

Article

Rotating Intercrops in Continuous Maize Cultivation: Interaction Between Main Crop, Intercrops, and Weeds

Austėja Švereikaitė^{1,2}, Jovita Balandaite^{1,2} , Ugnius Ginelevičius¹, Aušra Sinkevičienė^{1,2}, Rasa Kimbirauskienė¹ , Lina Juodytė^{1,2} and Kęstutis Romaneckas^{1,2,*} 

¹ Department of Agroecosystems and Soil Sciences, Agriculture Academy, Vytautas Magnus University, Studentu Str. 11, LT-53361 Akademija, Kaunas Distr., Lithuania; austėja.svereikaite@vdu.lt (A.Š.); jovita.balandaite@vdu.lt (J.B.); ugnius.ginelevicius@vdu.lt (U.G.); ausra.sinkeviciene@vdu.lt (A.S.); rasa.kimbirauskienė@vdu.lt (R.K.); lina.juodyte@vdu.lt (L.J.)

² Bioeconomy Research Institute, Vytautas Magnus University, Studentu Str. 11, LT-53361 Akademija, Kaunas Distr., Lithuania

* Correspondence: kestutis.romaneckas@vdu.lt; Tel.: +370-656-300-44

Abstract

Continuous cropping leads to declines in soil productivity and biodiversity, as well as a deterioration of overall phytosanitary conditions. What if we rotate the intercrops instead of the main crops? In a stationary three-year field experiment, maize was intercropped with *Fabaceae* (faba bean, crimson and Persian clovers, and blue-flowered alfalfa), *Poaceae* (winter rye, annual ryegrass, spring barley, and common oat), and *Brassicaceae* (white mustard, spring oilseed rape, oilseed radish, and spring Camelina) intercrops in separate growing seasons. *Fabaceae* intercrops developed slowly and competed poorly with weeds. The highest air-dried biomass (ADM) was produced by Persian and crimson clovers (approx. 86 g m⁻²). Intercrops of the *Poaceae* family, particularly rye and oats, as well as ryegrass, which was the most productive at 200 g m⁻² ADM, germinated faster and competed effectively with weeds. *Brassicaceae* intercrops also developed rapidly, especially mustard, Camelina, and radish (the most productive 206 g m⁻² ADM). Most intercrops competed with maize and reduced its biomass productivity; however, their competitive effects were weaker than those of weeds. A strong negative correlation between maize and weed biomass was detected (max. $r = -0.946$; $p < 0.01$). Complex evaluation index (CEI) showed that the crimson clover–annual ryegrass–spring oilseed rape rotation (CC–AR–SR) was the most productive and was effective in suppressing major weeds *Echinochloa crus-galli*, *Chenopodium album*, *Polygonum lapathifolium*, and *Cirsium arvense*, less competitive with maize (CEI 4.82), and can be used as an Integrated Pest Management tool.

Keywords: competition; development; *Fabaceae*; *Poaceae* and *Brassicaceae* companions; endogenous rotation; segetal flora; *Zea mays*



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1. Introduction

Maize is a multifunctional crop that provides food for humans and animal feed [1,2]. However, the large part of arable land devoted to maize cultivation poses environmental challenges [3], as it initiates soil erosion and nitrate leaching and increases phytosanitary risks [4]. In addition, maize is particularly sensitive to weed competition at the beginning of the growing season [5]. During this stage, it is necessary to ensure effective weed control to avoid yield losses [6].

Crops and weeds share the same limited resources, which leads to competition among them. Weeds compete with crops for nutrients, light, water, and space [7]. Due to their suppressive effect, 40% [8] or even 85% [9] of the yield is lost. Yield loss depends on the weed species, time of emergence, abundance, and crop type [10]. The spread of weeds results in adverse economic and environmental consequences [11]. Therefore, weed management throughout the crop growing season remains very important [12].

Weed abundance can be effectively managed using Integrated Pest Management (IPM) or Agroecological Strategies as alternatives for sustainable weed control, including cover cropping, crop rotation, intercropping, mulching (living or non-living), tillage technologies, mechanical weeding, innovative sowing methods and timing, and other cultural methods [13–15]. Crop rotation and simple or multiple intercropping systems can significantly reduce weed population density [16,17]. These systems are characterized by higher overall productivity and stability [18,19] because plants use available growth resources—nutrients, water, and light—more efficiently [20,21]. Intercropping is usually based on growing two or more crop species simultaneously in the same field without mixing [22]. Intercropping could be implemented as crop mixtures, relay intercropping, or strip intercropping [23]. Intercropping can be classified into parallel (where component crops do not compete), associated (where intercropping contributes equally to the agroecosystem), and multi-tiered (where crops occupy different vertical and horizontal spatial niches, and crop architecture principles are applied to optimize the use of environmental resources) [24].

Legumes are often intercropped with maize [25] because they provide nitrogen, which is much needed by the main crop [26]. Maize–legume mixed crops produce more biomass [27,28] and higher maize grain yields [29,30]. Unfortunately, these intercropping systems cannot completely prevent the spread of weeds [31] in both conventional and organic farms [32]. The understanding of the specific impacts of intercrops by various botanical families on weed suppression and maize development rate is still not complete. There is also a lack of research on how to combine maize and intercrop botanical families and species with each other in short rotations.

The objectives of our pilot investigations were to (i) evaluate the effect of different intercrops families and species on weed-suppression capacity and maize development, (ii) assess the strength and direction of the relationships among intercrops, weeds, and maize, and (iii) evaluate the complex effect of short-term intercrop (endogenous) rotations, and identify the most effective schemes for recommendation. The research results will contribute to the development of more diverse and effective IPM strategies in the maize crop.

2. Materials and Methods

2.1. Characteristics of Experimental Site

The present study was carried out at the Experimental Station of Vytautas Magnus University, Lithuania (54°53' N, 23°50' E). The soil of experimental field is a light loam (*Endohypogleyic-Eutric*) Planosol [33]. The soil has a pH_{HCl} ranging from 7.3 to 7.8, a total nitrogen content of 0.08–0.13%, humus content of 1.5–1.7%, available phosphorus content of 189–280 mg kg^{-1} , available potassium content of 97–118 mg kg^{-1} , available sulfur content of 1.2–2.6 mg kg^{-1} , and magnesium content of 436–790 mg kg^{-1} . The water regime is controlled by subsurface (tile) drainage, and the micro-relief was leveled. The topsoil layer is 27–30 cm thick.

In terms of precipitation, Lithuania is in a zone of surplus moisture. On average, annual precipitation ranges from 600 to 650 mm, of which approximately 500 mm is lost through evaporation. The warm period extends for 230–260 days.

2.2. Design of Experiment

A pilot stationary experiment was conducted from 2023 to 2025. The experiment compared continuous maize grown as a sole crop and in combination with various companion plants (Table 1). Two control treatments were included. In the C1 treatment, maize was grown completely without companions, i.e., without weeds and intercrops. In the C2 treatment, the permacultural principle was applied, with maize interrows mulched using weeds. In the other treatments, companion crops were changed annually, as crop rotation is an effective method for weed management [34]. In catch or intercropping systems, the most used crops belong to *Fabaceae*, *Brassicaceae*, and *Poaceae* families [35]; therefore, we also included them in the design of our experiment. In 2023, maize (*Zea mays* L.) was grown in combination with *Fabaceae* species, including faba bean (*Vicia faba* L.), crimson clover (*Trifolium incarnatum* L.), Persian clover (*Trifolium resupinatum* L.), and blue-flowered alfalfa (*Medicago sativa* L.) (Table 1). In 2024, maize was intercropped with *Poaceae* species, such as winter rye (*Secale cereale* L.), spring barley (*Hordeum vulgare* L.), annual ryegrass (*Lolium multiflorum* L.), and common oats (*Avena sativa* L.). In 2025, maize was grown with *Brassicaceae* intercrops, including white mustard (*Sinapsis alba* L.), spring oilseed rape (*Brassica napus* L.), oilseed radish (*Raphanus sativus* L.), and spring Camelina (*Camelina sativa* L.).

Table 1. Maize cultivation diversity.

Years	Treatment No.	Diversity Level	Treatments	Cultivar	Sowing Rate kg ha ⁻¹	Abbreviation
2023–2025	1	Single crop	Interrow loosening	hybrid P7034	27–30	C1
	2		Interrow cutting and mulching with weeds			C2
2023	3	Binary crop	Faba bean	“Trumpet”	200	FB
	4		Crimson clover	“Kardinal”	30	CC
	5		Persian clover	“Rusty”	18	PC
	6		Blue-flowered alfalfa	“Giulia”	20	AA
2024	3	Binary crop	Winter rye	“Elias”	200	WR
	4		Annual ryegrass	“Prospect”	30	AR
	5		Spring barley	“Mowestra C”	200	SB
	6		Common oat	“Delfin”	220	CO
2025	3	Binary crop	White mustard	“Maryna”	15	WM
	4		Spring oilseed rape	“Mirakel”	5	SR
	5		Oilseed radish	“Arena”	25	OR
	6		Spring Camelina	“Peredovik”	8	SC

In our study, we examined not only the impact of intercrop families on other components of the agroecosystem but also conducted a comprehensive assessment of three-year rotations of individual interrow species. This evaluation included both control treatments, as well as the FB-WR-WM, CC-AR-SR, PC-SB-OR, and AA-CO-SC rotations.

The field experiment was conducted in four replicates using a randomized design. In the first replication of the experiment, treatments were distributed sequentially (1, 2, 3 ...) as shown in Table 1. In other replications, we applied randomization (second replication: 3, 5, 1, 4, 6, 2; third: 5, 3, 1, 6, 2, 4; fourth: 4, 6, 5, 2, 3, 1). The initial plot size was 18.4 m², with a reference area of 18.0 m². A total of 24 plots was established. The experiment was established in a field following a period of bare fallow. In each year of the trial, maize was re-sown, and different companion crops were intercropped between the maize rows.

2.3. Agronomy Practices and Weather Conditions

In autumn, before the beginning of experimentation, the soil was ploughed by a plough with semi-screw “Kverneland” (Kverneland Group (Kverneland AS), Klepp Stasjon, Norway) shares. In spring, when the soil reached physical maturity, it was cultivated using a KLG-4 compound cultivator (“Laumetris Ltd”, Keleriškiai village, Kaunas, Lithuania) to a depth of 3–4 cm. Maize was sown with a pneumo-mechanical drill “Kverneland Accord Optima” (Kverneland Group (Kverneland AS), Klepp Stasjon, Norway) in rows 45 cm apart, with a seed spacing of 21 cm. After the maize emergence, the rows were loosened, and the intercrops were sown using a hand seeder designed for greenhouses, which sows six rows simultaneously. Before loosening the rows, the initial dose of mineral fertilizer (NPK 5:15:29) was applied at a rate of 300 kg ha^{−1}. Maize and intercrops were sown according to the planned sowing rates (Table 1).

During the maize vegetative season, in the C1 plots, maize interrows were loosened, and all vegetation in the interrows was chopped. In the other treatments, intercrops and weeds were (mowed) one to two times until the maize reached a height of 50–70 cm (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) stage was 61–63). The intercrops were cut when they reached approximately 20–25 cm in height. All biomass of weeds and intercrops was cut, chopped, and left on the topsoil as mulch (following principles of living mulch technology). In 2023 and 2025, the operation was carried out two times, and in 2024, it was performed only once due to the slow development of intercrops under drought conditions. The intercrops were cut with a manual brush cutter “Stihl” FS-550 (Andreas Stihl AG & Co. KG, Waiblingen-Neustadt, Germany) using a trolley with a protective cover that reduces the operator’s load, which evenly spreads the biomass in the interrows and protects the maize crop from mechanical damage. No pesticides were used in the agrotechnological system.

In 2023 and 2025, the spring was cold and arid, and in 2024, it was warmer and more humid (Table 2). Unlike in 2023 and 2025, the summer months of 2024 were exceptionally warmer than average. In 2023, only August was wetter than average, while in 2024 and 2025, July experienced above-average rainfall. Precipitation during the maize vegetative period totalled 250 mm in 2023, approximately 280 mm in 2024, and nearly 300 mm in 2025. Although 250 mm of precipitation is sufficient for maize, intercrops growing in our climate exhibit poor growth and produce limited biomass.

Table 2. Average air temperature and rainfall during maize vegetative seasons. Kaunas meteorological station, 2023–2025.

Months	2023	2024	2025	Long-Term (Since 1974) Average
Air temperature °C				
April	8.5	9.1	9.3	6.9
May	12.6	15.6	10.2	13.2
June	17.3	17.8	15.7	16.1
July	18.0	20.1	19.2	18.7
August	20.2	19.7	16.7	17.3
September	17.1	17.3	15.7	12.6
Rainfall mm				
April	26.7	63.0	19.9	41.3
May	14.3	25.1	31.5	61.7
June	64.0	36.8	82.3	76.9
July	36.8	109.4	118.0	96.6
August	96.2	40.9	31.3	88.9
September	11.6	52.6	34.4	60.0

The length of the maize growing season was 135 days in 2023, 122 days in 2024, and 156 days in 2025 (from germination at BBCH 09–10 to harvest at BBCH 86–88), due to the dry and excessively warm weather in 2024.

2.4. Data Collection

2.4.1. Coverage of Maize Interrows

The projected area of maize interrow components (intercrops, weeds, and ground) was determined in percentage before each interrow loosening/mulching (BBCH 16–17, 61–63) in at least four spots of each plot (Table 3). A 20 × 30 cm metal frame was used for the test.

Table 3. Agrotechnical operations and sampling/testing time.

Operation	2023	2024	2025
1. Maize sowing	4 May	2 May	28 April
2. Intercrop sowing	22 May	28 May	21 May
3. Interrow mellowing/cutting:			
– first	19 June	26 June	16 June
– second	18 July	16 July	21 July
4. Testing of interrow coverage:			
– first	19 June	26 June	16 June
– second	18 July	16 July	21 July
5. Test of chlorophyll concentration	17 July	22 July	21 July
6. Sampling for maize height and biomass	25 July	22 July	06 August
7. Sampling for weeds and intercrops biomass evaluation:			
– first	18 June	26 June	20 June
– second	-	22 July	18 July

2.4.2. Maize Crop Development Indicators and Weediness

These were determined before each interrow loosening or mulching—at least two times during the vegetative season (BBCH 16–17, 61–63). Maize development stages were assessed according to the BBCH scale [36]. In addition, the fresh and dried biomass of the main crop, intercrops, and weeds, as well as maize plant height and leaf chlorophyll concentration, were evaluated. For the study, five maize plants were cut in each experimental plot. The development stage was assessed visually. The height of the maize plants was measured, and they were weighed, thus determining their fresh biomass. Biomass samples were dried in a thermostat at 105 °C to determine the fully dry biomass (moisture content near 0%) capacity of the plants. Chlorophyll concentration in maize leaves was measured using a chlorophyll content meter MC-100 (“Apogee Instruments, Inc.”, Logan, UT, USA), which estimates chlorophyll concentration based on light absorption from red (653 nm) to short infrared (931 nm) waves. At least ten leaves per plant species were measured.

In each experimental plot, biomass samples of the intercrops and weeds were collected from at least ten 20 × 30 cm areas using a metal frame. Species composition and fresh biomass were assessed in the laboratory. About 20 weed species were identified in the experimental plots. Later, the biomass was dried under laboratory conditions to estimate air-dried biomass, which typically contains 3–5% moisture. In the same samples, weed abundance and biomass were evaluated. The most common annual weeds were white goosefoot (*Chenopodium album* L.), pale smartweed (*Polygonum lapathifolia* L.), barnyard grass (*Echinochloa crus-galli* L.), and white mustard (*Sinapis arvensis* L.). The most common

perennial weeds were perennial sow-thistle (*Sonchus arvensis* L.), creeping thistle (*Cirsium arvense* (L.) Scop.), and couch grass (*Elytrigia repens* (L.) Nevski).

2.5. Statistical Analysis and Calculations

The research data were statistically analyzed using one-way analysis of variance (ANOVA), as well as correlation method. The mutual relation among the studied parameters was assessed using correlation analysis with the STAT ENG program. Correlation coefficients marked “*” indicate significance at a 95% probability level ($p \leq 0.05$), while “**” indicates significance at the 99% probability level ($p \leq 0.01$). Treatment means were used for calculating correlations, with a calculation matrix of $n = 6$. Correlations were provided for individual years (corresponding to plant families) and maize development stages, with additional correlations presented in the Supplementary Material. ANOVA test was used to determine the limits of the significant difference for the 95% and 99% probability levels according to the F-test. Differences in treatments are marked with different letters (a, b, c, . . .) and are considered significant at $p \leq 0.05$. Statistical analyses were performed at the Agriculture Academy of Vytautas Magnus University.

The complex effect of intercropped plant rotations on weed infestation and maize crop was conducted following the methodologies proposed by G. Lohmann [37] and K. U. Heyland [38]. The evaluation involved the following steps: (1) determination of the values for indicators, including biomass of weeds, intercrops, and main crop, maize height, and chlorophyll concentration in leaves; (2) transformation of the actual values of each indicator onto a unified nine-point scale, where 1 corresponds to the minimum value and 9 to the maximum value. Intermediate values were assigned scores according to the following formula:

$$VBi = (Xi - Xmin)/(Xmax - Xmin) - 1 \times 8 + 1$$

where VBi is the score for a given indicator value, Xi is the expression for a given value, Xmin is the minimum value, and Xmax is the maximum value for a given indicator; (3) representation of the converted indicators as scores in radial grid diagrams, with a scale ranging from 1 to 9; (4) presentation of the scale along with the average value of the individual indicators (score threshold, set at five points), which distinguishes high from low scores, with the overall efficiency indicated by the area enclosed by all the indicator scores; (5) calculation of the Complex Evaluation Index (CEI), which consists of the mean of the scores, the standard deviation of the scores and the standard deviation of the mean of the scores below the cut-off point. We used CEI to evaluate the pilot study’s comprehensive effect of intercrop rotations on weediness level and on the previously described maize development parameters.

3. Results and Discussion

3.1. Interrow Surface Covering

In 2023, maize interrows were inter-sown with the leguminous crops. Before the first interrow cutting, the maize interrows were mostly occupied by weeds, and the uncovered area ranged from 41 to 55% because of arid conditions and the slow germination rate of intercrops (Table 4). Intercrops covered 5–11% of the interrow area only. Significantly, the highest coverage was observed by the Persian clover. At later stages, the intercrops covered 30 to 54% of the maize interrow area, and weeds covered 33 to 47%. The maize interrows were most extensively covered by Persian clover—about 54% of the interrow area. This difference was significant when compared to the faba bean intercrop alone.

Table 4. Coverage of maize interrows at different growth stages (%), 2023–2025.

Treatment	Coverage Component %					
	BBCH 16–17			BBCH 61–63		
	Ground	Weeds	Intercrops	Ground	Weeds	Intercrops
<i>Fabaceae</i> intercrops (2023)						
C1	55.2 a	44.8 a	-	83.1 a	16.9 d	-
C2	55.6 a	44.4 a	-	35.0 b	65.0 d	-
FB	48.7 a	42.3 a	9.0 ab	26.3 b	43.5 bc	30.3 b
CC	41.1 a	54.0 a	4.9 b	16.3 bc	47.3 b	36.5 ab
PC	41.5 a	47.5 a	11.0 a	12.8 c	32.8 c	54.4 a
AA	51.0 a	42.2 a	6.8 ab	13.3 c	40.3 bc	46.5 a
<i>Poaceae</i> intercrops (2024)						
C1	71.2 a	28.8 b	-	90.7 a	9.3 c	-
C2	55.2 b	44.8 a	-	59.3 b	40.8 a	-
WR	33.8 c	16.0 c	50.2 a	54.0 bc	27.8 b	18.3 b
AR	24.2 d	26.5 b	49.3 a	25.9 d	20.1 bc	55.0 a
SB	31.6 cd	23.4 bc	45.0 a	53.8 bc	25.8 b	21.0 b
CO	27.0 cd	20.5 bc	52.5 a	44.0 c	25.8 b	30.3 b
<i>Brassicaceae</i> intercrops (2025)						
C1	54.0 a	46.0 b	-	75.5 a	24.5 c	-
C2	40.0 b	60.0 a	-	19.0 c	81.0 a	-
WM	14.0 d	12.0 d	74.0 a	46.8 b	49.8 b	3.5 c
SR	29.5 c	23.7 c	46.8 c	24.5 c	55.3 b	20.3 b
OR	28.4 c	24.2 c	47.4 c	17.5 c	29.5 c	53.0 a
SC	18.8 d	19.8 cd	61.5 b	26.3 c	58.8 b	15.0 bc

Notes: C1—interrow loosening (control 1), C2—interrow cutting and mulching with weeds (control 2), FB—faba bean, CC—crimson clover, PC—Persian clover, AA—blue-flowered alfalfa, WR—winter rye, AR—annual ryegrass, SB—spring barley, CO—common oat, WM—white mustard, SR—spring oilseed rape, OR—oilseed radish, SC—spring Camelina. Different letters (a, b, c, ...) within columns mean significant difference between treatments at $p \leq 0.05$.

Correlation between interrow coverage proportion of intercrops and weeds was weak and mostly related to ground percentage (Supplementary Material, Tables S1 and S2).

In 2024, in maize interrows, according to the principles of crop rotation, *Poaceae* intercrops were sown, which developed faster than *Fabaceae*. Before the first interrow cutting, the intercrops covered up to 52% of the ground surface, but the differences were not significant (Table 4). A moderate negative correlation was found between interrow coverage and weeds ($r = -0.797$; $p > 0.05$) (Supplementary Material, Table S1). According to other scientists, intercrops are considered a key weed-management strategy [39], as they effectively suppress weed growth through competition [40].

A significant part of the intercrops did not regrow after the first cut, except for annual ryegrass, which occupied the largest interrow area—up to 55%. A significant number of new oats also germinated. The correlations between intercrop and weed cover were weak (Supplementary Material, Table S2).

In 2025, plants from another distant family, *Brassicaceae*, were sown in the maize interrows. Before the first intercrops cutting, white mustard was particularly abundant, covering up to 74% of the surface area, while weeds occupied only 12%, and 14% of the unoccupied ground remained. A large area of the interrows was also occupied by spring Camelina. The differences were significant (Table 4). A strong negative correlation was found between the proportions of the area covered by intercrops and weeds ($r = -0.965$; $p \leq 0.01$) (Supplementary Material, Table S1). Before the second harvest (second test), weeds in the C1 plots decreased to 25% because they were intensively loosened. Mustard

showed the greatest decline, dropping to only 3.5%. Radish remained in sufficient quantity—it occupied as much as 53% of the maize interrows (Table 3). Despite this, the correlations between the proportional areas of the intercrops and weeds became weak.

3.2. The Air-Dried Biomass of Weeds and Intercrops

In 2023, *Fabaceae* intercrops developed slowly, resulting in low biomass (Table 5). McKenzie-Gopsill et al. [41] pointed out that weed control success strongly depends on intercrops' biomass production. In our experiment, without competition, weeds developed rapidly, reaching a total biomass of 182 g m⁻². Annual weeds dominated, while perennial weeds were either not present or their biomass only reached 2.8 g m⁻².

Table 5. The air-dried biomass of weeds and intercrops at different maize growth stages, 2023–2025.

Treatment	Air-Dried Biomass, g m ⁻²							
	BBCH 16–17				BBCH 61–63			
	Annual	Perennial	Total	Intercrops	Annual	Perennial	Total	Intercrops
<i>Fabaceae</i> intercrops (2023)								
C1	95.9 b	1.2 a	97.1 b	-	77.0 c	0.0 b	77.0 c	-
C2	142.4 ab	2.8 a	145.2 ab	-	133.1 bc	0.7 b	133.8 bc	-
FB	181.2 a	0.4 a	181.6 a	-	250.7 a	44.2 a	256.4 a	18.0 a
CC	164.9 ab	0.0 a	164.9 ab	-	116.7 c	0.0 b	116.7 c	28.8 a
PC	154.4 ab	0.0 a	154.4 ab	-	227.1 a	0.0 b	227.1 a	30.0 a
AA	140.6 ab	0.0 a	140.6 ab	-	178.2 ab	23.5 ab	201.7 ab	36.9 a
<i>Poaceae</i> intercrops (2024)								
C1	26.8 b	0.0 a	26.8 b	-	11.6 c	0.55 a	12.3 b	-
C2	107.9 a	8.7 a	116.6 a	-	71.4 a	0.0 a	71.4 a	-
WR	108.6 a	6.6 a	115.2 a	84.1 a	37.0 bc	0.6 a	37.6 ab	16.2 b
AR	108.3 a	0.0 a	108.3 a	110.6 a	48.3 ab	0.4 a	48.7 a	89.3 a
SB	92.7 ab	0.0 a	92.7 ab	63.9 a	56.4 ab	0.0 a	56.4 a	31.5 b
CO	126.1 a	6.1 a	132.2 a	58.8 a	46.8 ab	0.0 a	46.8 a	65.6 ab
<i>Brassicaceae</i> intercrops (2025)								
C1	92.6 a	0.8 a	93.4 ab	-	7.9 b	3.7 a	11.6 a	-
C2	93.8 a	2.3 a	96.1 a	-	38.2 a	10.9 a	49.1 a	-
WM	21.7 c	11.6 a	33.3 c	133.4 a	22.5 ab	32.0 a	54.5 a	10.0 c
SR	37.2 bc	3.2 a	40.4 bc	50.5 b	29.9 a	1.6 a	31.5 a	55.7 b
OR	75.2 ab	0.0 a	75.5 abc	73.0 ab	31.3 a	0.0 a	31.3 a	109.3 a
SC	36.0 bc	2.3 a	38.3 bc	89.3 ab	33.5 a	0.0 a	33.5 a	41.4 bc

Notes: C1—interrow loosening (control 1), C2—interrow cutting and mulching with weeds (control 2), FB—faba bean, CC—crimson clover, PC—Persian clover, AA—blue-flowered alfalfa, WR—winter rye, AR—annual ryegrass, SB—spring barley, CO—common oat, WM—white mustard, SR—spring oilseed rape, OR—oilseed radish, SC—spring Camelina. Different letters (a, b, c, ...) within columns mean significant difference between treatments at $p \leq 0.05$.

After the first interrow cut, when the space between the rows was opened, the intercrops grew up to 37 g m⁻² biomass, but this did not reduce the weed abundance, and the correlation between the intercrop and weed biomass was weak (Supplementary Material, Tables S1 and S2). Similarly, Leoni et al. [42] pointed out that Persian clover (*Trifolium resupinatum* L.) and *Medicago* spp. increased weed density. Unlike these findings, Bilalis et al. [43] found that when maize was grown together with leguminous plants, weed density and weed air-dried biomass decreased significantly.

In 2024, the *Poaceae* intercrops started quickly and effectively competed with weeds already in the first stages of vegetation, and the biomass of annual ryegrass was even higher than that of weeds (Table 5). Similarly, Simić et al. [44] found that in a maize-ryegrass

cultivation, weed air-dried biomass decreased by up to 12 times compared to the biomass in the single maize crop.

After the first cut, the biomass of winter rye and spring barley significantly decreased two- to fivefold, while ryegrass and oats remained at a similar level. We did not find strong correlations between intercrop biomass, weed biomass, and the percentage of intercrop cover.

Unlike before the first cutting of the intercrops, perennial weeds significantly spread in the intercrops with faba bean and blue-flowered alfalfa intercrops, contributing up to 5–10% of the total weed biomass.

In 2025, the air-dry biomass of weeds was lower than in previous years, as *Brassicaceae* intercrops effectively covered the maize rows and produced competitive biomass (Table 5). For example, white mustard and spring Camelina produced about threefold greater biomass than the weeds. Unlike previous years, a higher biomass of perennial weeds was found in the maize interrows, reaching 11 g m^{-2} in the white mustard interrow, although the differences were not statistically significant. As the percentage of row coverage with intercrops and the biomass of intercrops increased, the weed biomass decreased significantly ($r = -0.916$ and $r = -0.839$; $p \leq 0.05$) (Supplementary Material, Table S1). Before the second interrow cutting, the air-dry biomass of mustard and Camelina decreased by thirteen and two times, respectively, while that of radish even increased by about 33%, so the correlations between the analyzed indicators were weak. The total weed biomass decreased compared to the first observation; however, in the white mustard intercrop, it increased by about three times. In contrast, no perennial weeds were detected in the oilseed radish and spring Camelina stands.

More detailed studies of individual weed species in the experiment revealed the following trends:

- Mulching with weeds (C2) was quite effective in controlling *Echinochloa crus-galli*. Over three years, the density of this weed decreased by about two times, and its biomass by approximately three times (Supplementary Material, Table S3). The amount of *Chenopodium album* did not change significantly, but its biomass decreased by more than five times. *Polygonum lapathifolium* remained in the maize interrows after the dry conditions of 2023, but during the wet conditions of 2025, its population recovered to the same level as at the start of the experiment, but its biomass decreased by about two times. *Cirsium arvense* was sparse in the experiment, but its population increased ninefold over three years, and its biomass doubled. This weed spread was most intensive in the wet conditions of 2025. The number of other weed species increased slightly, but their biomass remained similar. Donald [45] also indicated that cutting weed biomass effectively reduced its density, decreased seed bank capacity, and initiated long-term weed suppression.
- When applying the FB-WR-WM rotation of the intercrops, the density and biomass of *E. crus-galli* were similar in the arid years of 2023–2024. However, after the WM intercropping, both the density and biomass decreased by 1.5–1.8 times and up to 6 times, respectively. The number of *C. album* in the rotation remained similar, but its biomass changed: it decreased in the WR intercrop, while it increased approximately twofold in the WM intercrop. The effect of the rotation on the density of *P. lapathifolium* was uneven. In the FB intercrop, the biomass of this weed was very high (166.8 g m^{-2}). The WR intercrop reduced the density of *P. lapathifolium* by about six times, with a drastic reduction in biomass to 1.8 g m^{-2} . In the WM intercrop, the density of this weed increased again, though its biomass only reached 4.3 g m^{-2} . The abundance and biomass of *C. arvense* remained low after FB and WR intercrops, but during the humid 2025 season, its biomass increased significantly in the WM intercrop, rising

approximately sixfold. The density of other weed species remained similar over the three years, but their biomass decreased by 9- to 15-fold.

- When applying the CC-AR-SR rotation of intercrops, the density of *E. crus-galli* in the maize crop decreased consistently, and the biomass remained similar. The number of *C. album* in the rotation remained similar but nearly doubled in AR intercrops. Buraczyńska and Ceglarek [46] pointed out that a mix of alfalfa and annual ryegrass decreased the dry weight of *C. album* L.; *E. crus-galli* by 45–51%. Over three years, the biomass of this weed consistently decreased from 23.5 to 7.3 g m⁻². This rotation was effective in controlling the spread of *P. lapathifolium*, with the most effective control when grown with AR intercrop. The spread of *C. arvense* in the plots of this rotation was also effectively controlled, with both its density and biomass remaining low. The density and biomass of other weed species consistently decreased by about 3 and 11 times, respectively, over three years. Based on these results, we can recommend this rotation as the most effective for controlling the spread of weeds. Bärberi, P. and Mazzoncini [47] found that crimson clover (CC) cover crop reduced *E. crus-galli*, *C. album*, and *P. lapathifolium* biomass by 22–46%.
- When applying the PC-SB-OR rotation of intercrops, the density of *E. crus-galli* varied, although not significantly, but the biomass decreased, especially in OR seedlings. The number of *C. album* in the PC-SB rotation remained similar, but in the OR intercrop, it decreased by about six times, and the biomass decreased by approximately 13 times. Uchino et al. [48] found that Persian clover (PC) effectively reduced the dry weight of *C. album* biomass. This rotation was effective in controlling the spread of *P. lapathifolium*, though in the first year of the experiment, its biomass reached as much as 84.9 g m⁻² in the PC intercrop. After intercropping with AR and OR, it was most effectively controlled when growing with the AR intercrop. No *C. arvense* was detected in this rotation. The density and biomass of other weed species consistently decreased by about 2 and 17 times, respectively, over three years. Based on these findings, we can also recommend this rotation as an effective natural method to control weed spread.
- When applying the AA-CO-SC rotation of intercrops, the density and biomass of *E. crus-galli* did not change significantly, although its number decreased by about 20%. The number of *C. album* in the rotation remained similar, but its biomass decreased from 61.5 to 4.5 g m⁻² over three years. This rotation was also effective in controlling the spread of *P. lapathifolium*, with its density remaining low, and its biomass decreased from 84.9 g m⁻² to 3.8–3.4 g m⁻² or approximately 24 times. *Cirsium arvense* was rare in this rotation and completely disappeared within three years. Salonen and Ketoja [49] established that blue-flowered alfalfa (AA) cover crop reduced *C. arvense* density and biomass. The density of other weed species decreased by 1.5- to 3-fold over three years, but their biomass decreased drastically. If in the first year, the weed biomass in the AA stand reached 74.9 g m⁻², in the second year, in the CO intercrop, it reached 8.2 g m⁻², and in the third year, it dropped to only 1.9 g m⁻² in the SC intercrop. Based on these results, we can also recommend this rotation as an effective method for controlling weed spread, although it should be noted that blue-flowered alfalfa can suppress maize crop growth through allelopathic effects.

3.3. Chlorophyll Concentration in Maize Leaves

Chlorophyll is the main photosynthetic pigment of plants [50]. The concentration of chlorophyll in leaves has a decisive influence on the photosynthesis process of a plant and plays a key role in determining the physiological state of the plant, biotic and nutritional stress [51].

In the first year of the experiment (2023), after sowing intercrops of the *Fabaceae* family in the maize rows, at the beginning of the vegetation period, maize leaves contained 31–36 $\mu\text{mol m}^{-2}$ of chlorophyll and did not differ significantly (Table 6). Similar results were reported by Tuure et al. [52] in an experiment with cowpea intercrop. However, Pierre et al. [53] reported that when maize was grown together with peas, chlorophyll concentration in maize leaves increased by up to 13%. In our experiment, due to the slow development of intercrops, maize experienced less competition. Only the weeds slightly decreased the concentration of chlorophyll in maize leaves ($r = -0.426$; $p > 0.05$) (Supplementary Material, Table S1).

Table 6. Impact of intercrops on the chlorophyll concentration in maize leaves ($\mu\text{mol m}^{-2}$), 2023–2025.

<i>Fabaceae</i> Intercrops (2023)			<i>Poaceae</i> Intercrops (2024)			<i>Brassicaceae</i> Intercrops (2025)		
	BBCH 19	BBCH 69		BBCH 19	BBCH 69		BBCH 19	BBCH 69
C1	35.0 a	61.7 a	C1	21.6 a	32.1 a	C1	12.4 c	37.9 a
C2	32.4 a	49.8 b	C2	14.3 b	25.2 ab	C2	14.0 bc	24.8 b
FB	31.7 a	44.0 b	WR	14.4 b	21.4 b	WM	16.8 ab	25.4 b
CC	35.8 a	48.4 b	AR	15.0 b	21.9 b	SR	16.8 ab	17.9 c
PC	31.4 a	45.6 b	SB	15.6 b	24.6 ab	OR	17.7 a	16.0 c
AA	33.6 a	44.7 b	CO	15.1 b	28.9 ab	SC	12.5 c	18.5 c

Notes: C1—interrow loosening (control 1), C2—interrow cutting and mulching with weeds (control 2), FB—faba bean, CC—crimson clover, PC—Persian clover, AA—blue-flowered alfalfa, WR—winter rye, AR—annual ryegrass, SB—spring barley, CO—common oat, WM—white mustard, SR—spring oilseed rape, OR—oilseed radish, SC—spring Camelina. Different letters (a, b, c, ...) within columns mean significant difference between treatments at $p \leq 0.05$.

Warm and sunny conditions persisted throughout most of the growing season, resulting in a 0.5- to 2-fold increase in chlorophyll content in maize leaves. The highest chlorophyll content was found in maize without companions (Table 6). Chlorophyll concentrations were up to 29% lower in crops with legume intercrops. On the contrary, in Nasar et al.'s [54] studies with alfalfa intercrop, concentration increase was about 37% at the silking stage of maize. Similarly, in maize intercropped with cowpea, light interception was higher than in the single maize [55]. Wang et al. [56] found an increase of just about 5% in maize crops with mung beans. In contrast, Pandey et al. [57] reported that the lowest chlorophyll concentrations were recorded in single maize crops, and weeds were not controlled at the plots. Correlation analysis of our results revealed a strong negative relationship between the biomass of intercrops and weeds, and the chlorophyll content in maize leaves ($r = -0.710$, $p \leq 0.05$ and $r = -0.840$, $p < 0.05$) (Supplementary Material, Table S2).

In the second experimental year (2024), after the sowing of *Poaceae* intercrops, significantly the highest chlorophyll concentration in maize leaves was found in the control C1 plots without intercrops and weeds, because at other experimental plots companion plants competed with maize (Table 6), especially weeds ($r = -0.959$, $p < 0.01$) (Supplementary Material, Table S1). Similarly, in Gou et al.'s [58] experiment, competition with wheat reduced chlorophyll content in maize leaves. In the second half of the vegetation, chlorophyll in maize leaves increased, and the differences between treatments were no longer pronounced. Nevertheless, similar trends remained, and companion species did not act as major competitors of maize ($r = -0.864$, $p < 0.05$) (Supplementary Material, Table S2).

Unlike previous years, in the third year of the experiment (2025), at the beginning of the vegetation period, the chlorophyll concentration in maize leaves significantly differed between the treatments with *Brassicaceae* intercrops. The highest chlorophyll content was found in maize intercropped with radish, rapeseed, and mustard companions, likely due to reduced competition with maize (Table 6). Correlations between maize, intercrops, and

weed biomass were weak (Supplementary Material, Table S1). At later stages, intercrops and weeds competed more strongly with maize ($r = -0.758$ and $r = -0.806$; $p > 0.05$), resulting in significantly lower chlorophyll concentration in maize with intercrops, especially in plots with rapeseed, radish, and Camelina intercrops.

3.4. Maize Development Parameters

Maize is sensitive to environmental conditions, and the most common variable is its height. Our investigations have shown that without companions, maize grew taller, but not always significantly (Table 7). Similarly, Üstündağ et al. [59] found that the highest maize height occurred in single crops (224.3 cm), whereas maize grown together with soybean and pea reached a lower height. However, according to Zhang et al. [60], maize grown together with blue-flowered alfalfa promoted each other's growth. In our experiment, legumes reduced maize height more significantly than plants from other families, but in the maize $\times$ companion interaction, weeds exerted a greater effect than intercrops. We found a strong negative relationship between weed air-dried biomass and maize height ($r_{2023} = -0.909$, $r_{2024} = -0.864$, $r_{2025} = -0.971$, $p < 0.05$) (Supplementary Material, Table S2). We also found a strong correlation between maize height and its fresh biomass ($r_{2023} = 0.934$, $r_{2024} = 0.898$, $r_{2025} = 0.951$; $p < 0.01$). During the early flowering stage, the correlation with maize dry biomass was low and statistically weak.

Table 7. Impact of intercrops on maize development parameters at BBCH 61–63 stages, 2023–2025.

Fabaceae Intercrops (2023)				Poaceae Intercrops (2024)				Brassicaceae Intercrops (2025)			
Treatment	Height cm	Fresh Biomass g	Dried Biomass g	Treatment	Height cm	Fresh Biomass g	Dried Biomass g	Treatment	Height cm	Fresh Biomass g	Dried Biomass g
C1	168.7 a	270.4 a	17.3 ab	C1	153.1 a	268.8 a	48.7 a	C1	170.2 a	220.8 a	37.8 a
C2	142.1 bc	232.9 ab	16.9 b	C2	137.2 a	185.0 a	37.6 a	C2	143.4 b	148.0 bc	23.1 bc
FB	130.7 bc	188.9 bc	18.8 ab	WR	140.1 a	220.0 a	43.2 a	WM	161.3 ab	178.5 ab	30.0 ab
CC	147.1 ab	221.7 abc	19.6 a	AR	137.0 a	212.9 a	42.0 a	SR	148.4 ab	147.5 bc	22.1 bc
PC	125.9 c	181.7 bc	18.5 ab	SB	139.4 a	220.8 a	53.7 a	OR	147.7 ab	134.8 c	20.9 c
AA	131.5 bc	166.4 c	17.1 b	CO	137.9 a	222.1 a	47.9 a	SC	149.9 ab	148.8 bc	23.2 bc

Notes: C1—interrow loosening (control 1), C2—interrow cutting and mulching with weeds (control 2), FB—faba bean, CC—crimson clover, PC—Persian clover, AA—blue-flowered alfalfa, WR—winter rye, AR—annual ryegrass, SB—spring barley, CO—common oat, WM—white mustard, SR—spring oilseed rape, OR—oilseed radish, SC—spring Camelina. Different letters (a, b, c, . . .) within columns mean significant difference between treatments at $p \leq 0.05$.

Regardless of the botanical family of the intercrop, all intercrops slowed maize development and reduced average biomass per plant, but the reductions were not consistently significant. Blanco-Canqui et al. [61] indicated that cover crops can either increase or have no effect on main crop yields, but they primarily reduce yields in arid regions. According to Zhang et al. [62], barley and wheat intercrops slowed maize growth due to increased competition for resources during the early developmental stages.

In our experiment, crimson clover, most of *Poaceae* family intercrops, and white mustard competed less with maize in this respect (Table 7). Similar trends were observed for total maize dry biomass. In our earlier investigations on living mulch continuous cultivation under humid conditions, the most significant negative impacts on maize were observed with Italian ryegrass and legumes (black medic, Persian clover, and red clover), which produced high biomass and rapidly regrew after cutting. In contrast, spring oilseed rape, white mustard, and spring barley were found to suppress weeds effectively while having a lesser negative impact on maize productivity [63]. In the present experiment, a strong negative interaction was found between the air-dried biomass of intercrops of the *Fabaceae* family and the fresh biomass of maize ($r = -0.828$; $p < 0.05$), while interactions between intercrops of other families and maize biomass were weak (Supplementary Material, Table S2). Strong correlations were found between air-dried biomass of weeds (especially

annuals) and fresh biomass of maize in all years of the study ($r_{2023} = -0.831$, $r_{2024} = -0.946$, $r_{2025} = -0.936$; $p < 0.01$).

A moderate to strong correlation was found between the chlorophyll concentration in maize leaves and their green biomass ($r_{2023} = 0.917$, $r_{2024} = 0.649$, $r_{2025} = 0.946$) (Supplementary Material, Table S2).

3.5. The Complex Effect of Three-Year Intercrop Rotations

Evaluation of the complex impact of intercrop rotations on crop weediness and maize development parameters showed that the traditional technology without competitors (C1) outperformed the other treatments in this respect due to the absence of intercrops and mechanical weed control (Figure 1). It should be mentioned that this traditional weed control technology negatively affected soil fertility during the three years of continuous experimentation (data are not presented). Similarly, in our earlier investigations, three years of continuous interrow living mulching with weeds, Persian clover, white mustard, and spring barley were more beneficial than traditional technology [64].

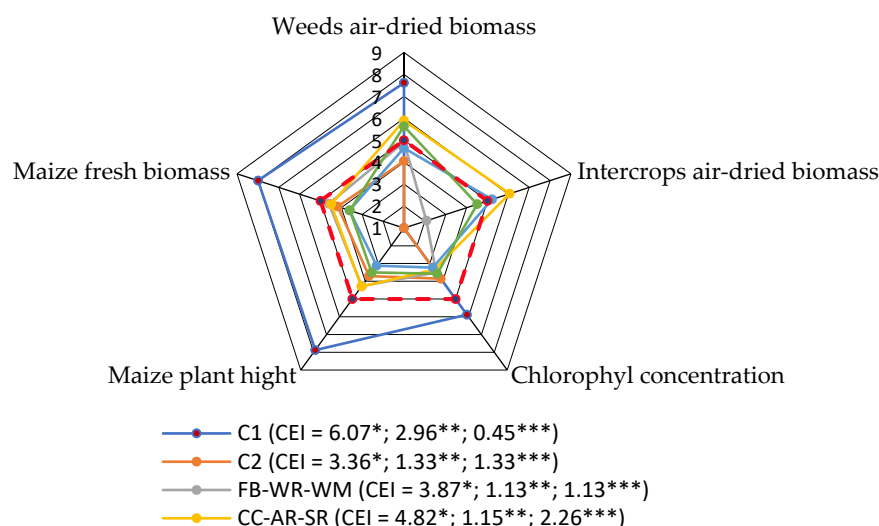


Figure 1. The complex effects of intercrop short-term rotations on maize three-year-continuing cultivation, 2023–2025. C1—interrow loosening (control 1), C2—interrow cutting and mulching with weeds (control 2), FB—faba bean, CC—crimson clover, PC—Persian clover, AA—blue-flowered alfalfa, WR—winter rye, AR—annual ryegrass, SB—spring barley, CO—common oat, WM—white mustard, SR—spring oilseed rape, OR—oilseed radish, SC—spring Camelina. CEI—complex evaluation index, *—average of evaluation points (EPs), **—standard deviation of EPs, ***—standard deviation of the average of the evaluation points below the evaluation threshold.

Weed mulching in maize interrows (C2) was the least effective for weed control (CEI 3.36); therefore, it had negative consequences for maize development. The lowest complex evaluation index was also given to the FB-WR-WM and PC-SB-OR intercrop short-term rotations.

The CC-AR-SR intercrop rotation was the most productive, more effective in suppressing weeds, and less competitive with maize. The CEI of this rotation was also the highest of all intercrop rotations (4.82). The AA-CO-SC rotation was also quite effective (CEI 4.16), but the final biomass production of the maize crop was reduced due to the negative allelopathy of blue-flowered alfalfa (AA) (data are not presented).

To summarize, it should be noted that the changing temperate climate conditions in the north-eastern European region often result in uneven distribution of precipitation, as observed in 2023–2024. Spring droughts are becoming more frequent, which leads to uneven and poor germination of intercrops. As a result, they fail to form a dense cover and

compete poorly with weeds. Toom et al. [65] suggest that intercrops should be sown as early as possible in the northern parts. If intercrops are sown at the same time as the maize, their germination would likely improve. However, we wait until the maize germinates, and after we loosen the interrows and sow the intercrops to optimize weed control. It is important to maximize the growing season of cover crops. In dry conditions, we loosen the interrows once, while in wetter conditions, we do so twice. With increased fertilization, the number of interrow loosening operations may increase to three.

Fabaceae intercrops tend to germinate slowly and develop gradually, so it is worth sowing them during humid springs or when the forecast predicts abundant rainfall. Drones could be highly useful for such “flash intercropping” practices. It is important to note that sowing *Fabaceae* intercrops is essential for maintaining soil fertility. In arid springs, it is worth sowing intercrops from the *Poaceae* and *Brassicaceae* families, as they develop quickly and effectively compete with weeds. Among the *Poaceae*, the ryegrass is the most competitive, while radishes and Camelina are most competitive in *Brassicaceae*. Camelina competes with weeds not only for space but also through allelopathic substances released into the soil (data not presented). The rate at which intercrops regrow or germinate after interrow mowing is also a key factor.

The AA-CO-SC rotation was quite effective, but blue-flowered alfalfa negatively affected maize due to its allelopathic properties (data not presented). Therefore, we recommend replacing alfalfa with Persian or Crimson clover, followed by oats and Camelina.

4. Conclusions

The effectiveness of intercrops as living mulch in controlling weeds varied by species and growth stage, with some species showing poor regrowth after cutting, which resulted in increased weed presence. *Fabaceae* intercrops germinated and developed slowly, providing poor coverage of the maize interrows and weak competition with weeds, which covered about 40–50% of the maize interrow area. *Poaceae* intercrops germinated faster and effectively competed with weeds from the early vegetative stage, especially winter rye and spring oats, with ryegrass emerging following the first cut. CC-AR-SR rotation of intercrops the most effectively controlled *Echinochloa crus-galli*, *Chenopodium album*, and *Polygonum lapathifolium*, and *Cirsium arvense* due to the strong weed suppression effect by the AR intercrop.

Brassicaceae intercrops germinated and developed rapidly, especially white mustard, Camelina, and oilseed rape. Among *Fabaceae* plants, the highest dry biomass was produced by Persian and crimson clover (about 86 g m⁻²), likely because certain seedlings did not survive following harvest. Within the *Poaceae* intercrops, annual ryegrass produced 200 g m⁻² of dry biomass, while among *Brassicaceae* intercrops, oilseed radishes reached 206 g m⁻² of dry biomass. Competition with weeds and intercrops led to a significant reduction in maize growth and chlorophyll concentration, compared to the control C1 plots without both intercrops and weeds. A strong negative correlation was found between weed air-dried biomass and maize dried biomass ($r_{2023} = -0.831$, $r_{2024} = -0.946$, $r_{2025} = -0.936$; $p < 0.01$).

The study concluded that while intercrops can be beneficial for weed control, their competitive nature can adversely affect maize productivity. It is recommended to use the CC-AR-SR short-term endogenous intercrop rotation, as it was the most productive, more effective in suppressing weeds, and less competitive with maize (CEI 4.82). Endogenous crop rotations can serve as a complementary strategy to the IPM Guidelines. Future research should continue to explore the balance between weed control and crop productivity in pesticide-free agriculture. Additionally, the effects of intercrops on soil health and the environment should also be considered.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy16020142/s1>, Table S1: Interactions between maize and companions at BBCH 16–17 stages, 2023–2025.; Table S2: Interactions between maize and companions at BBCH 61–63 stages, 2023–2025; Table S3: Abundance of main weed species (m²) at maize BBCH 61–63 stages, 2023–2025.

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