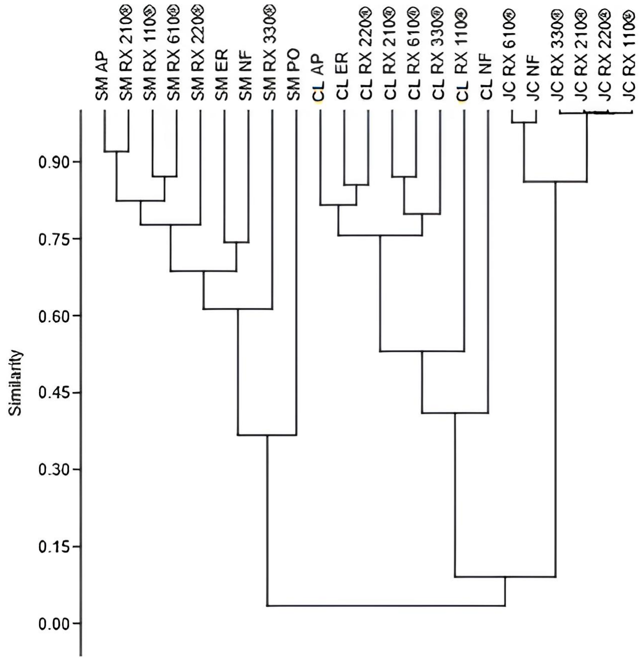

Figure 6. Cluster analysis for similarity between weeds observed at different sites (JC—Júlio de Castilhos; CL—Capão do Leão; SM—Santa Maria) for treatments with cover crops used in the 2020–2021 harvest. Cophenetic coefficient of 0.93. The composition of the treatments is provided in Table 1.

The first cluster was formed in Júlio de Castilhos, where the similarity between treatments had an SI greater than 0.8 (Figure 6). The treatments with RX 330®, RX 210®, RX 220®, and RX 330® formed a subgroup with an SI close to 1.0, similar to the RX 610® and NF treatments (Figure 6). The SI was equal to 0.4 in Santa Maria, while it was higher than 0.4 in Capão do Leão (Figure 6). In Santa Maria, fallow (SM PO) had a different floristic composition than the other treatments. For Capão do Leão, as there was no fallow, forage turnip (CL NF) had less similarity than the other treatments.

3.5. 2021–2022 Season—Barra do Ribeiro

Overall, eight families of weeds were observed in Barra do Ribeiro, with the most relevant families being Plantaginaceae (IVIR of 27.51%), Asteraceae (18.47%), and Poaceae (18.06%) (Figure 7). *Veronica arvensis* had the highest index and was present in all treatments. It stood out in a survey of *Conyza* spp. in treatments with NF (IVIR of 2.79%) and ER (5.22%). Another important species was *L. multiflorum,* which was only observed in treatments with NF (IVIR of 5.63%), ER (18.19%), and TB (23.19%). Additionally, *R. brasiliensis* was only observed in Mix 1 (IVIR of 11.09%).

The dry cover crop biomass formed two groups of statistically different means, with the superior treatments being AP, ER, NF, Mix 1, and Mix 2 with a dry mass of 5533.03 kg ha^{-1}, while the treatment with TB was lower with an average dry mass of 1137.43 kg ha^{-1} (Table 6). For soybean grain yield, two groups of statistically significant differences were formed, where the highest yield was obtained in the AP, ER, TB, NF, and Mix 1 treatments, with an average of 4554.08 kg ha^{-1} (Table 7).

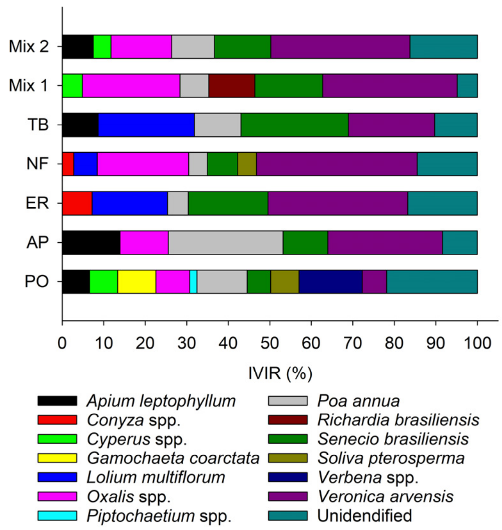

Figure 7. Phytosociological analysis of weeds using the importance value index (IVIR) during cover crop development in Barra in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Table 6. Dry biomass of cover crop treatments before burndown in Barra do Ribeiro in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Treatment	Dry Mass (kg ha^{-1})
Fallow [1]	1848.03
Black oats	5760.78 a [2]
Vetch	4188.97 a
Forage turnip	6248.20 a
White clover	1137.43 b
Mix 1	5121.42 a
Mix 2	6345.77 a

[1] Value referring to the total dry mass of spontaneous vegetation present in the fallow treatment not included in the statistical analysis. [2] Means followed by different letters in the column indicate statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

Table 7. Soybean yield for the different treatments in Barra do Ribeiro in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Treatments	Yield (kg ha^{-1})
Fallow	3791.68 b [1]
Black oats	4299.59 a
Vetch	4909.03 a
Forage turnip	4390.60 a
White clover	4831.62 a
Mix 1	4359.39 a
Mix 2	3642.68 b

[1] Means followed by different letters in the column show statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

3.6. 2021–2022 Season—Santa Maria

In the second Santa Maria experiment, nine families were observed, with the main families being Plantaginaceae (IVIR of 60.02%) and Lamiaceae (14.39%) (Figure 8). However, the most important weeds for soybean crops observed were *Conyza* spp. in TB (IVIR of 2.67%) and PO treatments (5.37%) and *L. multiflorum* observed in ER (5.22%), TB (4.30%), and NF treatments (6.02%). *Cyperus* spp. were only observed in NF and PO treatments, and *Echinochloa* spp. were only observed in NF.

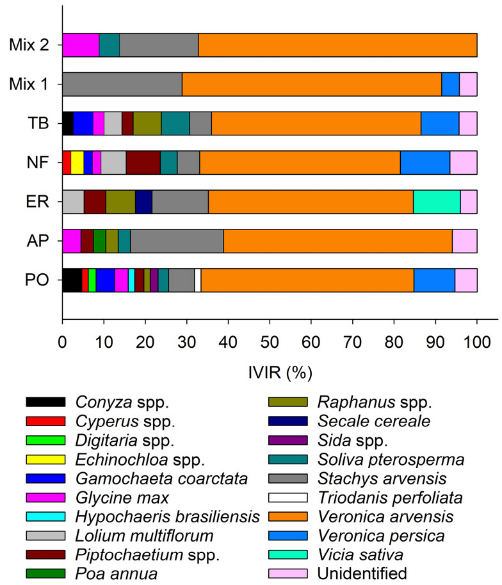

Figure 8. Phytosociological analysis of weeds using the importance value index (IVIR) during cover crop development in Santa Maria in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Regarding the dry biomass, two groups of statistically significant differences were formed between the treatments, with the upper one being formed by the treatments AP, NF, Mix 1, and Mix 2, obtaining an average dry mass of 5640.25 kg ha^{-1} (Table 8). The second group was formed by composite treatments with ER and TB, with an average of 2557.40 kg ha^{-1}. However, there was no statistical difference in the average grain yield.

Table 8. Dry biomass of cover crop treatments before burndown in Santa Maria in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Treatment	Dry Mass (kg ha^{-1})
Fallow [1]	2274.18
Black oats	6443.30 a [2]
Vetch	3426.42 b
Forage turnip	6452.53 a
White clover	1971.60 b
Mix 1	6925.02 a
Mix 2	8331.95 a

[1] Value referring to the total dry mass of spontaneous vegetation present in the fallow treatment not included in the statistical analysis. [2] Means followed by different letters in the column indicate statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

3.7. 2021–2022 Season—Santo Ângelo

In Santo Ângelo, the phytosociological survey identified 12 families, the main ones being Asteraceae with an IVIR of 37.96% and Poaceae with an IVIR of 18.72% (Figure 9). The main representative of the Asteraceae family was *Conyza* spp., which were observed in all treatments; however, the lowest value was in the TB coverage culture with an IVIR of 9.10%. Additionally, *L. multiflorum* was observed in all cover crops with a lower IVIR in NF (5.51%) and PO (5.02%). Weeds, such as *Amaranthus* spp., *Avena sativa*, and *Bidens subalternans*, were suppressed by all cover crops, being present only in the PO treatment.

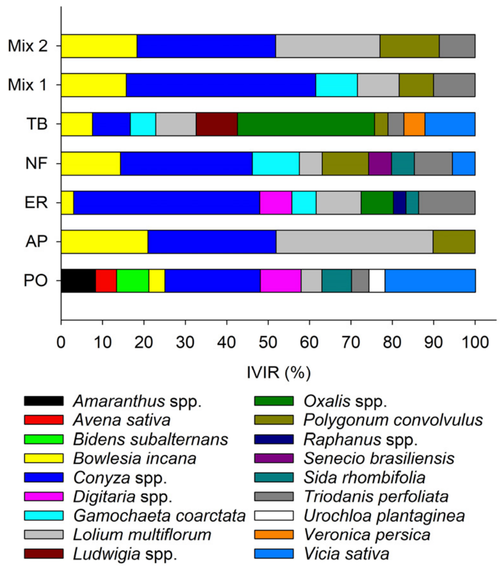

Figure 9. Phytosociological analysis of weeds using the importance value index (IVIR) during cover crop development in Santo Ângelo in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Regarding the dry biomass, the results corroborate those observed in the Santa Maria experiment. The formation of two groupings of significantly different means occurred, with the upper one being composed of AP, NF, Mix 1, and Mix 2, with an average of 7832.35 kg ha^{-1} and the lower group formed by ER and TB at 1128.56 kg ha^{-1} (Table 9).

Table 9. Dry biomass of cover crop treatments before burndown in Santo Ângelo in the 2021–2022 season. The composition of the treatments is provided in Table 1.

Treatment	Dry Mass (kg ha^{-1})
Fallow [1]	2958.44
Black oats	6374.96 a [2]
Vetch	2131.51 b
Forage turnip	7942.56 a
White clover	125.61 b
Mix 1	9253.41 a
Mix 2	7758.36 a

[1] Value referring to the total dry mass of spontaneous vegetation present in the fallow treatment not included in the statistical analysis. [2] Means followed by different letters in the column indicate statistically significant differences according to the Scott–Knott test ($p \leq 0.05$).

3.8. 2021–2022 Season—Similarity Analysis

Regarding the composition of weeds in the sites evaluated in the 2021–2022 harvest, in the Barra do Ribeiro experiment, the highest H′ index (Table 10) was observed in the PO plot, which was repeated in Santo Ângelo. However, in Santa Maria, the highest H′ indices were obtained in treatments with ER and NF, in the same way as in the previous harvest. The D index obtained results similar to those described.

Regarding the cluster analysis of weeds for the 2021–2022 season, two clusters were formed using the critical point criterion, with the greatest floristic similarity in the first cluster between the sites located in Barra do Ribeiro and Santa Maria, with a critical point SI close to 0.5 (Figure 10). The second group was composed of the municipality of Santo Ângelo, with a critical point SI close to 0.1.

Table 10. Diversity of weed species per cover crop by Simpson (D) and Shannon–Weiner (H′) indices in the 2021–2022 season. The composition of the treatments is provided in Table 1.

	2021–2022 Season					
Treatment	**Barra do Ribeiro**		**Santa Maria**		**Santo Ângelo**	
	D	**H′**	**D**	**H′**	**D**	**H′**
Fallow	0.88	3.29	0.39	1.42	0.79	2.74
Black oats	0.75	2.22	0.41	1.12	0.67	1.74
Vetch	0.72	2.11	0.47	1.52	0.57	1.85
Forage turnip	0.64	1.92	0.46	1.59	0.74	2.48
White clover	0.77	2.32	0.40	1.46	0.74	2.53
Mix 1	0.72	2.15	0.38	0.89	0.59	1.82
Mix 2	0.73	2.27	0.26	0.73	0.44	1.30

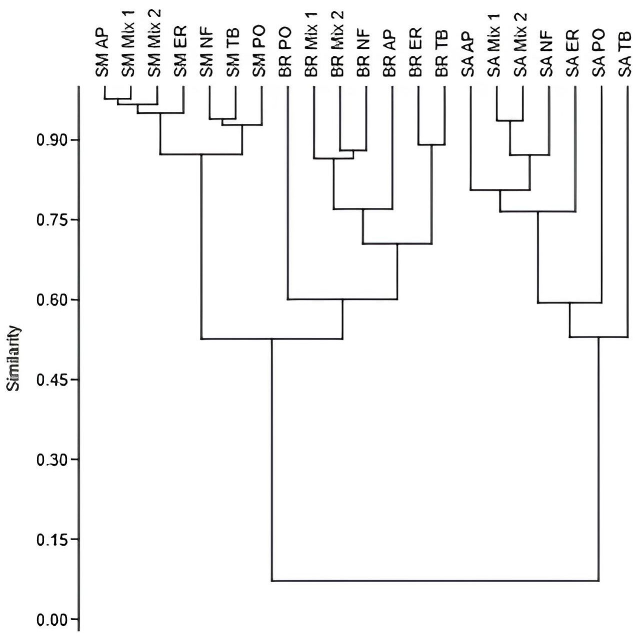

Figure 10. Cluster analysis for similarity between weeds observed at different sites (BR—Barra do Ribeiro; SA—Santo Ângelo; SM—Santa Maria) for treatments with cover crops used in the 2021–2022 harvest. Cophenetic coefficient of 0.97. The composition of the treatments is provided in Table 1.

Within the Barra do Ribeiro cover crops, the similarity between the weeds observed in the treatments was 60%, and the fallow (BR PO) presented a floristic composition of weeds with less similarity in relation to the other treatments. Within the same similarity grouping, in Santa Maria, there was an SI above 0.90. The cover crops implemented in Santo Ângelo obtained 60% floristic similarity. The fallow (SA PO) and white clover (SA TB) treatments presented different floristic compositions than the other treatments.

4. Discussion

The majority of weeds observed in studies are characterized as ruderal species that establish themselves in agricultural areas and adapt to the production system [25]. In this sense, cover crops can modify the environment, allowing efficient weed control [26]. For this to be possible, it is essential to understand the physiology of the main weeds present in production systems.

Cover crops have demonstrated effectiveness in controlling weed emergence since light is a limiting factor for the germination of many species. For this purpose, cover crops with rapid emergence and canopy closure are desired [2]. In this case, the absence of radiation can reduce germination by more than 90% for *Richardia brasiliensis* [27] and *Conyza* spp. [28].

Dry biomass above 3 tons ha^{-1} also plays a role in weed suppression [25,28]. The presence of *R. brasiliensis* in Júlio de Castilhos, whose IVIR from treatment with RX 330® represented 40% of this species, is highlighted, and this value was attributed to the lower dry mass of aerial parts obtained in this cover crop (Table 2). The same occurred with *R. brasiliensis* in the Santa Maria experiment in the first harvest, in which the highest IVIR and the lowest dry shoot biomass were observed in the ER and NF treatments (Table 2).

In subtropical environmental conditions, the establishment of *Conyza* spp. in autumn provides a prolonged period during winter for its development, resulting in an increased presence of weeds in agricultural areas [29]. In southern Brazil, *Conyza* spp. were identified as the main weeds in soybean due to their resistance to five herbicide mechanisms of action, making chemical control challenging [30]. The IVIR for *Conyza* spp. and *L. multiflorum* showed similar behavior in different locations, with the presence of these weeds being reduced or suppressed when using black oats or intercropping containing 45–68% oat species and 12–35% rye. One study reported that cover crops containing rye had up to 75% less *Conyza* spp. than red clover coverage [4]. Furthermore, there are approximate reductions of 68% in the mass of broad-leaved weeds and 62% in grasses, with the use of black oat as a cover crop [31]. In a study using oats as a cover crop preceding annual forage crops for animal feed, the importance of this cover crop in significantly reducing weeds such as *Avena fatua* L. and *Convolvulus arvensis* L. was demonstrated in all treatments [32].

Studies have indicated that, in the off-season of summer crops, the Poaceae family generally has a greater suppressive effect and greater biomass compared to the Brassicaceae and Fabaceae families [4,6]. In our study, the presence of weeds from the Poaceae family in the crops and locations evaluated was reduced, which may be related to the greater suppressive effect of cover crops from this family, which were present in almost all treatments. The literature also suggests the possibility of releasing allelopathic compounds in weed management, as exemplified by forage turnip, buckwheat, black oat [33], and rye plants [34], through direct interaction between root systems or through plant decomposition.

One study tested two cover crops and different soil preparations prior to corn cultivation [35]. The study shows that the use of white clover combined with rotational tillage obtained the highest dry mass of the cover crop and higher corn productivity, while the use of ryegrass combined with rotational tillage obtained the lowest dry mass of weeds, but, on average, productivity was lower than using white clover [35]. Determining why the cover crop suppressed weeds is complex. We considered the factors of greater production of dry mass and the possibility of allelopathy. However, isolating the allelopathic effect as being the only one to determine the suppression of a particular weed in the ecosystem is difficult. Therefore, given the results found, and due to the diversity of environmental and climatic conditions, we cannot conclude that there were allelopathic effects.

The similarity indices (SI) showed similar behavior in the study sites, where the floristic composition of the weeds showed less SI in the fallow, followed by crops with vetch or forage radish and with greater SI between consortia of cover crops containing Poaceae, such as oats and rye. In our study, the highest Shannon (H') and Simpson (D) indices were obtained in the lowest cover crop biomasses in the 2020–2021 and 2021–2022 seasons. Regarding the diversity indices, a study showed that in treatments without herbicide application, low diversity indicates the predominance of some competitive species, occupying most of the available area [36]. Another study evaluating spring wheat, triticale, and winter wheat reported the highest frequency of dicotyledonous weeds in the plots evaluated. In the study, the highest Shannon index was observed in triticale, which, in turn, denoted the greater biodiversity of weeds among the treatments, and also obtaining the highest dry mass of weeds [37]. Even though the dry mass of the crops was not evaluated, it is considered that the treatment with triticale may represent less soil cover, reflected in the greater dry mass of weeds. It can be inferred that the more homogeneous the vegetation cover and the greater its biomass, the lower the floristic diversity and, consequently, the greater the similarity among weeds.

Weeds with a history of resistance such as *Lolium multiforum*, *Conyza* spp., and *Bidens pilosa* were not observed in black oat cover crops in the crops and locations evaluated in our research. In contrast, weeds such as *C. dactylon* and *Echinochloa* spp. obtained variable responses in the treatment with forage radish, which also had no effect on *L. multiforum*, vetch, or white clover. However, work conducted with cover crops considers the results of suppressing *L. multiflorum* to be satisfactory using rye, vetch, black oat, and forage turnip [38]. Thus, the responses of the phytosociological indices differed between treatments, but the repetition of some phytosociological patterns was observed between experiments. Cultural control using cover crops had a positive impact on weed suppression in different locations. This makes a very important contribution to integrated weed management through the use of cover crops. Future research could contribute to advancing the use of these tools, indicating allelochemical potential and other species in pure stands or mixes to improve weed suppression responses.

5. Conclusions

The introduction of cover crop treatments caused the reduction or suppression of many important weeds, resulting in a decrease in weed density that influenced the relative importance value index (IVIR). The use of IVIR was important to compare sites with different soil and climate characteristics and different weed occurrence.

White or black oats suppressed or reduced the IVIR of weeds, such as *Lolium multiforum*, *Conyza* spp., and *Bidens pilosa*. Forage turnip did not suppress *L. multiflorum*, *Cynodon dactylon*, or *Echinochloa* spp. Cover crops with vetch and white clover expressed different responses in weed suppression. The fallow, white clover, and vetch treatments had the lowest dry matter and yield in relation to the other treatments.

The highest Shannon (H') and Simpson (D) indices were obtained in the lowest cover crop biomasses in the 2020–2021 and 2021–2022 seasons. The similarity index (SI) in the 2020–2021 and 2021–2022 seasons showed a trend of greater similarity in the weed flora between the cover crop treatments when compared to the fallow. It can be inferred that the more homogeneous the vegetation cover and the greater its biomass, the lower the floristic diversity and, consequently, the greater the similarity of the weeds.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture14091509/s1: Figure S1. Maximum and minimum temperatures (°C) and rainfall (mm) for Júlio de Castilhos (A), Santa Maria (B), and Capão do Leão (C) in 2020–2021 and for Barra do Ribeiro (D), Santa Maria (E), and Santo Ângelo (F) in 2021–2022. Table S1. Data on sowing dates for cover crops and soybeans, soybean cultivars, sowing density, and soybean fertilization in the 2020–2021 and 2021–2022 season experiments.

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