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Weed Spread and Caraway (*Carum carvi* L.) Crop Productivity in a Multi-Cropping System

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Abstract: The field experiment was carried out at the Experimental Station of Vytautas Magnus University Agriculture Academy (Lithuania) in 2017–2019. The aim of the study was to determine and to compare weed spread and caraway crop productivity in sole (spring barley, spring wheat, pea, caraway), binary (spring barley-caraway, spring wheat-caraway, pea-caraway) and trinary (spring barley-caraway-white clover, spring wheat-caraway-white clover, pea-caraway-white clover) crops. In the second and the third years of caraway cultivation, it was estimated that the abundance of perennial weeds in the crops increased. In the first year, significantly the highest dry matter mass of weeds was determined in non-sprayed with herbicides binary crops with undersown caraway and in trinary crops with undersown caraway and clover; in the second year—in the caraway binary crops, when they were grown after barley and wheat without clover; in the third year—in caraway binary and trinary crops when they were grown after barley, wheat and pea without clover and after barley and wheat with clover. In the second year, the highest yields of caraway seeds were obtained by growing them in peas, and in the third year by growing them in wheat together with clover. Caraway can be grown in trinary crops, including white clover, and harvested in the second or the third year of the vegetative season.

Keywords: *Carum carvi* L.; multi-cropping system; productivity; weed

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1. Introduction

Food production for a rapidly growing human population is constantly posing a huge challenge to agriculture. Rising production costs, deteriorating soil quality and health, and the spread and abundance of pests, diseases, and weeds threaten the ecological and economic sustainability of crop production. To address these challenges, multi-cropping systems could increase the overall production and diversity of products, stabilize the yield over growing seasons, and reduce the economic and environmental risks associated with sole-cropping systems—thus increasing sustainability [1].

The main goal of the multi-cropping model is to find synergies between different but complementary plants when the result of growing them together is better than growing them alone [2,3]. Natural systems are dominated by biodiversity, which is the cornerstone of their resilience and stability. Growing multiple crops is one of the ways to adapt this diversity to the agroecosystem [4]. Khan et al. [5] argue that growing several crops in the same field at the same time is an important strategy to increase cost efficiency (agricultural land, nutrients, and water) as well as crop yields and economic benefits [6].

Multi-cropping is the cultivation of two or more agricultural crops that differ in the length of the growing season and in biological and agronomic characteristics in the same field [7]. Cultivation of multi-crops (binary and trinary) better protects the soil from water and wind erosion [8], reduces nutrient leaching into deeper soil horizons, and improves soil agrochemical, physical and biological properties [9,10]. The roots of different agricultural crop species are also located differently in the soil and can take nutrients and water from different places [2,7,11]. Clover is beneficial as it fixes nitrogen from the atmosphere and supplies it to other plants growing together [12]. In a multi-cropping system, all plants can be combined: mixtures with only annuals or perennials, or mixtures containing both. Mixtures of crop species or mixtures of varieties can be grown in one stand [4,13,14].

Mennan et al. [15] emphasize that multi-cropping, especially including plants with allelopathic properties, can be an ecological alternative to chemical weed control. In these farming systems, it is very important to know and understand the regularities that determine the interaction within and between plants and weeds. In multi-crops, the arrangement of plant stems and leaves is different in both vertical and horizontal directions. This allows agricultural crops to make better use of solar radiation, while weeds receive less light and are suppressed [16,17]. Mixed crops are often less weedy than sole crops. By sowing a plant mixture, more ecological niches can be filled, thus providing less opportunities and resources for weeds to grow [18]. Sowing fast-growing cereals with weakly competitive plants can reduce the spread of weeds. However, balancing crop competitiveness can be difficult. It is more desirable for agricultural plants to compete with weeds than with each other.

Yield is considered to be the most important aspect when assessing the applicability of multi-crops [19]. Some researchers note that the yield of multi-crops is more stable compared to monocultures [20]. The main reason for higher yields of multi-crops is that plants make better use of natural environmental resources than plants grown separately [1,13]. Higher yields are generated because growth resources such as light, water and nutrients are much better absorbed and converted to crop biomass. This is due to differences in the competitive capacity of crop components to absorb the resources needed for growth. Plants in mixed crops differ in leaf width, thus the photosynthetic potential is not the same; the architecture of leaf arrangement and the rate of leaf development, the type of plant root system, and the depth of soil penetration differ [21]. Different root and leaf systems can absorb more light, water, and nutrients compared to the situation when only one species grows in a crop [22]. Depending on the needs of the farmer, agrotechnology can be designed to ensure productivity and weed control.

Caraway (*Carum carvi* L.) is an important biennial plant of the celery (*Apiaceae*) family. In Lithuania, their area is 3000 ha, and the average yield is 0.60 t ha^{-1}. Caraway seeds are widely used in the food, pharmaceutical, and perfumery industries [23]. Weed control is a very important factor, especially in the early stages of caraway development. Therefore, a multi-cropping system plays an important role in reducing the spread of weeds and increasing the productivity of caraway in comparison with a sole cropping system.

Lithourgidis et al. [24] point out that multi-cropping has some shortcomings. Achieving optimal growth requires deeper knowledge and responsible selection of compatible plant species, the right seed rate and the depth of seed placement for different crop species. Additional labour input is needed for seedbed preparation, sowing of seed mixture, crop management, and harvesting. Proper selection of the species composition of multi-crops is quite difficult, as in each case the success of the cultivation of such crops depends to a large extent on the interaction of the grown crop species, available crop cultivation practices, and environmental conditions.

The aim of the study was to compare weed spread and the crop productivity of caraway, which is a biennial plant, in sole, binary, and trinary crops. We hypothesized that the application of a multi-cropping system would inhibit the spread of weeds and increase the productivity of caraway crop.

2. Materials and Methods

2.1. General Experimental Conditions

The research was carried out at the Experimental Station of Vytautas Magnus University Agriculture Academy (VMU AA) (Figure 1), Lithuania, in 2017–2019. The soil was

Endocalcaric Amphistagnic Luvisol [25]. The agrochemical properties of the soil are the following: pH—6.70; humus—1.57–1.86%; mobile nutrients in the soil: P_2O_5—213–318 mg kg^{-1}, K_2O—103–125 mg kg^{-1}. The granulometric composition of the topsoil is sandy-loam.

(**a**) (**b**)

Figure 1. Experimental site: (**a**) caraway flowering in multi-cropping system. (**b**) Sentinel-2 map of Lithuania, available online (https://maps.eox.at/#data) accessed on 4 January 2021. Coordinates: 54°53′8.61″ N, 23°50′16.81″ E longitude.

2.2. Experimental Design

A one-factor field experiment with ten treatments was set up in 2017 (Table 1). The experiment was performed with four replications, and a randomized complete block design (RCBD) was used. The size of each experimental plot was 60 m^2 (5 m × 12 m), one replication block was 600 m^2. 2 m buffer rows were left between the individual blocks. In this experimental field, there were 40 plots in total (Table 1, Figure 2).

Table 1. The treatments of the experiment with their crops and varieties of sole, binary, and trinary crops.

1st Year of Caraway Vegetative Season, 2017		
Sole	**Binary**	**Trinary**
1. Spring barley (SB) 2. Spring wheat (SW) 3. Pea (P) 4. Caraway (CA)	5. Spring barley + Caraway (SB-CA) 6. Spring wheat + Caraway (SW-CA) 7. Pea + Caraway (P-CA)	8. Spring barley + Caraway + White clover (SB-CA-WC) 9. Spring wheat + Caraway + White clover (SCA-WC) 10. Pea + Caraway + White clover (P-CA-WC)
2nd Year of Caraway Vegetative Season, 2018		
Sole	**Binary**	**Trinary**
1. Spring barley (SB) 2. Spring barley (SB) 3. Spring barley (SB) 4. Caraway (CA)	5. Caraway (SB-CA) 6. Caraway (SW-CA) 7. Caraway (P-CA)	8. Caraway +White clover (SB-CA-WC) 9. Caraway + White clover (SCA-WC) 10. Caraway + White clover (P-CA-WC)
3rd Year of Caraway Vegetative Season, 2019		
Sole	**Binary**	**Trinary**
1. Spring barley (SB) 2. Spring barley (SB) 3. Spring barley (SB) 4. Bare fallow (BF)	5. Caraway (SB-CA) 6. Caraway (SW-CA) 7. Caraway (P-CA)	8. Caraway + White clover (SB-CA-WC) 9. Caraway + White clover (SCA-WC) 10. Caraway + White clover (P-CA-WC)

The experiment entails ten treatments. Four treatments were formed by sole crops, three treatments were combinations of caraway with the other crops as binary crops and three treatments had white clover added to trinary crops.

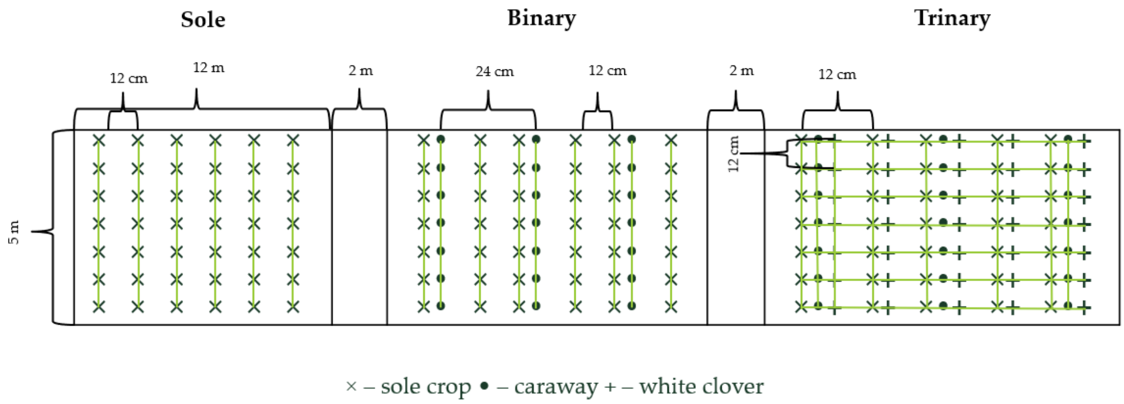

Figure 2. Sowing arrangement for the multi-cropping experiment.

2.3. Agrotechnologies of the Experiment

The experimental field was ploughed in autumn 2016, and in spring 2017 it was cultivated with a germinator twice and fertilized with complex fertilizer NPK 8-20-30 (300 kg ha^{-1}). The sown (multi-) crops were: spring barley (*Hordeum vulgare* L.), spring wheat (*Triticum aestivum* L.), and pea (*Pisum sativum* L., caraway (*Carum carvi* L.) for sole crops; spring barley and caraway, spring wheat and caraway, pea and caraway for binary crops; and spring barley, caraway, and white clover (*Trifolium repens* L.), spring wheat, caraway, and white clover, and pea, caraway, and white clover for trinary crops (Figure 2). For further information on crop establishment, see Appendix A. We chose to grow caraway in binary and trinary crops because they are biennial plants and the seeds ripen only in the second or the third year. In the first year of vegetation, caraway is sensitive to weed competition.

During the growing season, spring barley and spring wheat crops and the crops with undersown caraway were fertilized with ammonium nitrate at a rate of 180 kg ha^{-1}, and those with undersown caraway and white clover—at a rate of 150 kg ha^{-1}. The crop stands were kept healthy in a conventional manner using pesticides if needed (Appendix A). Peas were harvested on 16 August, spring barley on 23 August, and spring wheat on 31 August using a combine harvester Wintersteiger Delta (Ried im Innkreis, Austria).

After the main crops—spring barley, spring wheat, and peas—in 2017 and 2018 and after the sole caraway crop in 2018, the harvested plots were disked and deep-ploughed. In 2018, spring barley was harvested on 1st August; and in 2019, it was done on 5 August. In the second and the third years of the growing season, caraway was not fertilized with mineral fertilizers and no plant protection products were used. In 2018, caraway was harvested on 9 July; and in 2019, it was done on 5 July using a combine harvester Wintersteiger Delta (Austria).

2.4. Meteorological Conditions

In 2017, plant vegetative growth resumed on 31st March. April was cold and humid (Figure 3). May was very dry. The amount of precipitation in June was close to the climate normal. July was cool. In August, HTC was 1.00 (optimal humidity). September was warm. In October, precipitation exceeded the climate normal several times. In January 2018, the temperature was 2.2 °C higher than the multiannual average. February and March were colder than usual. Plant vegetative growth resumed on 4 April. The temperature in April was 3.3 °C higher compared to the multiannual average. The temperature in May was 4.0 °C higher than the climate normal, and the precipitation was 44.1 mm lower than usual.

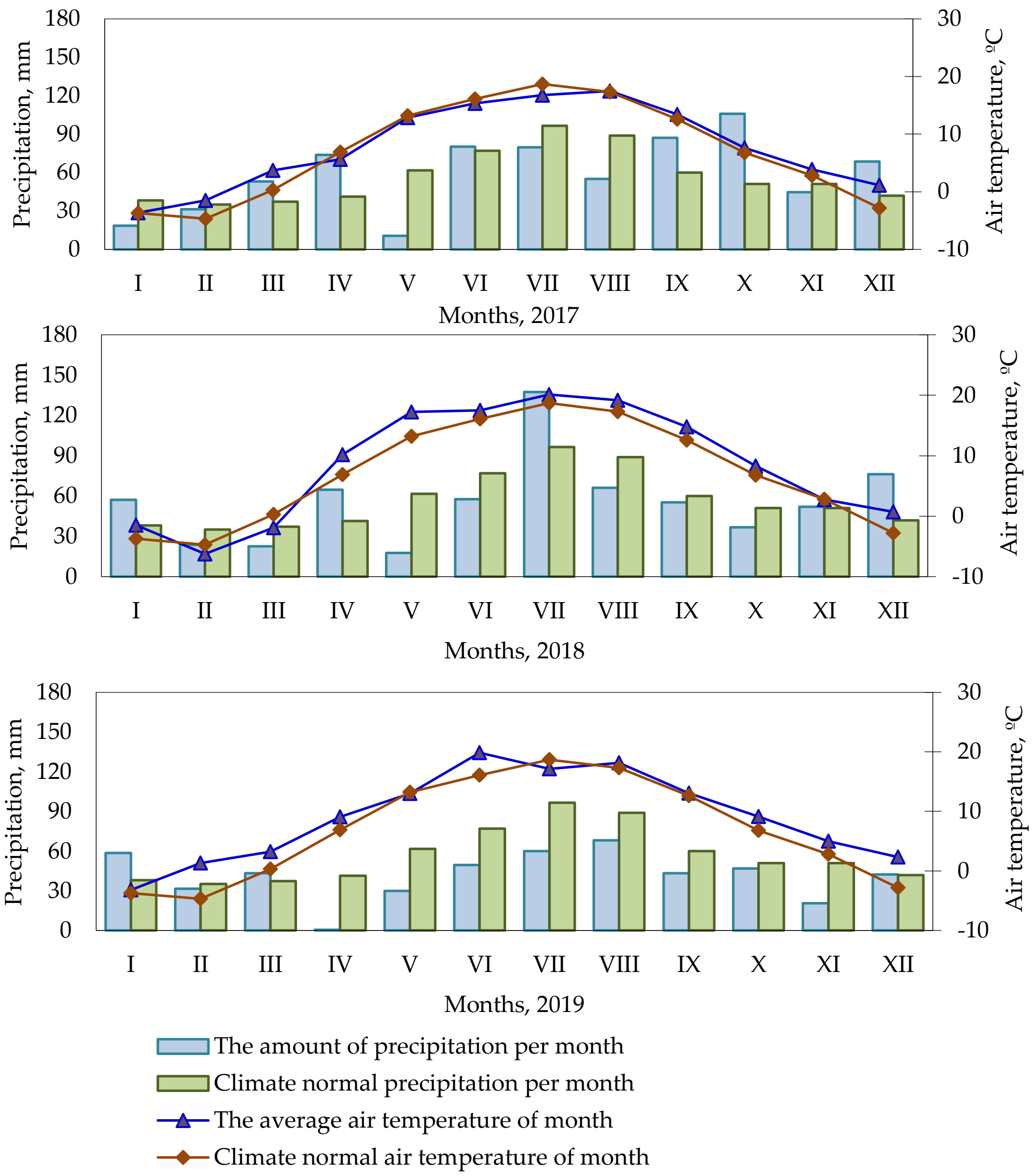

Figure 3. Meteorological conditions during the experimental period, Kaunas Weather Station. Note: Climate normal = The average data for 40 years (1974–2013).

The temperature in June was 1.4 °C lower than the multiannual average. The temperature in July was 1.4 °C higher than the climate normal, and the precipitation was 40.9 mm higher than usual. August was warm. Temperatures in the autumn and winter months were higher than usual. In 2019, plant vegetative growth resumed on 5 April. April temperature was 2.2 °C higher compared to the multiannual average. In May, humidity was optimal. The temperature in June was 4.4 °C higher than the climate normal. Humidity was optimal in July and August.

2.5. Research Methods

Soil agrochemical properties were determined before the installation of the experiment. Soil samples were collected in 15 spots, about 300 g from the 0–25 cm of plough layer of each experimental plot, using a soil auger. Soil pH was determined potentiometrically in 1 n KCl extract, mobile phosphorus P_2O_5 and mobile potassium K_2O (mg kg^{-1} soil) were estimated by using the Egner–Rim–Domingo (A–L) method, and the organic carbon (%) was calculated by incineration of samples at 900 °C using a Heraeus incinerator. The analyses were performed at the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry.

Air-dry biomass of weeds was harvested before harvesting the main crops (spring barley, spring wheat, and pea) (2017), and during the second (2018) and the third (2019) years of caraway vegetative season—before harvesting caraway and spring barley in 10 randomly selected spots of 0.06 m^2 in each harvested plot. The weeds were collected from the harvested plots and wrapped in paper packages. The number and species composition of the weeds were determined in the laboratory, and the weeds were dried in an oven at 60 °C and weighed. The number of weeds was recalculated to pcs. m^{-2} and the air-dry biomass to g m^{-2}.

Caraway crop density was assessed before harvesting. The plants were counted in 10 randomly selected spots within a running meter of each plot. Caraway crop density was calculated in pcs. m^{-2}.

Caraway seed yield calculation was based on a standard 12% moisture content and absolutely clean seed content (t ha^{-1}).

Dry matter biomass of the aboveground part of white clover was estimated after the main crop had been harvested at the end of the vegetative season, before the second- and the third-year caraway harvest. The aboveground mass of clover was cut from each spot of 0.10 m^2 in size in four randomly selected harvested plots. The samples were weighed in the laboratory, three samples of about 20 g were taken to dry in an oven at 105 °C, and the percentage of dry matter was calculated. The aboveground biomass of white clover was converted to the absolute dry matter content t ha^{-1}.

2.6. Statistical Analysis

The research data was statistically evaluated by one-way analysis of variance. Statistical analysis of the experimental data was performed using the software ANOVA from the statistical analysis package SELEKCIJA [26]. The Duncan criterion was used to assess the significance of the differences. Experimental data that did not fit the normal distribution law were transformed using the function $y = ln(x)$ prior to the statistical evaluation (number of weed and biomass of weed). Differences between averages of treatments marked with different letters are significant at 95% confidence level ($p < 0.05$). There are no significant differences when $p > 0.05$.

3. Results

3.1. Weed Species Composition

The year of growing the main crops. In 2017, 25 weed species were found in multi-crops, including 20 annual weeds and 5 perennial ones. The weeds found belong to 14 different families: *Boraginaceae*, *Equisetaceae*, *Asteraceae*, *Brassicaceae*, *Amaranthaceae, Plantaginaceae, Caryophyllaceae, Euphorbiaceae, Poaceae*, *Violaceae, Lamiaceae*, *Fabaceae*, *Rubiaceae*, and *Polygonaceae*. Annual dicotyledonous weed species predominated: white goosefoot (*Chenopodium album* L.), pale persicaria (*Persicaria lapathifolia* (L.) Gray), scentless chamomile (*Tripleurospermum perforatum* (Merat) M. Lainz), wild mustard (*Sinapis arvensis* L.) and a monocotyledonous weed species—barnyard grass (*Echinochloa crus-galli* L.) (Table 2).

The greatest amount of white goosefoot was found in binary spring barley and caraway crop, and the highest dry matter mass was found in trinary spring barley and pea crop with caraway and undersown white clover without the application of herbicides. Scentless chamomile was most prevalent in sole caraway crop and binary pea and caraway crop. The highest dry matter mass of wild mustard was found in trinary pea crop with undersown caraway and white clover. The highest dry matter mass of pale persicaria was found in spring barley and caraway, and spring barley, caraway, and white clover crops.

The second year of caraway vegetative season. In 2018, 22 weed species were found in multi-crops, including 14 annual weeds and 8 perennials (Table 3). The weeds found belonged to 12 different families: *Equisetaceae, Asteraceae, Brassicaceae, Scrophulariaceae, Amaranthaceae, Plantaginaceae, Caryophyllaceae, Poaceae, Violaceae, Lamiaceae, Fabaceae*, and *Polygonaceae.*

Annual dicotyledonous weeds predominated: white goosefoot (*Chenopodium album* L.), pale persicaria (*Persicaria lapathifolia* (L.) Gray), dwarf snapdragon (*Chaenorhinum minus* (L.) Lange) in spring barley, and scentless chamomile (*Tripleurospermum perforatum* (Merat) M. Lainz) in binary and trinary crops. The highest dry matter mass of scentless chamomile was found in the binary spring wheat and caraway crop.

Table 2. The average number and the average biomass of dominant weed species in sole, binary, and trinary crops in 2017.

Treatment	Weed Species									
	C. album L.		*P. lapathifolia* L.		*T. perforatum* L.		*S. arvensis* L.		*E. crus-galli* L.	
	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}
Sole										
S. barley	36.7	13.8	16.2	18.6	0.42	0.11	0	0	0.42	0.04
S. wheat	5.00	1.64	14.6	3.09	1.67	0.89	0	0	0	0
Pea	3.75	1.69	2.08	0.59	0.83	2.40	2.08	2.72	0	0
Caraway	0.42	0.34	0	0	5.00	54.6	0	0	5.42	28.0
Binary										
S. barley + caraway	172.5	59.7	74.2	35.3	4.58	6.75	8.33	10.6	0.83	0.75
S. wheat + caraway	80.8	30.3	23.7	10.2	4.17	10.0	10.0	7.76	0	0
Pea + caraway	0.83	1.68	0	0	6.25	30.5	0.83	0.81	3.33	12.3
Trinary										
S. barley + caraway + white clover	148.3	110.2	71.2	50.8	1.67	0.78	7.08	12.5	2.91	0.73
S. wheat + caraway +white clover	74.6	43.6	11.7	19.5	3.75	11.7	12.5	21.3	0	0
S. wheat + caraway +white clover	90.4	96.7	0	0	2.92	10.5	19.2	256.3	0.42	1.96

Table 3. The average number and the average biomass of dominant weed species in sole, binary, and trinary crops in 2018.

Treatment	Weed Species									
	C. album L.		*P. lapathifolia* L.		*T. perforatum* L.		*C. minus* L.		*T. officinale* L.	
	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}
Sole										
S. barley	22.5	2.78	18.3	2.00	0	0	3.75	0.62	0	0
S. barley	13.3	2.72	11.3	2.79	0	0	0	0	0	0
S. barley	11.7	1.91	33.3	15.5	0	0	1.67	0.13	0	0
Caraway	0	0	0	0	3.33	26.8	0		0	0
Binary										
S. barley + caraway	0	0	0	0	2.50	34.4	0	0	4.18	3.38
S. wheat + caraway	0	0	0	0	4.17	42.7	0	0	2.08	0.52
Pea + caraway	0	0	0	0	5.00	9.26	0	0	1.25	2.21
Trinary										
S. barley + caraway + white clover	0	0	0	0	1.25	15.6	0	0	0	0
S. wheat + caraway + white clover	0	0	0	0	3.33	33.2	0	0	0.42	0.16
S. wheat + caraway + white clover	0	0	0	0	2.92	17.0	0	0	0	0

The third year of caraway vegetative season. In 2019, 25 weed species were found in multi-crops, including 14 annual weeds and 11 perennials (Table 4). The weeds identified belonged to 10 different families: *Equisetaceae*, *Asteraceae*, *Brassicaceae*, *Amaranthaceae*, *Caryophyllaceae*, *Plantaginaceae*, *Poaceae*, *Violaceae*, *Fabaceae* and *Polygonaceae*. White goosefoot, scentless chamomile, and common dandelion (*Taraxacum officinale* F.H. Wigg.) were dominant. The highest incidence of common dandelion was found in caraway grown after peas, while scentless chamomile was the most common in the caraway grown with white clover after barley. The highest mass of creeping thistle was found in the binary crop of spring wheat and caraway.

Table 4. The average number and the average biomass of dominant weed species in sole, binary, and trinary crops in 2019.

Treatment	Weed Species									
	T. officinale		*T. perforatum* L.		*C. album* L.		*E. crus-galli* L.		*C. arvense* L.	
	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}	pcs. m^{-2}	g m^{-2}
Sole										
S. barley	10.0	12.5	0.83	0.88	10.8	1.71	6.25	0.62	2.08	10.4
S. barley	9.17	13.9	0	0	16.3	2.29	15.8	2.04	1.67	2.50
S. barley	9.17	21.6	9.58	39.4	9.17	1.62	28.3	15.0	0.83	3.33
Bare fallow	7.08	8.29	3.33	1.42	6.67	5.79	6.25	5.83	2.08	8.33
Binary										
S. barley + caraway	11.7	54.8	11.2	20.5	2.92	5.17	0	0	1.67	3.58
S. wheat + caraway	10.0	60.7	15.4	46.8	0.42	0.67	5.00	1.67	4.58	24.5
Pea + caraway	11.7	172.4	11.2	75.8	6.25	4.42	0	0	0	0
Trinary										
S. barley + caraway + white clover	7.50	76.3	9.17	86.1	7.50	16.5	0	0	0.83	13.3
S. wheat + caraway +white clover	3.75	21.7	17.5	57.1	8.75	16.6	0	0	1.25	10.9
S. wheat + caraway +white clover	14.2	91.5	10.4	31.5	11.2	20.4	0	0	0.42	0.92

3.2. Number of Weeds

The year of growing the main crops. Before harvesting the main crops in 2017, herbicide-free binary spring barley and spring wheat crop with undersown caraway, and trinary spring barley, spring wheat, and pea crop with undersown caraway and white clover had a significantly higher number of weeds, compared to sole crops of those plants—3.5, 4.3, 3.2, 3.8, and 9.0 times, respectively (Figure 4).

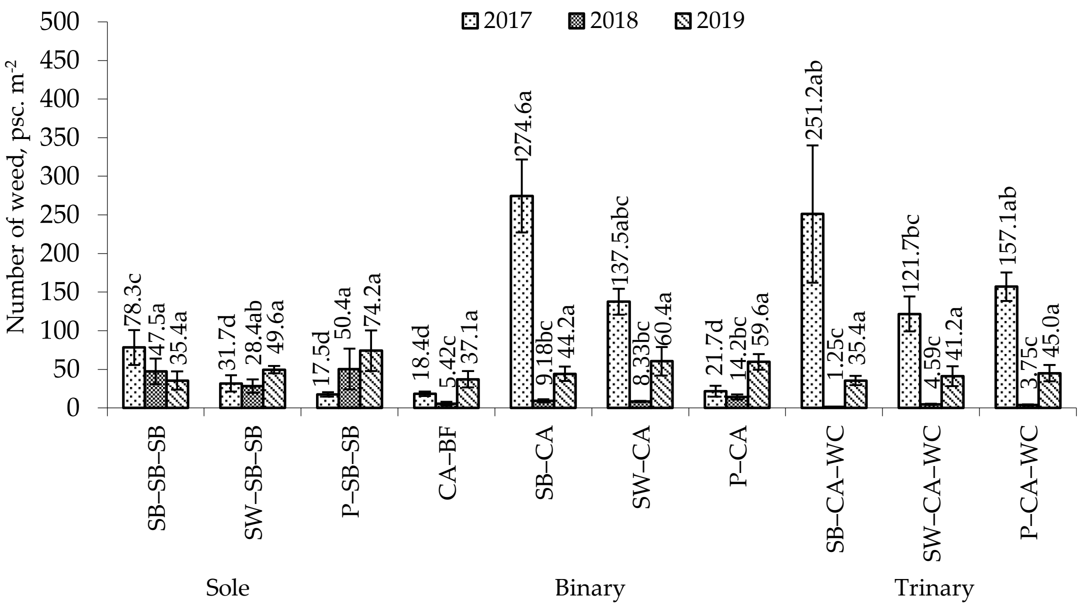

Figure 4. The number of weed in sole, binary, and trinary crops in 2017–2019. Note. CA—caraway, SB—spring barley, SW —spring wheat, P—pea, WC—white clover, BF—black fallow. Differences between the averages of treatments marked with different letters (a, b, c, d) are significant ($p < 0.05$); error bars indicate the standard error.

The number of weeds in binary pea and caraway crop did not differ significantly from the sole crop and was significantly, 7.2 times, lower than that in trinary crop with undersown caraway and white clover that had not been sprayed with herbicides.

The second year of caraway vegetative season. In 2018, the number of weeds in caraway crop grown after barley, wheat, and peas without white clover (binary crop) and together with white clover (trinary crop) was significantly lower compared to their sole crops, by 5.2, 3.4, and 3.5 times and 38.0, 6.2, and 13.4 times, respectively (Figure 4).

The third year of caraway vegetative season. In 2019, the number of weeds in sole, binary, and trinary crops did not differ significantly due to large variations in the data (Figure 4).

3.3. Weed Dry Biomass

The year of growing the main crops. Before the harvesting of spring barley, spring wheat, and peas with undersown caraway in binary as well as trinary crops with undersown, white clover was found to have a significantly higher weed mass compared to the sole crops of spring barley, spring wheat, peas, and caraway by 3.0, 7.8, 4.5, 4.5, 12.8, and 31.6 times, respectively (Figure 5). The weed mass in binary pea and caraway crop was significantly, 7.0 times, lower compared to trinary crop with undersown caraway and white clover with zero herbicide application. That was determined by a very intense spread of wild mustard in trinary crop. The dry matter mass of weeds in sole caraway crop was higher than that in binary spring wheat and caraway, and pea and caraway crops, but not significantly.

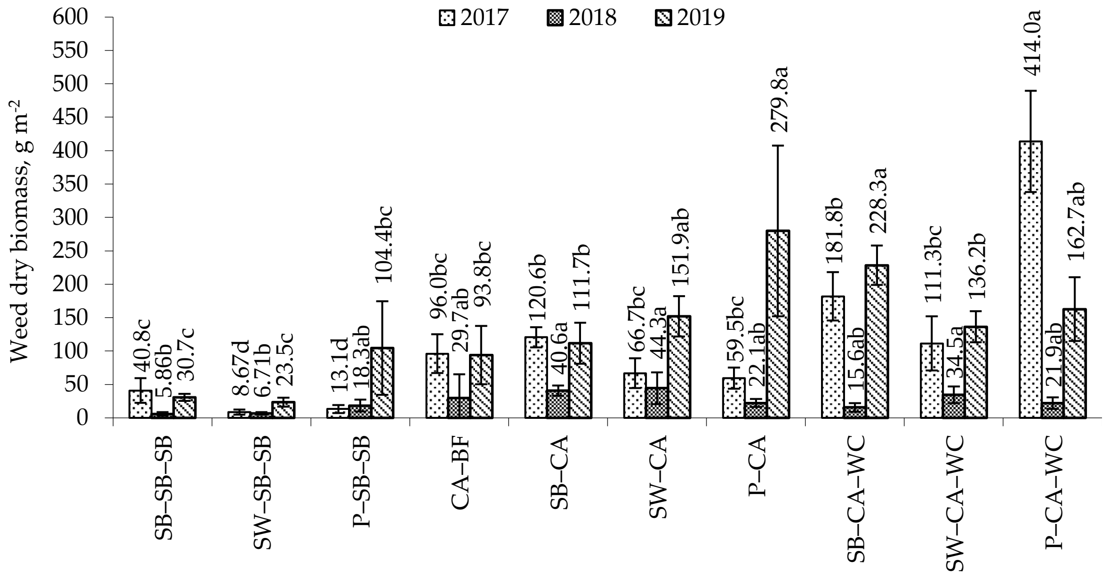

Figure 5. Weed dry biomass in sole, binary, and trinary crops in 2017–2019. Note. CA—caraway, SB—spring barley, SW—spring wheat, P—pea, WC—white clover, BF—black fallow. Differences between the averages of treatments marked with different letters (a, b, c) are significant ($p < 0.05$); error bars indicate the standard error.

The second year of caraway vegetative season. The dry matter mass of weeds in caraway crop grown after barley and after wheat without white clover, and after wheat with white clover was significantly higher than the sole crop—by 6.9, 6.6, and 5.1 times, respectively (Figure 5). The dry matter mass of weeds in caraway crop grown after barley and pea with clover was not significantly different from that of the sole crops. Apparently, the lush clover growing in the lower layer suppressed the weeds well.

The third year of caraway vegetative season. The weed mass of caraway grown after barley, after wheat, and after pea without white clover (binary crops) and in combination with white clover grown after barley and after wheat (trinary crop) was significantly higher than that in sole crops (by 3.6, 6.5, 2.7, 7.4, and 5.8 times, respectively) (Figure 5). Apparently, this was caused by a more abundant spread of common dandelion and scentless chamomile in the latter crops. The dry matter mass of weeds in the bare fallow left after caraway harvesting did not differ significantly from that of sole, binary, and trinary crops, except for the caraway crops grown after peas and after barley with white clover.

3.4. Caraway Crop Density

In 2018, the caraway grown after wheat, after barley, and after wheat together with clover did not form rosettes of sufficient size to bloom and ripen the seeds. The crop density of productive caraway grown as the sole crop and after peas without white clover was found to be significantly higher than when grown after barley without clover and after peas together with clover, by 1.4 and 3.0 times, respectively (Figure 6). The density of caraway crop grown after peas in combination with white clover was the lowest. This was due to interspecific competition for environmental resources.

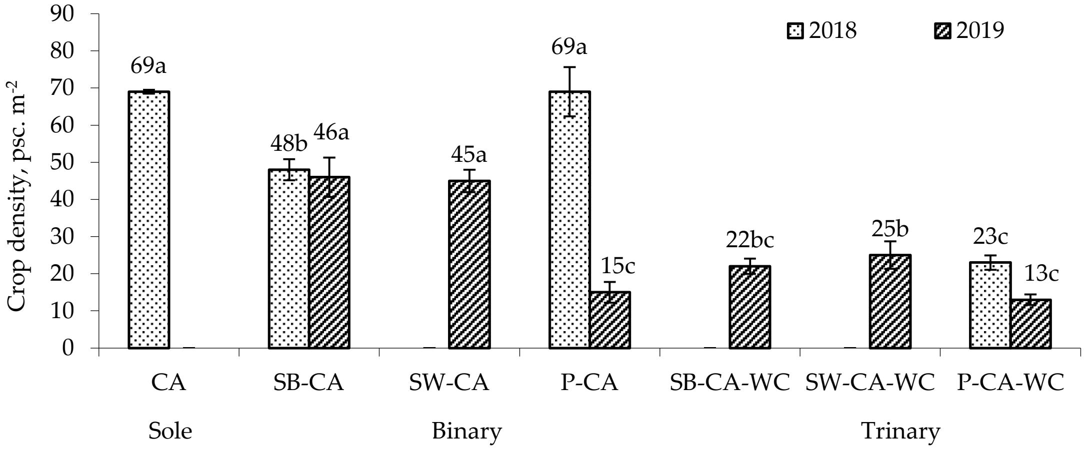

Figure 6. Caraway crop density before harvest in 2018–2019. Note. CA—caraway, SB—spring barley, SW—spring wheat, P—pea, WC—white clover. Differences between the averages of treatments marked with different letters (a, b, c) are significant ($p < 0.05$); error bars indicate the standard error.

In 2019, the density of the sole caraway crop grown after barley and after wheat before harvesting was found to be significantly higher than that of the caraway grown in other crops—from 1.8 to 3.5 times, respectively. The lowest number of productive caraway plants was found in cultivation after peas without and with white clover.

3.5. Caraway Seed Yield

In 2018, the highest yield of caraway seeds was obtained by growing it after peas without white clover (Figure 7). The seed yield of caraway grown after barley without white clover and that grown after peas together with clover were found to be 2.6 and 1.9 times lower compared to those grown after peas. The seed yield of the sole caraway crop was lower than that of caraway grown after peas without clover, but no significant difference was found.

In the third year of growth (2019), the seed yield of caraway grown after barley without white clover was the same as in the second year (2018). The seed yield of caraway grown after peas together with clover was 1.9 times lower than that of the second year. The yield of caraway seeds grown after peas without white clover was very low. The caraway grown after wheat in combination with clover had a significantly higher seed yield (from 2.0 to 16.0 times) compared to that of other multi-crops. The lowest seed yield of caraway was obtained by growing it after peas together with white clover.

The highest total seed yield of caraway was measured when it was grown after peas without white clover and after wheat with clover. The seed yield of caraway grown after barley without clover was lower compared to that of the aforementioned crops, however, no significant differences were found. The lowest seed yield was obtained by growing caraway after wheat without white clover and after barley with clover.

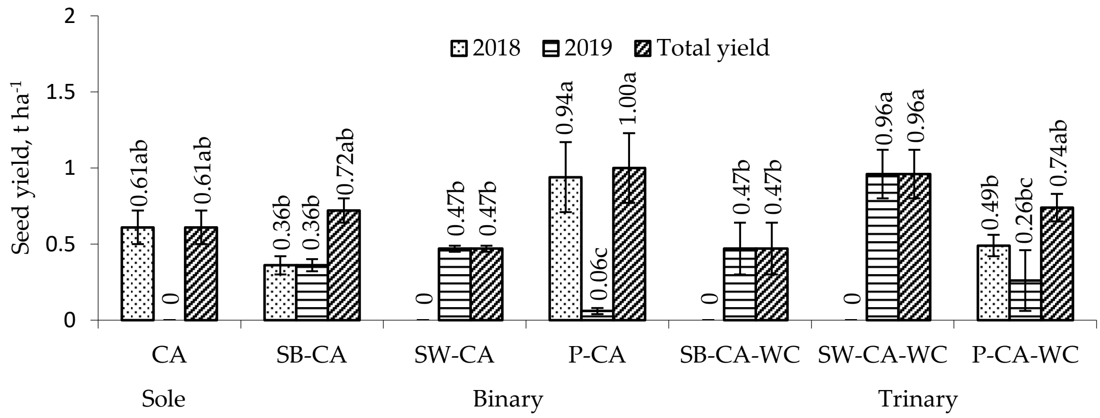

Figure 7. Caraway seed productivity, 2018–2019. Note. CA—caraway, SB—spring barley, SW—spring wheat, P—pea, WC—white clover. Differences between the averages of treatments marked with different letters (a, b, c) are significant ($p < 0.05$); error bars indicate the standard error.

3.6. Aboveground Dry Biomass of White Clover

After harvesting the main crops in 2017, white clover regrew best and its maximum dry matter mass was determined when grown after peas (Figure 8). Clover regrew worse after wheat compared to the regrowth after peas, however, its dry matter mass did not differ significantly. The dry matter mass of the clover regrown after barley was significantly (40.0%) lower than after peas.

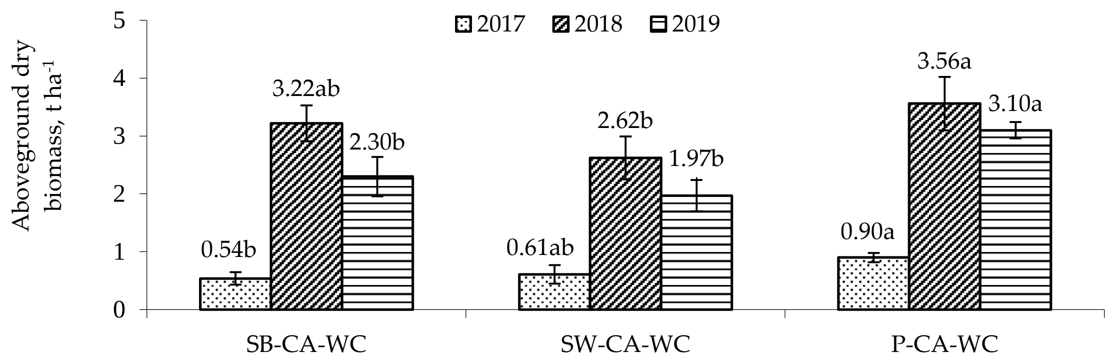

Figure 8. Aboveground dry biomass of white clover in trinary crops in 2017–2019. Note. CA—caraway, SB—spring barley, SW—spring wheat, P—pea, WC—white clover. Differences between the averages of treatments per one experimental year separately (2017–2019) marked with different letters (a, b), are significant ($p < 0.05$); error bars indicate the standard error.

Before caraway harvesting in 2018, the highest dry matter mass of white clover was found when growing it after peas. The dry matter mass of clover grown after barley was lower than that after peas, however, insignificantly. The dry matter mass of clover grown after wheat was significantly (26.4%) lower than after peas.

Before caraway harvesting in 2019, the highest dry matter mass of white clover was found when growing it after peas. The dry matter mass of clover grown after barley and after wheat was significantly (25.8% and 36.5%, respectively) lower than that after peas.

4. Discussion

4.1. Weed Spread in the Multi-Cropping System

During the first year of growth, caraway is very demanding of light and sensitive to weed suppression. Therefore, it is not recommended to sow it with perennials or to grow it in weedy fields. Such caraway is not productive in the second year and demonstrates very low productivity in the third year [27].

The most important operations in caraway cultivation after sowing are soil loosening, weed control, and plant protection. It is important to keep weed populations to a minimum in order to reduce competition between crops and weeds [28]. The highest prevalence of weeds in multi-crops is observed where herbicides cannot be sprayed [29]. The results of this study showed that in the first year, in the cultivation of the main crops, the total dry matter mass of weeds was found to be significantly (from 3.0 to 31.6 times) higher in non-sprayed with herbicides binary crops with undersown caraway and in trinary crops with undersown caraway and white clover, compared to sole crops (Figure 5). The most common weeds in crops were *T. perforatum*, *Ch. album* and *S. arvensis* (Table 2). Weed control in multi-crops is often determined by the biomass of multi-crop cultivation and plant diversity. When the primary crop is harvested, the secondary plants remain growing to cover the soil and at the same time prevent the growth of weeds [30]. Other authors suggest that growing binary and trinary crops allows the improvement of weed control and good crop rotation [31]. Plants with small leaves compete with weeds in the second year, preventing a reduction in overall field productivity [32]. Our research data showed that in the second year of cultivation, white clover formed a high aboveground biomass (from 2.62 to 3.56 t ha^{-1}) in trinary crops, and, therefore, has a good potential for weed control (Figure 8). Significantly (6.9 and 6.6 times) higher total dry matter mass of weeds was found in the caraway binary crops, when they were grown after spring barley and spring wheat without clover compared to sole crops, respectively. In the third year, significantly (from 2.7 to 7.4 times) higher total dry matter mass of weeds was found in the caraway binary and trinary crops when they were grown after barley, wheat, and pea without clover and after barley and wheat with clover compared to sole crops (Figure 5). Apparently, this was determined by a more abundant spread of *T. officinale* and *T. perforatum* in the latter crops (Table 4).

Arlauskienė et al. [33] have shown that the cultivation method (multi-crop or sole cropping) has a significant positive effect on weed density, weed control and dry matter mass. Šarūnaitė et al. [34] state that *Vicia sativa* L. has the best weed control effect in multi-crops compared to other legumes (narrow-leaved lupin (*Lupinus angustifolius* L.), faba bean (*Vicia faba* L.) and pea). Multi-crops reduced the dry matter mass of the most predominant weeds effectively. Arlauskienė et al. [35] state that weed control was significantly better in binary pea and barley crop compared to binary wheat and triticale crop. Bilalis et al. [36] point out that the shade formed by agricultural plants is undoubtedly a key factor in inhibiting weed growth. Effective weed control is highly dependent on productive crop density [37,38]. Our research showed that weeds were better controlled in denser caraway crops (Figure 6). *T. officinale* was best suppressed in the caraway crop when they grew after the spring wheat with clover, and *T. perforatum*—in the caraway crop when they grew after the spring barley without clover. Moreover, meteorological conditions can also affect weed spread and caraway productivity.

4.2. Caraway Crop Productivity in the Multi-Cropping System

According to our research data, in the second year of cultivation the highest yield of caraway seeds was obtained when growing them in binary crop after peas, and in the third year—in trinary crop after spring wheat with white clover. A lower, but insignificant, total yield of caraway seeds was obtained by growing them under barley without white clover and under peas with white clover, compared to the aforementioned crops (Figure 7). Šarūnaitė et al. [34] and Kadžiulienė et al. [39] have concluded that the yields of individual plant species in multi-cropping differ significantly between experimental years due to different weather conditions prevailing in the particular year analyzed. Kozera et al. reported that the highest yield of caraway seeds in the second year of cultivation was obtained by growing it together with peas (2.45 t ha^{-1}). Due to the ability of peas to fix nitrogen from the atmosphere, caraway had favorable growth conditions, resulting in higher yields. The lowest yield of caraway seeds in the second year of cultivation was obtained when it was grown together with white mustard. The yield of caraway seeds was only 1.25 t ha^{-1}. The intensive growth and high demand for water, nutrients, and light of white mustard severely limited the development of caraway, resulting in lower yields [31].

Taddese et al. [40] argue that competition for light, water, nutrients, and allelopathic effects can reduce plant yields in multi-crops. Based on the studies of multi-crops, Živanov et al. [41] hypothesized that reciprocal growth inhibition occurred between different plants grown as multi-crops due to limited environmental factors (resources and space). Our research showed that the later the main crop was harvested, the more effectively caraway competed with the main crop and with white clover in trinary crops. Launay et al. [42] state that the density of agricultural plant species and their proportion in multi-crops had a small effect on the overall crop yield. Other researchers have found that doubling the seed rate increased grain yields and weed suppression [43]. Hauggaard-Nielsen et al. [44] highlight several aspects of multi-crop production that need to be considered in order to be successful. Careful planning of the crop structure is necessary, taking into account the environmental conditions of the area and the available plants or varieties [21,44]. An economically viable multi-crop is highly dependent on the application of a sowing model and the choice of compatible crops [45]. Before setting up the experiment, we also carefully selected and planned sowing of groups of annual, biennial, and perennial plants that are important commercial plants in organic farming. Moreover, caraway as a biennial plant is perfect for growing with annual and perennial plants. For example, plants that are deeply rooted should be sown with plants that have a shallow root system; to combine early maturing plants with later maturing plants; to sow tall plants with dwarf plants that can survive partial shade [21,46]. We applied this knowledge to our experiment. In the first year of caraway vegetative season, annual crops grown together produced harvest, and biennials, such as caraway, developed root systems. In the second year of caraway vegetative season, white clover and caraway covered the interrows and controlled weeds perfectly.

The highest benefit of growing different plants at the same time is that the plants in crop complement each other. When two plant species grown as multi-crops do not compete for the same resources, they can grow together more efficiently [47]. The result indicated that the dry matter mass of the clover regrown after barley and wheat was lower than that after peas (Figure 8). This can be explained by the fact that the peas were harvested 7 and 15 days earlier than barley and wheat, respectively. In addition, the growth of clover after barley and wheat was more hindered by the remaining stubble, which decomposed more slowly.

Synergies are essential for the development of sustainable food production systems, especially in agricultural systems with limited resources where grasses and legumes are grown in mixed cropping. For example, the yield of mixtures of grasses and legumes is more stable and the risk of crop failure is lower, which is often associated with cropping of plants in a monoculture [1,48,49]. A multi-crop system is beneficial compared to sole cropping due to the positive interactions between the components [3,50]. The combination of grasses and legumes in mixed cropping offers particularly great opportunities for the efficient and sustainable use of resources [43,51]. Plants of the *Fabaceae* family can form symbiotic relationships with Rhizobium bacteria—nitrogen from the atmosphere is assimilated and can be transferred to other plants such as cereals [52]. The results of our study showed that caraway could use nitrogen accumulated by peas and clover in the topsoil. Due to competition in the early growth stages, the growth dynamics of multi-crops may differ from the growth dynamics of sole crops. For example, the roots of a plant may be forced to penetrate deeper soil layers. This competitive effect may diminish later in the season, as the roots of different plants spread over a larger volume of soil due to higher root distribution [53].

5. Conclusions

Growing caraway in a multi-cropping system is beneficial because it increases the productivity and reduces the prevalence of weeds. Biennial caraway can be grown in binary crops as an undersowing in peas. The success of this strategy is based on the fact that the same herbicides are suitable for weed control in both pea and caraway crops. Caraway can be grown in trinary crops including white clover and harvested in the second or third year of growing.

In the second year, the highest yields of caraway seeds were obtained when they were grown as a binary crop after pea without white clover, and in the third year—when they were grown as a trinary crop after wheat with white clover.

Caraway can be grown in trinary crops including white clover and harvested in the second or the third year of the vegetative season.

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Appendix A

The experimental field was ploughed in autumn 2016, and in spring 2017 it was cultivated with a germinator KLG-4.0 twice and fertilized with complex fertilizer NPK 8-20-30 (300 kg ha^{-1}). On 5 May spring barley (*Hordeum vulgare* L.) "Orphelia KWS" (160 kg ha^{-1}), spring wheat (*Triticum aestivum* L.) "Quintus" (250 kg ha^{-1}) and pea (*Pisum sativum* L.) "Salamanca" (280 kg ha^{-1}) were sown (12 cm interrow spacing). On 5 May sole caraway crop (*Carum carvi* L.) "Gintaras" (7 kg ha^{-1}); caraway ("Gintaras", and white clover (*Trifolium repens* L.) ("Sūduviai" (2 kg ha^{-1}) 12 cm interrow spacing crosswise to the direction of sowing) were sown into spring barley, spring wheat and peas (Figure 2). After sowing, sole crops of peas and peas with undersown caraway were sprayed with herbicide Fenix (aclonifen 600 g L^{-1}) (3 L ha^{-1}). During the growing season, the latter crops were sprayed with fungicide Signum (boscalid 267 g kg^{-1} + pyraclostrobin 67 g kg^{-1}) (0.50 L ha^{-1}) and insecticide Cyperkill 500 EC (cypermethrin 500 g L^{-1}) (0.05 L ha^{-1}). Sole spring barley and spring wheat crops were sprayed with herbicide Elegant 2 FD (florasulam 6.25 g L^{-1} + 2.4-D 300 g L^{-1}) (0.40 L ha^{-1}), insecticide Karate Zeon 5 CS (lambda-cyhalothrin 50 g L^{-1}) (0.14 L ha^{-1}) and fungicide Bumper 25 EC (propiconazole 250 g L^{-1}) (0.50 L ha^{-1}) during the growing season, and the crop with undersown caraway (binary) and that with undersown caraway and white clover (trinary) were sprayed with fungicide Bumper 25 EC (0.50 L ha^{-1}). During the growing season, sole spring barley and spring wheat crops and the crops with undersown caraway were fertilized with ammonium nitrate at the rate of 180 kg ha^{-1}, and those with undersown caraway and white clover—at the rate of 150 kg ha^{-1}. Peas were harvested on 16 August, spring barley—on 23 August, and spring wheat—on 31 August using a combine harvester Wintersteiger Delta (Austria).

After the main crops, spring barley, spring wheat and peas in 2017 and 2018 and after sole caraway crop in 2018, the harvested plots were disked and deep ploughed. On 20 April 2018 spring barley "Orphelia KWS" (180 kg ha^{-1}) was sown. In 2018, spring barley crop was sprayed with a herbicide Elegant 2 FD (florasulam 6.25 g L^{-1} + 2.4-D 300 g L^{-1}) (0.40 L ha^{-1}), insecticides Karate Zeon 5 CS (lambda-cyhalothrin 50 g L^{-1}) (0.14 L ha^{-1}) and Bulldock 025 EC (beta-cyflutrinas 25 g L^{-1}) (0.30 L ha^{-1}), fungicides Bumper 25 EC (propiconazole 250 g L^{-1}) (0.50 L ha^{-1}) and Miradol 250 SC (azoksistrobinas 250 g L^{-1}) (0.60 L ha^{-1}). On 18 April 2019 spring barley was sown. In 2019 spring barley crop was sprayed with herbicides Elegant 2 FD (florasulam 6.25 g L^{-1} + 2.4-D 300 g L^{-1}) (0.40 L ha^{-1}) and Trimmer (tribenuronmetilas 500 g kg^{-1}) (0.10 kg ha^{-1}), insecticide Karate Zeon 5 CS (lambda-cyhalothrin 50 g L^{-1}) (0.14 L ha^{-1}), fungicide Bumper 25 EC (propiconazole 250 g L^{-1}) (0.50 L ha^{-1}). In 2018 spring barley was harvested on 1 August; and in 2019 it was done on 5 August. During the second and the third years of growth, caraway was not fertilized with mineral fertilizers and no plant protection products were used. In 2018 caraway was harvested on 9 July; and in 2019 it was done on 5 July.

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