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Do Intercropped Legumes Alter Weed Communities in Organic Field Crops? A Taxonomic and Functional Perspective

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Abstract

Transitioning from traditional to organic production is gaining popularity worldwide with significant challenges including weed management. We evaluated how legumes sown as cover crops in a synchronous intercropping (SI) system with organic oat (*Avena sativa*) as the main crop impacted weed communities. A split-plot design was set up on a farm in Poularies (Quebec, Canada) to compare *Melilotus officinalis*, *Trifolium incarnatum*, *Trifolium repens* and a control without legumes for two years (2019–2020). We determined the botanical composition, calculated diversity indices, and measured plant functional traits. Species richness was similar (S = 5.5 ± 0.4) across treatments in 2019, but higher in the control (S = 12.2 ± 2.6) and lower (S = 6.0 ± 1.2) under *T. incarnatum* in 2020. Shannon diversity was lower in 2019 (H′ = 1.49 ± 0.07) than in 2020 (H′ = 1.99 ± 0.04), and higher under the control (H′ = 1.87 ± 0.05) than under *T. incarnatum* (H′ = 1.46 ± 0.04). Weeds under *T. incarnatum* had a high specific leaf area and a resource-acquisition strategy, while those in the control had a higher leaf dry matter content and a resource-conservation strategy. Our study brings novel results on the use of legumes in SI systems to control weeds. Using *T. incarnatum* in a SI system with oat had the greatest capacity to cover the ground, control weeds and reduce their diversity, but this species and the acquisitive weeds in this treatment could compete with the main crop. Future research should evaluate the quantity and quality of yields to complete this ecological study and give appropriate agronomic recommendations. Our results could provide agronomists and farmers with indications on the level of competition weeds exert on the cropping system depending on the SI treatment.

Keywords: weed species; legume cover crops; synchronous intercropping; organic oats; taxonomic analysis; functional traits; agroecology

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1. Introduction

Organic farming has experienced unprecedented growth worldwide in recent years, covering over 96 million ha and representing now 2.0% of the world's agricultural land [1]. In 2023, Canada ranked 11th in the world in terms of farmland under organic management [1]. The 1.4 million ha of organic field crops grown make up around 4.4% of the 31.6 million hectares seeded to field crops in Canada [2]. Organic field crop production is based on sustainable, environmentally friendly practices aimed at restricting the use of synthetic inputs such as pest control products and chemical fertilizers [3]. Organic

farming can play a major role in establishing sustainable agricultural systems, but no single approach can provide food security for the entire planet [3]. Indeed, the organic production method faces major challenges, particularly in terms of weed management [4].

Unlike conventional agriculture, where weed management relies heavily on synthetic inputs, organic agriculture favors alternative control strategies that require an integrated approach combining cultural practices and agronomic innovations [5]. Mechanical tillage, involving weeding and plowing, is a common weed management method [6]. However, it is energy-intensive and requires multiple passes of machinery, which can compact the soil. Crop rotation is another effective method because it disrupts the life cycle of weeds and reduces their presence [7,8]. However, the effects of this approach are only visible after several growing seasons. In order to effectively control weeds in organic field crops, it is necessary to find a method that protects the soil and is fast and effective.

Cover crops, particularly legumes, are emerging as a sustainable weed control solution in organic field crops throughout the world. The growth of legumes sown as cover crops accelerates canopy closure, reducing light availability for weeds and limiting their establishment and growth [9,10]. In addition to helping suppress weeds, legume cover crops can increase biodiversity and improve the soil's physical and chemical properties [11]. They boost the amount of nitrogen and organic matter in the soil while increasing biological activity [12], help to improve its structure, encourage water infiltration, and limit soil loss through erosion [13,14]. However, the capacity of the legume cover crops to control weeds and provide other ecosystem services can vary depending on the species and the way they are sown within the main crop. This is particularly the case in regions of the world with a cool, humid continental climate and hot summers, where only one growing season is possible.

Intercropping legumes with field crops can be done in the spring at the same time as the cereal crop is sown, a practice known as synchronous intercropping (SI) [15]. The success of this practice, however, depends on climatic conditions, and the species chosen have to grow slowly so as not to harm the main crop [11]. The use of legumes in SI systems could be a good strategy, as they compete little with cereals thanks to their ability to fix atmospheric nitrogen [10]. Studies have shown that *T. repens* can modify plant-plant interactions and alter the dynamics of weed communities [16]. *M. officinalis* offers little competition to early-growing weeds, has a low tolerance for poorly drained soils, but tends to be heat-tolerant [11]. In contrast, *T. incarnatum* is adapted to a cool, humid climate and could produce high biomass when intercropped [11]. *T. repens*, *T. incarnatum*, and *M. officinalis* are among the legumes that can be used as intercrops in organic field crops. These species are commonly recommended as cover crops in cereal production in a cool, humid continental climate such as in Eastern Canada [11]. However, their impact on weeds remains poorly understood, particularly when they are used in an SI system where oats (*A. sativa*) are the main crop. Oats are the cereal of choice in cool and humid continental climates and one of the most important crops worldwide [17,18]; we thus need to understand how legumes used in a SI system can limit weed infestation and benefit oat production.

The nature of the sown cover crops directly influences the dynamics of weed communities [19], particularly the richness and diversity of their composition [20]. Flora communities can be studied using a number of indices, including the species richness index, which corresponds to the total number of species present [21], and the Shannon diversity index, which also takes into account the distribution of individuals among these species [22]. These indices enable us to quantify the biodiversity of plant communities from a taxonomic viewpoint, but do not allow us to study their functions from an ecological viewpoint. Unlike the taxonomic approach, the functional approach analyzes the ecological

roles and interactions between species within a community [23]. Traits such as specific leaf area (SLA), leaf dry matter content (LDMC), and plant height provide information about competition and coexistence processes [24]. A study of species' functional traits could facilitate understanding of interactions between legumes and weeds, particularly in terms of competition for resources [23]. The functional approach could thus help to optimize cover crop management because it is based on the study of resource acquisition and conservation strategies specific to each plant [25]. However, there remains a lack of comprehension of the current application of functional traits in weed management. Indeed, very few studies take a taxonomic and functional perspective on weed management practices in organic field crops, and virtually no studies use such an approach to investigate weed communities in oat production under cool and humid climatic conditions. By doing so, this novel work aims at deepening our understanding of weed population dynamics in the context of organic farming.

In this study, we used a dual approach (i.e., both taxonomic and functional) to gain complementary knowledge on the effect of legumes used in an SI system with oats on the abundance and diversity of weed species, on the one hand, and on their functional traits and growth strategies, on the other. The main objectives of this study were to evaluate the impact of three legume species intercropped synchronously with an organic oat crop on (1) the botanical composition of weeds, (2) the richness and diversity of plant communities, and (3) the functional traits of weed species and communities, over two consecutive years. Our first hypothesis is that the presence of intercropped legumes will modify the composition of weed communities compared with control plots without legumes. Our second hypothesis is that the diversity and composition of weed communities evolve differently between 2019 and 2020, depending on the intercropping treatments applied. Our third hypothesis is that the growth strategies of weeds will vary depending on the intercropping treatments.

2. Materials and Methods

2.1. Characteristics of the Study Site

The study site is located in Poularies (48°39′41.5″ N; 79°01′03.8″ W), in the Abitibi-Ouest regional county municipality of Quebec, Canada. Organic oats had already been planted in the field in 2019 and the same crop was planted in 2020. The region has a cold, humid continental climate with warm summers and mean annual temperature and precipitation of 1.0 °C and 985 mm, respectively, based on the 1981–2010 climate normals at the Mont-Brun station [26]. This corresponds to the Köppen classification Dfb [27]. The meteorological data from the two growing seasons are presented in Table 1, as well as those associated with the historical monthly averages between 1981 and 2010 for comparison purposes. The study site is located on a heavy clay soil in the Roquemaure series. The soils in this series are characterized by poor drainage and typically contain ~900, ~100, and ~0 g kg^{-1} of clay (<2 µm), silt (2–50 µm), and sand (50–2000 µm), respectively, in the surface layer and are classified as Humic Gleysols in the Canadian System of Soil Classification [28,29]. The percentage of soil organic matter, the C and N concentrations and the bulk density of the soil at 0–15 cm depth were 7.7%, 44.6 g C kg^{-1}, 3.62 g N kg^{-1}, and 1.26 g cm^{-3}, respectively. The region's topography is relatively flat, as the site is located on a vast clay plain at around 300 m altitude [28].

Table 1. Weather data during the 2019 and 2020 growing seasons in Poularies [†].

Months	Mean Temperature (°C)			Precipitation (mm)			Days with Precipitation (No.)			Growing Degree-Days (Base 5 °C) (No.)		
	2019 *	2020 *	Avg *	2019 *	2020 *	Avg *	2019 *	2020 *	Avg *	2019 *	2020 *	Avg *
May	6.9	7.5	9.3	56	41	76	11	11	na	63	147	134
June	14.0	15.5	14.3	133	84	88	12	13	na	249	300	280
July	18.8	19.7	16.9	65	125	100	9	16	na	397	441	368
August	15.7	15.4	15.3	91	61	97	14	11	na	318	309	320
September	11.1	10.6	10.2	95	114	108	13	19	na	163	166	154
October	5.3	1.6	4.0	97	127	82	16	20	na	42	13	8

[†] Data from the weather station located in Palmarolle, approximately 15 km from Poularies. * Data provided by La Financière Agricole du Québec and obtained from the Agrométéo Québec service provided by Mesonet Solutions (Solutions Mesonet, Québec, QC, Canada) na = data not available.

2.2. Description of the Experimental Design

A split-plot experimental design was set up under actual on-farm conditions in an organic oat crop. Four treatment modalities were tested at the main plot level: three intercropped legumes—(1) *M. officinalis*, (2) *T. incarnatum*, and (3) *T. repens*—and (4) a control with no legumes, resulting in a spontaneous weed cover. These species were selected since they are frequently used as legume cover crops in Quebec, Canada [11]. The field was divided into two distinct blocks within which the four treatments were randomly applied in four separate plots of approximately 9 m × 125 m each. Two 1 m × 1 m quadrats were arbitrarily placed at least 60 m apart in each plot and each block so as to form four independent experimental units (i.e., repetitions) for each treatment. The experimental design thus consisted of 32 experimental units: 4 legume modalities × 2 quadrats per plot × 2 blocks × 2 years. The same design was used at the same location in 2019 and 2020, and the year factor was considered at the subplot level. The *T. repens*, *T. incarnatum*, and *M. officinalis* were sown at rates of 6, 15, and 5 kg ha^{-1} according to local agronomic prescription, respectively, using a John Deere cereal seeder (John Deer, Moline, IL, USA). The rows of oats were spaced 16.5 cm apart. The sowing rate for oats was 220 kg ha^{-1}; oats and legumes were sown at the same time (i.e., synchronous intercropping) in early June 2019 and 2020. No organic fertilization, irrigation, or mechanical weed control were used.

2.3. Botanical Survey and Composition

In each plot, 1 m × 1 m wire frame quadrats were laid out to include the five oat rows in the center of the plot and exclude those at the lateral ends in order to avoid edge effects. A botanical survey of all individuals in the quadrat was carried out in the field in mid-July, about seven weeks after seeding, to identify them to species level, including the main crop, intercropped legumes sown, and weeds. Species were identified in the field, first using the Pl@ntNet mobile application version 3.0.1. This platform uses machine learning to identify RGB images with high accuracy and is widely used by scientists and citizens to identify plant species through pictures of their organs [30,31]. Then, species identity was confirmed using the reference books Flora of North America: North of Mexico [32–37] to validate the identification of all weeds. The total botanical composition was calculated from the percentage cover of all the species found in the quadrats. This approach makes it possible to evaluate the structure of the plant cover, including the main crop, weeds, and sown intercrops [38]. It was calculated using the following equation:

$$\text{Total botanical composition } (\%) = \left(\frac{\text{Cover of a species}}{\text{Total cover of all species}} \right) \times 100 \quad (1)$$

Species cover was determined according to Daubenmire [39] by making a direct visual estimate of coverage in order to determine the proportion of the area occupied by oats, intercropped legumes, and weeds so the sum of the percentages equals 100. The cover

percentages were determined during the plants' active growing season in the second half of July, around seven weeks after sowing.

2.4. Species Richness and Diversity of Communities

The number of species found in each quadrat (oats, sown legumes, and weeds) was measured to assess the species richness of the plant communities per unit area (S, number of species per m^2) [22,38,40]. Diversity of the plant communities was determined by calculating the Shannon diversity index (H′) [22,41] using the following equation:

$$H' = \sum_{i=1}^{S} p_i \cdot \log_2 p_i \quad (2)$$

where S is the total number of species and p_i is the relative abundance of species i. The relative abundance of each species is calculated by dividing the number of individuals in that species by the total number of individuals in all the species present. This method provides a percentage representation of each species' contribution, thus playing an essential role in the assessment of diversity within the plant community [22]. A higher value in this index reflects greater diversity.

2.5. Functional Traits of Weed Species and Communities

Standardized protocols were used to measure traits [42]. In each of the quadrats, the traits of dominant weed species, i.e., those who made up at least 80% of the botanical composition, were measured [40,43–45]. According to Garnier et al. [40], the choice of species for trait measurements should be concentrated on the most abundant species to improve the identification of response traits to environmental gradients. The main crop and intercropped legumes were excluded from this calculation to focus the functional traits analysis solely on the weed communities. The botanical composition of weeds was calculated as follows:

$$\text{Weed botanical composition } (\%) = \left(\frac{\text{Cover of a weed species}}{\text{Total cover of all weed species}} \right) \times 100 \quad (3)$$

For each dominant weed species, seven individuals were selected for trait measurements in mid-July. These individuals were in the adult stage prior to the reproductive stage and showed no apparent damage (e.g., herbivory). The actual vegetative height of the plants (i.e., the height reached by the outermost adult leaves, expressed in cm) and canopy area (i.e., the ellipse within which their foliage lies, expressed in cm^2) were measured in the field, disturbing the existing vegetation as little as possible [42,46]. A tape measure was used to measure the height of the plants, from the base to the outermost adult leaves. The canopy area was calculated by measuring the area of the ellipse (A, cm^2) formed by the foliage using the formula:

$$A = \frac{\pi \times L \times l}{4} \quad (4)$$

where L (cm) is the length of the major axis of the ellipse representing maximum foliage length, and l (cm) is the length of the minor axis representing maximum foliage width.

To measure leaf traits, a fully developed and intact leaf (or several leaves if they were very small) was manually removed and placed in a plastic container filled with distilled water. The rest of the individual was manually harvested at the base of the stem and placed in a plastic bag containing a moist paper towel. The samples were transported to the laboratory less than 12 h after sampling and left for a minimum of 6 h in the dark at low temperature (4 °C). The leaves were then weighed to determine their water-saturated fresh mass, scanned with an Epson Perfection v800 Photo scanner (Epson, Hillsboro, OR, USA), and oven dried (60 °C) for 72 h before being weighed again to determine their dry

mass. The scanned images were analyzed with WinFOLIA Pro software version 2006a [47] to determine leaf area (LA, cm^2) and specific leaf area (SLA, $m^2\ kg^{-1}$). The leaf dry matter content (LDMC, mg g^{-1}) was calculated by dividing the dry mass of a leaf by its water-saturated fresh mass. To characterize the weed plant communities found in the quadrats, we measured the aggregated traits of these communities (i.e., $Trait_{CWM}$) using the equation adapted from Garnier et al. [44]:

$$Trait_{CWM} = \sum_{i=1}^{n} p_i \cdot trait_i \quad (5)$$

where p_i is the relative abundance of the weed species i, and $trait_i$ is the trait value of that species i. The aggregated traits were calculated using the height, canopy area, LA, SLA, and LDMC values of the species representing 80% of the weed botanical composition [40,44,45].

2.6. Statistical Analyses

The split plot statistical model was used to analyze the species richness index (S) and Shannon diversity index (H′) data with the "legume" factors (4 levels) at the main plot level and the "year" factor (2 levels) at the subplot level. These factors and their interactions are the fixed terms in the model, while "block" and "block*legume" make up the random part of the model. In the presence of significant interactions between fixed factors, this model can be used to examine variations between levels of one factor as a function of the levels of the other. One of its major advantages is its ability to make comparisons by reducing the influence of variations between blocks. Model fitting was performed using the *lme* function in the *nlme* library in R, version 4.4.2 [48]. The species richness index (S) was calculated using the *specnumber* function and the Shannon diversity index (H′) was calculated using the *diversity* function, both from the *vegan* library.

The statistical model used to compare the five aggregated leaf traits of the weed communities (i.e., height, canopy area, LA, SLA, and LDMC) is similar to the one presented above, with the difference that 2019 and 2020 were analyzed separately. This difference is justified by the fact that the dominant weed species used to achieve 80% coverage differed between the two years; the composition of the weed communities is strongly influenced by year, which made it difficult to perform an analysis combining years without hiding some significant dynamics. Model validation was based on residual analysis and assessment of homogeneity of variances. Where necessary, the data underwent a Box–Cox transformation to ensure the normality of the variables. No outliers were removed. Where the analysis revealed a significant effect of one factor, multiple comparisons were carried out using the Tukey correction, thus controlling for overall error. The differences between treatments and years were assessed by estimating the marginal means of treatment effects each year, obtained via the *emmeans* function of the *vegan* library. A redundancy analysis (RDA) was carried out to explore the relationship between aggregated leaf traits of the weed communities as response variables and intercropping treatments as explanatory variables. Weed species were also projected into the ordination to facilitate ecological interpretation of the relationship between traits and treatments. ANOVA tests were used to evaluate the results with 10,000 permutations to test the significance of the axes and explanatory variables. Lastly, a visual representation of the results was created in the form of a graph of the first two axes (RDA1 and RDA2) to provide a better understanding of the relationship between the different traits, treatments, and species, as well as the contribution of each axis to the total variance. All the statistical tests were performed at a significance level of $\alpha = 5\%$ and comparisons made with Tukey's test.

3. Results

3.1. Botanical Surveys and Composition

In total, 11 weed species were identified during botanical surveys carried out in 2019 (Table 2), the most frequent being *A. millefolium*, *D. carota*, *P. major*, *S. asper*, *T. officinale*, *U. urens*, and *V. sativa*. The last two species are the only two weeds found in all the treatments. In 2020, 26 weed species were identified, the most frequent being *E. repens*, *E. arvense*, *P. major*, *S. arvensis*, *S. asper*, *U. urens*, and *V. sativa* (Table 3). The species *E. repens*, *P. major*, and *V. sativa* were the only three weed species found in all the treatments in 2020. During the two years that the experiment ran, intercropping with *T. incarnatum* was the treatment in which weeds made up the smallest proportion of the total botanical composition (i.e., approximately 47% averaged across both years), while the *M. officinalis* treatment and the control resulted in the highest proportion of weeds (i.e., approximately 71% averaged across both years).

Table 2. Total botanical composition in 2019 in organic oat plots with or without intercropped legumes.

Species	Intercropped Legume Treatments				Family
	M. officinalis (%)	*T. incarnatum* (%)	*T. repens* (%)	Control (%)	
Avena sativa	15	18	25	38	Poaceae
Melilotus officinalis	10	0	0	0	Fabaceae
Trifolium incarnatum	0	35	0	0	Fabaceae
Trifolium repens	0	0	22	1	Fabaceae
Achillea millefolium	4	7 *	10 *	3	Asteraceae
Daucus carota	16 *,†	2	0	0	Apiaceae
Elytrigia repens	0	0	0	2	Poaceae
Gernium molle	0	2	1	1	Geraniaceae
Picris ecoides	0	0	1	0	Asteraceae
Plantago major	4	8 *	5 *	14 *	Plantaginaceae
Sonchus asper	3	3	9 *	11 *	Asteraceae
Taraxacum officinale	16 *	4 *	4	9 *	Asteraceae
Urtica urens	18 *	11 *	11 *	10 *	Urticaceae
Veronica arvensis	0	0	0	1	Plantaginaceae
Vicia sativa	14 *	10 *	12 *	10 *	Fabaceae
Total	100	100	100	100	

† In each intercropping treatment, weed species marked with an asterisk (*) are the dominant species.

Table 3. Total botanical composition in 2020 in organic oat plots with or without intercropped legumes.

Species	Intercropped Legume Treatments				Family
	M. officinalis (%)	*T. incarnatum* (%)	*T. repens* (%)	Control (%)	
Avena sativa	10	13	13	20	Poaceae
Melilotus officinalis	21	0	0	0	Fabaceae
Trifolium incarnatum	0	40	0	0	Fabaceae
Trifolium repens	0	0	25	0	Fabaceae
Carduus pycnocephalus	1	0	0	0	Asteraceae
Centranthus calcitrapae	0	1	0	0	Valerianaceae
Convolvulus arvensis	0	0	1	0	Convolvulaceae
Crepis sancta	0	2	1	1	Asteraceae
Daucus carota	0	0	0	1	Apiaceae
Diplotaxis erucoides	0	0	0	1	Brassicaceae
Elymus repens	10 *,†	10 *	9 *	15 *	Poaceae

Table 3. *Cont.*

Species	Intercropped Legume Treatments			Control (%)	Family
	M. officinalis (%)	*T. incarnatum* (%)	*T. repens* (%)		
Equisetum arvense	0	4 *	9 *	3	Equisetaceae
Erodium cicutarium	0	1	0	0	Geraniaceae
Erigeron sumatrensis	0	1	0	0	Asteraceae
Geranium rotundifolium	1	0	0	0	Geraniaceae
Medicago sp.	0	0	0	1	Fabaceae
Plantago major	13 *	6 *	11 *	20 *	Plantaginaceae
Poa annua	2	0	0	1	Poaceae
Rumex pulcher	0	0	0	1	Polygonaceae
Sonchus arvensis	6 *	4 *	0	7 *	Asteraceae
Sonchus asper	24 *	0	5 *	0	Asteraceae
Stellaria media	1	0	5	0	Caryophyllaceae
Urtica urens	6 *	12 *	15 *	16 *	Urticaceae
Veronica arvensis	1	0	1	0	Plantaginaceae
Veronica persica	0	1	0	1	Plantaginaceae
Vicia sativa	1	5 *	5 *	11 *	Fabaceae
Vicia sp.	0	0	0	1	Fabaceae
Vicia villosa	1	0	0	0	Fabaceae
Vulpia myuros	1	0	0	0	Poaceae
Vulpia sp.	1	0	0	0	Poaceae
Total	100	100	100	100	

† In each intercropping treatment, weed species identified with an asterisk (*) are the dominant species.

3.2. Species Richness (S) and Shannon Diversity (H′)

Table 4 shows the ANOVA results for the effect of the legume intercropping treatment, the year, and their interactions on the species richness index and Shannon diversity index. The results reveal a significant interaction between treatment and year ($p = 0.0222$) on the species richness index, indicating that the effect of treatments varies from one year to the next. In 2019, the *T. incarnatum*, *T. repens*, and *M. officinalis* treatments and the control had a similar mean species richness (i.e., S = 5.5 ± 0.4) and no significant differences were found between them. However, in 2020, there was a clearer hierarchy among the treatments, with the species richness of the control treatment (i.e., S = 12.2 ± 2.6) significantly higher than that of the other treatments, while the species richness of *M. officinalis* and *T. repens* (i.e., S = 8.5 ± 1.5) was significantly higher than that of the *T. incarnatum* treatment (i.e., S = 6.0 ± 1.2), which was the lowest observed.

Table 4. Analysis of variance (ANOVA) for species richness and Shannon index as affected by the intercrop legume treatment, year, and their interaction.

Term	Species Richness (S)		Shannon Index (H)	
	F-Ratio	*p*-Value	F-Ratio	*p*-Value
Treatment	1.913	0.2160	17.649	**0.0012**
Year	256.000	**<0.0001**	157.332	**<0.0001**
Treatment × Year	5.667	**0.0222**	2.045	0.1861

Our results also show that the intercropped legume treatment ($p = 0.0012$) and the year ($p < 0.0001$) have a significant impact on Shannon diversity (Table 4). The Shannon diversity indices under the *M. officinalis* and control treatments were similar and significantly higher than those of the other two treatments. It was ~10% higher than under the *T. repens* treatment and ~25% higher than under the *T. incarnatum* treatment, which had the lowest Shannon diversity index (Figure 1). Lastly, the Shannon diversity index was ~33% higher

in 2020 (i.e., H′ = 1.99 ± 0.04) than in 2019 (i.e., H′ = 1.49 ± 0.07). This shows that the communities' diversity increased in 2020.

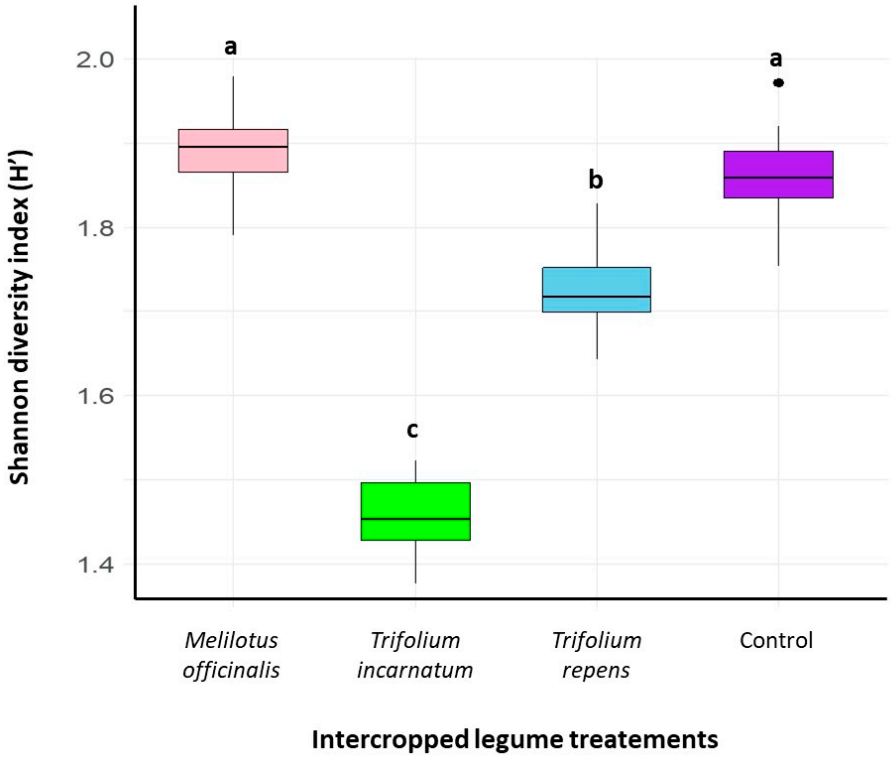


Figure 1. Comparison of Shannon diversity indices (H′) in an organic oat crop synchronously sown without (Control) or with intercropped legumes averaged over the two years of the study. The lower and upper bounds of the box represent the first and third quartiles, respectively, while the line inside the box represents the median. The vertical bars indicate the minimum and maximum values within 1.5× the interquartile range. Points above the box represent outlier data situated outside 1.5× the interquartile range. All data were included in the statistical analysis. Treatments with values associated with different letters differ significantly from each other according to Tukey's test at $p \leq 0.05$.

3.3. Species' Functional Traits

Figures 2 and 3 show the impact of treatments on the aggregated leaf traits of weed communities measured in 2019 and 2020, respectively. Mean leaf trait values for the most abundant weed species found in each treatment in 2019 and 2020 are shown in Tables A1 and A2, respectively. For information, the mean leaf trait values for the intercropped legumes in 2019 and 2020 are shown in Table A3. In 2019, the analyses revealed significant differences between the treatments only for weed SLA (Figure 2b). The SLA of weeds under *T. incarnatum* was 2.8 times higher than the SLA of those under *M. officinalis* and without intercropped legumes (i.e., the control). The SLA of weeds in the presence of *T. repens* fell between the SLA of those with *T. incarnatum* and in the control but remained higher than the SLA of those under *M. officinalis*. With respect to the other weed traits measured in 2019, the results suggest that despite certain variations observed between species, the treatments had no significant effects (Figure 2). This suggests a homogeneity of responses from these traits, with differences between treatments being limited under the experimental conditions. In 2020, our results showed that the SLA of weeds in the presence of *T. incarnatum* was, as in 2019, higher than the SLA of other treatments, but this time it was much greater than in the previous year (Figure 3b). We also noted that the LDMC was significantly higher in the weeds in the control than those in the presence of intercropped legumes (Figure 3c). The LA of the weeds in the control was also ~2-times higher than that

of weeds in the presence of *T. repens*, while the LA of the weeds with *T. incarnatum* and *M. officinalis* was between those of the other treatments (Figure 3d).

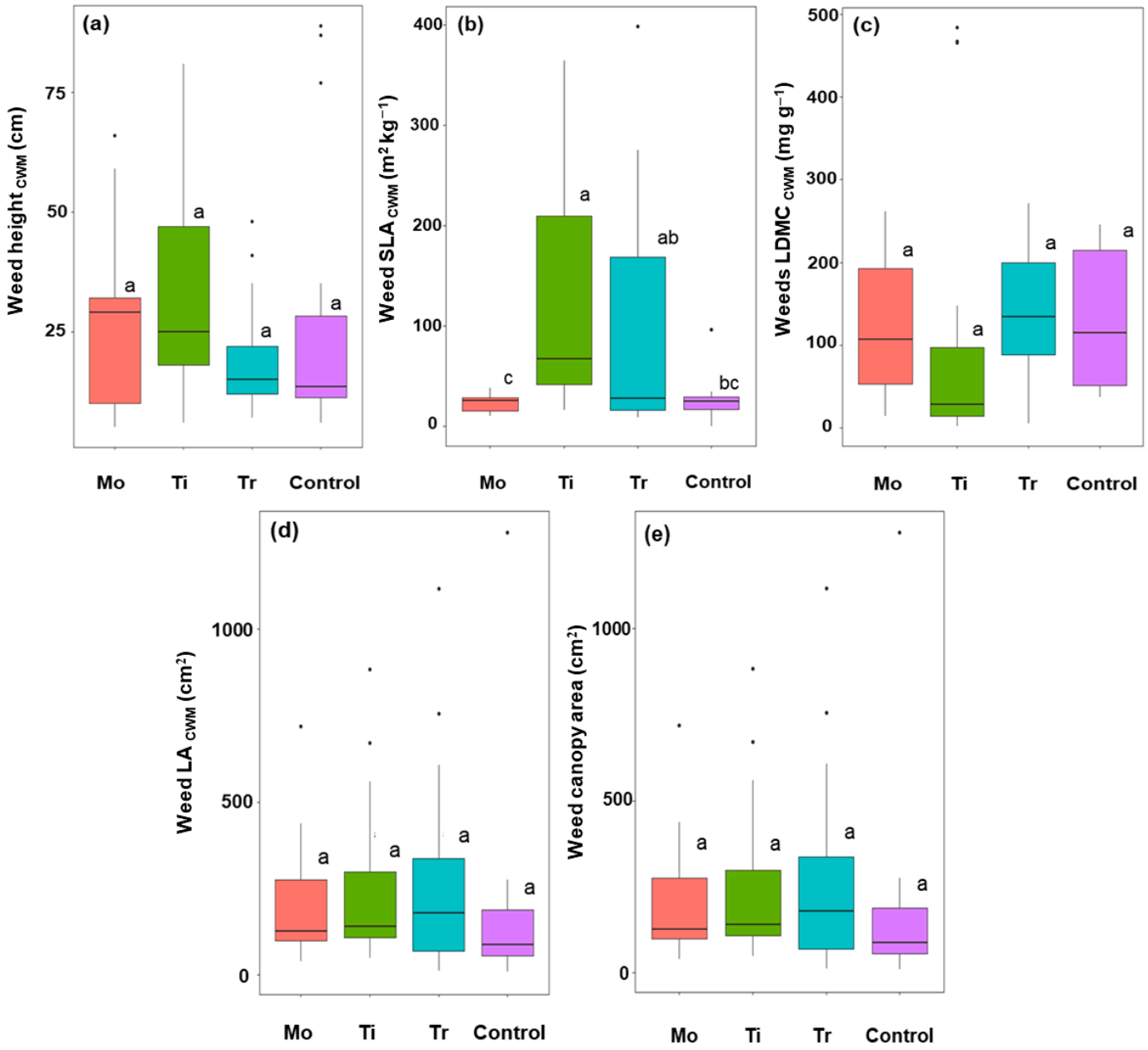


Figure 2. Aggregated traits of weed communities [i.e., (**a**) height, (**b**) specific leaf area (SLA), (**c**) leaf dry matter content (LDMC), (**d**) leaf area (LA) and (**e**) canopy area] observed in an organic oat crop in 2019, synchronously sown without (Control) or with intercropped legumes (Mo = *Melilotus officinalis*, Ti = *Trifolium incarnatum*, Tr = *Trifolium repens*). The lower and upper bounds of the box represent the first and third quartiles, respectively, while the line inside the box represents the median. The vertical bars indicate the minimum and maximum values within 1.5× the interquartile range. Points above the box represent outlier data situated outside 1.5× the interquartile range. All data were included in the statistical analysis. For each aggregated trait, treatments with values labeled with different letters are significantly different from each other according to Tukey's test at $p \leq 0.05$.

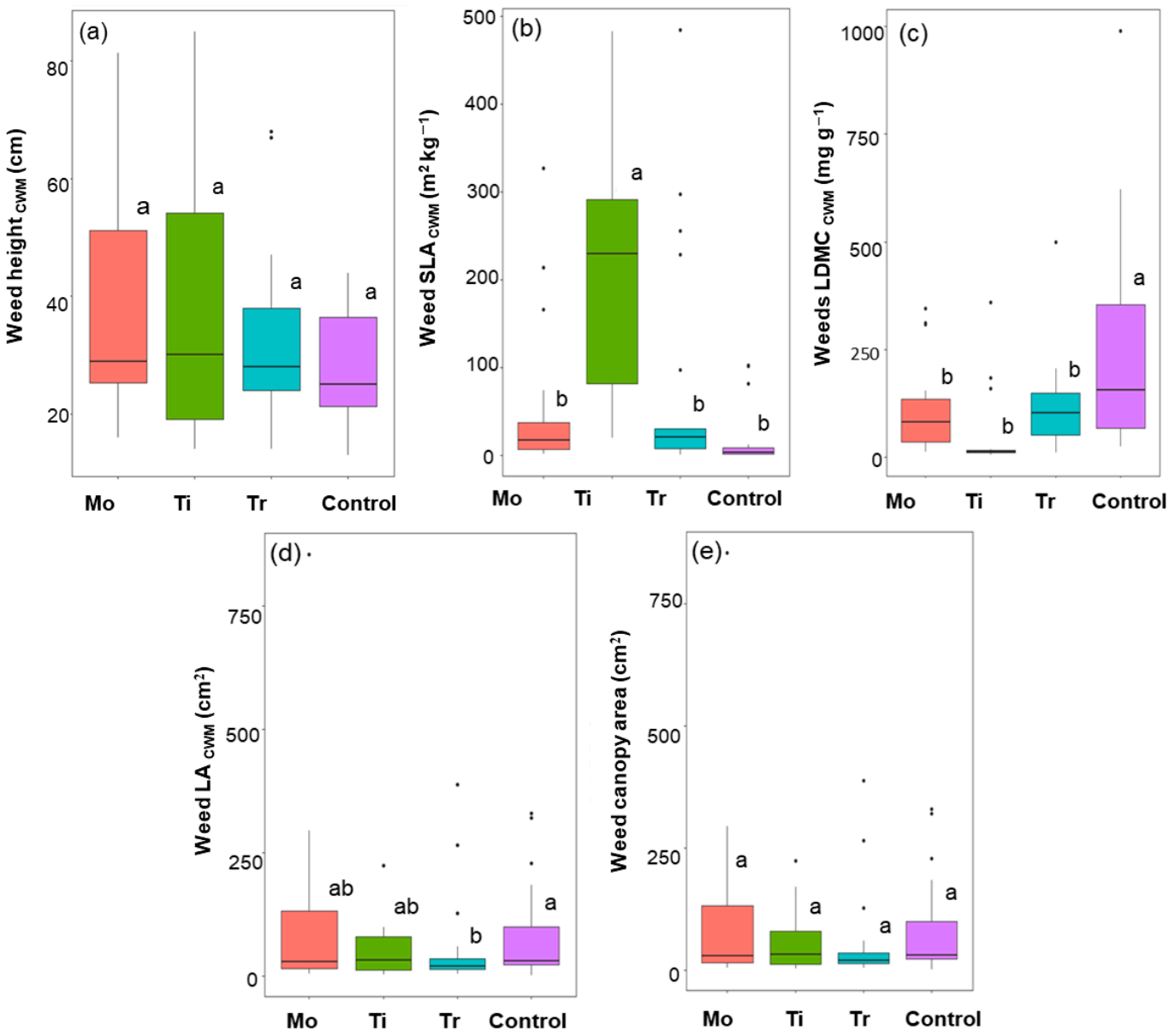


Figure 3. Aggregated traits of weed communities [i.e., (**a**) height, (**b**) specific leaf area (SLA), (**c**) leaf dry matter content (LDMC), (**d**) leaf area (LA) and (**e**) canopy area] observed in an organic oat crop in 2020, synchronously sown without (Control) or with intercropped legumes (Mo = *Melilotus officinalis*, Ti = *Trifolium incarnatum*, Tr = *Trifolium repens*). The lower and upper bounds of the box represent the first and third quartiles, respectively, while the line inside the box represents the median. The vertical bars indicate the minimum and maximum values within 1.5× the interquartile range. Points above the box represent outlier data situated outside 1.5× the interquartile range. All data were included in the statistical analysis. For each aggregated trait, treatments with values labeled with different letters are significantly different from each other according to Tukey's test at $p \leq 0.05$.

3.4. Functional Structuring of the Weed Communities

The results of the 2019 and 2020 redundancy analyses brought to light similar aspects as well as notable distinctions between the structuring of the weed communities based on the species' functional traits. In 2019, the first (RDA1) and second (RDA2) axes explained 26.79% and 17.41% of the variance, respectively, showing that a major part of the data structure can be summarized by these two axes. Nevertheless, around 55.8% of the variance remains unexplained (Figure 4). However, the ANOVA results for 2019 showed that RDA1 was significant ($p = 0.0153$) while RDA2 was not ($p = 0.1838$). The RDA1 axis distinguishes

weeds primarily on the basis of leaf dry matter content (LDMC, negative scores) on the one hand and leaf area (LA) and specific leaf area (SLA, positive scores) on the other (Figure 4). The species with positive scores on this axis are mainly *S. asper* and *D. carota*. The species with negative scores on the RDA1 axis are mainly *A. millefolium* and *U. urens*. The RDA2 axis separates the weeds primarily according to canopy area (positive scores) and height (negative scores) (Figure 4). The species with a positive score on this axis are mostly *T. officinale* and *D. carota*, while *V. sativa* and *S. asper* had mostly negative scores. The intercropping treatments are more distributed along the RDA2 axis, with the *T. repens* treatment (positive score) opposed to the *T. incarnatum* treatment (negative score), whose positioning is found in the direction of taller species (Figure 4). Nevertheless, the *T. repens* and *T. incarnatum* treatments are the only ones with positive scores on the RDA1, like SLA.

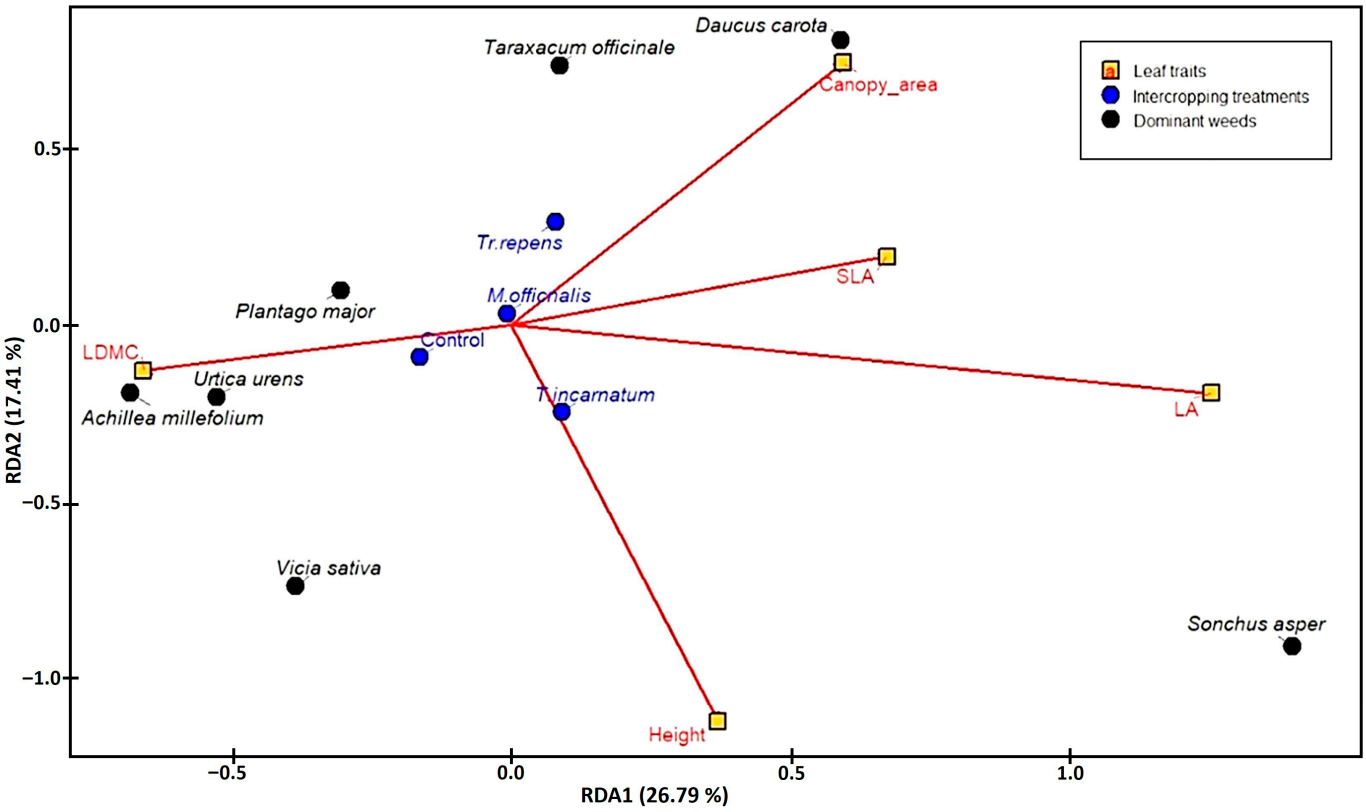


Figure 4. Redundancy analysis showing the distribution of weed leaf traits according to the dominant species in an organic oat crop in 2019, synchronously sown without (Control) or with intercropped legumes (*M. officinalis*, *T. incarnatum*, *T. repens*). SLA = specific leaf area, LDMC = leaf dry matter content, LA = leaf area.

The results of the 2020 RDA analysis indicate that the first two axes captured 29.15% (RDA1) and 18.99% (RDA2) of the variance. They accounted for 48.14% of the total variance and captured the strongest relationships between leaf traits and explanatory variables (Figure 5). The ANOVA results for 2020 showed that both RDA1 ($p < 0.001$) and RDA2 ($p < 0.0001$) were significant. The RDA1 axis contrasts LDMC (positive score) with other traits, primarily LA (negative scores). The species with positive scores on this RDA1 axis are mostly *V. sativa* and *E. arvense*, while those with negative scores are mostly *S. arvensis* and *P. major*, which is also associated with the canopy area (Figure 5). The RDA2 axis distinguishes weeds mainly on the basis of height and SLA (positive scores) on the one hand, and canopy area (negative scores) on the other.

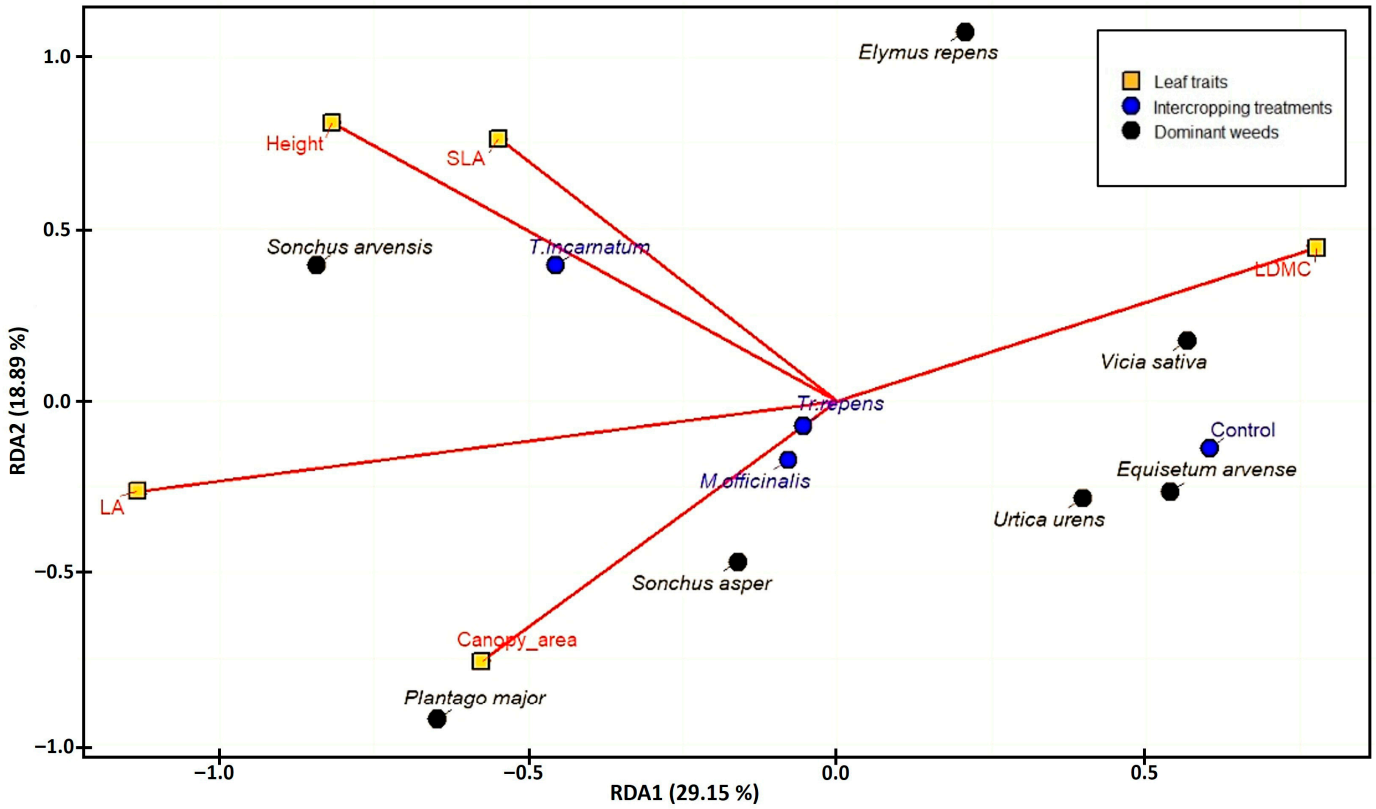


Figure 5. Redundancy analysis showing the distribution of weed leaf traits according to the dominant species in an organic oat crop in 2020, synchronously sown without (Control) or with intercropped legumes (*M. officinalis*, *T. incarnatum*, *T. repens*). SLA = specific leaf area, LDMC = leaf dry matter content, LA = leaf area.

The main species with positive scores on this axis are *E. repens* and *S. arvensis*, while *S. asper* and, especially, *P. major* had negative scores. The intercropping treatments are mainly distributed along the RDA1 axis, with the control treatment (positive scores) located opposite the *T. incarnatum* treatment (negative scores). The *T. incarnatum* treatment is strongly associated with SLA (as in 2019) as well as weed height, while the control treatment is strongly associated with LDMC (Figure 5).

4. Discussion

4.1. Structure, Diversity, and Composition of Weed Communities

Our results show that the presence of intercropped legumes in an organic oat crop favors certain species adapted to competition compared with the control without legumes, which confirms our first hypothesis. This observation is consistent with the work of Smith et al. [14], who demonstrated that cover crops such as legumes influence plant community structure by favoring certain competitive species. We found seven dominant weed species, which compares with the work of Campiglia et al. [49] where six weed species were found to be dominant. Interspecific competition between intercropped legumes and weeds leads to significant changes in the structure, diversity, and composition of weed communities, supporting certain species based on their ability to exploit resources in a competitive environment [14,50].

We observed a different evolution in the composition and diversity of weed communities between 2019 and 2020, which validates our second hypothesis. Our results show that species richness varies from one year to the next, depending on the intercropping treatments, with values comparable to those of others working in cropping systems [49,51,52].

While species richness was similar for all the treatments in 2019, it evolved in the following order: control > *M. officinalis* = *T. repens* > *T. incarnatum* in 2020. The significant interaction between treatments and year could be explained by variability in climatic conditions. The effects of agricultural practices can fluctuate depending on each year's specific environmental conditions [53]. In spring 2019, there were fewer growing degree-days and precipitation was more abundant (Table 1); growing conditions were less favorable than they were in spring 2020. The failure of intercropping treatments to impact species richness could be attributed to complex ecological factors, such as limited resource availability under less favorable environmental conditions [50]. In spring 2020, more favorable conditions may have reduced constraints on the growth of intercropped legumes and weeds, allowing for a better expression of differences between treatments. Overall, our observations concur with those of previous studies showing that climatic and environmental conditions strongly influence the composition of plant communities from one year to the next [54].

The values of Shannon diversity indices (H′) found in our work are <2, which is similar to values reported in the literature in cropping systems [49,51,52]. Furthermore, Shannon diversity is significantly influenced by year and treatments, which suggests that inter-row management, through the use of intercropped legumes, can play a key role in structuring plant communities. More specifically, the ~33% increase in H′ observed in 2020 compared with 2019 concords with what Légère et al. [51] observed in a barley-red clover rotation on a heavy clay soil. Possible explanations could be linked to more favorable climatic conditions, as mentioned above, or to adjustments in interspecific competition, as suggested by Werner et al. [54]. Data presented by Yue et al. [55] showed that warming increased H′ values of grassland species under similar climatic conditions as in our study. However, as underlined by Légère et al. [51], more data covering consecutive years are needed to determine whether this trend is sustained over time.

The *M. officinalis* treatment and the control presented the highest Shannon diversity indices, reflecting greater weed species diversity than the *T. repens* and *T. incarnatum* treatments. As suggested by Campligia et al. [49], a reduced H′ under *T. incarnatum* indicates strong suppressive ability of this species against weeds. Sowing *T. incarnatum* resulted in a decrease in weed diversity compared with other intercropping treatments, an indication of the legume's dominance and its soil cover ability, thereby limiting resources and weed growth. The height of *T. incarnatum* was 2.0 to 2.2 times greater than that of *T. repens* in our study (see Table A3), which is comparable to what was found by Ross et al. [56]. The latter study demonstrated that *T. incarnatum* has good weed suppression capacity. Its long and erect stem provides an advantage over shorter intercropped species in reducing weed density and biomass through competition for light, water, and nutrients [9,56]. Using *T. incarnatum* in our SI system likely modified environmental factors that affected weed germination, establishment and growth; the presence of this species may have accelerated canopy closure and increased soil cover, thus decreasing the amount of radiation available for weeds and restricting their establishment [10,57–60]. The use of this legume in rotations or as an intercropped crop results in effective weed control, particularly in organic agricultural systems [53].

The weeds *V. Sativa* and *U. urens* are two species found in all the intercropping treatments in 2019. The species *V. sativa* is a nitrogen-fixing leguminous plant with a competitive edge in nutrient-poor systems and is highly resistant to the main crop and other weeds [61]. Meanwhile, *U. urens* is regularly found in disturbed environments since it is highly competitive for light and resources [62]. Both of these species demonstrate their ability to colonize and dominate the environment in which they are found, while resisting environmental variations. Among the species found in 2020, some were very abundant in all the treatments, particularly *E. repens*, *P. major*, and *U. urens*. These species

are among the most generalist weeds able to withstand a wide range of management and ecological conditions in annual crop fields [63]. The presence of the two latter species (i.e., *P. major*, and *U. urens*) among the most abundant ones during both years could be the result of sowing the same crop two years in a row in the same field. This may have led to increased seed production and addition to the soil seedbank for these species and favored their specialization and dominance [64]. Overall, our results underscore the importance of considering both temporal factors and specific treatments in the study of ecological community diversity [63].

4.2. Functional Structure Response

Our third hypothesis stipulating that weed growth strategies vary according to treatment and that this influences the functional structure of plant communities was validated. Weed growth strategies reveal marked differences in their responses to intercropping treatments. In particular, our results show that (1) the SLA of weeds was higher under the *T. incarnatum* treatment in 2019 and even more so in 2020, and (2) weed LDMC was higher in the control than in the presence of intercropped legumes in 2020. There is a fundamental trade-off between leaf traits for rapid acquisition and effective resource conservation [65]. Plant species characterized by a high SLA and low LDMC are positioned among the "acquisitive" species along the leaf economic spectrum, while "conservative" species are characterized by a low SLA and a high LDMC [20,65,66]. Acquisitive plants species have a high rate of resource (i.e., light, water, nutrients) acquisition and poor resource conservation, while conservative ones have opposite characteristics [40]. The values noted for the SLA of the weed community under *T. incarnatum* in our work correspond to those positioned at highest end (i.e., >100 m^2 kg^{-1}) of the leaf economic spectrum [40]. *T. incarnatum* is the intercropped legume that contributed the most to total botanical composition in both years of the trial. We postulated that this species may have enriched the soil by fixing atmospheric N and returning N-rich biomass, creating a resource-rich environment favorable to acquisitive species with a high SLA, such as *S. arvensis*, *P. major*, and *V. sativa*, although this would need to be confirmed experimentally. Nevertheless, these species adopt a rapid growth strategy, with larger, thinner leaves, typical of R strategies that favor rapid reproduction and high competitiveness [67,68].

According to Lambers & Poorter [69], a high SLA seems to be the trait that most explains a higher specific growth rate observed in some species than in others, i.e., a greater gain in grams of biomass produced per gram of existing biomass per day. Weeds with a high SLA such as *S. arvensis*, *P. major*, and *V. sativa* could thus have a high specific growth rate. There is a positive relationship between specific growth rate and leaf nitrogen content [70]. Since the weed community associated with the intercropped legume *T. incarnatum* has a high SLA, perhaps the leaf nitrogen content is also high. This would further enrich the environment, further encouraging the growth of weeds whose growth strategy is based on resource acquisition. In contrast, the weed community found in the control treatment had a lower SLA than that of the *T. incarnatum* treatment in 2019 and a higher LDMC than those of the other treatments in 2020. These species are characterized by a growth strategy focused on effective resource conservation and an ability to persist under less favorable conditions [20,65,66]. They include *A. millefolium*, *U. urens*, and *Elymus repens*. The low specific growth rate of "conservative" species appears to be better adapted to poor environments [71]. From a weed management perspective, the use of *T. incarnatum* as an intercrop with oats in an SI system reduced weed diversity and establishment but promoted a weed community whose resource-acquisition strategy could compete with the main crop. In contrast, the control treatment without legumes in intercropping led to the development of a less competitive weed community with a resource conservation strategy,

but one that was much more diverse and able to establish and persist. Further work over several consecutive years is needed to determine which weed management strategy is most sustainable in the long term.

5. Conclusions

The novelty of this study highlighted the fact that legumes synchronously intercropped with an organic oat crop influence the richness, abundance, and taxonomic and functional diversity of weeds. The *T. incarnatum* treatment reduced weed cover due to competition from its canopy area, offering a considerable advantage over the other three treatments. It could enrich the soil through nitrogen fixing and the above-ground and root biomass produced, but this was not measured in our work and would need to be evaluated experimentally. However, this sown cover favors weeds whose growth strategy is focused on acquiring resources that could compete with the main crop. In contrast, *M. officinalis* and *T. repens* treatments and the control promoted more diverse communities focused on resource conservation. The effect of year on botanical composition underscores the importance of climatic conditions that modulate weed responses to cultural practices. The assessment of the functional traits of dominant species and the aggregated traits of communities offers a mechanistic look at the response of weeds to changes in agronomic practices and environmental conditions. Our results demonstrate the importance of intercropped legumes as agroecological levers to better manage weeds in organic field crops. The novel results presented in this work could provide agronomists and crop producers indications on the level of competition that weeds exert on cropping system depending on the SI treatment chosen. Regardless of the legumes used in SI, our finding emphasizes the need to vary crops from year to year through rotations to limit the development and dominance of weeds. However, further research is needed to assess the impacts of synchronous intercropping from an agronomic viewpoint, particularly its impact on the quantity and quality of oat yields and soil nutrients, to offer a complementary vision to the ecological perspective of our work. Future work could also be carried out at other sites under different pedoclimatic conditions to assess whether our results can be replicated.

Author Contributions: Conceptualization, I.C. and V.P.; methodology, I.C. and V.P.; software, I.C.; validation, I.C., N.Z. and V.P.; formal analysis, I.C.; investigation, I.C. and V.P.; resources, V.P. and N.Z.; data curation, I.C. and V.P.; writing—original draft preparation, I.C.; writing—review and editing, I.C., N.Z. and V.P.; visualization, I.C. and V.P.; supervision, N.Z. and V.P.; project administration, V.P.; funding acquisition, I.C., N.Z. and V.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SLA	Specific Leaf Area
LA	Leaf area
LDMC	Leaf Dry Matter Content

Appendix A

Table A1. Mean (±standard deviation) of leaf trait values for the most abundant weed species in each intercropped legume treatment (Mo = *Melilotus officinalis*, Ti = *Trifolium incarnatum*, Tr = *Trifolium repens*, Control = control) in 2019.

Weeds	Mo	Ti	Tr	Control
Height (cm)				
Achillea millefolium	-	32.7 (14.0)	12.3 (5)	-
Daucus carota	7.0 (2.2)	-	-	-
Sonchus asper	-	-	41.0 (7.0)	29.3 (6.0)
Plantago major	-	11.7 (1.5)	11.0 (1.5)	13.0 (2.6)
Taraxacum officinale	12.0 (1.7)	21.0 (11.5)	-	10.7 (4.2)
Urtica urens	30.3 (1.5)	41.7 (13.8)	32.0 (17.7)	12.7 (6.4)
Vicia sativa	31.3 (1.2)	16.3 (9.6)	17.7 (4.9)	84.3 (6.4)
Specific Leaf Area (SLA, m^2 kg^{-1})				
Achillea millefolium	-	25.9 (6.5)	19.4 (13.9)	-
Daucus carota	28.8 (5.4)	-	-	-
Sonchus asper	-	-	44.9 (31.4)	38.0 (20.0)
Plantago major	-	134 (115)	231.9 (55.7)	49.6 (40.6)
Taraxacum officinale	33.7 (4.5)	38.1 (25.2)	-	20.1 (6.9)
Urtica urens	25.1 (2.0)	218 (2)	17.8 (1.2)	28.5 (3.5)
Vicia sativa	17.8 (8.2)	299 (80)	24.2 (9.3)	13.8 (14.7)
Leaf Dry Matter Content (LDMC, mg g^{-1})				
Achillea millefolium	-	472 (9)	315 (111)	-
Daucus carota	182 (111)	-	-	-
Sonchus asper	-	-	24 (5)	63.1 (34)
Plantago major	-	129 (114)	123 (103)	45.0 (35.0)
Taraxacum officinale	38.0 (16.0)	89 (63)	-	42.6 (4.5)
Urtica urens	232 (33)	179 (148)	233 (33)	240 (6)
Vicia sativa	152 (4)	15.7 (2.1)	163 (36)	76.6 (35.6)
Leaf area (LA, cm^2)				
Achillea millefolium	-	1.8 (0.1)	0.7 (0.4)	-
Daucus carota	16.6 (5.4)	-	-	-
Sonchus asper	-	-	14.6 (2.5)	13.0 (4)
Plantago major	-	4.7 (0.4)	20.4 (8.4)	17.8 (5.1)
Taraxacum officinale	2.5 (0.9)	1.9 (1.03)	-	1.7 (0.8)
Urtica urens	6.9 (7.5)	1.3 (0.4)	1.1 (0.1)	1.4 (0.4)
Vicia sativa	2.5 (0.4)	3.1 (0.5)	3.1 (0.9)	0.9 (0.5)
Canopy area (cm^2)				
Achillea millefolium	-	141 (106)	176 (98)	-
Daucus carota	464 (230)	-	-	-
Sonchus asper	-	-	71 (40)	68 (35)
Plantago major	-	93 (29)	192 (110)	123 (90)
Taraxacum officinale	211 (196)	501 (332)	-	186 (94)
Urtica urens	187 (134)	302 (238)	95 (88)	90 (30)
Vicia sativa	146 (40)	89 (35)	103 (52)	130 (103)

Table A2. Mean (±standard deviation) of leaf trait values for the most abundant weed species in each intercrop legume treatment (MO = *Melilotus officinalis*, TI = Trifolium *incarnatum*, TR = *Trifolium repens*, Control = without legumes) in 2020.

Weeds	Mo	Ti	Tr	Control
Height (cm)				
Elymus repens	26.7 (1.7)	2.4 (1.1)	33.0 (5.0)	42.2 (0.8)
Equisetum arvense	-	2.4 (1.3)	30.2 (3.4)	-
Plantago major	30.6 (1.4)	23.4 (5.8)	31.0 (7.8)	25.7 (2.1)
Sonchus arvensis	30.4 (1.4)	26.2 (0.9)	-	36.6 (3.5)
Sonchus asper	77.2 (3.5)	-	17.9 (3.7)	-
Urtica urens	22.3 (5.5)	3.1 (0.6)	32.6 (7.6)	22.6 (0.3)
Vicia sativa	-	3.8 (1.1)	23.9 (1.7)	14.7 (0.5)
Specific Leaf Area (SLA, m^2 kg^{-1})				
Elymus repens	235 (83)	335 (35)	254 (56)	8.3 (3.6)
Equisetum arvense	-	38.9 (24.1)	76.8 (59.2)	-
Plantago major	6.5 (1.1)	222 (80)	260 (35)	2.78 (2.8)
Sonchus arvensis	38.5 (3.0)	220 (50)	-	2.7 (2.1)
Sonchus asper	33.7 (5.2)	-	15.4 (4.4)	-
Urtica urens	4.5 (2.9)	88.4 (52.8)	23.4 (13.5)	3.2 (0.3)
Vicia sativa	-	358 (110)	23.4 (8.4)	1.5 (0.5)
Leaf Dry Matter Content (LDMC, mg g^{-1})				
Elymus repens	322 (21)	235 (109)	201 (26)	396 (1)
Equisetum arvense	-	16.2 (0.6)	152 (21)	-
Plantago major	18.3 (7.3)	10.3 (3.2)	11.8 (0.6)	301 (2)
Sonchus arvensis	38.8 (22.8)	11.5 (0.9)	-	77.2 (3.6)
Sonchus asper	98.6 (16.3)	-	116 (42.2)	-
Urtica urens	49.5 (22.2)	8.6 (3.3)	63.5 (47.8)	92.1 (0.3)
Vicia sativa	-	15.6 (2.2)	164 (37)	525 (1)
Leaf area (LA, cm^2)				
Elymus repens	2.3 (0.3)	9.9 (9.7)	5.1 (0.5)	1.7 (0.9)
Equisetum arvense	-	2.4 (1.3)	0.7 (0.2)	-
Plantago major	1.9 (0.8)	158 (72)	28.4 (4.9)	8.5 (1.3)
Sonchus arvensis	16.8 (6.6)	37.6 (24)	-	7.4 (3.6)
Sonchus asper	22.2 (1.7)	-	20.3 (5.7)	-
Urtica urens	1.3 (0.5)	14.1 (2.1)	5.1 (0.5)	1.2 (0.3)
Vicia sativa	-	99.9 (25.3)	3.0 (0.7)	0.9 (0.5)
Canopy area (cm^2)				
Elymus repens	6.3 (2.1)	55.9 (6.3)	42.1 (21.7)	113 (1)
Equisetum arvense	-	26.1 (18.2)	29.3 (5.5)	-
Plantago major	431 (375)	20.9 (6.7)	260 (130)	292 (2)
Sonchus arvensis	173 (67)	83.4 (2.1)	-	26.3 (3.5)
Sonchus asper	20.8 (1.9)	-	4.9 (1.2)	-
Urtica urens	2.2 (3.4)	20.1 (6.7)	15.9 (5.7)	23.0 (7.8)
Vicia sativa	-	37.9 (5.5)	16.3 (3.3)	3.9 (0.5)

Table A3. Mean (standard ± deviation) of leaf trait values for intercrop legume species in 2019 and 2020.

Legume Species	Height (cm)	SLA [1] (m^2 kg^{-1})	LDMC [2] (mg g^{-1})	LA [3] (cm^2)	Canopy Area (cm^2)
2019					
Melilotus officinalis (Mo)	29.0 (2.1)	17.8 (1.2)	222 (62)	3.0 (0.8)	159 (138)
Trifolium incarnatum (Ti)	44.5 (6.7)	38.1 (25.2)	119 (62)	1.9 (1.0)	173 (114)
Trifolium repens (Tr)	19.8 (1.9)	26.3 (5.7)	198 (57)	1.7 (0.5)	323 (234)
2020					
Melilotus officinalis (Mo)	9.9 (2.7)	33.4 (2.8)	231 (28)	3.8 (0.9)	133 (62)
Trifolium incarnatum (Ti)	34.0 (2.0)	36.0(13.6)	180 (14)	10.5 (3.0)	36.9 (9.1)
Trifolium repens (Tr)	16.8 (1.6)	45.0 (15.0)	96.2 (32.6)	6.7 (1.9)	40 (15)

[1] SLA = Specific Leaf Area; [2] LDMC = Leaf Dry Matter Content; [3] LA = Leaf Area.

References

1. Willer, H.; Trávníček, J.; Schlatter, B. (Eds.) *The World of Organic Agriculture. Statistics and Emerging Trends 2025*; Research Institute of Organic Agriculture FiBL, Frick, and IFOAM—Organics International: Bonn, Germany, 2025; 350p.
2. Agriculture et Agroalimentaire Canada (AAC). *Canada: Perspectives des Principales Grandes Cultures 2025—Rapport du Groupe de L'analyse du Marché, Division des Cultures et de L'horticulture, Direction du Développement et de L'analyse du Secteur, Direction Générale des Services à L'industrie et Aux Marchés*; Gouvernement du Canada: Ottawa, ON, Canada, 2025; 15p.
3. Reganold, J.P.; Wachter, J.M. Organic agriculture in the twenty-first century. *Nat. Plants* **2016**, *2*, 15221. [CrossRef]
4. Halde, C.; Gagné, S.; Charles, A.; Lawley, Y. Organic No-Till Systems in Eastern Canada: A Review. *Agriculture* **2017**, *7*, 36. [CrossRef]
5. Gaba, S.; Fried, G.; Kazakou, E.; Chauvel, B.; Navas, M.-L. Agroecological weed control using a functional approach: A review of cropping systems diversity. *Agron. Sustain. Dev.* **2014**, *33*, 103–119. [CrossRef]
6. Reboud, X.; Bedoussac, L.; Cellier, V.; Cordeau, S.; Delzon, S.; Leclerc, M.; Jouan, J. Mobiliser les agroéquipements et le numérique pour des systèmes de culture sans pesticides—Chapitre 6. In *Zéro Pesticide. Un Nouveau Paradigme de Recherche Pour Une Agriculture Durable*; Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Malausa, T., Reboud, C., Huyghe, C., Eds.; Éditions Quae: Versailles, France, 2022; pp. 117–194.
7. MacLaren, C.; Storkey, J.; Menegat, A.; Metcalfe, H.; Dehnen-Schmutz, K. An ecological future for weed science to sustain crop production and the environment: A review. *Agron. Sustain. Dev.* **2020**, *40*, 24. [CrossRef]
8. Singh, S.P.; Rani, V.; Sengar, R.S.; Gupta, S. Weed management in organic farming for better crop production. *Progress. Agric.* **2022**, *22*, 117–125. [CrossRef]
9. Liebman, M.; Dyck, E. Crop rotation and intercropping strategies for weed management. *Ecol. Appl.* **1993**, *3*, 92–122. [CrossRef]
10. Verret, V.; Gardarin, A.; Pelzer, E.; Médiène, S.; Makowski, D.; Valantin-Morison, M. Can legume companion plants control weeds without decreasing crop yield? A meta-analysis. *Fiedl Crops Res.* **2017**, *204*, 158–168. [CrossRef]
11. Vannasse, A.; Thibaudeau, S.; Weil, A. *Guide des Cultures de Couvertures en Grandes Cultures*; Centre de Référence en Agriculture et Agroalimentaire du Québec (CRAAQ): Québec, QC, Canada, 2022; 204p.
12. Abad, J.; Hermoso de Mendoza, I.; Marín, D.; Orcaray, L.; Santesteban, L.G. Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard. *OENO One* **2021**, *55*, 295–312. [CrossRef]
13. Garcia, L.; Celette, F.; Gary, C.; Ripoche, A.; Valdés-Gómez, H.; Métay, A. Management of service crops for the provision of ecosystem services in vineyards: A review. *Agric. Ecosyst. Environ.* **2018**, *251*, 158–170. [CrossRef]
14. Smith, R.G.; Lounsbury, N.P.; Palmer, S.A. Mechanisms of Weed Suppression by Cover Crops, Intercrops, and Mulches—Chapter 10. In *Weed Management in Organic Agriculture*; Korres, N.E., Travlos, I.S., Gitsopoulos, T.K., Eds.; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2023; pp. 172–195. [CrossRef]
15. Gardarin, A.; Celette, F.; Naudin, C.; Piva, G.; Valantin-Morison, M.; Vrignon-Brenas, S.; Verret, V.; Médiène, S. Intercropping with service crops provides multiple services in temperate arable systems: A review. *Agron. Sustain. Dev.* **2022**, *42*, 39. [CrossRef]
16. Gerhards, R. Weed suppression ability and yield impact of living mulch in cereal crops. *Agriculture* **2018**, *8*, 39. [CrossRef]
17. Zhang, H.; Liu, C.; Mao, L.; Li, Y.; Shen, Y. Divergent response of hay and grain yield of oat: Effects of environmental factors and sowing rate. *J. Sci. Food. Agric.* **2023**, *103*, 233–242. [CrossRef]
18. Food and Agriculture Organization of the United Nations. FAOSTAT Database: Oats. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 8 December 2025).
19. Damour, G.; Garnier, E.; Navas, M.L.; Dorel, M.; Risède, J.-M. Using functional traits to assess the services provided by cover plants: A review of potentialities in banana cropping systems. *Adv. Agron.* **2015**, *130*, 81–133. [CrossRef]
20. Tribouillois, H.; Fort, F.; Cruz, P.; Charles, R.; Flores, O.; Garnier, E.; Justes, E. A functional characterisation of a wide range of cover crop species: Growth and nitrogen acquisition rates, leaf traits and ecological strategies. *PLoS ONE* **2015**, *10*, e0122156. [CrossRef]
21. Brown, R.L.; Jacobs, L.A.; Peet, R.K. Species richness: Small scale. In *Encyclopedia of Life Sciences*; John Wiley & Sons, Ltd.: Chichester, UK, 2007. Available online: https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470015902.a0020488 (accessed on 8 December 2025).
22. Spellerberg, I.F.; Fedor, P.J. A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the 'Shannon–Wiener' Index. *Glob. Ecol. Biogeogr.* **2003**, *12*, 177–179. [CrossRef]
23. Violle, C.; Navas, M.-L.; Vile, D.; Kazakou, E.; Fortunel, C.; Hummel, I.; Garnier, E. Let the concept of trait be functional! *Oikos* **2007**, *116*, 882–892. [CrossRef]
24. Díaz, S.; Kattge, J.; Cornelissen, J.H.C.; Wright, I.J.; Lavorel, S.; Dray, S.; Gorné, L.D.; Wirth, C. The global spectrum of plant form and function. *Nature* **2016**, *529*, 167–171. [CrossRef] [PubMed]
25. Kazakou, E.; Fried, G.; Richarte, J.; Gimenez, O.; Violle, C.; Metay, A. A plant trait-based response-and-effect framework to assess vineyard inter-row soil management. *Bot. Lett.* **2016**, *163*, 373–388. [CrossRef]

26. Environment and Climate Change Canada. Canadian Climate Normals and Averages (1981–2010). 2025. Available online: https://climate.weather.gc.ca/climate_normals/index_e.html (accessed on 30 December 2025).
27. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
28. Rompre, M.; Carrier, D. *Études Pédologiques des Sols Défrichés de L'Abitibi-Témiscamingue*; Centre de Recherche et D'expérimentation en sols, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec: Québec, QC, Canada, 1997; 133p.
29. *Groupe de Travail sur la Classification des Sols. Le Système Canadien de Classification des Sols*, 3rd ed.; Direction de la Recherche, Agriculture et Agro-Alimentaire du Canada: Ottawa, ON, Canada, 2002; 196p.
30. Joly, A.; Bonnet, P.; Goëau, H.; Barbe, J.; Selmi, S.; Champ, J.; Dufour-Kowalski, S.; Affouard, A.; Carré, J.; Molino, J.-F.; et al. A look inside the Pl@ntNet experience. *Multimed. Syst.* **2016**, *22*, 751–766. [CrossRef]
31. Neto-Bradley, B.M.; Bonnet, P.; Goëau, H.; Joly, A.; Cavender-Bares, J.; Coomes, D.A. Using reflectance spectra and Pl@ntNet to identify herbarium specimens: A case study with Lithocarpus. *New Phytol.* **2025**. [CrossRef]
32. Flora of North America Editorial Committee. *Flora of North America: North of Mexico—Volume 2, Pteridophytes and Gymnosperms*; Oxford University Press: Oxford, UK, 1993; 496p.
33. Flora of North America Editorial Committee. *Flora of North America: North of Mexico—Volume 3, Magnoliophyta: Magnoliidae and Hamamelidae*; Oxford University Press: Oxford, UK, 1997; 616p.
34. Flora of North America Editorial Committee. *Flora of North America: North of Mexico—Volume 11, Fabaceae*; Oxford University Press: Oxford, UK, 2013; 1108p.
35. Flora of North America Editorial Committee. *Flora of North America: North of Mexico—Volume 17, Tetrachondraceae to Orobanchaceae*; Oxford University Press: Oxford, UK, 2019; 768p.
36. Flora of North America Editorial Committee. *Flora of North America: North of Mexico—Volume 19, Asteraceae, Part 1*; Oxford University Press: Oxford, UK, 2006; 610p.
37. Flora of North America Editorial Committee. *Flora of North America: North of Mexico—Volume 24, Poaceae, Part 1*; Oxford University Press: Oxford, UK, 2007; 944p.
38. Peratoner, G.; Pötsch, E.M. Methods to describe the botanical composition of vegetation in grassland research. *Die Bodenkultur J. Land Manag. Food Environ.* **2019**, *70*, 1–18. [CrossRef]
39. Daubenmire, R.F. A canopy-coverage method of vegetational analysis. *Northwest Sci.* **1959**, *33*, 43–64.
40. Garnier, E.; Navas, M.-L.; Grigulis, K. *Plant Functional Diversity: Organism Traits, Community Structure, and Ecosystem Properties*; Oxford University Press: Oxford, UK, 2016; 231p.
41. Shannon, C.E.; Weaver, W. *The Mathematical Theory of Communication*; University of Illinois Press: Urbana, IL, USA, 1949; 125p.
42. Pérez-Harguindeguy, N.; Díaz, S.; Garnier, E.; Lavorel, S.; Poorter, H.; Jaureguiberry, P.; Bret-Harte, M.S.; Cornwell, W.K.; Craine, J.; Gurvich, D.E.; et al. New handbook for standardised measurement of plant functional traits worldwide. *Aust. J. Bot.* **2013**, *61*, 167–234, Corrigendum in *Aust. J. Bot.* **2016**, *64*, 715–716. [CrossRef]
43. Grime, J.P.; Hodgson, J.G.; Hunt, R. *Comparative Plant Ecology: A Functional Approach to Common British Species*; Springer: Dordrecht, The Netherlands, 1988; 742p.
44. Garnier, E.; Cortez, J.; Billès, G.; Navas, M.-L.; Roumet, C.; Debussche, M.; Laurent, G.; Blanchard, A.; Aubry, D.; Bellmann, A.; et al. Plant functional markers capture ecosystem properties curing secondary succession. *Ecology* **2004**, *85*, 2630–2637. [CrossRef]
45. Laughlin, D.C. The intrinsic dimensionality of plant traits and its relevance to community assembly. *J. Ecol.* **2014**, *102*, 186–193. [CrossRef]
46. Cornelissen, J.H.C.; Lavorel, S.; Garnier, E.; Díaz, S.; Buchmann, N.; Gurvich, D.E.; Poorter, H.; Steege, H.T.; Morgan, H.D.; Van Der Heijden, M.G.A.; et al. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. *Aust. J. Bot.* **2003**, *51*, 335–380. [CrossRef]
47. Regent Instruments. *WinFOLIA Software Pro Version 2006a for Windows*; Regent Instruments Inc.: Québec, QC, Canada, 2006.
48. R Core Team. *R: A Language and Environment for Statistical Computing Version 4.1.1*; R Foundation for Statistical Computing: Vienna, Austria, 2021. Available online: https://www.R-project.org/.
49. Campiglia, E.; Radicetti, E.; Mancinelli, R. Weed control strategies and yield response in a pepper crop (*Capsicum annuum* L.) mulched with hairy vetch (*Vicia villosa* Roth.) and oat (*Avena sativa* L.) residues. *Crop Prot.* **2012**, *33*, 65–73. [CrossRef]
50. Aerts, R. Interspecific competition in natural plant communities: Mechanisms, trade offs and plant soil feedbacks. *J. Exp. Bot.* **1999**, *50*, 29–37. [CrossRef]
51. Légère, A.; Stevenson, F.C.; Benoit, D.L. Diversity and assembly of weed communities: Contrasting responses across cropping systems. *Weed Res.* **2005**, *45*, 303–315. [CrossRef]
52. Stevenson, F.C.; Légère, A.; Simard, R.R.; Angers, D.A.; Pageau, D.; Lafond, J. Weed species diversity in spring barley varies with crop rotation and tillage, but not with nutrient source. *Weed Sc.* **1997**, *45*, 798–806. [CrossRef]
53. Teasdale, J.R.; Brandsæter, L.O.; Calegari, A.; Neto, F.S. Cover crops and weed management. In *Non-Chemical Weed Management: Principles, Concepts and Technology*; Upadhyaya, M.K., Blackshaw, R.E., Eds.; CABI: Wallingford, UK, 2007; pp. 49–64. [CrossRef]

54. Werner, C.M.; Stuble, K.L.; Groves, A.M.; Young, T.P. Year effects: Interannual variation as a driver of community assembly dynamics. *Ecology* **2020**, *101*, e03104. [CrossRef]
55. Yue, K.; Jarvie, S.; Senior, A.M.; Van Meerbeek, K.; Peng, Y.; Ni, X.; Wu, F.; Svenning, J.-C. Changes in plant diversity and its relationship with productivity in response to nitrogen addition, warming and increased rainfall. *Oikos* **2020**, *129*, 939–952. [CrossRef]
56. Ross, S.M.; King, J.R.; Izaurralde, R.C.; O'Donovan, J.T. Weed suppression by seven clover species. *Agron. J.* **2001**, *93*, 820–827. [CrossRef]
57. Liebman, M.; Davis, A.S. Integration of soil, crop and weed management in low-external-input farming systems. *Weed Res.* **2002**, *40*, 27–47. [CrossRef]
58. Uchino, H.; Iwama, K.; Jitsuyama, Y.; Yudate, T.; Nakamura, S. Yield losses of soybean and maize by competition with interseeded cover crops and weeds in organic-based cropping systems. *Field Crops Res.* **2009**, *113*, 342–351. [CrossRef]
59. Jamshidi, K.; Yousefi, A.R.; Oveisi, M. Effect of cowpea (*Vigna unguiculata*) intercropping on weed biomass and maize (*Zea mays*) yield. *N. Z. J. Crop Hortic. Sci.* **2013**, *41*, 180–188. [CrossRef]
60. Bilalis, D.; Papastylianou, P.; Konstantas, A.; Patsiali, S.; Karkanis, A.; Efthimiadou, A. Weed-suppressive effects of maize-legume intercropping in organic farming. *Int. J. Pest. Manage.* **2010**, *56*, 173–181. [CrossRef]
61. Juhász, C.; Mendler-Drienyovszki, N.; Magyar-Tábori, K.; Zsombik, L. Evaluation of chemical weed-control strategies for common vetch (*Vicia sativa* L.) and sweet white lupine (*Lupinus albus* L.) under field conditions. *Agronomy* **2025**, *15*, 916. [CrossRef]
62. Coleman, M.; Kristiansen, P.E.; Sindel, B.M.; Fyfe, C. *Dwarf Nettle (Urtica urens): Weed Management Guide for Australian Vegetable Production*; School of Environmental and Rural Science, University of New England: Armidale, Australia, 2018; 12p.
63. Fried, G.; Blanchet, C.; Cazenave, L.; Bopp, M.C.; Kazakou, E.; Metay, A.; Cordeau, S.; Rouifed, S. Consistent response of weeds according to Grime's CSR strategies along disturbance and resource gradients in Bordeaux vineyards. *Weed Res.* **2022**, *62*, 347–359. [CrossRef]
64. Bitarafan, Z.; Andreasen, C. Seed retention of ten common weed species at oat harvest reveals the potential for harvest weed seed control. *Weed Res.* **2020**, *60*, 343–352. [CrossRef]
65. Wright, I.J.; Reich, P.B.; Westoby, M.; Ackerly, D.D.; Baruch, Z.; Bongers, F.; Cavender-Bares, J.; Chapin, T.; Cornelissen, J.H.C.; Diemer, M.; et al. The worldwide leaf economics spectrum. *Nature* **2004**, *428*, 821–827. [CrossRef]
66. Wilson, P.J.; Thompson, K.; Hodgson, J.G. Specific leaf area and leaf dry matter content as alternative predictors of plant strategies. *New Phytol.* **1999**, *143*, 155–162. [CrossRef]
67. Grime, J.P.; Hunt, R. Relative growth rate: Its range and adaptive significance in a local flora. *J. Ecol.* **1975**, *63*, 393–422. [CrossRef]
68. Grime, J.P. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. *Am. Nat.* **1977**, *111*, 1169–1194. [CrossRef]
69. Lambers, H.; Poorter, H. Inherent variation in growth rate between higher plants: A search for physiological causes and ecological consequences. *Adv. Ecol. Res.* **1992**, *23*, 187–261. [CrossRef]
70. Poorter, H.; Remkes, C. Leaf area ratio and net assimilation rate of 24 wild species differing in relative growth rate. *Oecologia* **1990**, *83*, 553–559. [CrossRef]
71. Chapin, F.S., III. The mineral nutrition of wild plants. *Annu. Rev. Ecol. Syst.* **1980**, *11*, 233–260. [CrossRef]

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