Revista Ciência Agronômica, v. 56, e202494091, 2025
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Scientific Article
ISSN 1806-6690

Diversified grain production systems improve phytosociological indices and reduce the cost of weed control[1]

Maria Beatriz Funari de Souza[2], Ivan Bordin[3], Tiago Santos Telles[4]*

ABSTRACT - The soya bean/maize double-crop is seen as the principal grain production system in Brazil; it is, however, vulnerable to competition and infestation by volunteer plants. In crop rotation systems which include different species, cultural weed control can be effective, improving phytosociological indices and reducing costs. The aim of this study was to evaluate the phytosociology and cost of weed control in a soya bean/maize double-crop and in crop rotation systems with different species, between the 2014/2015 and 2022/2023 crop years. Six treatments were used, with four replications. Phytosociological indices were calculated and analysed following the soybean harvest in 03/2014, 03/2017, 03/2020 and 03/2023. The ground cover was evaluated in 03/2023. The costs of weed control were calculated based on the cost of the active ingredients and the agricultural operations. The treatment that included cereal crops in the winter and grain crops in the summer (T2) showed less weed diversity and greater control of *Commelina benghalensis* and *Euphorbia heterophylla* compared to the soya bean/maize double-crop. Each of the treatments had adequate ground cover. Costs in the soya bean/maize double-crop were 22.72% higher for the treatment with cereal crops in the winter and grain crops in the summer (USD 162.32 ha^{-1} yr^{-1}). It was found that winter cereals are effective in controlling *C. benghalensis* and *E. heterophylla*, and that the soya bean/maize double-crop results in higher costs for weed control.

Keywords:Crop rotation. Economic impact. Herbicides. Soya beans. Long term.

DOI: 10.5935/1806-6690.20250072
Editor-in-Chief: Prof. Bruno França da Trindade Lessa - bruno.ftlessa@univasf.edu.br
*Author for correspondence
The research data are available from the corresponding author upon reasonable request
Received for publication 03/09/2024; approved on 14/04/2025
[1]This study was financed in part by the Itaipu Binacional, the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)
[2]Department of Agronomy, Universidade Estadual de Londrina (UEL), Londrina-PR, Brazil, m.beatrizfunari@uel.br (ORCID ID 0009-0007-6942-5196)
[3]Department of Crop Sciences, Instituto de Desenvolvimento Rural do Paraná/IAPAR-EMATER (IDR-Paraná), Londrina-PR, Brazil, ivanbordin@idr.pr.gov.br (ORCID ID 0000-0002-4904-6283)
[4]Department of Agricultural and Resource Economics, Instituto de Desenvolvimento Rural do Paraná/ IAPAR-EMATER (IDR-Paraná), Londrina-PR, Brazil, telles@idr.pr.gov.br (ORCID ID 0000-0001-5817-3420)

INTRODUCTION

The principal grain-production system in Brazil includes soya beans followed by maize as a secondary-crop. This type of double-crop system is more vulnerable to pests, diseases, nematodes and weeds than are more-diversified systems (Bordin *et al*., 2021; Hunt; Hill; Liebman, 2019). In addition, double-crop system has a lower economic yield (Volsi *et al*., 2021).

Crop diversification brings several benefits to the soil, such as good ground cover during the off-season, nutrient cycling and an increase in organic matter, in addition to improving the physical, chemical and biological conditions of the soil (Albrecht *et al*., 2021). Crop diversification can therefore be used as a strategy for the cultural control of weeds, including the use of ground cover plants, which help to reduce the weed seed bank due to their physical and allelopathic effects, or from the change in the sequence of commercial crops and the consequent use of different active ingredients (Araújo *et al*., 2021; Bordin *et al*., 2021; Marochi *et al*., 2018).

Weed phytosociology has been widely applied in research, associated with a specific region, cultivated species or production system. The regular use of phytosociological indices in any one area helps in understanding the weed community and population dynamics of weed species when adopting new control strategies, production systems and crop diversification schemes (Kuva; Salgado; Alves, 2021). According to Mas *et al*. (2010) and Andrade *et al*. (2017), it is extremely important to evaluate the population dynamics of weeds over long periods to gain greater knowledge of the interaction between the management system, the cultivated species and the invasive flora.

Weed control represents one of the main costs of agricultural production, especially in the soya bean, and can have a direct impact on profitability. Related costs, which involve the application of herbicides and other operations, vary according to the adopted management strategy and the invasive species found in the cultivated area. In this respect, choosing more efficient methods is essential to reduce costs, contributing to more sustainable and economically viable production. In addition, a careful analysis of these investments allows for more accurate decisions for balancing productivity and expenses, which is essential to minimise the financial and environmental impact (Canalli *et al*., 2020).

Weeds have a series of negative consequences for agricultural production, resulting in increased control costs and a possible loss of productivity. Weed control represents the search for a balance between investment (herbicides, agricultural operations and labour) and results (economic return) (Snyder *et al*., 2016). The aim of this study was to evaluate the phytosociology and costs of weed control in grain production systems that include crop diversification, between the 2014/2015 and 2022/2023 crop years.

MATERIALS AND METHODS

Study location and treatments

The experiment was conducted at the Instituto of Rural Development of Paraná-IAPAR-EMATER (IDR-Paraná), in Londrina, Paraná, located at 23º22'01" S and 51º10'07" W, at an altitude of 585 m. According to the Köppen classification, the climate of the region is humid subtropical (Cfa), with an average annual temperature of 21.1 ºC and an average annual rainfall of 1641 mm. The soil is classified as a typical Eutroferric Red Latosol, moderate type A, with a clayey texture (Santos *et al*., 2018). The history of the area before setting up the experiment included 11 years cultivation under a no-tillage (NT) system of black oats during the winter and rotated maize and soya beans during the summer.

The experimental design was of randomised blocks, with six treatments and four replications, where each plot was 300 m² (20 m x 15 m) in size. The six treatments (Table 1) were designed to compare the most-widely used production system in the north of Paraná, secondary crop soya/maize, with more-diverse systems that include ground cover plants under a NT system, divided into three three-year cycles. Treatment T1 involves double-crop systems, the standard, both in the region and throughout Brazil, with soya beans grown during the summer, followed by a secondary maize crop. Treatment T2 alternates summer crops of maize and soya beans, with white oats, rye and wheat grown during the autumn-winter seasons, with the focus on grain production. In Treatment T3, cover crops are grown during the autumn-winter to improve the quality of the soil and of the NT system, while soya beans and maize crops are alternated during the summer. T4 includes winter oilseeds that can be used for biodiesel production, while during the summer one crop of soya beans is sown for every two of maize. Treatment T5 has one maize crop for every two of soya beans, with buckwheat and beans grown during the winter for commercial purposes, while turnips and oats are used for producing straw at the end of the winter season. Treatment T6 includes the largest number of crops within the three-year cycle, all of which are intended for the market (Table 1). The herbicides used in weed management during the nine years of the experiment are shown in Table 2.

Phytosociological analysis

For the phytosociological analysis, the weed survey (area characterisation) was carried out before the start of the experiment in March 2014, and on one day after each soya bean harvest in 03/2017, 03/2020 and 03/2023. The square inventory method was used, where a 0.25 m² frame was thrown into each plot four times to identify and count each species. From these data, the following phytosociological variables were calculated: frequency, density, abundance, relative frequency, relative density, relative abundance, importance value index and relative importance value index, in addition to the similarity coefficient. The data were evaluated during the first (2014/2015 to 2016/2017), second (2017/2018 to 2019/2020) and third (2020/2021 to 2022/2023) cycles. The variables were determined as per the equations described in Table 3.

In evaluating the similarity coefficient, each of the three-year cycles were compared, the results ranging from 0 to 1, where 1 is the maximum similarity, i.e. when all the species are common in each cycle in relation to the area characterisation, and 0 when there are no species common to the treatments and the area characterisation.

Ground cover analysis

The ground cover was analysed using a digital camera to take four images of a 0.25 m² area one day after the soya bean harvest in 03/2023. The images were processed using the SisCob software (Jorge; Silva, 2009) to determine the percentage of each component (exposed soil, straw and weeds). The data were transformed into arcsin √(P%)/100. The variables relating to ground cover underwent analysis of variance and Tukey's test at 5% probability.

Table 1 - Production systems used during the 2014/2015 and 2022/2023 crop years

Treatment.	Autumn/Winter	Spring/Summer	Autumn/Winter	Spring/Summer	Autumn/Winter	Spring/Summer
First cycle						
	2014/2015		2015/2016		2016/2017	
T1	M	S	M	S	M	S
T2	WO	S	TC	M	W	S
T3	R + BO	S	WO + T	M	BR	S
T4	CA	M	CB	M	SA	S
T5	M + T	M	B	S	FE + WO	S
T6	W	M + B	CA	M	B	S
Second cycle						
	2017/2018		2018/2019		2019/2020	
T1	M	S	M	S	M	S
T2	WO	S	TC	M	W	S
T3	R + BO	S	WO + T	M	BR	S
T4	CA	M	CB	M	SA	S
T5	M + T	M	B	S	FE + WO	S
T6	W	M + B	CA	M	B	S
Third cycle						
	2020/2021		2021/2022		2022/2023	
T1	M	S	M	S	M	S
T2	WO	S	TC	M	W	S
T3	R + BO	S	WO + T	M	BR	S
T4	CA	M	CB	M	SA	S
T5	M + T	M	B	S	FE + WO	S
T6	W	M + B	CA	M	B	S

Note: M – Maize (*Zea mays*); S – Soya Beans (*Glycine max*); WO – White Oats (*Avena sativa*); TC – Triticale (X *triticosecale* Wittmack); W – Wheat (*Triticum* spp); R – Rye (*Secale cereale*); BO – Black Oats (*Avena strigosa* Schreb); T – Turnip (*Raphanus sativus*); BR – Brachiaria (*Brachiaria decumbens*); CA – Canola (*Brassica napus*); CB – Crambe (*Crambe abyssinica*); SA – Safflower (*Carthamus tinctorius*); MO – Common Buckwheat (*Fagopyrum esculentum* Moench); B – Common Beans (*Phaseolus vulgaris*)

Table 2 - Accumulated amount (L ha^{-1}) of active ingredient used to control weeds in the production systems during the 2014/2015 to 2022/2023 crop years

Treat	Gly	Atr	Car	Par	Cle	Tem	2,4 D	Diq	Bem	Met	Fom	Mes	Tri	Saf	Nic	Del	Tot.
T1	28.1	13.8	1.1	0.9	0.2	0.7	-	-	-	-	-	0.2	0.0	-	-	0.0	45.0
T2	24.5	7.5	0.7	0.9	0.3	0.3	0.7	-	-	0.3	-	-	0.0	0.0	-	0.0	35.2
T3	23.9	7.5	0.6	0.9	0.2	0.3	0.7	0.6	-	-	-	-	0.0	0.0	-	0.0	34.8
T4	21.1	13.5	1.0	0.4	0.2	0.7	-	-	-	-	-	-	0.0	0.0	-	0.0	36.8
T5	28.3	9.5	0.9	0.9	0.3	0.3	-	-	0.6	-	-	-	0.0	0.0	-	0.0	40.8
T6	20.5	13.5	0.7	0.9	0.4	0.3	0.7	-	-	-	0.3	0.1	0.0	0.0	0.0	0.0	37.4
Total	146.3	65.3	4.9	4.9	1.5	2.7	2.0	0.6	0.6	0.3	0.3	0.3	0.2	0.2	0.0	0.0	230
%	63.6	28.4	2.1	2.1	0.7	1.2	0.9	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.0	0.0	

Note: Treat. – Treatment; Gly – Glyphosate; Atr – atrazine; Car - Carfentrazone-ethyl; Par - Paraquat; Cle – Clethodim; Tem – Tembotrione; 2,4 D; Diq – Diquat; Bem – Bentazone; Met – Metsulfuron-methyl; Fom – Fomesafem; Mês – Mesotrione; Tri – Trifloxysulfuron; Saf – Saflufenacil; Nic - Nicossufuron; Del – Deltamethrin

Table 3 - Indicators, equations and descriptions of the phytosociological variables

Indicator	Equation	Description
Frequency (FRE)	FRE= NPCS/ NTPU	Number of plots containing the species (NPCS) / Total number of plots used (NTPU)
Density (DEN)	DEN= TNIPS / TAS	Total number of individuals per species (TNIPS) / Total area sampled (TAS)
Abundance (ABU)	ABU= TNIPS / TNPCS	Total number of individuals per species (TNIPS) / Total number of plots containing the species (TNPCS)
Relative Frequency (RFR)	RFR = SFR / TSFR	Species frequency (SFR) / Total species frequency (TSFR)
Relative Density (RDE)	RDE = DEN / TDEN	Species density (DEN) / Total species density (TDEN)
Relative Abundance (RAB)	RAB = RAB /TRAB	Species abundance (RAB) / Total species abundance (TRAB)
Importance Value Index (IVI)	IVI = RFR + RDE + RAB	Relative Frequency (RFR) + Relative Density (RDE) + Relative Abundance (RAB)
Relative Importance Value Index (RIVI)	RIVI = SIVI / TSIVI	Species importance value index (SIVI) / Total species importance value index (TSIVI)
Similarity coefficient (SCO)	SCO = 2 x NSCH / NSHA + NSHB	Number of species common to both habitats (NSCH) / number of species in habitat A (NSHA) + number of species in habitat B (NSHB)

Economic analysis

The costs of the chemical weed control included the herbicides and agricultural operations (spraying and desiccation) for each crop in each treatment. To obtain the values of the herbicides and agricultural operations, surveys were conducted each year of the average prices paid by producers, which were provided by cooperatives or companies in the region. The values of the agricultural operations were adjusted based on the applied herbicides, considering the mixtures of the active ingredients and the individual applications. In each case, the costs were calculated separately according to the specific value of each active ingredient. The monetary values were corrected for June 2023 based on the Extended National Consumer Price Index (IPCA), and converted to USD on 29 December 2023 (USD 1.00 = BRL 4.84).

RESULTS AND DISCUSSION

Phytosociological indices

The weed community in the experimental area before the start of the experiment and during the three three-year cycles comprised 10 families and 24 species, with the eudicotyledonous group accounting for 62.5% of the species, and the monocotyledonous group for 37.5%. The families Poaceae and Asteraceae were the most numerous, with seven species each (Table 4), and are considered the principal weed families in Brazil (Oliveira; Freitas, 2008). The predominance of these families was also noted by Ferreira *et al*. (2019) when evaluating maize crops, and by Caetano *et al*. (2018) in soya bean crops, illustrating a pattern for the predominance of weed families in phytosociological surveys carried out in systems of grain production. Only one species per family was identified for the Brassicaceae, Euphorbiaceae, Malvaceae, Phyllanthaceae and Commelinaceae.

In the area characterisation, *Euphorbia heterophylla* had the highest RIVI among the weed species, of 37.8% (Figure 1). The species was present throughout the three cycles under evaluation, but its occurrence varied: during the first cycle, it was found in all of the treatments; during the second cycle, it was found only in treatments T1, T3 and T4; and during the third cycle, it was found only in T1 and T3. *E. heterophylla* was present during all of the cycles in treatments T1 and T3. In the case of T1, this can be explained by the period between sowing the soya beans and harvesting the maize, which had no ground cover and may have created favourable conditions for the species to develop. The same result was found in T3 by Forte *et al*.

Table 4 - Families, species and local names of weeds found in the area characterisation for the 2014/2015 to 2022/2023 crop years

Family	Species	Local name
	Eudicotyledonous	
Amaranthaceae	*Alternanthera tenella* Colla	Apaga-fogo
	Amaranthus deflexus L.	Caruru
	Amaranthus hybridus L.	Caruru-roxo
Asteraceae	*Bidens Pilosa* L.	Picão-preto
	Conyza bonariensis (L.) Cronquist	Buva
	Gamochaeta coarctata (Willd.) Kerguélen	Macela
	Parthenium hysterophorus	Coentro-do-mato
	Sonchus oleraceus	Serralha
	Crambe abyssinica Hochst	Crambe
	Raphanus raphanistrum	Nabo
Euphorbiaceae	*Euphorbia heterophylla* L.	Leiteiro
Malvaceae	*Sida spinosa* L.	Guanxuma
Oxalidaceae	*Oxalis acetosella* L.	Trevo
Phyllanthaceae	*Phyllanthus niruri* L.	Quebra-pedra
Portulacaceae	*Portulaca oleracea* L.	Beldroega
	Monocotyledonous	
Commelinaceae	*Commelina benghalensis* L.	Trapoeraba
Poaceae	*Avena sativa* L.	Aveia
	Cynodon dactylon	Grama-ceda
	Digitaria horizontalis Willd.	Capim-colchão
	Digitaria insularis (L.) Fedde	Capim-amargoso
	Echinochloa spp.	Capim-arroz
	Rottboellia exaltata	Camalote
	Sorghum halepense	Sorgo alepense
	Urochloa plantaginea (Link) R. D. Webster	Capim-marmelada

(2018), who concluded that ground cover plants, in this case black oats and black oats + vetch, were unable to control the emergence of *E. heterophylla*.

Commelina benghalensis had an RIVI of 23.1%, and was the second most-abundant species in the area. During the first cycle, the species was not seen in treatments T2, T5 or T6; during the second cycle, it was absent in treatments T2 and T3; and during the third cycle, it was not seen in T2 (Figure 1). *C. benghalensis* was controlled only by T2 during each of the three cycles. This can be explained by the fact that cultivating winter cereals (white oats, triticale and wheat) maintains the ground cover of crop residue between harvesting the autumn/winter crop and sowing the soya beans during the spring/summer, which helps reduce weed emergence (Table 1). These results are in line with those of Andrade *et al*. (2017), who found that winter cereals are an excellent option for reducing weed populations when grown before the soya bean crop. On the other hand, in the remaining treatments, where *C. benghalensis* remained uncontrolled, the main source of infestation can be attributed to the seed bank, whose dynamics are influenced by the low ground cover of straw between sowing the soya beans in the summer and the secondary maize harvest in the winter. This creates a favourable environment for the germination, development, flowering and dispersal of weed seeds (Giraldeli *et al*., 2018). *C. benghalensis* is one of the most problematic weeds in Brazil, and causes great losses to agricultural production. This species stands out for its allelopathic effect on soya beans (Ahamed, 2015), competing for space, nutrients and light, in addition to producing different types of seeds – subterranean, aerial and propagative (Martins; Gonçalves; Silva Junior, 2016; Raimondi *et al*., 2014).

Raphanus raphanistrum was not found during the area characterisation. However, during the first cycle, it was identified in each of the treatments except T1; during the second cycle, it was not found in T2; while during the third cycle, it was found in all of the treatments (Figure 1a, b and c). The forage radish is widely used as a ground cover plant in crop rotation systems, and has allelopathic characteristics which inhibit the emergence and development of undesirable weeds, such as the wild peanut (*Euphorbia heterophylla*), marmalade grass (*Urochloa plantaginea*) and crabgrass (*Digitaria horizontalis*) (Cherubin, 2022). However, as seen in the experiment, this species showed a high potential for infestation due to its significant production of viable seeds (Souza *et al*., 2019).

Urochloa plantaginea was not seen in the area characterisation during the first or second cycles, but was identified during the third cycle in treatments T2, T4, T5 and T6 (Figure 1a, b and c). This species stands out as one of the most damaging to crops due to its competitive ability for rapid shading, high phenological plasticity, ability to produce a high number of seeds and C4 metabolism (Khatounian *et al*., 2016). C4 plants demonstrate greater ability to take advantage of the resources available in the environment thereby becoming generally more competitive than C3 plants (Wang *et al*., 2018).

For the similarity coefficient, it was found that during the first three-year cycle each of the treatments showed some level of similarity, ranging from 0.29 to 0.5 (Table 5). During the second cycle, after six years of management, treatments T2 and T3 showed no similarity, differing from the other treatments, which varied from 0.2 to 0.48. During the third cycle, after nine years of management, only T2 had a similarity coefficient of 0, while the remaining treatments varied between 0.13 and 0.42. These results show that T2 had a greater impact on the weed flora in terms of the area characterisation. Furthermore, in T1, which characterises a double-crop system, the similarity coefficients were more stable between each crop cycle, with a variation of 0.43 to 0.48.

Ground cover

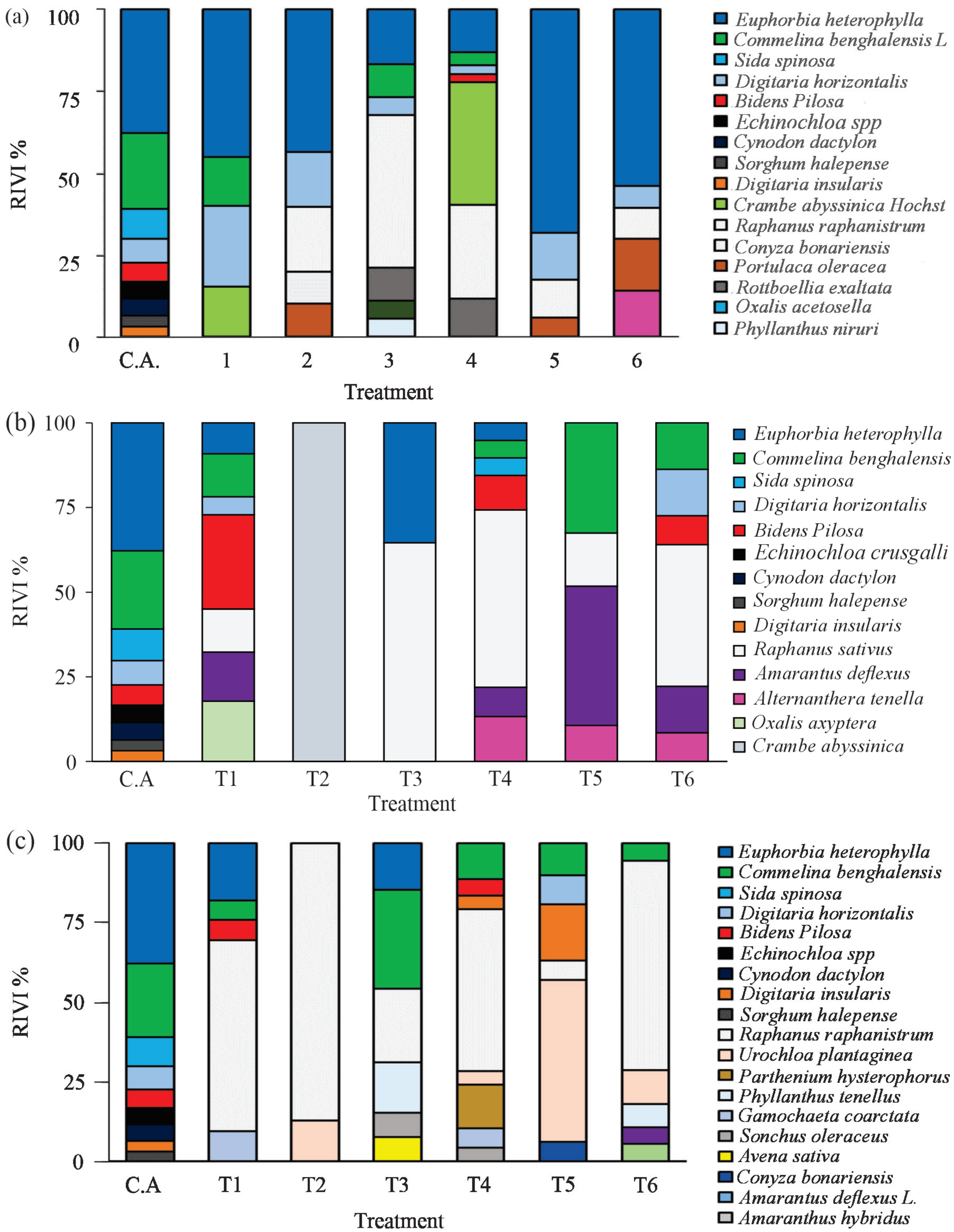
In terms of ground cover, there were no statistical differences between the production systems for the straw, exposed soil or weed components (Table 6). Straw covered 87% to 96% of the soil, exposed soil varied from 3.5% to 10.5%, while weeds represented only 0.6% to 1.4%. According to Alvarenga *et al*. (2001), good ground cover should include at least 50% of the soil; as such, all the treatments had good ground cover, with little exposed soil and only a small proportion of the area occupied by weeds.

The fact that, for each treatment, there was good ground cover following the soya bean harvest at the time of the weed assessment (Table 6), with little variation in the total amount of herbicides used over the nine years, and 91.37% of the active ingredients concentrated in two molecules (63.61% glyphosate and 28.36% atrazine) (Table 3) without rotating the active ingredients, suggests that the better phytosociological indices seen in T2 are correlated with the cultural weed management, especially the cultivation of winter cereals. These results corroborate the work of Mas *et al*. (2010) and Andrade *et al*. (2017), who showed a lower incidence of weeds when using cultural management, influenced by the competition for resources (particularly solar radiation) between the commercial crops and the weeds over the two- to five-year period under evaluation.

Cost of weed control

The cost of weed control was higher in T1 (USD 199.24 ha^{-1} yr^{-1}), with similar values for T4 (USD

Figure 1 - Relative Importance Value Index (RIVI%) of the weeds in the area characterisation (AC) and in the treatments, during (a) the first cycle (2014/2015 to 2016/2017), (b) second cycle (2017/2018 to 2019/2020) and (c) third cycle (2020/2021 to 2022/2023)



180.12 ha^{-1} yr^{-1}) and T5 (USD 185.31 ha^{-1} yr^{-1}), while for T2, T3 and T6 the costs were lower: USD 162.32 ha^{-1} yr^{-1}, USD 151.29 ha^{-1} yr^{-1} and USD 164.53 ha^{-1} yr^{-1}, respectively (Table 7). These results are in line with a study by Volsi *et al*. (2020), who found that the average cost of weed control was USD 158.46 ha^{-1} yr^{-1}.

Treatment T1 showed the highest accumulated costs over nine years. This can be explained by T1 using the largest amount of active ingredients for weed control (approximately 45.0 L ha^{-1}) and including the second-highest number of agricultural operations (40), as shown in Table 7. Volsi *et al*. (2021) and Garbelini *et al*. (2020) also found that the cost of herbicides, fungicides, and insecticides in systems that include double-cropping (soya bean/maize) are highest for weed control, which is in line with the present results.

Table 5 - Accumulated similarity coefficients for the area characterisation (AC) and production systems over the nine crop years

Treatment	First Cycle	Second Cycle	Third Cycle
AC	1	-	-
T1	0.46	0.48	0.43
T2	0.29	0.00	0.00
T3	0.38	0.00	0.27
T4	0.50	0.20	0.35
T5	0.31	0.27	0.40
T6	0.29	0.36	0.13

Note: First cycle – 2014/2015 to 2016/1017; Second Cycle – 2017/2018 to 2019/2020; Third cycle – 2020/2021 to 2022/2023

Table 6 - Percentage ground cover and the soil, straw and weed ratioin each production system after nine crop years

Treatment	Soil	Straw	Weeds
T1	95.8 a*	3.6 a	0.6 a
T2	95.5 a	3.9 a	0.7 a
T3	93.1 a	6.0 a	1.4 a
T4	93.6 a	5.5 a	0.8 a
T5	93.9 a	4.6 a	1.0 a
T6	87.8 a	10.4 a	0.5 a

Note: *Not significant at 0.05% probability by Tukey's test. Mean values followed by the same lowercase letter in a column do not differ by Tukey's test at 5% probability

Table 7 - Average costs of weed control in production systems, per hectare and year, between the 2014/2015 and 2022/2023 crop years

Treatment	Number ofAO	Costs for AO	Costs for AI	Total Costs
	ha^{-1} yr^{-1}	US$. ha^{-1} yr^{-1}	US$ ha^{-1} yr^{-1}	US$ ha^{-1} yr^{-1}
T1	4.44	37.74	161.50	199.24
T2	4.33	36.76	125.56	162.32
T3	3.67	32.25	119.04	151.29
T4	3.89	33.02	147.10	180.12
T5	4.56	42.25	143.06	185.31
T6	4.00	33.87	130.66	164.53

Note: AO – agricultural operations; AI – active ingredients; Total - sum of the costs for agricultural operations and active ingredients

Treatment T4 used a total of 36.9 L ha^{-1} active ingredients, carrying out 35 agricultural operations during the experimental period. Treatment T5 used a larger amount, with a total of 40.8 L ha^{-1} active ingredients in 41 agricultural operations, resulting in similar costs.

Treatment T2 used a total of 35.2 L ha^{-1} active ingredients in 39 agricultural operations over the nine years. Treatment T3, which used the lowest amount of active ingredients, applied a total of 34.8 L ha^{-1} over 33 agricultural operations. In Treatment T6, a total of 37.4 L ha^{-1} active ingredients were applied in 36 agricultural operations, the lowest costs for weed control during the nine crop years.

Crop rotation systems that are more diversified tend to reduce their production costs over time due to the improved physical, chemical and biological conditions of the soil (Canalli*et al*., 2020) and a reduction in the incidence of weeds. In this respect, agricultural systems that have lower costs for chemical control can benefit from crop rotation, which helps to suppress weeds naturally and reduces the need for herbicides.

CONCLUSIONS

1. The treatment that included winter cereals for grain harvesting (white oats/soya beans, triticale/maize, wheat/soya beans) controlled all of the species identified in the area characterisation, and presented the lowest similarity coefficient for the soya bean crop after nine years;
2. *Raphanus raphanistrum* was not controlled by any of the treatments evaluated in the soya bean crop after nine years;
3. The treatment that included the soya bean/secondary maize double-cropping had the highest costs for weed control.

ACKNOWLEDGMENTS

The authors wish to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and Itaipu Binacional. The authors would also like to express their gratitude to Nelcir Aparecido Rodrigues, agricultural technician, for his dedication and commitment.

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