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The Emerging Flora Does Not Reflect the Soil Reinfestation Potential: Integrating Phytosociology and the Seed Bank in Cropping Systems

Antonio Marcos Loureiro da Silva [1], Gabriela Madureira Barroso [2], Grazielly Gomes de Oliveira [2,*], Caique Menezes de Abreu [2], Otávio Augusto Dassoler [1], Sayane Zanchet [1], José Barbosa dos Santos [2] and Leandro Galon [3]

[1] Graduate Programme in Environmental Science and Technology, Universidade Federal da Fronteira Sul, Erechim 99700-000, RS, Brazil; antoniomarcoslsr@gmail.com (A.M.L.d.S.); odassoler@yahoo.com (O.A.D.); sayanezanchet123@gmail.com (S.Z.)
[2] Department of Agronomy, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina 39100-000, MG, Brazil; gabriela.madureira@ufvjm.edu.br (G.M.B.); menezes.abreu@ufvjm.edu.br (C.M.d.A.); jbarbosa@ufvjm.edu.br (J.B.d.S.)
[3] Department of Agronomy, Universidade Federal da Fronteira Sul, Erechim 99700-000, RS, Brazil; leandro.galon@uffs.edu.br
* Correspondence: grazielly.oliveira@ufvjm.edu.br

Abstract

The integrated assessment of the emerging weed community and the soil seed bank is essential for understanding the persistence and reinfestation potential of weeds in agricultural systems. This study aimed to evaluate the phytosociological structure and the germinable seed bank under no-tillage, conventional tillage and fallow systems, associated with chemical desiccation with glyphosate and mechanical mowing at pre-sowing, over four agricultural seasons (2017/2018 to 2020/2021) in Erechim, RS, Brazil. Phytosociology was assessed using the random quadrat method, and the seed bank was evaluated through seedling emergence from soil samples collected from the 0–10 and 10–20 cm layers. A total of 23,913 individuals were recorded in the phytosociological survey, with predominance of *Lolium multiflorum* (61.9%) and *Sida rhombifolia* (21.5%). In the seed bank, 5812 seedlings emerged, of which 56.7% occurred in the 0–10 cm layer. Desiccation reduced the emergence of *L. multiflorum* by 34.7% in the surface layer compared with mowing. The similarity index between phytosociology and the seed bank was 0.35, showing that the community observed in the field does not fully represent the reinfestation potential stored in the soil.

Keywords: seed bank; phytosociology; no-tillage; cover crops; integrated weed management; *Lolium multiflorum*

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1. Introduction

Weeds are among the main biotic components limiting agricultural productivity. The increasing occurrence of herbicide-resistant populations has increased the complexity of weed management, reinforcing the need for integrated strategies that not only reduce the infestation observed during the crop cycle, but also limit seed production and seed input into the soil [1–4]. In this context, understanding the mechanisms that determine the persistence of weed communities is essential for developing more durable management systems and reducing dependence on corrective interventions.

The soil management system is one of the main factors determining the dynamics of weed communities. No-tillage (NT), compared with conventional tillage (CT), alters the physical, chemical and biological conditions of the soil surface layer and modifies the amount and distribution of straw, factors that may affect the germination, emergence and establishment of weed species [5–7]. The adoption of crop rotation may enhance these effects by modifying patterns of competition, soil cover, residue deposition and resource availability over time [8]. However, changes in the emerging flora do not necessarily represent equivalent changes in the seed reservoir present in the soil.

Changes in tillage intensity can alter weed community composition rather than simply reducing overall weed abundance. Long-term studies have shown that conventional tillage may favour annual broadleaved species, whereas reduced or no-tillage systems may increase the relative importance of annual grasses and, in some environments, perennial weeds. For example, it has been reported that annual grasses, such as *Digitaria sanguinalis* and *Panicum dichotomiflorum*, dominated the weed community in the no-till system, whereas monocotyledonous and dicotyledonous species occurred in more similar proportions in the conventional tillage system [9]. Similarly, Tuesca et al. [10] observed higher populations of annual broadleaved weeds under conventional tillage, while grassy annuals increased under no-tillage over time in a maize–soybean rotation. In a long-term study in Spain, *Anthemis arvensis*, *Hirschfeldia incana* and *Lolium rigidum* were associated with no-tillage, whereas species such as *Polygonum aviculare* and *Phalaris paradoxa* were favoured by conventional soil disturbance [11]. More recently, a 36-year experiment in the United States showed greater densities of the perennial *Sorghum halepense* and other weed species under no-tillage than under conventional tillage [12]. These findings indicate that the direction and magnitude of weed community shifts depend on species traits, crop rotation, environmental conditions and the intensity of soil disturbance, rather than following a universal pattern.

The soil seed bank constitutes an important reservoir of propagules responsible for the persistence and recruitment of weeds in agroecosystems [13]. Previous studies have shown that tillage and cropping practices can modify both the density and vertical distribution of viable weed seeds in the soil. Chauhan et al. [14] demonstrated that tillage influenced the vertical distribution and recruitment of *Lolium rigidum* seeds, whereas Hosseini et al. [15] showed that crop rotation and soil disturbance affected weed seed-bank composition. Other studies conducted under different agricultural systems have also documented changes in seed-bank density and species composition in response to management practices [16–18].

Despite the close relationship between the seed bank and the weed community, these components are frequently evaluated independently. Phytosociological surveys characterise the community that emerges and establishes at a given time, whereas seed bank emergence assays allow the potential composition of the soil propagule reservoir to be estimated [19,20]. The isolated assessment of these compartments may therefore provide distinct perspectives on infestation dynamics, especially when species present in the seed bank are not proportionally represented in the emerging flora. Quantifying the overlap between these compartments may help determine the extent to which the community observed in the field represents the recruitment potential present in the soil.

The integration of phytosociological surveys and seed bank assessments allows the composition, abundance and relative importance of the species present in both compartments to be compared, identifying shared and exclusive species and quantifying the degree of floristic overlap. Similarity indices, such as the Sørensen index, can be used to assess this correspondence and complement the phytosociological metrics traditionally applied [21]. This integrated approach is particularly relevant in systems subjected to different management practices, in which changes in emergence may not occur with the same magnitude or direction as changes in the seed reservoir.

In addition to the soil management system, the strategy used for pre-sowing vegetation termination may modify weed dynamics. Chemical desiccation and mechanical mowing or shredding differ in timing, intensity and form of vegetation suppression, and may affect survival, seed production and seed deposition and, consequently, the composition of the emerging community and the seed bank [22,23]. However, the magnitude of these effects may depend on species identity, regrowth capacity, phenology and seed distribution in the soil profile.

The hypothesis of this study is that soil management systems, namely no-tillage, conventional tillage and fallow, and pre-sowing vegetation management practices, namely chemical desiccation and mechanical mowing, modify the phytosociological structure of the weed community and the composition of the soil seed bank, and that the joint assessment of these two components reveals differences not detected by isolated methods. The objective was to evaluate the phytosociological structure and the germinable seed bank in no-tillage, conventional tillage and fallow systems, associated with chemical desiccation with glyphosate and mechanical mowing at pre-sowing, over four agricultural seasons (2017/18 to 2020/21).

2. Materials and Methods

2.1. Characterisation of the Experimental Area

The experiments were conducted in the experimental area of the Universidade Federal da Fronteira Sul (UFFS), Erechim Campus, RS, Brazil, during the 2017/18, 2018/19, 2019/20 and 2020/21 growing seasons, at the geographical coordinates 27°43′43.16″ S, 52°17′02.60″ W, at an altitude of 783 m. The regional climate is classified as Cfa (humid temperate climate with hot summers), according to the Köppen classification. The soil is classified as a humic aluminoferric Rhodic Ferralsol [24]. The weather conditions during the experiment period are shown in Figure 1.

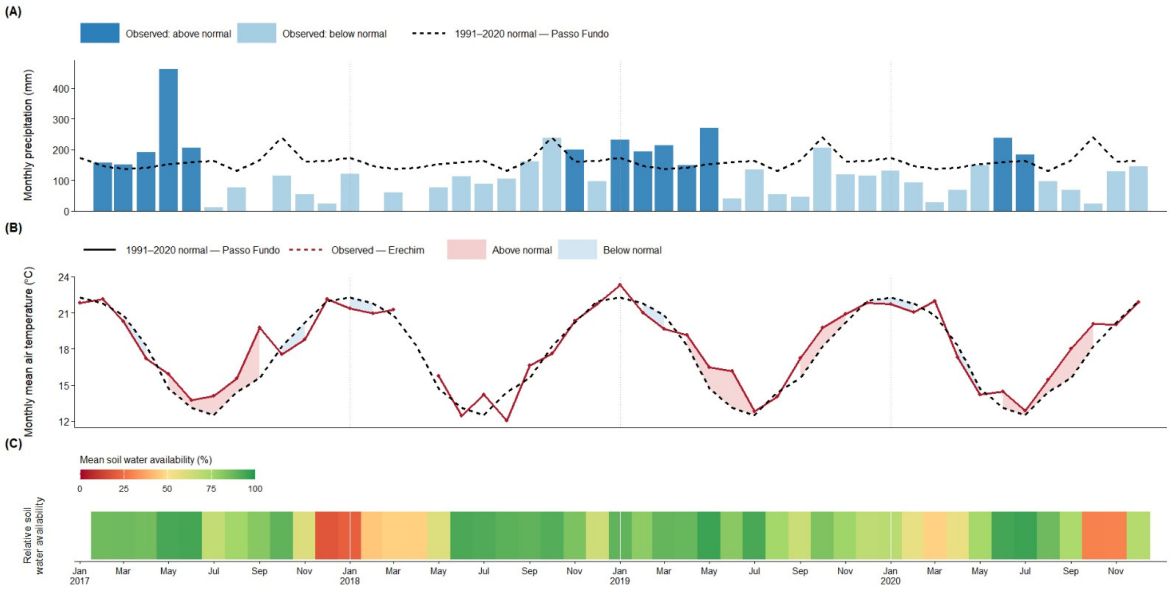


Figure 1. Climatic conditions during the experimental period (2017–2020): (**A**) monthly precipitation, (**B**) monthly mean air temperature, and (**C**) mean relative soil water availability. Observed precipitation and air temperature values are presented in relation to the 1991–2020 climatological normal for Passo Fundo, Rio Grande do Sul, Brazil. Because meteorological observations were not available from a station in Erechim during the experimental period, data from Passo Fundo, the closest location with available meteorological records, were used to characterize the climatic conditions during the study period. Panel (**C**) presents the mean relative soil water availability during the same period.

2.2. Experimental Design

The experiment was conducted in a randomised complete block design, with four replications, over four consecutive growing seasons (2017/18, 2018/19, 2019/20 and 2020/21). The evaluated factors were: (i) soil management system, consisting of three levels—no-tillage system (NT), in which the crops were grown on straw, without soil disturbance; conventional tillage system (CT), with ploughing using a disc plough and levelling harrowing before sowing; and fallow, in which no winter crop was grown, and the summer crops were established directly on the spontaneous vegetation; (ii) pre-sowing vegetation management, consisting of two levels—chemical desiccation, with glyphosate application at 1335 g a.i. ha^{-1}, and mechanical mowing/shredding, using a crop shredder attached to a tractor, performed 15 days before sowing the summer crops; (iii) soil sampling depth, with two levels, 0–10 and 10–20 cm, applied exclusively to the seed bank assessment; (iv) winter cover crop; and (v) summer crop.

Each experimental unit consisted of a plot measuring 10 m in length × 3 min width (30 m^2), previously corrected and fertilised according to the technical recommendations for each crop [25]. For each response variable, a specific factorial arrangement was adopted, defined by the combination of the factors relevant to that analysis, as described in Table 1.

Table 1. Treatment combinations resulting from the factorial arrangement, number of experimental units per growing season and total number of observations over four growing seasons (2017/18 to 2020/21).

Response Variable	Factors	Factorial Arrangement	Nº of Treatments	EU
Emerged seedling species kg^{-1} of soil	Emerged seedlings × soil depth	6 × 2	12	48
Seedlings kg^{-1} of soil	Vegetation management × soil depth	2 × 3	6	24
Cover crop dry matter (kg ha^{-1})	Winter cover crop × vegetation management	7 × 2	14	56
Yield of *Phaseolus vulgaris* (kg ha^{-1})	Summer crop × vegetation management	3 × 2	6	24
Yield of *Glycine max* (kg ha^{-1})	Summer crop × vegetation management	4 × 2	8	32
Yield of *Zea mays* (kg ha^{-1})	Summer crop × vegetation management	4 × 2	8	32

EU = experimental unit. Blocks (four replications) were considered as a random effect in the statistical model.

2.3. Cropping Sequences and Vegetation Management

Over the four agricultural seasons evaluated, the experimental plots were subjected to different sequences of winter and summer crops. During the winter period, the following species were used: *Triticum aestivum* L. (cv. TBIO Toruk; 280 plants m^{-2}), *Hordeum vulgare* L. (cv. BRS Cauê; 280 plants m^{-2}), *Secale cereale* L. (cv. BRS; 250 plants m^{-2}), *Avena strigosa* Schreb. (cv. Embrapa 139; 130 plants m^{-2}), *Vicia sativa* L. (cv. Common; 150 plants m^{-2}), the intercropping of *Avena strigosa* + *Vicia sativa* (80 + 40 plants m^{-2}), *Brassica napus* L. (Hyola 401 hybrid; 15 plants m^{-2}) and *Lupinus albus* L. (cv. Common; 20 plants m^{-2}). The fallow treatment remained uncultivated during the winter period.

During the summer period, *Glycine max* (L.) Merr. (DM 59i58; 12 plants m^{-2}), *Zea mays* L. (FS670 PW hybrid; 7.5 plants m^{-2}), *Phaseolus vulgaris* L. (cv. IPR Tuiuiú; 24 plants m^{-2}), *Crotalaria juncea* L. (cv. Common; 70 plants m^{-2}), *Mucuna pruriens* (L.) DC. (cv. Common; 25 plants m^{-2}) and *Canavalia ensiformis* (L.) DC. (cv. Common; 12 plants m^{-2}) were cultivated. The crops were established according to the experimental design and the crop sequences described in Table S1.

Under no-tillage, crop establishment was performed on the straw of the preceding crop, with plant residues maintained on the soil surface. Under conventional tillage, soil

preparation was carried out by ploughing and harrowing before sowing. In the plots maintained under fallow during the winter, no crop was established during this period, and the summer crop was implemented according to the defined experimental sequence.

All crops in the no-till system were sown without prior soil preparation. Sowing was performed using a no-till seed drill equipped with a residue-cutting disc and a furrow opener, allowing seed placement directly into the soil in the presence of crop residues on the soil surface. The cutting disc sectioned the residue along the sowing row, while the furrow opener created a narrow furrow for seed placement at approximately 5 cm depth, followed by furrow closure. Thus, soil disturbance was restricted to the sowing rows, while the vegetation cover between rows was maintained.

In the plots under winter fallow, no cover crops were established during the winter period. However, the subsequent summer crop was established using the same no-tillage system adopted in the other treatments, without prior soil disturbance. Therefore, the winter fallow treatment differed from the other treatments by the absence of a cover crop during the winter period, rather than by the soil preparation system or sowing method used to establish the subsequent summer crop.

Fertilisation was performed according to the management defined for each species. For the winter crops *T. aestivum*, *H. vulgare*, *S. cereale*, *A. strigosa*, *V. sativa* and the intercropping of *A. strigosa* + *V. sativa*, 350 kg ha^{-1} of NPK and 120 kg ha^{-1} of N were applied. For *B. napus*, 350 kg ha^{-1} of NPK and 60 kg ha^{-1} of N were applied, whereas for *L. albus*, 350 kg ha^{-1} of NPK was applied, with no additional nitrogen fertilisation. Among the summer crops, *G. max*, *P. vulgaris*, *C. juncea*, *M. pruriens* and *C. ensiformis* received 350 kg ha^{-1} of NPK; additionally, 120 kg ha^{-1} of N was applied to *P. vulgaris*, *C. juncea*, *M. pruriens* and *C. ensiformis*. For *Z. mays*, 433 kg ha^{-1} of NPK and 120 kg ha^{-1} of N were applied (Tables S2 and S3).

2.4. Phytosociological Assessment

To characterise the weed community, a phytosociological survey was carried out at the end of each agricultural year using the random quadrat method [26]. In each cropping area, eight points were sampled using a 0.5 × 0.5 m quadrat (0.25 m^2). All weeds present within the quadrat were identified and counted.

Based on the data obtained, the phytosociological indices of frequency, density, abundance, relative frequency, relative density, relative abundance, relative dry matter, Importance Value Index (IVI) and Relative Importance Value Index (RIVI) were calculated according to Mueller-Dombois and Ellenberg [27]. After identification and counting, the weeds were uprooted, and the roots were removed before drying. The aboveground plant material was then dried in a forced-air circulation oven at 65 °C until constant weight.

2.5. Seed Bank Assessment

The seed bank was assessed after the harvest of the summer crops by collecting soil samples with a cutting spade at depths of 0–10 and 10–20 cm. In each sampling unit, four subsamples were collected to form one composite sample per experimental unit. For each depth, 1 kg of soil was used separately, placed in plastic trays (15 × 15 cm) and maintained in a greenhouse at UFFS under automatic sprinkler irrigation. The number of emerged seedlings was assessed and the species were identified at 15, 30, 45 and 60 days after installation, following the seedling emergence method [28]. After each count, the seedlings were removed and the soil was stirred to favour new emergence flushes. For each species, the density of emerged seedlings per kilogram of soil was calculated (seedlings kg^{-1}).

2.6. Phytosociology and Seed Bank

The similarity between the species recorded in the phytosociological survey and in the seed bank was assessed using the Sørensen Similarity Index [21], calculated using the following formula:

$$SI = 2c/(a + b),$$

where c = the number of species common to both methods, a = the number of species recorded in the phytosociological survey, and b = the number of species recorded in the seed bank.

2.7. Cover Crop Dry Matter and Yield

The shoot dry matter of winter cover crops was determined at the end of the cycle of each species, before sowing the summer crops. The samples were placed in paper bags and dried in a forced-air circulation oven at 65 °C until constant weight. The yield of the summer crops, *G. max*, *P. vulgaris* and *Z. mays*, was determined by harvesting the useful area of each plot, with grain moisture content adjusted to 13%, and the results were expressed in kg ha^{-1}.

2.8. Statistical Analysis

The data were checked for the assumptions of residual normality using the Shapiro–Wilk test and homogeneity of variances using Levene's test. When the assumptions were met, analysis of variance was performed using the F-test. For phytosociology, cover crop dry matter and crop yield, the statistical model included the fixed effects of soil management system (main plot), pre-sowing vegetation management (subplot) and the interaction between these factors, with blocks considered as a random effect. When the interaction between factors was significant ($\alpha \leq 0.05$), the simple effects were analysed within each level of the other factor. Means were compared using Tukey's test at a 5% significance level. For species with low occurrence or irregular distribution among the sampling units, the results were interpreted descriptively, without the application of inferential tests. All analyses were performed in the R statistical environment, version 4.4.1 [29], using the agricolae package for mean comparison and the ExpDes.pt package for the analysis of split-plot experiments.

3. Results

3.1. Floristic Composition of the Weed Community

In the phytosociological survey, over the four growing seasons evaluated (2017/18 to 2020/21), 23,913 weed individuals were recorded, distributed among 18 species and 11 botanical families, with predominance of the families Asteraceae (five species) and Poaceae (four species) (Figure 2). The most frequent species were *Lolium multiflorum* (14,803 individuals; 61.9%) and *Sida rhombifolia* (5141 individuals; 21.5%), which together represented 83.4% of all individuals recorded (Figure 2a).

The total number of weed individuals varied significantly among growing seasons (Figure 2c). The highest mean number was recorded in 2019/20 (7460 individuals), whereas the lowest was observed in 2020/21 (3925 individuals). The 2017/18 and 2019/20 growing seasons did not differ significantly from each other, but both had higher weed abundance than 2018/19 and 2020/21, which also differed significantly from each other (Figure 2c). This interannual variation occurred under different precipitation, air temperature, and soil water availability conditions (Figure 1). Species richness remained stable, ranging from 13 to 15 species, indicating that the system maintained a diversified floristic composition over time, with no trend towards progressive simplification (Figure 2d).

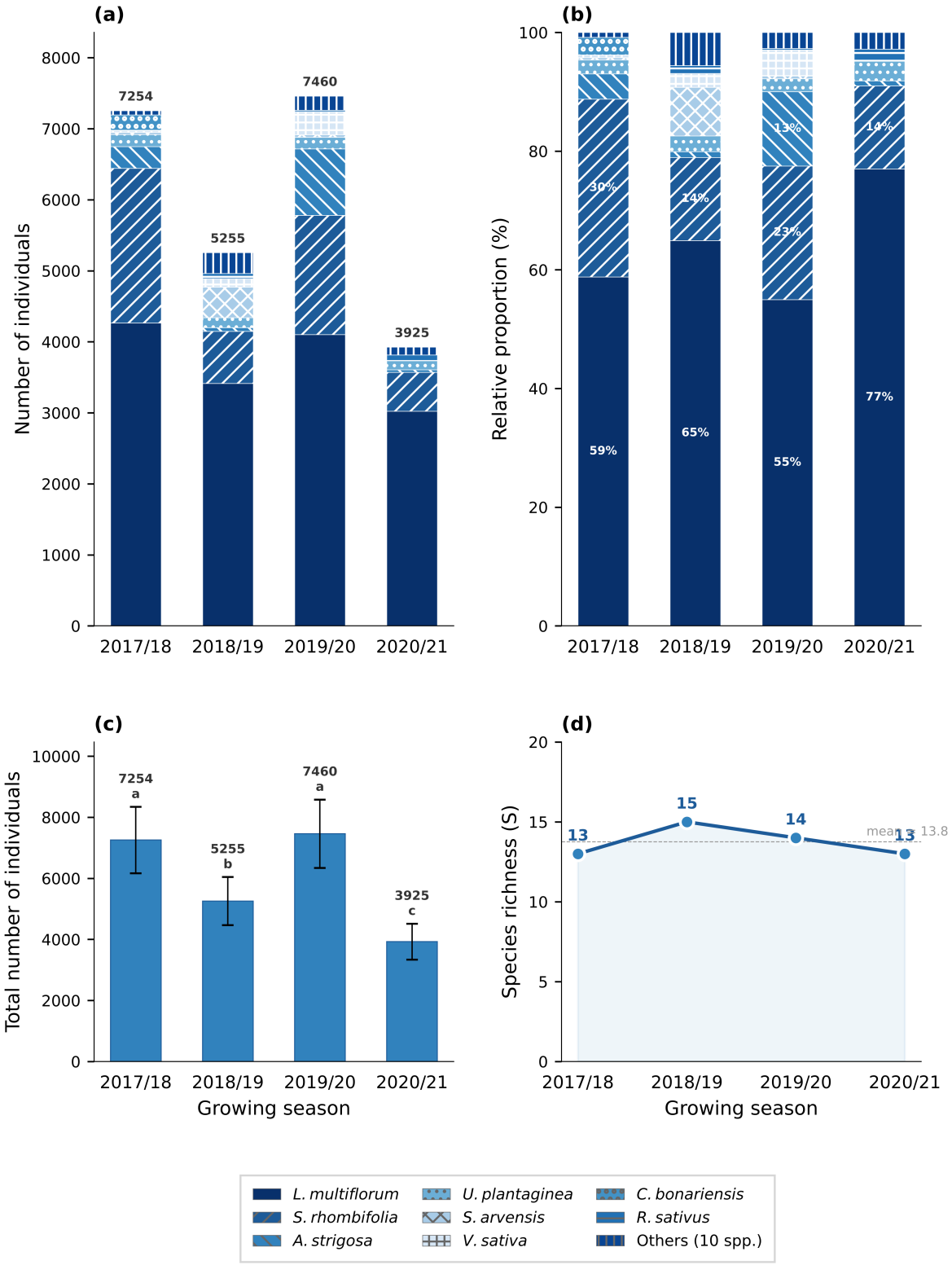


Figure 2. Weed community composition and variation across growing seasons (2017/18–2020/21): (**a**) mean number of individuals per growing season, showing the contribution of the main weed species and other species; (**b**) relative proportion of each species; (**c**) mean total number of weed individuals per growing season ± standard error (SE); and (**d**) species richness (number of species). Different lowercase letters in panel (**c**) indicate significant differences among growing seasons according to Tukey's test ($p < 0.05$). The dashed line in panel (**d**) represents the overall mean species richness across growing seasons. "Other species" represents the eight less abundant species included in the floristic assessment.

The dominance of *L. multiflorum* was observed in all growing seasons; however, its relative contribution ranged from 55% in 2019/20 to 77% in 2020/21 (Figure 2b). In the 2019/20 growing season, the lower contribution of this species was offset by an increase in *A. strigosa* (933 individuals; 13% of the total for that season), representing an 18-fold increase compared with the previous season. The contribution of *S. rhombifolia* ranged from 14% in 2018/19 and 2020/21 to 30% in 2017/18, and the dominance ratio of *L. multiflorum* to *S. rhombifolia* ranged from 1.96:1 in 2017/18 to 5.37:1 in 2020/21, showing that the selective pressure exerted by management over the years favoured *L. multiflorum*. Among the less frequent species, *S. arvensis* (492 individuals) concentrated 87.2% of its occurrence in the 2018/19 growing season, whereas *C. bonariensis* (217 individuals) was restricted to the 2017/18 growing season.

L. multiflorum was the species with the highest RIVI in most combinations of growing season, soil management system and cover crop, followed by *S. rhombifolia*. The relative importance of these two species varied according to vegetation management: under desiccation, *the L. multiflorum: S. rhombifolia* ratio ranged from 3:1 to 2.84:1, whereas under mowing this ratio decreased to between 1.57:1 and 2.78:1, reflecting the greater regrowth capacity of *S. rhombifolia* under mechanical control.

Under specific conditions, *S. rhombifolia* surpassed *L. multiflorum* in relative importance, such as after *H. vulgare* under mowed NT in the 2017/18 growing season, when it reached 100% RIVI, and after *Triticum* sp. under mowed NT in the same season, when it presented an RIVI of 64.41%. These results indicate that the preceding cover crop and the vegetation termination method interact to determine the dominant species.

In fallow areas, the weed community showed greater density under mowing. In the 2017/18 growing season, total density in mowed fallow was 2.1 times higher and abundance was 1.58 times greater than under desiccation, indicating that fallow associated with mechanical management favoured weed occurrence.

Four species reached 100% RIVI under specific conditions: *L. multiflorum* (desiccated fallow, *Z. mays*, 2019/20), *S. rhombifolia* (*H. vulgare*, mowed NT, 2017/18), *U. plantaginea* (*A. strigosa* + *V. sativa*, mowed NT, *Z. mays*, 2020/21) and *D. horizontalis* (*A. strigosa* + *V. sativa*, desiccated NT, *Z. mays*, 2019/20) (Table 2).

Table 2. Highest point values of RIVI observed for weed species under specific combinations of growing season, management practice and system/cover crop.

Species	Growing Season	Management	Condition Under Which the Highest RIVI Was Observed	RIVI (%)
Lolium multiflorum	2019/2020	Desiccation	Fallow, under *Z. mays* cultivation	100
Sida rhombifolia	2017/2018	Mowing	*H. vulgare*, under no-tillage system	100
Urochloa plantaginea	2020/2021	Mowing	*A. strigosa* + *V. sativa*, under no-tillage system, before *Z. mays*	100
Digitaria horizontalis	2019/2020	Desiccation	*A. strigosa* + *V. sativa*, under no-tillage system, before *Z. mays*	100
Vicia sativa	2019/2020	Mowing	*V. sativa*, under conventional tillage, before *Z. mays*	79.51
Avena strigosa	2019/2020	Desiccation	*A. strigosa*, under no-tillage system, before *G. max*	75.78
Richardia brasiliensis	2020/2021	Desiccation	*A. strigosa*, under conventional tillage, before *G. max*	75.18

Table 2. *Cont.*

Species	Growing Season	Management	Condition Under Which the Highest RIVI Was Observed	RIVI (%)
Raphanus sativus	2020/2021	Desiccation	Fallow, before *G. max*	67.7
Conyza bonariensis	2018/2019	Desiccation	*Triticum* sp., under no-tillage system, before *G. max*	67.68
Bidens pilosa	2020/2021	Desiccation	Fallow, before *Phaseolus vulgaris*	62.88

RIVI = Relative Importance Value Index. The values represent the highest RIVI observed for each species in the evaluated combinations of growing season, system/cover crop and management. RIVI values equal to 100% indicate that the species was dominant under the respective experimental condition.

Less frequent species also reached high importance values in specific combinations: *V. sativa* (RIVI = 79.51% in mowed *V. sativa* under CT, before *Z. mays*, 2019/20), *A. strigosa* (75.78% in desiccated *A. strigosa* under NT, before *G. max*, 2019/20), *R. brasiliensis* (75.18% in desiccated *A. strigosa* under CT, before *G. max*, 2020/21), *R. sativus* (67.70% in desiccated fallow, before *G. max*, 2020/21), *C. bonariensis* (67.68% in desiccated *Triticum* sp. under NT, before *G. max*, 2018/19) and *B. pilosa* (62.88% in desiccated fallow, before *P. vulgaris*, 2020/21) (Table 2).

3.2. Seed Bank

The interaction between management and depth was significant for only three species ($p < 0.05$). For *L. multiflorum*, mowing in the 0–10 cm layer resulted in 145.28 seedlings kg^{-1}, a value 53.1% higher than that observed under desiccation (94.90 seedlings kg^{-1}); in the 10–20 cm layer, there was no difference between management practices. For *V. sativa*, a similar pattern was observed, with greater emergence under surface mowing (7.61 vs. 3.66 seedlings kg^{-1}). For *C. bonariensis*, the opposite pattern was observed: greater emergence occurred under surface desiccation (5.98 vs. 3.55 seedlings kg^{-1}), which may be related to the known difficulty of controlling this species with glyphosate. For *U. plantaginea*, *S. rhombifolia* and *R. sativus*, there was no effect of management or depth ($\alpha > 0.05$).

The 0–10 cm layer concentrated 3296 seedlings (56.7%), whereas the 10–20 cm layer contained 2516 seedlings (43.3%). The species with the greatest emergence were *U. plantaginea*, *L. multiflorum* and *S. rhombifolia* (Table 3).

Table 3. Mean seedling density per kilogram of soil (seedlings kg^{-1}), calculated as the average across all soil management systems (NT, CT, and fallow) for each combination of vegetation management (mowing vs. desiccation) and depth (0–10 and 10–20 cm), over four growing seasons (2017/18 to 2020/21). Erechim, RS, Brazil.

Species	0–10 cm		10–20 cm	
	Mowing	Desiccation	Mowing	Desiccation
Urochloa plantaginea	3.76 Aa	5.40 Aa	3.03 Aa	3.98 Aa
Sida rhombifolia	3.52 Aa	4.20 Aa	1.70 Aa	1.90 Aa
Lolium multiflorum	145.28 Bb	94.90 Ab	38.46 Aa	13.94 Aa
Raphanus sativus	29.48 Aa	24.70 Aa	18.18 Aa	5.77 Aa
Vicia sativa	7.61 Bb	3.66 Aa	1.48 Aa	1.26 Aa
Conyza bonariensis	3.55 Ab	5.98 Bb	1.80 Aa	1.55 Aa

Means followed by the same uppercase letter within a row (between management practices within each depth) and lowercase letter within a column (between depths within each management practice) do not differ by Tukey's test ($\alpha \leq 0.05$).

For *U. plantaginea*, *S. rhombifolia* and *R. sativus*, the different management practices and soil depths did not significantly affect emergence from the seed bank. *Vicia sativa* showed greater emergence under mowing in the 0–10 cm layer, whereas *C. bonariensis* showed greater emergence under desiccation in the same layer, associated with this species' resistance to glyphosate (Table 3).

The composition of the seed bank differed markedly from that of the phytosociological survey: of the 28 species recorded in the seed bank, only 8 were shared with the 18 species recorded in the phytosociology survey (Sørensen = 0.35). Species such as *A. satureioides*, *S. glaziovii*, *P. maximum* and *F. convolvulus* were exclusive to the seed bank, constituting a reinfestation reservoir not detected by the phytosociological surveys (Figure 3).

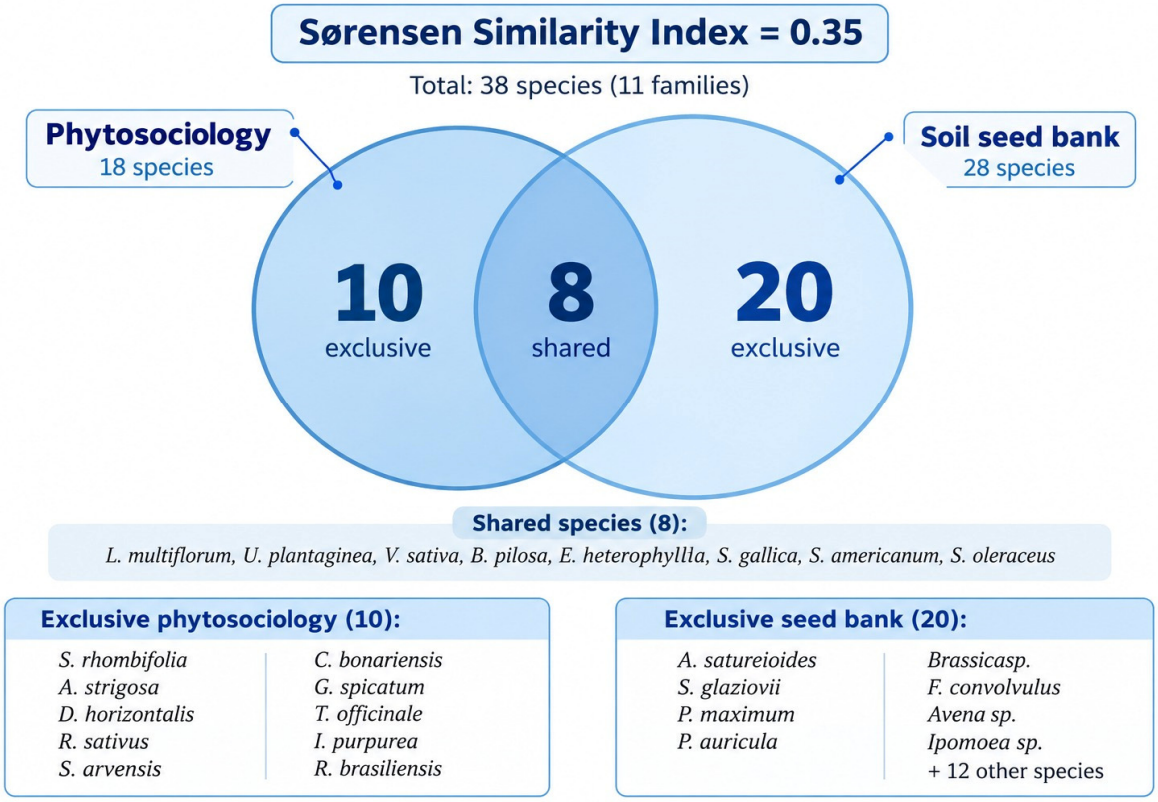


Figure 3. Floristic similarity between the aboveground weed community assessed by phytosociological survey and the soil seed bank. A total of 38 weed species belonging to 11 families were recorded, including 18 species in the phytosociological survey and 28 species in the soil seed bank. Eight species were shared between the two assessments, whereas 10 species were exclusive to the phytosociological survey and 20 were exclusive to the soil seed bank. The Sørensen similarity index was 0.35, indicating 35% floristic similarity between the two assessments.

Seedling density in the soil seed bank was influenced by the soil management system at both depths evaluated (Figure 4). In the 0–10 cm layer, the fallow and conventional tillage (CT) systems exhibited higher seedling density compared to no-tillage (NT), regardless of the crop management method. In the 10–20 cm layer, the same pattern was observed, with the lowest densities in the NT system, intermediate values in the CT system, and the highest values in the fallow system. At both depths, mechanical mowing resulted in numerically higher values than chemical desiccation within each management system (Figure 4).

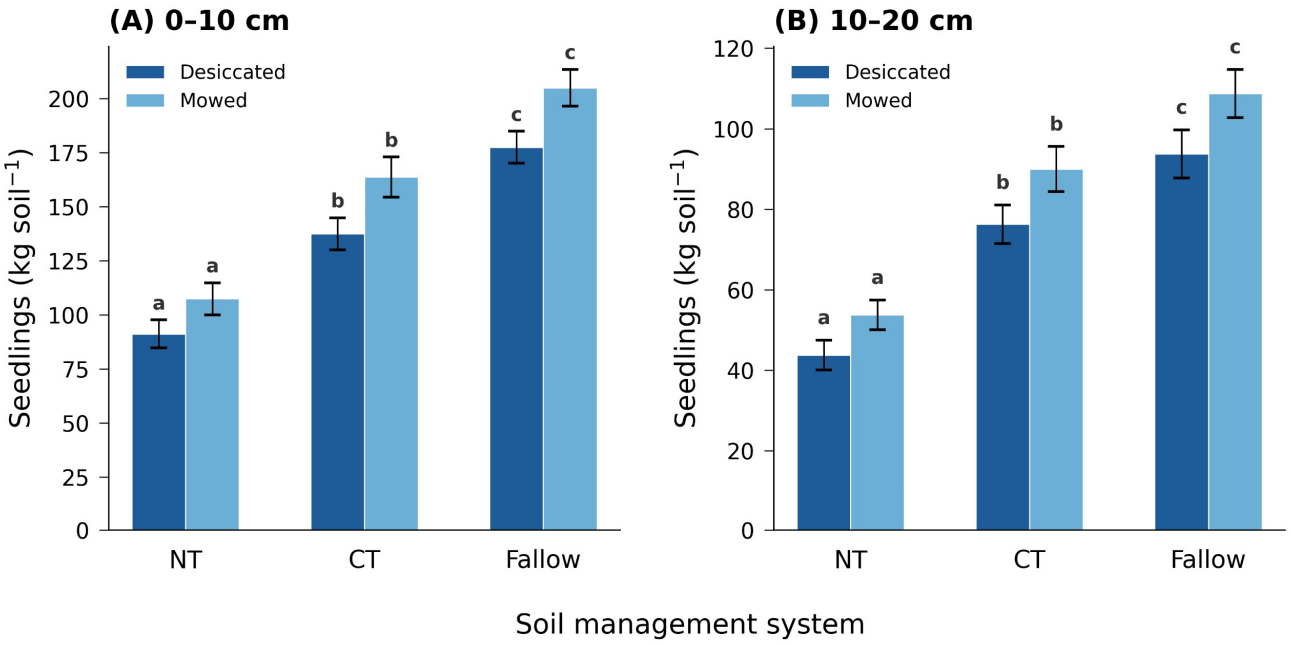


Figure 4. Density of emerged seedlings from the soil seed bank under no-tillage, conventional tillage and fallow systems, with chemical desiccation and mowing, in the 0–10 cm (**A**) and 10–20 cm (**B**) soil layers. Bars represent the mean number of emerged seedlings per kilogram of soil, and the error bars correspond to the standard error of the mean. Means followed by the same letter do not differ according to Tukey's test at the 5% significance level.

3.3. Cover Crop Dry Matter

Shoot dry matter production of the winter cover crops was evaluated to characterize the amount of aboveground biomass available for residue formation before establishment of the summer crops. Overall, desiccation resulted in greater dry matter accumulation than mowing for most of the cover crops evaluated, with significant differences for *V. sativa* under no-tillage, *V. sativa* under conventional tillage, *A. strigosa* under conventional tillage, *A. strigosa* + *V. sativa*, *A. strigosa* under no-tillage and *S. cereale* (Table 4). For *L. albus*, although the numerical value was higher under mowing, with 1058.40 kg ha^{-1}, compared with desiccation, with 844.80 kg ha^{-1}, there was no significant difference between management practices.

Table 4. Mean shoot dry matter production (DM) by soil cover crops preceding the summer crops during the 2017/18, 2018/19, 2019/20 and 2020/21 growing seasons in which the experiments were conducted. Erechim, RS, Brazil, UFFS. NT (No-till farming system) and CT (Conventional tillage system).

Winter Cover Crop	System	Management (kg ha^{-1})	
		Mowing	Desiccation
Lupinus albus	NT	1058.40 Ac [1]	844.80 Ad
Vicia sativa	NT	895.70 Bc	3603.25 Abc
Vicia sativa	CT	1176.53 Bc	2482.06 Abd
Avena strigosa	CT	2929.00 Bab	3885.05 Abc
A. strigosa + *V. sativa*	NT	1518.10 Bbc	3666.80 Abc
A. strigosa	NT	3392.70 Ba	4874.10 Ab
Secale cereale	NT	3094.80 Bab	8358.20 Aa

[1] Means followed by different uppercase letters within a row and lowercase letters within a column differ by Tukey's test ($\alpha \leq 0.05$).

Among the cover crops, *S. cereale* showed the highest dry matter production under desiccation, with 8358.20 kg ha^{-1}, a value 170.1% higher than that observed under mowing (3094.80 kg ha^{-1}). *A. strigosa* under no-tillage also showed high production, with 4874.10 kg ha^{-1} under desiccation and 3392.70 kg ha^{-1} under mowing, corresponding to a 43.7% increase under desiccation. For *A. strigosa* under conventional tillage, dry matter increased from 2929.00 kg ha^{-1} under mowing to 3885.05 kg ha^{-1} under desiccation, representing an increase of 32.6%.

The greatest relative differences between management practices were observed for *V. sativa* under no-tillage and for the intercropping of *A. strigosa* + *V. sativa*. *V. sativa* under no-tillage produced 895.70 kg ha^{-1} under mowing and 3603.25 kg ha^{-1} under desiccation, corresponding to an increase of 302.3%. In the *A. strigosa* + *V. sativa* intercropping, production increased from 1518.10 kg ha^{-1} under mowing to 3666.80 kg ha^{-1} under desiccation, an increase of 141.5%. For *V. sativa* under conventional tillage, the values were 1176.53 kg ha^{-1} under mowing and 2482.06 kg ha^{-1} under desiccation, representing an increase of 110.9%.

The lowest dry matter production values were observed for *L. albus*, with 1058.40 kg ha^{-1} under mowing and 844.80 kg ha^{-1} under desiccation, with no significant difference between management practices, and for *V. sativa* under no-tillage and mowing, with 895.70 kg ha^{-1}. These results demonstrate that the amount of aboveground biomass available for residue formation varied among cover crop species and vegetation management practices. This variation is relevant to the interpretation of the weed community and seed-bank results because the amount of residue returned to the soil surface can modify the environmental conditions governing weed seed germination and seedling establishment. However, cover crop dry matter was considered as a characterization of the vegetation management system rather than as an independent predictor of weed or seed-bank dynamics.

3.4. Crop Yield

Crop yield varied according to the crop grown, the winter cover crop and pre-sowing vegetation management (Table 5).

Table 5. Mean yields (kg ha^{-1}) of the summer crops obtained during the 2017/18, 2018/19, 2019/20 and 2020/21 growing seasons, as affected by winter cover crop and pre-sowing vegetation management. Erechim, RS, Brazil.

Crops	Winter Cover Crop	Management	
		Desiccation	Mowing
Phaseolus vulgaris	*Avena strigosa*	2291.18 cA [1]	2369.41 aA
	Secale cereale	2824.18 bA	1677.47 bB
	Fallow	3526.19 aA	2494.65 aA
Zea mays	*Vicia sativa* NT	7543.19 aA	7305.96 aA
	V. sativa CT	8818.01 aA	7868.40 aB
	A. strigosa + *V.sativa*	7709.45 abA	7099.63 aA
	Pousio	6840.16 bA	6925.94 aA
Glycine max	*Triticum aestivum*	2545.56 abA	2321.33 cB
	A. strigosa NT	2385.31 bA	2500.86 bcA
	A. strigosa CT	2766.00 aA	2597.12 abA
	Fallow	2650.77 abA	2823.67 aA

[1] Means followed by different uppercase letters within a row and lowercase letters within a column differ by Tukey's test ($\alpha \leq 0.05$). NT—no-tillage system; CT—conventional tillage system.

For *P. vulgaris*, the highest numerical yield was observed under fallow with desiccation, with 3526.19 kg ha^{-1}, followed by desiccated *S. cereale*, with 2824.18 kg ha^{-1}, and desiccated *A. strigosa*, with 2291.18 kg ha^{-1}. Under mowing, the highest yields were observed under fallow (2494.65 kg ha^{-1}) and *A. strigosa* (2369.41 kg ha^{-1}), which did not differ from each other. *S. cereale* resulted in lower yield under mowing (1677.47 kg ha^{-1}) and differed from desiccation, indicating greater productive performance of *P. vulgaris* after *S. cereale* when the vegetation was managed chemically.

For *Z. mays*, the differences between desiccation and mowing were smaller than those observed for *P. vulgaris* and *G. max*. Desiccation exceeded mowing by 1.7% in the 2017/18 growing season, with yields of 7710.5 and 7584.5 kg ha^{-1}, respectively; by 7.6% in the 2018/19 growing season, with 10,101.0 and 9384.5 kg ha^{-1}; by 3.8% in the 2019/20 growing season, with 3040.8 and 2930.0 kg ha^{-1}; and by 11.8% in the 2020/21 growing season, with 2924.9 and 2615.7 kg ha^{-1}. These differences were smaller than those observed for *P. vulgaris*, for which desiccation exceeded mowing by up to 88.2% in the 2018/19 growing season, with yields of 3839.2 and 2039.8 kg ha^{-1}, respectively.

For *G. max*, the highest numerical value under desiccation occurred after *A. strigosa* under conventional tillage, with 2766.00 kg ha^{-1}, followed by fallow (2650.77 kg ha^{-1}) and *T. aestivum* (2545.56 kg ha^{-1}). Under mowing, the highest numerical yield was observed under fallow, with 2823.67 kg ha^{-1}, followed by *A. strigosa* under conventional tillage, with 2597.12 kg ha^{-1}. *T. aestivum* showed a significant difference between management practices, with higher yield under desiccation (2545.56 kg ha^{-1}) than under mowing (2321.33 kg ha^{-1}).

3.5. Integration of Phytosociology and Seed Bank

The integration of phytosociology and seed bank data showed that some species were recorded by both methods, including *L. multiflorum*, *U. plantaginea*, *V. sativa*, *B. pilosa*, *E. heterophylla*, *S. gallica*, *S. americanum* and *S. oleraceus*. This pattern indicates that part of the species present in the emerging community also remains as a viable reserve in the soil seed bank.

Considering the two assessment methods, 38 species were recorded. Of these, 8 species occurred in both the phytosociological survey and the seed bank, 10 species were exclusive to the phytosociological survey and 20 species were exclusive to the seed bank. The Sørensen Similarity Index was 0.35, indicating low to moderate floristic similarity between the weed community observed in the field and the germinable seed bank (Figures 3 and 5).

In the phytosociological survey, *L. multiflorum* and *S. rhombifolia* were the most representative species of the weed community. In the seed bank, the highest emergence values were observed for grasses such as *U. plantaginea* and *L. multiflorum*, as well as species such as *A. satureioides*, *Sida* spp. and *Panicum*/*Megathyrsus* spp. Therefore, the vegetation observed in the field does not fully represent the soil seed bank, although there is overlap between the dominant species of the weed community and those capable of emerging from the soil samples.

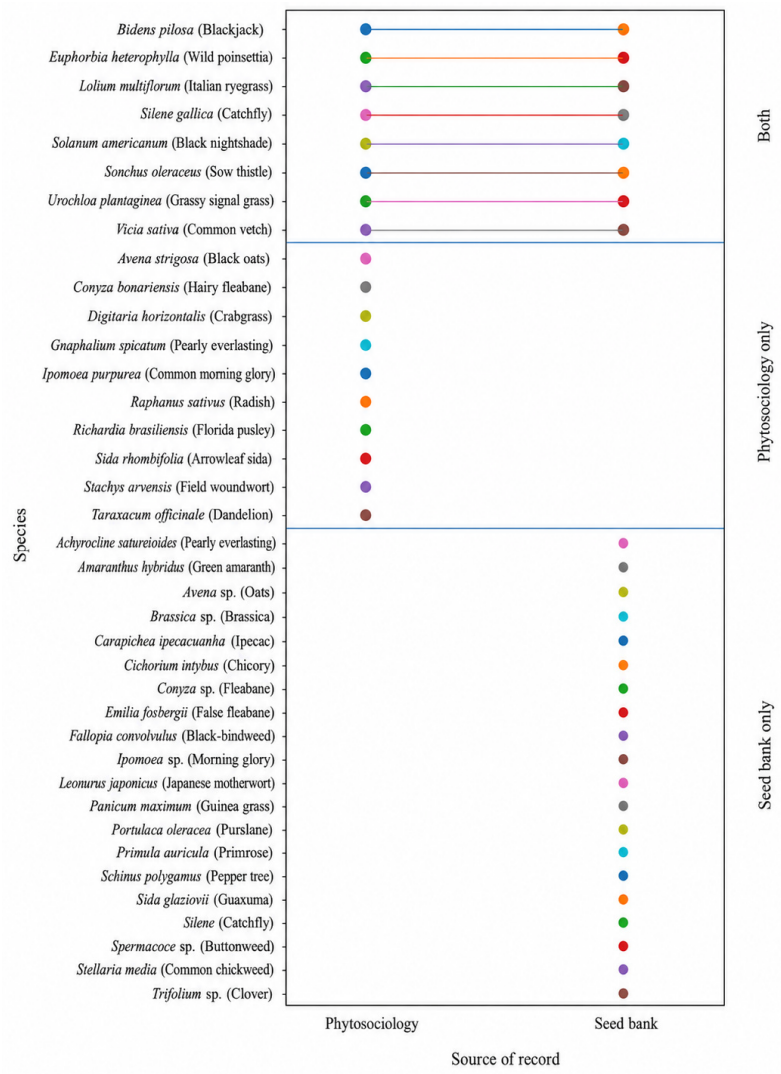


Figure 5. Relationship between weed species recorded in the phytosociological survey and in the soil seed bank. The points indicate the presence of species in each source of record, and the lines connect those observed both in the weed community in the field and in the seed bank. The horizontal divisions indicate species common to both methods, species exclusive to phytosociology and species exclusive to the seed bank.

4. Discussion

4.1. Dominance of Lolium Multiflorum and Sida Rhombifolia

The predominance of *L. multiflorum* in the phytosociological survey (61.9% of individuals) and in the seed bank reflects the adaptation of this species to the cropping systems evaluated, together with its high seed production capacity and resistance to EPSPS- and ACCase-inhibiting herbicides [1,30]. Under no-tillage, the maintenance of straw on the soil surface favours the concentration of seeds in the surface layer, whereas under conventional tillage, soil disturbance redistributes seeds deeper in the soil profile, promoting their persistence [15,18].

The closer relationship between *L. multiflorum* and *S. rhombifolia* under mowing (1.57:1) compared with desiccation (3:1) shows that mechanical mowing is less efficient for controlling *S. rhombifolia*, a species with high competitive ability and adaptability to crop environments [31]. Chemical desiccation, by acting systemically, eliminates the shoots and also compromises root viability, reducing the recovery capacity of this species.

The contrasting responses of the dominant species indicate that the effect of pre-sowing vegetation management was species dependent rather than uniform across the weed community. Mechanical mowing removes aboveground biomass but may leave viable belowground structures, allowing species with high regrowth capacity to resume vegetative growth. In contrast, systemic chemical desiccation can provide more persistent suppression by affecting both aboveground tissues and, depending on species susceptibility, belowground recovery. Therefore, the relative contribution of individual species to the weed community may change according to the interaction between their biological traits and the type of vegetation management adopted.

The timing of vegetation termination is also likely to be important for these responses. The effectiveness of pre-sowing management depends not only on the method used but also on the phenological stage of the weeds at the time of intervention. Management performed before flowering and seed maturation can reduce the opportunity for surviving plants to replenish the soil seed bank, whereas late interventions may suppress existing vegetation without preventing seed production [32]. This distinction is particularly relevant for species capable of regrowth after mowing, for which the interval between cutting and crop establishment may determine whether plants remain suppressed or recover sufficiently to reproduce.

The marked interannual variation in weed abundance may partly reflect differences in climatic conditions among growing seasons. Precipitation, temperature, and soil water availability influence the environmental conditions required for weed seed germination and seedling establishment, and the climatic data indicate substantial variation among years (Figure 1).

4.2. Vertical Distribution of the Seed Bank

The concentration of 56.7% of emerged seedlings in the 0–10 cm layer is consistent with the expected dynamics in agricultural areas, where natural seed deposition occurs on the soil surface and redistribution depends on the intensity of soil disturbance [14,17]. Under no-tillage, the absence of soil disturbance keeps most seeds on the surface, where they are exposed to predation, desiccation and fluctuations in temperature and moisture, factors that reduce their viability over time [33]. Under conventional tillage, soil disturbance incorporates seeds into deeper layers, where they are protected from deterioration and may remain viable for long periods, emerging when they return to the surface during subsequent soil preparation operations [18].

The vertical position of seeds also affects their probability of responding to environmental cues for germination [34]. Seeds located near the soil surface are more directly exposed to fluctuations in light, temperature and moisture, which may favour the emergence of species whose germination is stimulated by these environmental signals. In contrast, incorporation into deeper soil layers can reduce exposure to such cues while increasing physical protection from environmental deterioration. Consequently, conventional tillage may simultaneously reduce the immediate concentration of seeds near the soil surface and maintain a deeper reservoir of viable propagules that can contribute to future recruitment when subsequent soil disturbance redistributes them toward the surface.

The proportion observed in the 10–20 cm layer (43.3%) indicates that a relevant fraction of viable propagules remains below the first 10 cm, reinforcing the importance of assessing multiple depths for a complete characterisation of reinfestation potential.

4.3. Effect of Vegetation Management on the Seed Bank

The 53.1% greater emergence of *L. multiflorum* under mowing in the 0–10 cm layer (145.28 vs. 94.90 seedlings kg^{-1}) shows that mechanical mowing allows the production

and return of viable seeds to the soil. Chemical desiccation, by interrupting the vegetative and reproductive cycle before the production of mature seeds, reduces the input of new propagules into the seed bank [22,33].

These differences may reflect not only the immediate effect of vegetation removal but also differences in seed input between management practices. When mechanical mowing is performed after weeds have reached advanced reproductive stages, surviving or regrowing plants may continue their reproductive development and contribute viable seeds to the soil. Repeated seed input over successive growing seasons can gradually increase or maintain the soil seed bank, even when the aboveground vegetation appears temporarily suppressed. Chemical desiccation performed before seed maturation, when effective, may reduce this input by interrupting the reproductive cycle before viable seeds are returned to the soil. Thus, the effects of pre-sowing vegetation management on the seed bank may become more evident over time than its immediate effects on aboveground weed abundance.

For *C. bonariensis*, the opposite pattern, with greater emergence under desiccation, is attributed to the resistance of this species to glyphosate [1], which results in control failure and subsequent seed production, thereby replenishing the soil seed bank.

The contrasting response of *C. bonariensis* illustrates the importance of species-specific susceptibility when interpreting the effects of vegetation management. A management practice that effectively suppresses one species may provide insufficient control of another, allowing surviving individuals to complete their reproductive cycle and contribute to seed-bank replenishment. Therefore, the reduction of total weed biomass or abundance at a given sampling time does not necessarily indicate an equivalent reduction in future reinfestation potential.

4.4. Relationship Between Phytosociology and the Seed Bank

The Sørensen Index of 0.35 indicates that only 35% of the floristic composition is shared between the emerging community and the germinable seed bank. The presence of 20 species exclusive to the seed bank demonstrates that the soil maintains a reserve of species that is not expressed in the emerging vegetation in each agricultural cycle, representing a latent reinfestation potential. Conversely, the 10 species exclusive to the phytosociological survey may represent species with rapid germination and low persistence in the soil, whose seeds are consumed, deteriorate rapidly or lose viability between growing seasons.

The low floristic similarity between the two compartments can be interpreted as the result of different temporal and ecological processes. The aboveground community represents the subset of species that successfully germinated, established and persisted under the environmental and management conditions prevailing during a particular growing season. In contrast, the soil seed bank represents the cumulative outcome of seed production, dispersal, burial, dormancy, deterioration and mortality over previous seasons [35]. Consequently, the composition of the two compartments is not expected to be identical at a given point in time.

This temporal decoupling also explains why the absence of a species from the aboveground survey does not necessarily indicate its absence from the agricultural system. Species-specific dormancy, seasonal germination requirements, seed longevity and competition during seedling establishment may prevent some viable propagules from emerging during a particular growing season. Conversely, species observed aboveground but not detected in the germinable seed bank may have contributed few seeds during previous seasons, may have short-lived seeds, or may have experienced rapid deterioration or mortality in the soil. The joint assessment of both compartments therefore provides a more complete representation of current weed occurrence and potential future recruitment.

In summary, weeds can exhibit multiple emergence flushes; therefore, the timing of management affects emergence dynamics [36]. This reinforces that phytosociology and seed bank assessment are complementary methods and that their joint analysis provides more robust information for decision-making in integrated weed management [19,20].

4.5. Agronomic Context of the Management Systems

Cover crops may influence weed population dynamics through multiple demographic processes, including seedling emergence, plant survival and seed production [37].

The amount of biomass produced by the preceding cover crop provides an additional ecological context for interpreting weed recruitment. The cover crops evaluated in this study differed substantially in shoot dry matter production, and vegetation management also modified biomass accumulation for several cover crop species. Higher amounts of surface residue can modify the soil microenvironment and influence weed seed germination and seedling establishment [38], primarily by reducing light availability and altering temperature and moisture conditions [39]. The high biomass production observed for *S. cereale* under chemical desiccation may be particularly relevant because greater residue amounts can provide stronger physical suppression of weed emergence [40].

The evaluation of crop yield was included to provide an agronomic context for the management systems in which the weed community and soil seed bank were assessed. Crop yield varied according to the preceding cover crop and pre-sowing vegetation management, with differences among management practices being more pronounced for *P. vulgaris* and *G. max* than for *Z. mays* (Table 5). The higher yields observed under chemical desiccation may be associated with the more effective interruption of the growth of the preceding vegetation, which can favour water and nutrient availability during the early stages of crop development [41]. In addition, desiccation promotes the formation of a uniform layer of dry straw on the soil surface, which can reduce light incidence and thermal fluctuation, potentially limiting the emergence of positive photoblastic species.

Although crop yield was not directly correlated with weed community structure or seed-bank density in the present study, its inclusion provides an agronomic context for interpreting the management systems as a whole. In practical agricultural systems, weed management decisions must consider both the suppression of weed populations and the maintenance of crop productivity. Therefore, the yield results complement the ecological assessment without being interpreted as a direct determinant of weed community or seed-bank dynamics.

Taken together, the results indicate that vegetation management should be considered from both ecological and agronomic perspectives. Management practices influence not only current weed abundance and crop performance but may also modify the future recruitment potential represented by the soil seed bank. Therefore, the agronomic benefits of effective vegetation suppression should be considered alongside its potential effects on seed-bank replenishment and long-term weed community dynamics.

5. Conclusions

Soil management systems and pre-sowing vegetation management influence both the structure of the weed community and the composition and density of the weed seed bank. The no-tillage system combined with chemical desiccation showed the lowest weed incidence in the phytosociological survey and the smallest seed bank for key species such as *Lolium multiflorum*.

The 0–10 cm layer concentrated 56.7% of the emerged seedlings from the seed bank, confirming it as the main recruitment zone. The effect of vegetation management was

dependent on species and depth, with mowing associated with greater emergence of *L. multiflorum* and desiccation associated with greater emergence of *Conyza bonariensis*.

The weed community observed in the field does not represent the reinfestation potential stored in the soil, reinforcing the need for integrated strategies that consider both components for sustainable weed management.

From a practical perspective, the joint assessment of the aboveground weed community and soil seed bank can provide more comprehensive information for weed management, particularly by identifying species with potential for future recruitment that may not be evident in the current weed flora. This information can support the selection and timing of pre-sowing vegetation management practices and contribute to more targeted and preventive weed management strategies in different soil management systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy16212139/s1, Table S1: History of cropping sequences used across four agricultural seasons (2017/2018 to 2020/2021), serving as the experimental conditions for residue accumulation and soil management in no-till, conventional tillage, and fallow systems; Table S2: Management of winter cover crops for the 2018/19, 2019/20, and 2020/21 growing seasons. Erechim/RS, UFFS, 2022; Table S3: Management of summer crops for the 2018/19, 2019/20, and 2020/21 growing seasons. Erechim/RS, UFFS, 2022.

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