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The Effects of Incorporating Caraway into a Multi-Cropping Farming System on the Crops and the Overall Agroecosystem

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Abstract: The scientific aim of this article is to investigate the potential benefits of implementing a multi-cropping system, specifically focusing on the incorporation of caraway, to improve soil agrochemical and biological properties, prevent soil degradation and erosion, and ultimately enhance soil quality and health to better adapt to climate change. This study aims to provide valuable insights into the comparative analysis of various soil parameters and biological indicators to showcase the promising perspectives and importance of perennial crop production for improving soil quality and agricultural sustainability. These crops are designed to provide multiple benefits simultaneously, including improved yields, enhanced ecosystem services, and reduced environmental effects. However, an integrated assessment of their overall effects on the agroecosystem is crucial to understand their potential benefits and trade-offs. The field experiment was conducted over three consecutive vegetative seasons (2017 to 2021) at the Experimental Station of Vytautas Magnus University Agriculture Academy (VMU AA) in Kaunas district, Lithuania. The experimental site is located at 54°53′7.5″ N latitude and 23°50′18.11″ E longitude. The treatments within a replicate were multi-cropping systems of sole crops (spring barley (1), spring wheat (2), pea (3), caraway (4)), binary crops (spring barley–caraway (5), spring wheat–caraway (6), pea–caraway (7)), and trinary crops (spring barley–caraway–white clover (8), spring wheat–caraway–white clover (9), pea–caraway–white clover (10)) crops. However, an integrated assessment of their impact on the agroecosystem is needed to understand their potential benefits and processes. To determine the complex interactions between indicators, the interrelationships between indicators, and the strength of impacts, this study applied an integrated assessment approach using the comprehensive assessment index (CEI). The CEI values showed that integrating caraway (*Carum carvi* L.) into multi-cropping systems can have several positive effects. The effect of the binary spring barley and caraway and the trinary spring barley, caraway, and white clover crops on the agroecosystem is positively higher than that of the other comparative sole, binary, and trinary crops. Caraway, after spring wheat together with white clover, has a higher positive effect on the agroecosystem than caraway without white clover. Specifically, this study addresses key aspects, such as soil health, nutrient cycling, weed management, and overall agricultural sustainability, within the context of multi-cropping practices. By evaluating the effects of these cropping systems on soil agrochemical properties and ecosystem dynamics, the research provides valuable insights into sustainable agricultural practices that promote environmental conservation and long-term soil health.

Keywords: *Carum carvi* L.; multi-cropping system; soil properties; ecology; integrated assessment

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1. Introduction

Over the past five decades, advances in agricultural technology have successfully met the world's large needs for food, feed, and fibre [1,2]. However, the challenge of sustaining the needs of an ever-increasing population persists due to urbanization, land degradation, and climate change [3]. Intensive farming systems, while ensuring plant protection and mineral nutrition, rely on energy-intensive inputs and quality planting material without ensuring agroecosystem sustainability [4]. Consequently, ecological imbalances and deteriorating soil conditions necessitate the search for new technological solutions [5]. To successfully adapt to and mitigate climate change through agricultural management, there is a need for simple, cost-effective, and scalable approaches [6,7] that promote the long-term sustainable use of resources and eco-efficiency [8].

Multi-cropping system crops are the growing of two or more agricultural crops on the same field with different growing seasons and biological and agrotechnical characteristics [9–12]. The main objective of multi-cropping models is to identify synergies between different but complementary crops, resulting in improved growth and better space and time management compared to monoculture systems [13,14]. This approach optimizes space utilization and provides environmental benefits beyond what can be achieved with sole cropping in different seasons [15]. A deeper understanding of the ecological and physiological processes influencing weed, pest, and disease dynamics holds the potential for significant enhancements in crop productivity and the adoption of sustainable farming practices.

Caraway (*Carum carvi* L.), a biennial herb belonging to the family *Apiaceae*, is a valuable plant native to Europe, Asia, and North Africa [16]. Besides its use as a spice, caraway finds applications in the pharmaceutical industry and cosmetics [17]. The increasing demand for caraway motivates growers to enhance the quality of raw materials and cultivate caraway plants with higher contents of essential oils, improved soil health, and increased yield. Being a biennial, caraway can be grown in conjunction with annuals, such as peas and beans, as well as various herbs, like mustard, dill, or coriander [16], enabling seed production in the second and third years.

Recent studies have highlighted the significance of multi-cropping system crops, encompassing the cultivation of two or three crops together, representing 12% of the world's crop area, with floodplain farming accounting for 85 million hectares out of a total of 135 million hectares between 1998 and 2002. Rice constituted 34% of the multi-cropping system crop area, followed by wheat (13%) and maize (10%), grown in combination with other crops. These cropping patterns demonstrate the global importance and benefits of multi-cropping crops, leading to higher production volumes, healthier crops, and improved grain quality [18].

Growing multi-cropping system crops is not only an effective way to promote plant biodiversity but also facilitates the formation of plant relationships. In this system, legumes are a key functional group particularly valued for their soil improvement properties [19,20]. A large body of research has focused on co-cropping mixtures of legume, *brassica,* and cereal crops [21], the amount of essential nutrients accumulated in their mass and returned to the soil [22,23], and the influence of these crops on the yield of other crops grown [24]. Legumes are also used as a source of biological nitrogen input, ensuring the sustainability of the agroecosystem and its ability to recover from heat waves [20]. Combinations of legume and cereal crops can be used to improve low-productivity soils. The use of combinations with legumes can not only reduce nitrogen fertilization but also expand the area under environmentally friendly crops [25]. Growing crops in multi-cropping system crops offers potential advantages in terms of using local resources and reducing production costs [26]. Growing multi-cropping system crops increases the amount of total nitrogen, mobile phosphorus and potassium, and humus in the soil and increases soil biological activity [27,28].

Studies on multi-cropping system crops have been carried out on both above- and below-ground plants growing in the same soil zone [6,29,30]. Wang et al. [31] found that in multi-cropped crops, the arrangement of plant stems and leaves is heterogeneous in both the vertical and horizontal directions. This allows crops to make better use of solar radiation, while weeds receive less light and are smothered [32]. The roots of agricultural plant species are also more widely spaced [11]. In a multi-cropping agroecosystem, a dense upper and lower plant root horizon protects the soil from water and wind erosion [30] and improves the soil's agrochemical, agrophysical, and biological properties [10,27,33,34]. In addition, the soil is less stressed during the harvesting period, and its water regime is improved [35]. In a multi-cropping system, the roots of the plants are intertwined, thus facilitating nitrogen supply not only to the legume crop but also to other co-growing plants [36]. Such soils are rich in mycorrhizal fungi, which improve plant nutrition and growth [37] and activate soil enzymes [38]. The hyphae network of mycorrhizal fungi has been observed to significantly improve soil structure and especially water retention properties, making mycorrhizal-associated crops more resilient to drought stress [19].

Soil quality indicators include soil organic matter, soil pH, nutrient content (nitrogen, phosphorus, potassium), soil structure and its persistence, density, compaction, compression, electrical conductivity, infiltration, earthworm abundance, biodiversity, and soil respiration. All of these indicators reflect the chemical, physical, and biological properties of the soil. The most important and basic indicator of soil quality is soil organic matter and its content, which shows the soil's resistance to physical and biological degradation. The amount of organic matter (humus) directly determines soil fertility, which is closely linked to the multi-layered plant root system [39].

Research confirms that cultivation of multi-cropping system crops increases soil carbon sequestration [40] while increasing soil nutrient availability and optimizing nutrient utilization [41]. Growing multi-cropping system crops reduces soil erosion, conserves water [42], contributes to pest management, reduces dependence on agrochemicals, and promotes biodiversity conservation [43].

The importance of plant roots extends across various ecosystem capabilities, encompassing carbon cycling, metabolism, soil stability, structural integrity, and the help of soil organisms [44]. Different cropping patterns of cropping systems can influence rhizosphere soil enzyme activity and soil microbial biomass carbon and nitrogen content, which in turn influence soil carbon and nitrogen mineralization [27]. Based on this, plants growing in a multi-cropping system form a more abundant plant root biomass, allowing for greater nutrient uptake from the soil [45]. Studies by Oelmann et al. [46] and Zhu et al. [47] show that biologically diverse plant communities make better use of phosphorus resources than less diverse ones. Well-developed roots cover a larger soil volume, leading to higher plant uptake of phosphorus, potassium, and other elements [28], such as nitrogen [48]. Simplification of crop rotations, monocropping, and desalination reduce soil microorganism content and biodiversity. One reason for this is that root secretions from a particular plant species attract and provide shelter or a neighborhood for only a few microorganism species. A reduction in the number and diversity of pathogen-neutralizing antagonist microorganisms creates the conditions for pathogens to take over the remaining space near the roots, subsequently establishing themselves and infecting the living plant tissues. Multi-cropping system crops not only save space and provide environmental benefits but also control pest and disease dynamics [15].

Soil enzymes, denoted as precise proteins, are catalysts in numerous cell chemical tactics, facilitating the microbial absorption of insoluble materials. Among the significantly investigated enzymes are urease and saccharase, both categorized as hydrolases. Upon exposure to water, hydrolases actively cleave chemical bonds related to C-O, C-S, and C-N [38]. Urease governs nitrogen metabolism, while saccharase orchestrates the conversion of natural carbon in the soil matrix [38]. The interplay of soil enzymes profoundly affects important soil parameters, inclusive of the respiratory rate of biota, nitrification potential, microbial abundance, humus stages, mobile phosphorus and potassium concentrations, pH, and crop yields [49]. Variations in soil attributes attributable to awesome tillage structures intricately correlate with fluctuations in enzyme activity. The adoption of conservation agriculture practices, characterized by multiplied crop residue retention, proves efficacious in stimulating soil enzyme interest, thereby improving average soil fertility [50,51]. Concurrently, soil enzyme interest statistics emerge as a pivotal metric for gauging soil fertility and organic energy [52,53], presenting a promising avenue for complete soil assessment [54]. The microbial domain predominantly serves as the source for soil enzymes, with comparatively lesser contributions from flowers and animals. The collective enzymatic diversity exhibited by plant life and fauna signifies the soil's power as a particular temporal example. Enzymes wield massive impact over approaches consisting of the mineralization of plant residues, nutrient cycling, organic count accrual, and soil structural integrity [38,55]. Research suggests that perennial bean crops in multi-cropping system crops have much lower nitrate leaching, as nitrate and water uptake take longer than in annual crops. Nitrate leaching can occur when harvesting perennial crops and preparing the soil for sowing other crops. It is important to regulate the timing of harvesting of perennial and annual crops and the uptake of nitrogen by subsequent crops [9,10]. Aerial nitrogen (biological nitrogen) fixed by tuber bacteria in legumes benefits the soil by increasing organic matter, optimizing soil structure, maintaining soil porosity and nutrient balance, influencing soil pH, increasing biodiversity, and controlling pests [21,56,57].

In 2019, the agricultural sector emitted about 429 million metric heaps (Mt) of carbon dioxide equivalent, constituting about 11% of the full greenhouse fuel (GHG) emissions in Europe. The CO_2 emissions from agriculture, accounting for nearly 3% of the full GHG emissions within the agricultural zone, often arise from activities associated with soil control and land use trade [58]. As of 2021, the atmospheric concentration of CO_2 reached 414.72 parts according to million (ppm) [59]. Lithuania is actively engaged in mitigating GHG emissions from the agricultural sector in adherence to the mandates mentioned in the UN Framework Convention on Climate Change and the environmental policies set via the European Union. Noteworthy findings by Chai et al. [60] and Hu et al. [61] underscore a decline in soil CO_2 emissions in the context of multi-cropping structures. Beedy et al. [62] attribute the reduction in soil CO_2 emissions in multi-cropping setups to the technique of carbon sequestration. Skinuliene et al. [63] found that the maximum stated depth of CO_2 emission from soil occurs after a pre-crop, leaving a good-sized quantity of plant residues in the soil. Romaneckas et al. [64] have validated that in multi-cropping systems, the concentrations of CO_2 and soil respiration usually hinge on elements that include soil structural composition, temperature, and moisture content. In this study, we aimed to investigate the potential benefits of implementing a multi-cropping system to improve soil agrochemical and biological properties, prevent soil degradation and erosion, and ultimately improve soil quality and resilience to better adapt to climate change. This study aimed to reveal the complex effects of multi-cropping crops by combining them into a coherent system. We will provide valuable insights into the comparative analysis of soil agrochemical parameters, such as total nitrogen, organic carbon, mobile phosphorus and mobile potassium, soil macro-aggregates, and shear resistance, as well as the assessment of the biological indicators, such as dry root biomass, saccharase and urease activity, soil CO_2 emission, and weed dry biomass. Through our research, we aim to show the promising potential and importance of perennial crop production to improve soil quality and agricultural sustainability.

2. Materials and Methods

2.1. Site Description

The field experiment was conducted over three consecutive vegetative seasons (2017–2019, 2018–2020, 2019–2021) at the Experimental Station of Vytautas Magnus University Agriculture Academy (VMU AA) in the district of Kaunas, Lithuania. The experimental site is located at 54°53′7.5″ N latitude and 23°50′18.11″ E longitude. The soil of the experimental site is *Endocalcaric Amphistagnic Luvisol* according to the World Reference Base classification [65].

The topsoil at the experimental site has a sandy loam texture, and its agrochemical properties are as follows: pH_{KCl}—6.70; organic carbon (OC)—0.91–1.08%; plant available phosphorus (P_2O_5)—213–318 mg kg^{-1}; and potassium (K_2O)—103–125 mg kg^{-1}. Based on these soil characteristics, it can be observed that the organic carbon (OC) content in the topsoil is relatively low. However, the available phosphorus (P_2O_5) content falls within the "very high amount" category (Group V), and the potassium (K_2O) content falls within the "average amount" category (Group III), as per the evaluation of Lithuanian soil agrochemical properties [66].

2.2. Experimental Design

The experimental treatments applied were as follows: sole crops of spring barley, spring wheat, peas, and caraway, binary crops with added caraway, and trinary crops with added caraway and white clover (experimental treatments can be found in the online version at https://doi.org/10.3390/plants11060774 (accessed on 14 March 2023) [67]).

A one-factor field experiment with 10 treatments was set up in 2017. The experiment was performed in 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), and one replication block was 600 m^2. Furthermore, 2 m buffer rows were left between the individual blocks. In the experimental field, there were a total of 40 plots.

The field underwent deep ploughing in autumn, followed by two spring cultivations using a KLG-4.0 (UAB "Laumetris", Lithuania) germinator and fertilization with complex fertilizer NPK 8-20-30 at a rate of 300 kg ha^{-1}.

The main crops were sown as follows:

In 2017 (5 May): spring barley (*Hordeum vulgare* L.) variety 'Orphelia KWS' at 160 kg ha^{-1}, spring wheat (*Triticum aestivum* L.) variety 'Quintus' at 250 kg ha^{-1}, and peas (*Pisum sativum* L.) variety 'Salamanca' at 280 kg ha^{-1}.

In 2018 (20 April): spring barley (*Hordeum vulgare* L.) variety 'Orphelia KWS' at 160 kg ha^{-1}, spring wheat (*Triticum aestivum* L.) variety 'Wicki' at 250 kg ha^{-1}, and peas (*Pisum sativum* L.) variety 'Salamanca' at 280 kg ha^{-1}.

In 2019 (30 April): spring barley (*Hordeum vulgare* L.) variety 'Orphelia KWS' at 160 kg ha^{-1}, spring wheat (*Triticum aestivum* L.) variety 'Wicki' at 250 kg ha^{-1}, and peas (*Pisum sativum* L.) variety 'Salamanca' at 280 kg ha^{-1}.

The row spacing for these crops was maintained at 12 cm. In the binary and trinary crops, caraway (*Carum carvi* L.) was sown in 24 cm rows opposite to the main crop. In trinary crops, white clover (*Trifolium repens* L.) variety 'Sūduviai' was sown at a rate of 2 kg ha^{-1} with 12 cm row spacing in the opposite direction to the main crop.

Throughout the growing season, the main crops, including sole crops of caraway, spring barley, and spring wheat, as well as the caraway-including crops, were fertilized with ammonium nitrate at a rate of 180 kg ha^{-1}. Additionally, the caraway-including crops, along with caraway and white clover, received extra fertilization at a rate of 150 kg ha^{-1}. Plant protection products were applied according to established technology (refer to Appendix A). Notably, no mineral fertilizers were utilized in the second or third years of caraway growth, and plant protection products were omitted during this period.

2.3. Soil Agrochemical Studies

Soil agrochemical properties were determined before the experiment was set up and in the second and third year of caraway cultivation after the harvest. For the analyses, soil samples were taken in each experimental field with a Nekrasov drill from at least 15 locations about 300 g from the 0–25 cm of plough soil. Soil pH was determined potentiometrically in a 1 n KCl extract; mobile phosphorus P_2O_5 and mobile potassium K_2O (mg kg^{-1} soil) were determined using the Egner–Rimm–Domingo (A-L) method, and organic carbon (%) was determined through combustion of the samples at 900 °C with a Heraeus machine. Total nitrogen content (mg kg^{-1}) was assessed using the Kjeldahl method. The analyses were carried out in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry.

2.4. Soil Shear Resistance

Shear resistance was determined during the main crop harvesting in the second and third years after harvesting caraway seeds with a field hardness tester Geonor 72,407 (kPa read S2M1L 0.5). It was measured in 10 randomly selected locations at a soil depth of 8–10 cm in each experimental field.

2.5. Soil Aggregate–Size Distribution

The soil aggregate–size distribution was determined before the main crop harvesting in the second and third years of caraway cultivation and after harvesting the main crop and the caraway with a Retsch sieving apparatus. In each field, a soil sample of about 300 g was taken with a shovel in at least 3 places from 0–25 cm of the plough soil layer. The soil was dried in the laboratory. Then, 200 g soil samples were sieved for 2 min, with a sieving amplitude of 60%.

2.6. Soil CO_2 Emission

Soil CO_2 emission (μmol m^{-2} s^{-1}) was determined in the 0–10 cm plough soil layer with a portable analyzer Li-Cor 6400-09 before the main crop harvesting and before the second- and third-year caraway harvests [68]. In each experimental field, CO_2 emission was measured at two recording sites. The measures were taken between 11.00 and 16.00 h.

2.7. Plant Root Studies

Root investigations were conducted using the small monolith method (dimensions: 10 cm × 10 cm × 10 cm) [69]. These investigations were performed during the harvesting of the main crop and all throughout the second and third years of caraway cultivation following the caraway harvest. Samples were procured from two distinct soil layers, particularly 0–10 cm and 10–20 cm, at three unique locations inside every area. Subsequently, the roots were subjected to thorough washing through sieves and subjected to desiccation in a drying oven at a temperature of 105 °C. The quantification of plant root biomass was then translated into absolute dry counted values expressed in metric lots per hectare (t ha^{-1}).

2.8. Soil Enzyme Activity

The activity of soil hydrolases (urease and saccharase) was determined according to the following methods: urease–Hofmann and Schmidt (1953) and saccharase–Hofmann and Seegerer (1950), as modified by A. I. Chunderova [70] for harvesting the main crop and the second and third years of caraway cultivation. For the studies, soil samples were taken from each field in at least 15 places with a soil auger at a depth of 0–25 cm. The samples were dried at natural moisture content in open boxes at laboratory temperature. The tests were carried out in the Laboratory of Food Raw Materials, Agronomic and Zootechnical Research at the VMU Agriculture Academy.

2.9. Weed Dry Biomass

Assessment of weediness was carried out before the harvest of the main crop and in the caraway sole crop and the second and third years of caraway cultivation before the harvest of the caraway in each field in at least 10 randomly selected locations in plots of 0.06 m^2. The weeds from the plots were uprooted and wrapped in paper packets. In the laboratory, the number and species composition of weeds were determined, and the weeds were dried in a drying oven at 60 °C and weighed [71]. The weed dry biomass was converted to g m^{-2}.

2.10. Meteorological Conditions

In 2017, plant vegetative growth resumed on 31 March. April was cold and humid. May was very dry. The sum of precipitation in June was close to the standard climate. July was cool. In August, the HTC (Hydrothermal coefficient) was 1.00 (optimal humidity). September was warm. In 2018, February and March were colder than usual. Plant vegetative growth resumed on 4 April. April was warm. May was warm and dry. June was cool. July and August were warm. Temperatures in the autumn and winter months were higher than usual. In 2019, plant vegetative growth resumed on 5 April. April was warm. In May, the humidity was optimal. June was warm. In July and August, humidity was optimal (Table 1). In 2020, February and March were warmer than usual. Plant growth resumed on 7 April. April was very dry. May was warm and humid. June was warm, and the HTC was 1.74 (excess humidity). The temperature in July was 1.3 °C below the perennial average, with an HTC of 1.12 (optimum humidity). August was warm, with an HTC of 1.61 (excess humidity). September was warm and dry. October, November, and December were warmer than normal, and precipitation was lower than normal. In 2021, plant growth resumed on 11 April. May was cool and wet. The monthly HTC was 4.04 (excess humidity). June and July were hot and dry. The HTC for these months was 0.69 (arid). In August, the HTC was 2.40 (excess humidity) (Table 1).

Table 1. Meteorological conditions during the experimental period, Kaunas Weather Station.

Year/Month	01	02	03	04	05	06	07	08	09	10	11	12	SAT
						Average air temperature (°C)							
2017	−3.7	−1.5	3.7	5.6	12.9	15.4	16.8	17.5	13.4	7.6	3.9	1.2	2344.0
2018	−1.5	−6.2	−1.9	10.2	17.2	17.5	20.1	19.2	14.8	8.3	2.8	0.7	2645.6
2019	−3.2	1.3	3.2	9.1	13.0	19.8	17.1	18.1	13.1	9.1	5.0	2.3	2800.6
2020	2.5	2.2	3.6	6.9	10.5	19.0	17.4	18.7	14.9	10.3	5.2	0.6	2458.6
2021	−3.5	−5.0	1.7	6.2	11.4	19.5	22.6	16.5	11.6	8.1	4.2	−2.3	2668.9
Long-term average	−3.7	−4.7	0.3	6.9	13.2	16.1	18.7	17.3	12.6	6.8	2.8	−2.8	-
						Average precipitation rate (mm)							
2017	18.4	31.3	53.1	73.7	10.5	80.2	79.6	55.0	87.1	105.8	44.6	68.6	707.9
2018	57.2	23.7	22.7	64.8	17.6	57.6	137.5	66.2	55.3	36.7	51.9	76.3	667.5
2019	58.5	31.6	43.4	0.6	29.9	49.4	60.1	68.2	43.3	46.8	20.5	42.3	494.6
2020	52.8	54.9	29.3	4.0	94.4	99.3	60.4	92.8	13.3	52.5	30.0	17.1	600.8
2021	82.2	12.3	22.0	33.7	121.6	40.3	48.4	122.2	29.1	27.2	55.5	38.0	632.5
Long-term average	38.1	35.1	37.2	41.3	61.7	76.9	96.6	88.9	60.0	51.0	51.0	41.9	697.7

Note. Long-term average data for 40 years (1974–2013).

2.11. Statistical Analysis

Based on the methodology of G. Lohmann [72] and K. U. Heyland [73], an integrated assessment of the effect of multi-cropping system crops with caraway on the agroecosystem was implemented. The following studies and mathematical calculations were carried out: (1) the values of different indicators were determined; (2) the values of these indicators that were expressed in different units of measurement were converted into a single scale. A score of 1 corresponds to the lowest or minimum value, and 9 corresponds to the highest or maximum value. For all other values of the same indicator, the scores were calculated according to the following formula:

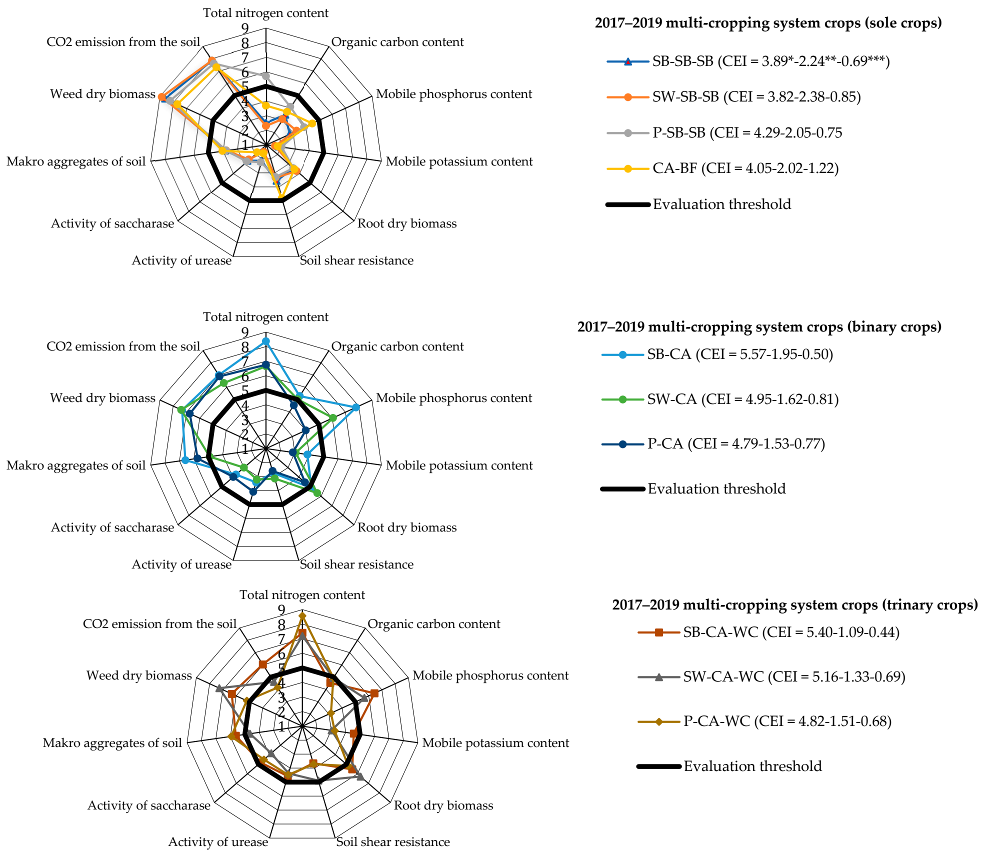
$$VBi = (Xi - Xmin) \times (Xmax - Xmin) - 1 \times 8 + 1, \quad (1)$$

where VBi is the score for a value of a given indicator, Xi is the expression for a given value, Xmax is the maximum value for a given indicator, Xmin is the minimum value for a given indicator; (3) the indicators converted to scores were shown in grid diagrams with a radius from 1 to 9; (4) the scale also showed the average value of the individual indicators—the score threshold—which is equal to 5 points and which separates high and low scores. The effectiveness of the measure is indicated by the area bounded by the scores of all its indicators; (5) calculation of the comprehensive assessment index (CEI), which consists of the average and the standard deviation of the assessment scores as well as the standard deviation of the average assessment scores below the assessment threshold.

3. Results

3.1. An Integrated Assessment of the Effect of Multi-Cropping System Crops on the Agroecosystem in 2017–2019

In terms of soil agrochemical properties of multi-cropping system crops, trinary and, in some cases, binary crops outperformed sole crops. The influence of binary and trinary crops led to a significant increase in total nitrogen scores above the assessment threshold. The highest scores were obtained when caraway was grown in a binary crop after spring barley and in a trinary crop with white clover after peas (Figure 1).



Experimental Treatments/ Indicators	Sole				Binary			Trinary		
	SB-SB-SB	SW-SB-SB	P-SB-SB	CA-BF	SB-CA	SW-CA	P-CA	SB-CA-WC	SW-CA-WC	P-CA-WC
Total nitrogen content	2.49	2.28	5.69	3.67	8.36	6.65	6.76	7.40	7.19	8.57
Organic carbon content	3.44	3.07	4.08	3.67	5.28	5.02	4.53	4.53	4.94	4.94
Mobile phosphorus content	2.78	3.30	3.87	4.49	7.79	6.06	4.00	6.43	5.67	3.15
Mobile potassium content	1.87	1.63	2.08	1.81	3.87	3.06	2.86	4.56	3.02	3.24
Root dry biomass	3.48	3.77	3.47	3.58	5.13	5.66	4.54	5.52	6.28	5.16
Soil shear resistance	3.58	3.37	3.32	4.84	2.74	3.14	2.60	3.65	4.89	3.72
Urease activity	2.16	1.52	2.26	1.63	3.42	3.22	4.09	4.57	4.38	4.48
Saccharase activity	2.69	2.56	2.76	1.81	3.72	3.00	3.97	4.80	3.83	4.50
Macro-aggregate content	3.84	3.76	3.78	4.02	6.59	4.90	5.74	5.62	4.64	5.94
Weed dry biomass	8.61	8.86	8.23	7.68	7.33	7.40	6.75	6.33	7.27	5.20
Soil CO_2 emission	7.86	7.85	7.61	7.30	6.99	6.35	6.89	6.03	4.61	4.15

Figure 1. An integrated assessment of multi-cropping system crops in 2017–2019. Note: SB—spring barley, SW—spring wheat, P—peas, CA—caraway, BF—bare fallow, WC—white clover, CEI—integrated assessment indices, *—an average of assessment scores (EP), **—standard deviation of EP, ***—standard deviation of the average of assessment scores below the assessment threshold.

Organic carbon scores rose above the assessment threshold when caraway was grown in binary crops after spring barley and spring wheat without white clover. However, the increase was small. Due to the more abundant root formed by the crop after spring barley and wheat without white clover (binary crop) and together with white clover (trinary crop), the mobile phosphorus score rose above the assessment threshold. The mobile potassium score did not rise above the assessment threshold as a result of the measures taken. However, the highest score was obtained when caraway was grown in a trinary crop after barley in combination with white clover (Figure 1).

In terms of soil agrophysical properties, there was an uneven distribution of scores, but there was a clear advantage of trinary crops over sole crops. The soil shear resistance scores for binary and trinary crops, although not above the assessment threshold, were found to be slightly higher for trinary crops compared to sole crops. The highest shear resistance score was found for caraway in the trinary crop after spring wheat together with white clover. Macro-aggregate content was positively affected both by growing caraway in the binary crop after spring barley and pea without white clover and with white clover (trinary crop). Under the complex assessment system, the performance of these crops rose above the assessment threshold (Figure 1).

In terms of the soil biological properties under multi-cropping system crops, caraway was the most influential in the trinary cropping of spring barley together with white clover. The plant root dry biomass scores of binary and trinary crops were found to be above the assessment threshold, except for the binary crop of pea and caraway, which was below the assessment threshold. The soil CO_2 emission scores for sole, binary, and trinary caraway crops after spring barley in combination with white clover were above the assessment threshold. Saccharase and urease activity was most affected by growing caraway in the trinary crop after spring barley with white clover, but the scores were below the assessment threshold (Figure 1).

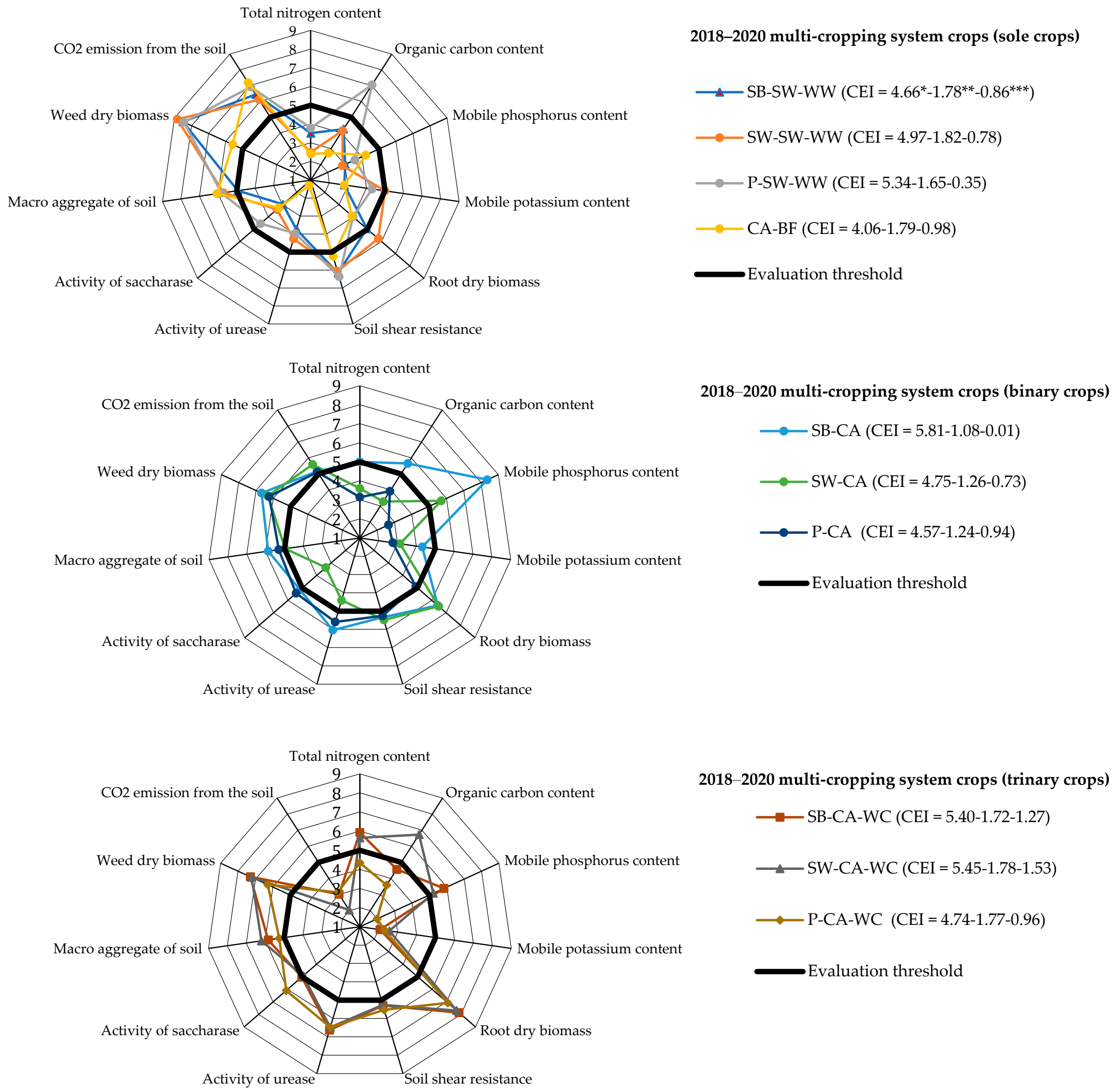
The scores for competition with weeds in sole, binary, and trinary crops were found to be above the assessment threshold. The highest scores were found for sole and binary crops after spring barley and wheat and for trinary crops after spring wheat. This distribution of scores may have been influenced by the dense stubble remaining in the binary crop, while in the trinary crop, the cover of white clover inhibited weed growth (Figure 1).

The calculated indicators for the integrated assessment and the areas bounded by the assessment scores showed that the effect of the binary crops of spring barley and caraway and the trinary crops of spring barley, caraway, and white clover, as well as spring wheat, caraway, and clover crops, on the agroecosystem was higher than that of the other sole, binary, and trinary crops compared.

3.2. An Integrated Assessment of the Effect of Multi-Cropping System Crops on the Agroecosystem in 2018–2020

In terms of soil agrochemical properties, the binary crop after spring barley and the trinary crop after spring wheat with white clover were superior to the sole crop (Figure 2).

The highest total nitrogen content, which rose above the assessment threshold, was obtained when caraway was grown in the binary crop after spring barley and in the trinary crop after spring barley and wheat with white clover. The organic carbon scores rose above the assessment threshold for caraway in the binary crop after spring barley without white clover and in the trinary crop after spring wheat with white clover. The more abundant root mobile phosphorus scores of the binary crop after spring barley and wheat without white clover (binary crop) and in combination with white clover (trinary crop) raised the scores above the assessment threshold. The mobile potassium scores in binary and trinary crops did not rise above the assessment threshold, but the highest score was obtained when caraway was grown in the binary crop after barley without white clover (Figure 2).



	Sole				Binary			Trinary		
Experimental Treatments/ Indicators	**SB-SW-WW**	**SW-SW-WW**	**P-SW-WW**	**CA-BF**	**SB-CA**	**SW-CA**	**P-CA**	**SB-CA-WC**	**SW-CA-WC**	**P-CA-WC**
Total nitrogen content	3.51	2.49	3.79	2.40	5.00	3.60	3.14	5.93	5.65	4.35
Organic carbon content	4.24	4.14	7.05	2.73	5.65	3.27	3.92	4.57	6.73	3.59
Mobile phosphorus content	3.02	2.86	3.59	4.23	8.36	5.70	2.66	5.83	5.22	1.99
Mobile potassium content	2.81	5.00	4.31	2.81	4.31	3.13	2.75	2.06	2.56	2.31
Root dry biomass	4.96	5.77	3.98	3.91	6.41	6.48	4.89	7.86	7.69	7.08
Soil shear resistance	6.17	6.06	6.37	5.24	5.34	5.48	5.26	5.29	5.26	5.53
Urease activity	3.73	4.26	3.96	1.30	6.04	4.41	5.59	6.63	6.48	6.48
Saccharase activity	2.97	3.39	4.55	3.25	5.15	3.37	5.43	5.02	4.92	6.09
Macro-aggregate content	4.94	5.71	5.82	6.05	5.86	4.96	5.30	5.84	6.20	5.26
Weed dry biomass	8.51	8.84	8.45	5.59	6.68	6.31	6.24	7.30	7.22	6.30
Soil CO_2 emission	6.44	6.11	6.92	7.19	5.16	5.59	5.12	3.02	2.04	3.13

Figure 2. An integrated assessment of multi-cropping system crops in 2018–2020. Note: SB—spring barley, SW—spring wheat, P—peas, CA—caraway, BF—bare fallow, WC—white clover, WW—winter wheat, CEI—integrated assessment indices, *—an average of assessment scores (EP), **—standard deviation of EP, ***—standard deviation of the average of assessment scores below the assessment threshold.

In terms of soil agrophysical properties, the scores were unevenly distributed, but a positive effect on soil shear resistance and macro-aggregate formation was found for both binary and trinary crops (Figure 2). Soil shear resistance scores for binary and trinary crops rose above the assessment threshold, but the advantage was marginal compared to sole crops. Macro-aggregate content was positively influenced by both the cultivation of caraway in the binary crop followed by spring barley and pea and the cultivation of all trinary crops. The highest score for macro-aggregate content was found in the trinary crop after spring wheat together with white clover.

In terms of the biological properties of the soil under multi-cropping system crops, higher root biomass of binary and trinary crops had a positive effect on enzyme activity. The plant root dry biomass scores for binary and trinary crops were found to be above the assessment threshold. The highest plant root dry biomass score was found when caraway was grown in a trinary crop after spring barley together with white clover. The scores for the assessment of soil CO_2 emission for sole crops and binary crops were above the assessment threshold. Saccharase activity was most affected by the cultivation of caraway in the binary crop after spring barley and pea without white clover and in the trinary crop of the same plants with white clover (scores above the assessment threshold). The most significant effect on urease activity was observed when caraway was grown in the binary crop after spring barley and pea without white clover and in the trinary crop after spring barley, spring wheat, and pea with white clover (Figure 2).

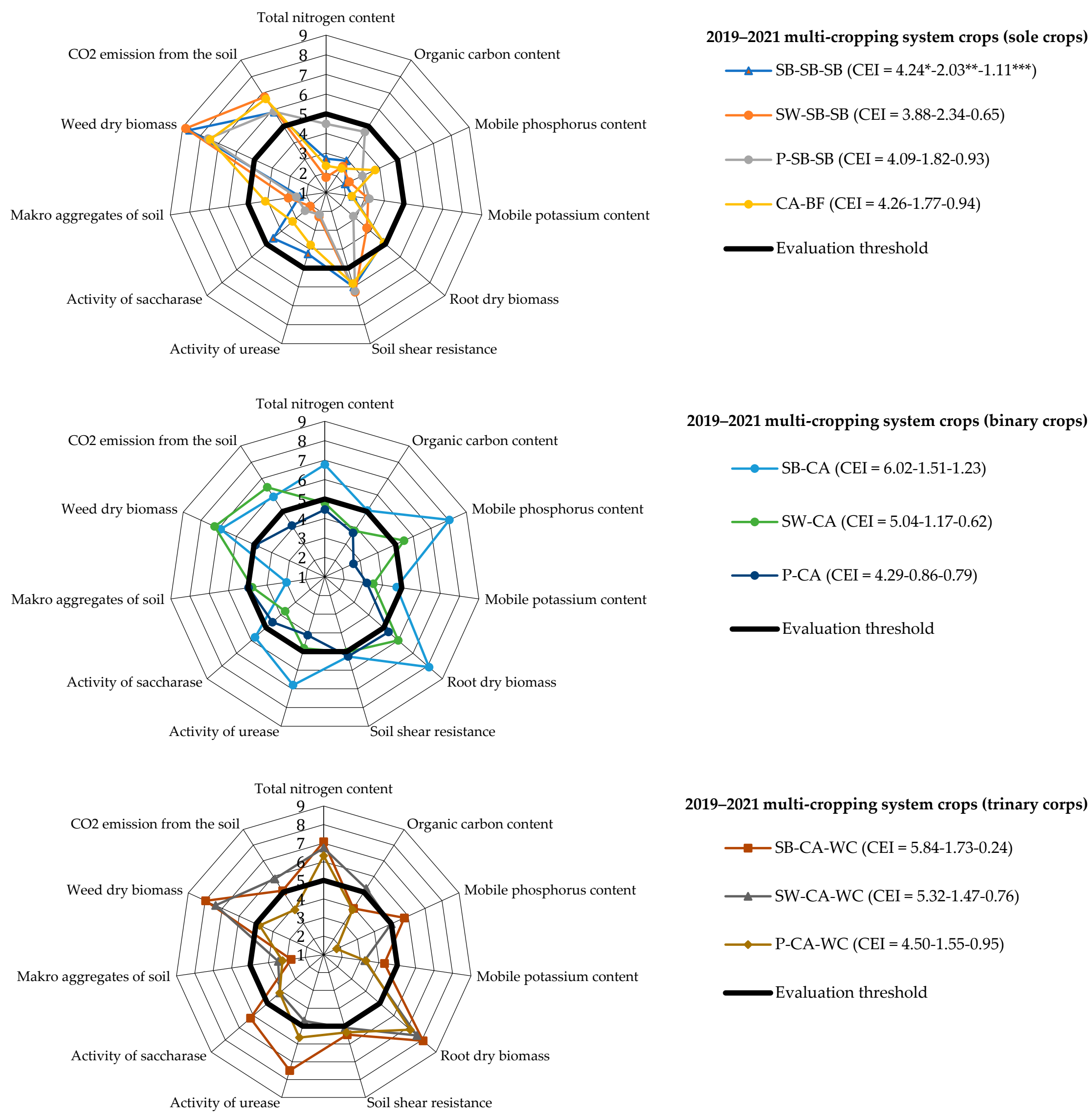
Weed dry biomass assessment scores for sole, binary, and trinary crops were found to be above the assessment threshold (Figure 2). The highest scores were found in sole and trinary crops after spring barley and wheat in combination with white clover. In the sole crop, weeds were controlled by chemical means, while in the trinary crop, white clover acted as a control.

Considering the integrated assessment indicators and the areas delimited by the assessment scores, it can be concluded that the effect of the crops of binary spring barley and caraway and of the trinary spring barley, caraway, and white clover, as well as spring wheat, caraway, and white clover, on the agroecosystem was higher than that of the other crops compared.

3.3. An Integrated Assessment of the Effect of Multi-Cropping System Crops on the Agroecosystem in 2019–2021

In terms of soil agrochemical properties, the influence of the cultivation of binary and trinary crops resulted in a wide range of scores, both rising significantly above the assessment threshold and falling below it (Figure 3). Total nitrogen scores rose significantly above the assessment threshold due to the trinary crop. The highest score was obtained when caraway was grown in the trinary crop after spring barley with white clover. The organic carbon scores rose above the assessment threshold when caraway was grown in the binary crop after spring barley and in the trinary crop after spring wheat. The binary crop after spring barley and wheat and the trinary crop after spring barley with white clover resulted in more abundant root biomass and raised the mobile phosphorus score above the assessment threshold because of the bean crop. The mobile potassium scores for all crops did not rise above the assessment threshold, but for caraway in the binary crop after barley, the score was close to the assessment threshold.

In terms of soil agrophysical properties, the scores were unevenly distributed, but a positive effect on soil shear resistance was found for both binary and trinary crops (Figure 3). The soil shear resistance assessment scores for sole, binary, and trinary crops rose above the assessment threshold. Macro-aggregate content scores were below the assessment threshold for all crops, but slightly higher scores were found for the trinary crop compared to the sole crop.



Experimental Treatments/ Indicators	Sole				Binary			Trinary		
	SB-SB-SB	SW-SB-SB	P-SB-SB	CA-BF	SB-CA	SW-CA	P-CA	SB-CA-WC	SW-CA-WC	P-CA-WC
Total nitrogen content	2.72	1.77	4.49	2.36	6.77	4.79	4.46	7.08	6.74	6.33
Organic carbon content	2.92	2.57	4.66	2.46	5.05	3.81	3.68	3.96	5.23	3.88
Mobile phosphorus content	2.07	2.30	3.03	3.75	8.04	5.48	2.62	5.77	4.99	1.76
Mobile potassium content	2.38	3.16	3.23	2.32	4.73	3.52	3.18	4.30	3.23	3.30
Root dry biomass	4.85	3.75	2.84	4.90	8.09	5.99	5.33	8.07	7.63	7.16
Soil shear resistance	6.00	6.27	6.22	5.82	5.27	5.03	5.26	5.48	5.10	5.35
Urease activity	4.25	2.28	2.16	3.78	6.80	4.83	4.13	7.49	4.71	5.64
Saccharase activity	4.55	2.06	2.41	3.25	5.75	3.70	4.56	6.21	4.13	4.13
Macro-aggregate content	2.35	2.93	2.52	4.12	2.99	4.77	4.96	2.77	3.47	3.24
Weed dry biomass	8.63	8.84	7.59	7.49	6.89	7.23	4.92	7.98	7.39	4.79
Soil CO_2 emission	5.86	6.78	5.89	6.66	5.89	6.47	4.13	5.09	5.85	3.87

Figure 3. An integrated assessment of multi-cropping system crops in 2019–2021. Note: SB—spring barley, SW—spring wheat, P—peas, CA—caraway, BF—bare fallow, WC—white clover, CEI—integrated assessment indices, *—an average of assessment scores (EP), **—standard deviation of EP, ***—standard deviation of the average of assessment scores below the assessment threshold.

When assessing the soil biological properties under multi-cropping system crops, the most significant influence on these properties was the cultivation of caraway in the binary crop after spring barley without white clover and in the trinary crop after spring barley together with white clover (Figure 3). The plant root dry biomass scores for binary and trinary crops were found to be above the assessment threshold. The scores for soil CO_2 emission for sole and binary crops after spring barley and spring wheat without white clover and trinary crops with white clover were above the assessment threshold. The most significant effect on saccharase activity was observed when caraway was grown in the binary crop after spring barley and in the trinary crop of the same crop with white clover, with scores above the assessment threshold. The most significant effect on urease activity was observed when caraway was grown in the binary crop after spring barley without white clover and in the trinary crop after spring barley and peas with white clover.

The scores for weed competition were set above the assessment threshold for both sole crops and some binary and trinary crops. The highest scores were found for sole and binary crops following spring barley and wheat and for trinary crops of the same crops together with white clover (Figure 3).

The calculated indicators for the integrated assessment and the areas bounded by the assessment scores showed that the binary crop of spring barley and caraway had the highest effect on the agroecosystem compared to other crops. The effect of the crops of binary spring wheat and barley, trinary spring barley, caraway, and white clover, as well as spring wheat, caraway, and clover, on the agroecosystem was higher than that of the sole crop.

In conclusion, the effect of the binary spring barley and caraway and the trinary spring barley, caraway, and white clover crops on the agroecosystem was higher than that of the other comparative sole, binary, and trinary crops. Caraway after spring wheat together with white clover had a higher effect on the agroecosystem than caraway without white clover.

4. Discussion

Indicators determining the effects of multi-cropping system crops with caraway on the agroecosystem are often considered in isolation, without being combined in an integrated assessment framework. This makes it very difficult to decide which indicator has a greater or lesser effect on the agroecosystem. To our best knowledge, this is the first time that a study of multi-cropping system crops with caraway has been carried out in Lithuania and abroad on such a large scale with this topic addressed, where an integrated assessment has been carried out, and where the regularities of the cropping processes of multi-cropping system crops have been identified.

4.1. Soil Agrochemical Properties under Multi-Cropping System Crops

4.1.1. Total Nitrogen

The highest scores were obtained when caraway was grown in the binary crop after spring barley and in the trinary crop with white clover after peas (Figure 1). The authors' results showed that the fixed nitrogen content of bean plants in a multi-varietal crop depended on several factors, such as plant morphology, species, crop density, and available nitrogen in the soil [74]. Other authors have shown that the benefits of N_2 fixation are partially lost in the formation of multi-crops of bean and other crops if the selected plant is stronger and competes with the bean crop [75]. Hauggaard-Nielsen et al. [76] point out that the cultivation of multi-cropping system crops can have a positive effect on nutrient retention. Despite the competition between the crops, in the third year of caraway cultivation, higher total nitrogen scores were found in the soil in which binary and trinary crops with caraway were grown (Figure 1). In 2020 (the third year of the caraway vegetative season), after caraway harvest, the soil with binary and trinary crops did not show a significant difference in total nitrogen scores compared to the soil with sole crops (Figure 2). This is likely to have been influenced by the unusually high precipitation in May and June. In 2018–2020, in the multi-cropping system, the highest total nitrogen content, which rose above the assessment threshold, was obtained when caraway was grown in the binary crop after spring barley and in the trinary crop after spring barley and wheat with white clover. In the binary crop, a denser stubble layer after barley slowed down nitrogen leaching, while in the trinary crop, the positive soil nitrogen content was maintained with the help of white clover. Other authors also point to the contribution of bean crops to maintaining a positive total nitrogen balance [77–79]. Due to the influence of trinary crops, the total nitrogen scores have risen significantly above the assessment threshold. The highest score was found when caraway was grown in the trinary crop after spring barley with white clover (Figure 3). It is observed that the fixed and accumulated nitrogen content of bean plants is released over consecutive years [80], and this may likely have influenced the distribution of the total nitrogen composite assessment scores.

4.1.2. Organic Carbon

Organic carbon scores in the multi-cropping system crop system in 2017–2019 rose above the assessment threshold when caraway was grown in the binary cropping after spring barley and spring wheat without white clover, but the increase was small (Figure 1). Adamu and Yusuf [30] have presented data confirming this regularity, showing an increase in organic carbon in multi-cropping system crops compared to sole crops. This phenomenon can be explained by the ability of root exudates to provide favorable conditions for microorganisms and thus facilitate plant nutrition. In addition, the root system of perennial crops has a positive effect on the soil by increasing the activity of microorganisms. A study has shown that the carbon cycle increases the availability of carbon [81], leading to an increase in the release of nutrients vital for plant mineral nutrition. In addition, the denser soil cover resulting from growing several crops reduces the rate of mineralization and makes nutrient leaching more difficult [82]. In the 2018–2020 multi-cropping system, organic carbon scores rose above the assessment threshold for caraway in the binary crop after spring barley without white clover and in the trinary crop after spring wheat with white clover (Figure 2). The soil in the caraway binary crop after spring wheat showed a 7.6% decrease in organic carbon compared to the single caraway crop, but this decrease was not significant. These results could be influenced by the fact that the stubble of spring wheat, which is difficult to decompose, covers the soil surface and inhibits the mineralization process, while the remaining caraway plants continue to use nutrients [10,31]. Similar mechanisms were in place for the 2019–2021 multi-cropping system crops. Organic carbon scores rose above the assessment threshold for caraway in the binary crop after spring barley and in the trinary crop after spring wheat (Figure 3).

4.1.3. Mobile Phosphorus

The available phosphorus content also depends on the organic matter in the soil, as does the organic carbon content [83]. The more abundant root mobile phosphorus scores resulting from the formation of the crop after spring barley and wheat without white clover (binary crop) and with white clover (trinary crop) rose above the assessment threshold, and this was found in all three multi-cropping systems (Figures 1–3). These results could be explained by studies conducted by other authors showing that bean plants secrete a higher content of phosphorus-mobilizing root exudates [84], which may also support the phosphorus nutrition of other plant types in multi-cropping system crops with lower phosphorus uptake capacity [85]. Muofhe and Dakora [86] found that the co-cropping of beans and cereal increases phosphorus uptake when lactic anions are released. Under mobile phosphorus deficiency and drought, it has been observed that crops grown in mixtures directly take up the released phosphorus in the soil from bean plants, thus allowing for plant resistance [45]. In addition, the availability of organic phosphorus to plants and soil microorganisms is also increased by a variety of bean crops.

4.1.4. Mobile Potassium

In the 2017–2019 multi-cropping system, the mobile potassium scores did not rise above the assessment threshold as a result of the measures applied (Figure 1). However, the highest score was obtained when caraway was grown in a trinary crop after barley with white clover. A team of researchers from China conducted a study on multi-cropping to investigate the yield, agrochemical properties, and enzyme activity of crops grown over a period of ten years [31]. This study started with the same fertilizer application as in our experiment. Wang et al. [31] found that per year, a multi-cropping system crop removes up to 300 kg ha^{-1} of mobile potassium from the soil. In addition, multi-cropping also results in higher mobile potassium uptake [31,87,88], which could lead to a greater reduction of potassium in the soil under binary and trinary crops.

The same trend is observed in the other two multi-cropping systems in 2018–2020 and 2019–2021 (Figures 2 and 3). The potassium scores did not rise above the assessment threshold, but there was an increase in potassium content, which was most pronounced in the 2019–2021 multi-cropping system, and when caraway was grown in the binary crop followed by barley, the score was close to the assessment threshold. Most of the potassium is accumulated in plant by-products (straw) [89], which may have been the reason for the increase in mobile potassium content [90].

4.2. Soil Agrophysical Properties under Multi-Cropping System Crops

4.2.1. Soil Shear Resistance

Soil shear resistance depends on humus content, soil granulometric composition, hardness, density, porosity, as well as frost and thaw processes [91]. In the 2017–2019 multi-cropping system, there was a significant advantage of trinary crops over sole crops, and in the period of 2018–2020, the soil shear resistance scores rose above the assessment threshold for trinary crops, but with a marginal advantage compared to sole crops. In the 2019–2021 cropping system, the shear resistance assessment scores for sole, binary, and trinary crops rose above the assessment threshold. This may have been influenced by the geometry (root diameter and length) and distribution of the plant roots, as well as the rooting characteristics [92].

4.2.2. Macro-Aggregate Content

The formation of stable soil aggregates is crucial for promoting sustainable agroecosystem management, as it improves soil hydraulic conductivity, facilitates root respiration, accelerates soil gas diffusion, and fosters plant growth, thereby significantly enhancing ecosystem health and productivity. [93]. In the multi-cropping systems in 2017–2019 and 2018–2020, the macro-aggregate content was positively influenced by both the cultivation of caraway in the binary crop after spring barley and pea without white clover and in combination with white clover (trinary crop). Under the integrated assessment system, the performance of these crops rose above the assessment threshold (Figures 1 and 2). This can be attributed to the good rooting of the caraway and the large area of soil covered by the plants. The distribution of the integrated assessment scores in the 2019–2021 multi-cropping system was slightly different. Macro-aggregate assessment scores did not reach the assessment threshold for all crops, but trinary crops showed slightly higher assessment scores compared to sole crops (Figure 3). Studies have shown that smaller soil particles (micro-aggregate, silt, clay particles) need to be considered to preserve soil organic matter longer [94]. Soil aggregate structure is also strongly influenced by tillage intensity. Tillage mechanically breaks down persistent soil aggregates (reducing the content of persistent aggregates (>0.25 mm), changes soil properties, and accelerates the decomposition of organic matter [95].

4.3. Soil Biological Properties under Multi-Cropping System Crops

4.3.1. Root Dry Biomass

In the case of multi-cropping, resource uptake and competition between plant roots is more evenly distributed during the growing season. This is also observed in the 2017–2019 multi-cropping system, where the plant root biomass scores of the binary and trinary crops were above the assessment threshold, except for the binary crop of pea and caraway, which was below the assessment threshold. In both the 2018–2020 and 2019–2021 multi-cropping systems, the plant root biomass scores for the binary and trinary crops were above the assessment threshold. This could be because plant roots target all ecosystem processes: metabolism, carbon cycling, the formation of soil and its structural stability, and the diversity and ratio of soil macroorganisms and microorganisms [44]. In addition, the greater abundance and density of roots increase their suction capacity, the uptake of nutrients from the soil, and the supply of nutrients to the plants, making them more resilient to adverse environmental conditions, and the interactions and interspecific competition between the plants further stimulate rooting [37]. Interspecific competition between plants is also largely avoided during vegetation [96]. In contrast to the work cited above, Bellostas et al. [97] found that when a binary crop of two species is formed, the intermingling of their roots in the early stages of plant growth can lead to negative competitive effects. In our case, although the plants competed, a positive effect of the multi-cropping system was observed in both binary and trinary crops. In the third year of cultivation, the agroecosystem of the plant root communities started to emerge.

4.3.2. Soil Enzyme Activity

In the multi-cropping system in 2017–2019, enzyme activity (saccharase and urease) was most affected by the cultivation of caraway in the trinary crop rotation after spring barley in combination with white clover, but with scores below the assessment threshold (Figure 1). Data from other researchers show that particularly high enzyme activity was observed in the arable soil horizon and was related to the content of organic carbohydrates, mobile phosphorus and potassium, soil CO_2 emission, and the amount of plant residues [98,99].

In the 2018–2020 multi-cropping system, saccharase activity was most affected by the cultivation of caraway in binary crops after spring barley and pea without white clover and in trinary crops of the same plants together with white clover (scores above the assessment threshold) (Figure 2). Studies by Cui et al. [99] show that saccharase activity correlates with total nitrogen content, especially ammonia and nitrate, for which pH is an important indicator of changes. This suggests that multi-cropping can improve soil nutrient cycling by increasing the activity of the enzyme saccharase. In the period of 2019–2021, saccharase activity was most affected by the cultivation of caraway in the binary crop after spring barley and in the trinary crop of the same plants with white clover, with scores higher than the cut-off scores for its assessment (Figure 3).

The studies also showed that the reduction in tillage intensity and the cultivation of caraway in binary crops after spring barley and pea without white clover and in trinary crops after spring barley, spring wheat, and pea with white clover (2018–2020) (Figure 2) resulted in an improvement in the soil nutrient supply and the development of a more favorable soil biochemical environment, which contributed to the increase in enzyme activity and to the stabilization of soil nutrients. In the 2019–2021 multipurpose cropping system, the higher urease enzyme activity, especially in spring barley, caraway, and white clover trinary crop indicates that crop residues had a positive effect on urease enzyme activity and improved nitrogen availability and soil biological properties (Figure 3). As shown by other authors, trinary crops dominated by bean plants further increased the urease activity and the root system of the bean plants transformed the rhizosphere of the plants of that crop [100]. According to Liu et al. [100], bean plants also carry out biological nitrogen fixation and release higher levels of other soil enzymes.

4.3.3. Soil CO_2 Emission

In the 2017–2019 multi-cropping farming system, the soil CO_2 emission scores for sole, binary, and trinary crops of caraway after spring barley in combination with white clover were found to be above the assessment threshold (Figure 1). Cereal and legume multi-cropping systems use less fertilizer because bean plants fix nitrogen biologically, so GHG emissions are generally lower in cereal and bean multi-cropping systems than in sole cereal crops [101]. However, in some cases, bean plants may emit higher levels of CO_2 [102]. In 2018–2020, the soil CO_2 emission assessment scores for both sole and binary crops were set above the assessment threshold (Figure 2). In 2019–2021, the soil CO_2 emission scores for both sole and binary crops after spring barley and spring wheat without white clover, and trinary crops with white clover, were above the assessment threshold (Figure 3).

Ibrahim et al. [103] carried out field measurements of CO_2 emissions and found that wheat root respiration is more pronounced in sole crops compared to multi-cropping crops with legumes. At the same time, a decrease in root viability of legume plants was associated with an increase in microbial respiration. Another group of researchers observed increased CO_2 concentrations in the root zone of a sole bean crop compared to multi-cropping system crops. A study by Yan et al. [104] explained this phenomenon by suggesting that perennial cropping systems modulate the soil respiration rate by influencing both above-ground and below-ground plant biomass, and that an increase in below-ground biomass leads to an increase in soil CO_2 emissions.

4.4. Weediness of Multi-Cropping System Crops

Mennan et al. [105] stress that alternative weed control methods to chemical ones can be used in the case of multi-cropping system crops, especially those with allelopathic properties. Mixed crops are often less weedy than sole crops. Similar results were obtained in the 2017–2019 multi-cropping system, where weed competition scores for sole, binary, and trinary crops were found to be above the assessment threshold (Figures 1–3). Sowing a mixture of crops allows more ecological niches to be filled, thus providing fewer opportunities and resources for weed growth [106]. Sowing fast-growing cereals together with low-competition crops can reduce weed spread, but balancing crop competition can be challenging. It is more desirable for crops to compete with weeds than with each other. Crops grown in mixtures compete for sunlight, which inhibits weed growth [107]. The use of binary and trinary crops allows for improved weed control and good crop rotation results [26]. Weed control in multi-crops is often also determined by the amount of biomass produced in the multi-crop and the diversity of plants in the multi-crop. When the main crop is harvested, the cover crops are left to grow, covering the soil and thus preventing weed growth [108]. Gu et al. [109] conducted a meta-analysis to determine the effect of multi-cropping on weed suppression and control. Other authors have shown that organically growing medicinal and aromatic plants as an intercrop is effective in reducing pests and diseases, increasing biodiversity, optimizing the use of resources, and increasing yields while at the same time increasing the resistance of the plants to pests and pathogens compared to sole crops, all of which helps to alleviate the challenges posed by weeds in organic farming systems [110]. The researchers selected data from 39 publications and drew several key conclusions. Firstly, 58% lower weed biomass was found in multi-cropping system crops than in other sole crops. Secondly, the weed biomass in the multi-cropping system crops was found to be like that of the monoculture crops with stronger stopping power. Thirdly, the increase in density in multi-cropping system crops compared to sole crops was a major factor in weed suppression, and the role of multi-cropping system crop species in weed suppression and management has been inconsistently demonstrated.

4.5. Challenges of Multi-Cropping System Crop Cultivation

There are many advantages to multi-cropping systems, but the main disadvantages should also be mentioned. In order to sow a multi-cropping system crop, criteria, such as seed rate and depth of seed placement for different plant species, spacing between plants, and multi-stage sowing, must be taken into account. Harvesting is also carried out in several stages, which makes it difficult to harvest in time without damaging other plants. According to the authors, for optimum plant growth, it is essential to select the right species for each other [20,29]. In multi-cropping system crops, plants often compete for nutrients, light, moisture, and space [6,29,30]. Choosing the right species composition for a multi-cropping system crop is quite challenging, as in each case the success of such a crop depends heavily on the interactions between the different species, the available cropping practices, and the environmental conditions [26].

5. Conclusions

In conclusion, this study highlights the positive effect of multi-cropping systems on organic carbon content, highlighting the role of root exudates in facilitating microorganism activity and promoting plant nutrition. The carbon cycle increases the availability of carbon, resulting in the release of nutrients important for plant mineral nutrition. In addition, the denser soil cover resulting from the cultivation of several plants reduces the rate of mineralization and mitigates nutrient leaching. However, in certain cropping scenarios, stubble can have an effect on the organic carbon content. Further research is needed to investigate the long-term effects and dynamics of these findings.

In summary, the calculated indicators of the integrated assessment and the areas bounded by the assessment scores show that the positive impact on the agroecosystem of the binary crops of spring barley and caraway and the trinary crops of spring barley, caraway, and white clover is higher than that of the other comparative sole crops, binary crops, and trinary crops.

In the context of sustainable organic farming, to ensure the long-term sustainability of the agroecosystem, caraway can be grown in binary crops and sown in spring barley, spring wheat, and peas, or, even better, in a trinary crop (with white clover also in the binary) and harvested in the second or third year of cultivation (if not enough flowers form in the second year). In addition, white clover growing in the bottom furrow after harvesting of the legumes is good at suppressing weeds in the second and third year of caraway cultivation, increasing the organic matter content of the soil and improving the agrochemical, agrophysical, and biological properties of the soil, thus highlighting the promising prospects of biennial crops in sustainable agriculture. Furthermore, there is a pressing need for research focusing on soil health, quality, and biodiversity to ensure the long-term sustainability of the agroecosystem. Given the limited scientific data on multi-cropping system crops' application in cultivating caraway, additional research is imperative to deepen our comprehension of plant interactions in multi-cropping systems, which is essential for maintaining environmental integrity, a fundamental tenet of organic production practices.

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Appendix A. Supporting Information

Table A1. Scheme for the use of pesticides in the multi-cropping system crops.

Name of Pesticide	Type	Active Substance	Amount	Abbreviation
Fenix	herbicide	aclonifen 600 g L^{-1}	3.00 L ha^{-1}	F
Signum	fungicide	boscalid 267 g kg^{-1} + pyraclostrobin 67 g kg^{-1}	0.50 L ha^{-1}	S
Cyperkill 500 EC	insecticide	cypermethrin 500 g L^{-1}	0.05 L ha^{-1}	C
Elegant 2 FD	herbicide	florasulam 6.25 g L^{-1} + 2.4-D 300 g L^{-1}	0.40 L ha^{-1}	E
Karate Zeon 5 CS	insecticide	lambda-cyhalothrin 50 g L^{-1}	0.14 L ha^{-1}	KZ
Bumper 25 EC	fungicide	propiconazole 250 g L^{-1}	0.50 L ha^{-1}	B
Bulldock 025 EC	insecticide	beta-cyfluthrin 25 g L^{-1}	0.30 L ha^{-1}	Bu
Miradol 250 SC	fungicide	azoxystrobin 250 g L^{-1}	0.60 L ha^{-1}	M
Trimmer	herbicide	tribenuron-methyl 500 g kg^{-1}	0.10 kg ha^{-1}	T

		First year of caraway vegetative season			Second year of caraway vegetative season			Third year of caraway vegetative season		
		2017, 2019			2018, 2020			2019, 2021		
		T1	T2	T3	T1	T2	T3	T1	T2	T3
Sole	SB-SB-SB	–	E + KZ **	B **	–	E + KZ **	M + Bu **	–	E + T **	B **
	SW-SB-SB	–	E + KZ **	B **	–	E + KZ **	M + Bu **	–	E + T **	B **
	P-SB-SB	F *	–	S + C **	–	E + KZ **	M + Bu **	–	–	B **
	CA-BF	F *	–		–	–	–	–	–	–
Binary	SB-CA	–	–	B **	–	–	–	–	–	–
	SW-CA	–	–	B **	–	–	–	–	–	–
	P-CA	F *	–	S + C **	–	–	–	–	–	–
Trinary	SB-CA-WC	–	–	B **	–	–	–	–	–	–
	SW-CA-WC	–	–	B **	–	–	–	–	–	–
	P-CA-WC	–	–	S + C **	–	–	–	–	–	–
		First year of caraway vegetative season			Second year of caraway vegetative season			Third year of caraway vegetative season		
		2018			2019			2020		
		T1	T2	T3	T1	T2	T3	T1	T2	T3
Sole	SB-SW-WW	–	E + KZ **	B **	–	E + KZ **	M + Bu **	A + St **	Mr + MF **	O + Bu **
	SW-SW-WW	–	E + KZ *	B **	–	E + KZ **	M + Bu **	A + St **	Mr + MF **	O + Bu **
	P-SW-WW	F *	–	S + C **	–	E + KZ **	M + Bu **	A + St **	Mr + MF **	O + Bu **
	CA-BF	F *	–	–	–	–	–	–	–	–
Binary	SB-CA	–	–	B + KZ **	–	–	–	–	–	–
	SW-CA	–	–	B + KZ **	–	–	–	–	–	–
	P-CA	F *	–	S + C **	–	–	–	–	–	–
Trinary	SB-CA-WC	–	–	B + KZ **	–	–	–	–	–	–
	SW-CA-WC	–	–	B + KZ **	–	–	–	–	–	–
	P-CA-WC	–	–	S + C **	–	–	–	–	–	–

Note: SW—spring wheat, WW—winter wheat, SB—spring barley, SW—spring wheat, P—pea, CA—caraway, BF—bare fallow, WC—white clover, *—after sowing, **—growing season, T1—first spray, T2—second spray, T3—third spray.

References

1. Hertel, T.W. The global supply and demand for agricultural land in 2050: A perfect storm in the making? *Am. J. Agric. Econ.* **2011**, *93*, 259–275. [CrossRef]
2. Hemathilake, D.M.K.S.; Gunathilake, D.M.C.C. Agricultural productivity and food supply to meet increased demands. In *Future Foods*; Academic Press: Cambridge, MA, USA, 2022; pp. 539–553.
3. Arora, N.K.; Fatima, T.; Mishra, I.; Verma, M.; Mishra, J.; Mishra, V. Environmental sustainability: Challenges and viable solutions. *Environ. Sustain.* **2018**, *1*, 309–340. [CrossRef]
4. Maitra, S.; Hossain, A.; Brestic, M.; Skalicky, M.; Ondrisik, P.; Gitari, H.; Brahmachari, K.; Shankar, T.; Bhadra, P.; Palai, J.B.; et al. Intercropping–A low input agricultural strategy for food and environmental security. *Agronomy* **2021**, *11*, 343. [CrossRef]
5. Massawe, F.; Mayes, S.; Cheng, A. Crop diversity: An unexploited treasure trove for food security. *Trends Plant Sci.* **2016**, *21*, 365–368. [CrossRef] [PubMed]
6. Lizarazo, C.I.; Tuulos, A.; Jokela, V.; Mäkelä, P.S. Sustainable mixed cropping systems for the boreal-nemoral region. *Front. Sustain. Food Syst.* **2020**, *4*, 103. [CrossRef]
7. Naulleau, A.; Gary, C.; Prévot, L.; Hossard, L. Evaluating strategies for adaptation to climate change in grapevine production–A systematic review. *Front. Plant Sci.* **2021**, *11*, 607859. [CrossRef] [PubMed]
8. Keating, B.A.; Carberry, P.S.; Bindraban, P.S.; Asseng, S.; Meinke, H.; Dixon, J. Eco-efficient agriculture: Concepts, challenges, and opportunities. *Crop Prot.* **2010**, *50*, 109–119. [CrossRef]
9. Ghanbari-Bonjar, A.; Lee, H.C. Intercropped wheat (*Triticum aestivum* L.) and bean (*Vicia faba* L.) as a whole-crop forage: Effect of harvest time on forage yield and quality. *Grass Forage Sci.* **2003**, *58*, 28–36. [CrossRef]

10. Eskandari, H.; Ghanbari-Bonjar, A.; Galavi, M.; Salari, M. Forage quality of cow pea (*Vigna sinensis*) intercropped with corn (*Zea mays*) as affected by nutrient uptake and light interception. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2009**, *37*, 171–174.
11. Hiddink, G.A.; Termorshuizen, A.J.; Bruggen, A.H.C.V. Mixed cropping and suppression of soilborne diseases. In *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming*; Lichtfouse, E., Ed.; Sustainable Agriculture Reviews; Springer: Dordrecht, The Netherlands, 2010; pp. 119–146.
12. Frick, B.L.; Telford, L.; Martens, J.T. Intercropping. In *Organic Field Crop Handbook*, 3rd ed.; Wallace, J., Ed.; Canadian Organic Growers: Ottawa, ON, Canada, 2017; pp. 169–176.
13. Gill, S.; Abid, M.; Azam, F. Mixed cropping effects on growth of wheat (*Triticum aestivum* L.) and chickpea (*Cicer arietenum* L.). *Pak. J. Bot.* **2009**, *41*, 1029–1036.
14. Mahapatra, S.C. Study of grass-legume intercropping system in terms of competition indices and monetary advantage index under acid lateritic soil of India. *Am. J. Exp. Agric.* **2011**, *1*, 1. [CrossRef]
15. Wenda-Piesik, A.; Synowiec, A. Productive and Ecological Aspects of Mixed Cropping System. *Agriculture* **2021**, *11*, 395. [CrossRef]
16. Lizarazo, C.I.; Lampi, A.M.; Mäkelä, P.S. Can foliar-applied nutrients improve caraway (*Carum carvi* L.) seed oil composition? *Ind. Crops Prod.* **2021**, *170*, 113793. [CrossRef]
17. Raal, A.; Arak, E.; Orav, A. The content and composition of the essential oil found in *Carum carvi* L. commercial fruits obtained from different countries. *J. Essent. Oil Res.* **2012**, *24*, 53–59. [CrossRef]
18. Waha, K.; Dietrich, J.P.; Portmann, F.T.; Siebert, S.; Thornton, P.K.; Bondeau, A.; Herrero, M. Multiple cropping systems of the world and the potential for increasing cropping intensity. *Glob. Environ. Chang.* **2020**, *64*, 102131. [CrossRef] [PubMed]
19. Wahbi, S.; Prin, Y.; Thioulouse, J.; Sanguin, H.; Baudoin, E.; Maghraoui, T.; Maghraoui, T.; Oufdou, K.; Roux, C.L.; Galiana, A.; et al. Impact of wheat/faba bean mixed cropping or rotation systems on soil microbial functionalities. *Front. Plant Sci.* **2016**, *7*, 1364. [CrossRef] [PubMed]
20. Sears, R.R.; Shah, A.N.; Lehmann, L.M.; Ghaley, B.B. Comparison of resilience of different plant teams to drought and temperature extremes in Denmark in sole and intercropping systems. *Acta Agric. Scand.-B Soil Plant Sci.* **2021**, *71*, 645–655. [CrossRef]
21. Nyfeler, D.; Huguenin-Elie, O.; Suter, M.; Frossard, E.; Lüscher, A. Grass–legume mixtures can yield more nitrogen than legume pure stands due to mutual stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agric. Ecosyst. Environ.* **2011**, *140*, 155–163. [CrossRef]
22. Thorup-Kristensen, K.; Dresboll, D.B.; Kristensen, H.L. Crop yield, root growth and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops. *Eur. J. Agron.* **2012**, *37*, 66–82. [CrossRef]
23. Kadžiulienė, Ž.; Šarūnaitė, L.; Kadžiulis, L. The impact of nitrogen in red clover and lucerne swards on the subsequent spring wheat. *Org. Farming Syst. A Driv. Change* **2013**, *9*, 159–160.
24. Doltra, J.; Olesen, J.E. The role of catch crops in the ecological intensification of spring cereals in organic farming under Nordic climate. *Eur. J. Agron.* **2013**, *44*, 98–108. [CrossRef]
25. Raseduzzaman, M.D.; Jensen, E.S. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *Eur. J. Agron.* **2017**, *91*, 25–33. [CrossRef]
26. Kozera, W.; Barczak, B.; Orłowska, M.J.; Knapowski, T. Agrotechnical and economic assessment of intercropping of caraway (*Carum carvi* L.). *J. Cent. Eur. Agric.* **2018**, *19*, 227–244. [CrossRef]
27. Mu-chun, Y.; Ting-ting, X.; Peng-hui, S.; Jian-jun, D. Effects of different cropping patterns of soybean and maize seedlings on soil enzyme activities and MBC and MBN. *J. Northeast Agric. Univ.* **2012**, *19*, 42–47. [CrossRef]
28. Li, X.; Mu, Y.; Cheng, Y.; Liu, X.; Nian, H. Effects of intercropping sugarcane and soybean on growth, rhizosphere soil microbes, nitrogen and phosphorus availability. *Acta Physiol. Plant.* **2013**, *35*, 1113–1119. [CrossRef]
29. Dakora, F.D. Defining new roles for plant and rhizobial molecules in sole and mixed plant cultures involving symbiotic legumes. *New Phytol.* **2003**, *158*, 39–49. [CrossRef]
30. Adamu, G.K.; Yusuf, M.A. A comparative study of changes in soil fertility under two farming practices in the Kano close-settled zone. *Eur. Sci. J.* **2014**, *10*, 313–323.
31. Wang, Z.G.; Bao, X.G.; Li, X.F.; Jin, X.; Zhao, J.H.; Sun, J.H.; Christie, P.; Li, L. Intercropping maintains soil fertility in terms of chemical properties and enzyme activities on a timescale of one decade. *Plant Soil.* **2015**, *39*, 265–282. [CrossRef]
32. Yadollahi, P.; Abad, A.R.B.; Khaje, M.; Asgharipour, M.R.; Amiri, A. Effect of intercropping on weed control in sustainable agriculture. *Int. J. Agric. Crop Sci.* **2014**, *7*, 683–686.
33. Stöckle, C.O.; Donatelli, M.; Nelson, R. CropSyst, a cropping systems simulation model. *Eur. J. Agron.* **2003**, *18*, 289–307. [CrossRef]
34. Nongkling, P.; Kayang, H. Soil physicochemical properties and its relationship with AMF spore density under two cropping systems. *Curr. Res. Environ. Appl. Mycol.* **2017**, *7*, 33–39. [CrossRef]
35. Ghosh, P.K.; Mohanty, M.; Bandyopadhyay, K.K.; Painuli, D.K.; Misra, A.K. Growth, competition, yields advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India: II. Effect of nutrient management. *Field Crops Res.* **2006**, *96*, 90–97. [CrossRef]
36. Hiltbrunner, J.; Liedgens, M. Performance of winter wheat varieties in white clover living mulch. *Biol. Agric. Hortic.* **2008**, *26*, 85–101. [CrossRef]

37. Hauggaard-Nielsen, H.; Jensen, E. Facilitative root interactions in intercrops. In *Root Physiology: From Gene to Function*; Lambers, H., Colmer, T.D., Eds.; Plant Ecophysiology; Springer: Dordrecht, The Netherlands, 2005; pp. 237–250.
38. Rao, C.H.S.; Grover, M.; Kundu, S.; Desai, S. Soil Enzymes. In *Encyclopedia of Soil Science*; Taylor and Francis: Abingdon, UK, 2017; pp. 2100–2107.
39. Allen, D.E.; Singh, B.P.; Dalal, R.C. Soil Health Indicators Under Climate Change: A Review of Current Knowledge. In *Soil Health and Climate Change*; Singh, B., Cowie, A., Chan, K., Eds.; Soil Biology; Springer: Berlin/Heidelberg, Germany, 2011; Volume 29, pp. 25–45.
40. Freibauer, A.; Rounsevell, M.D.; Smith, P.; Verhagen, J. Carbon sequestration in the agricultural soils of Europe. *Geoderma* **2004**, *122*, 1–23. [CrossRef]
41. Betencourt, E.; Duputel, M.; Colomb, B.; Desclaux, D.; Hinsinger, P. Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. *Soil Biol. Biochem.* **2012**, *46*, 181–190. [CrossRef]
42. Hu, F.; Gan, Y.; Cui, H.; Zhao, C.; Feng, F.; Yin, W.; Chai, Q. Intercropping maize and wheat with conservation agriculture principles improves water harvesting and reduces carbon emissions in dry areas. *Eur. J. Agron.* **2016**, *74*, 9–17. [CrossRef]
43. Mthembu, B.E.; Everson, T.M.; Everson, C.S. Intercropping maize (*Zea mays* L.) with lablab (*Lablab purpureus* L.) for sustainable fodder production and quality in smallholder rural farming systems in South Africa. *Agroecol. Sustain. Food Syst.* **2018**, *42*, 362–382. [CrossRef]
44. Hirte, J.; Leifeld, J.; Abiven, S.; Oberholzer, H.R.; Hammelehle, A.; Mayer, J. Overestimation of crop root biomass in field experiments due to extraneous organic matter. *Front. Plant Sci.* **2017**, *8*, 284. [CrossRef]
45. Eichler-Loebermann, B.; Zicker, T.; Kavka, M.; Busch, S.; Brandt, C.; Stahn, P.; Miegel, K. Mixed cropping of maize or sorghum with legumes as affected by long-term phosphorus management. *Field Crops Res.* **2021**, *265*, 108120. [CrossRef]
46. Oelmann, Y.; Lange, M.; Leimer, S.; Roscher, C.; Aburto, F.; Alt, F.; Bange, N.; Berner, D.; Boch, S.; Boeddinghaus, R.S.; et al. Above-and belowground biodiversity jointly tighten the P cycle in agricultural grasslands. *Nat. Commun.* **2021**, *12*, 4431. [CrossRef]
47. Zhu, S.G.; Cheng, Z.G.; Yin, H.H.; Zhou, R.; Yang, Y.M.; Wang, J.; Zhu, H.; Wang, W.; Wang, B.Z.; Li, W.B.; et al. Transition in plant–plant facilitation in response to soil water and phosphorus availability in a legume-cereal intercropping system. *BMC Plant Biol.* **2022**, *22*, 311. [CrossRef] [PubMed]
48. Wang, D.; Zhao, P.; Xiang, R.; He, S.; Zhou, Y.; Yin, X.; Long, G. Nitrogen fertilization overweighs intercropping in promotion of dissolved organic carbon concentration and complexity in potato-cropped soil. *Plant Soil* **2021**, *462*, 273–284. [CrossRef]
49. Datt, N.; Singh, D. Enzymes in relation to soil biological properties and sustainability. In *Sustainable Management of Soil and Environment*; Meena, R., Kumar, S., Bohra, J., Jat, M., Eds.; Springer: Singapore, 2019; pp. 383–406.
50. Samuel, A.D.; Domuta, C.; Ciobanu, C.; Sandor, M. Field management effects on soil enzyme activities. *Rom. Agric. Res.* **2008**, *28*, 61–68.
51. Nath, C.P.; Kumar, N.; Das, K.; Hazra, K.K.; Praharaj, C.S.; Singh, N.P. Impact of variable tillage based residue management and legume based cropping for seven years on enzymes activity, soil quality index and crop productivity in rice ecology. *Environ. Sustain. Indicat.* **2021**, *10*, 100107. [CrossRef]
52. Utobo, E.B.; Tewari, L. Soil enzymes as bioindicators of soil ecosystem status. *Appl. Ecol. Environ. Res.* **2015**, *13*, 147–169.
53. Lee, S.H.; Kim, M.S.; Kim, J.G.; Kim, S.O. Use of soil enzymes as indicators for contaminated soil monitoring and sustainable management. *Sustainability* **2020**, *12*, 8209. [CrossRef]
54. Attademo, A.M.; Sanchez-Hernandez, J.C.; Lajmanovich, R.C.; Repetti, M.R.; Peltzer, P.M. Enzyme activities as indicators of soil quality: Response to intensive soybean and rice crops. *Water Air Soil Pollut.* **2021**, *232*, 295. [CrossRef]
55. Trap, J.; Riah, W.; Akpa-Vinceslas, M.; Bailleul, C.; Laval, K.; Trinsoutrot-Gattin, I. Improved effectiveness and efficiency in measuring soil enzymes as universal soil quality indicators using microplate fluorimetry. *Soil Biol. Biochem.* **2012**, *45*, 98–101. [CrossRef]
56. Heenan, D.P.; Chan, K.Y.; Knight, P.G. Long-term impact of rotation, tillage and stubble management on the loss of soil organic carbon and nitrogen from a *Chromic luvisol*. *Soil Tillage Res.* **2004**, *76*, 59–68. [CrossRef]
57. 53. Gulwa, U.; Mgujulwa, N.; Beyene, S.T. Benefits of grass-legume inter-cropping in livestock systems. *Afr. J. Agric. Res.* **2018**, *13*, 1311–1319. [CrossRef]
58. Andrés, P.; Doblas-Miranda, E.; Silva-Sánchez, A.; Mattana, S.; Font, F. Physical, chemical, and biological indicators of soil quality in Mediterranean vineyards under contrasting farming schemes. *Agronomy* **2022**, *12*, 2643. [CrossRef]
59. Lindsey, R. Climate Change: Atmospheric Carbon Dioxide, Nat'l Oceanic & Atmospheric Admin. 2022. Available online: https://www.climate.gov/news-features/understandingclimate/climate-change-atmospheric-carbon-dioxide (accessed on 15 July 2023).
60. Chai, Q.; Qin, A.; Gan, Y.; Yu, A. Higher yield and lower carbon emission by intercropping maize with rape, pea, and wheat in arid irrigation areas. *Agron. Sustain. Dev.* **2014**, *34*, 535–543. [CrossRef]
61. Hu, F.; Feng, F.; Zhao, C.; Chai, Q.; Yu, A.; Yin, W.; Gan, Y. Integration of wheat-maize intercropping with conservation practices reduces CO2 emissions and enhances water use in dry areas. *Soil Tillage Res.* **2017**, *169*, 44–53. [CrossRef]
62. Beedy, T.L.; Snapp, S.S.; Akinnifesi, F.K.; Sileshi, G.W. Impact of Gliricidia sepium intercropping on soil organic matter fractions in a maize-based cropping system. *Agric. Ecosyst. Environ.* **2010**, *138*, 139–146. [CrossRef]

63. Skinulienė, L.; Bogužas, V.; Steponavičienė, V.; Sinkevičienė, A.; Marcinkevičienė, A.; Sinkevičius, A. Impact of long-term crop rotation combinations on soil CO_2 emissions and earthworm abundance. *Agric. Sci.* **2019**, *26*, 83–93.
64. Romaneckas, K.; Balandaitė, J.; Sinkevčienė, A.; Kimbirauskienė, R.; Jasinskas, A.; Ginelevičius, U.; Romaneckas, A.; Petlickaitė, R. Short-Term Impact of Multi-Cropping on Some Soil Physical Properties and Respiration. *Agronomy* **2022**, *12*, 141. [CrossRef]
65. WRB IUSS Working Group. Global Soil Resources Reference Framework. In *International Soil Classification System for Naming Soils and Creating Soil Map Legends*, 4th ed.; International Union of Soil Sciences (IUSS): Vienna, Austria, 2022. Available online: https://www.fao.org/soils-portal/data-hub/soil-classification/universal-soil-classification/en/ (accessed on 17 July 2023).
66. Staugaitis, G.; Vaišvila, Z.J. Soil Agrochemical Research. In *Scientific-Methodical Material*; The Lithuanian Research Centre for Agriculture and Forestry Agrochemical Research Laboratory: Kėdainiai District, Lithuanian, 2019; p. 112.
67. Rudinskienė, A.; Marcinkevičienė, A.; Velička, R.; Kosteckas, R.; Kriaučiūnienė, Z.; Vaisvalavičius, R. The Comparison of Soil Agrochemical and Biological Properties in the Multi-Cropping Farming. *Syst. Plants* **2022**, *11*, 774. [CrossRef] [PubMed]
68. Butnor, J.R.; Johnsen, K.H.; Maier, C.A. Soil properties differently influence estimates of soil CO_2 efflux from three chamber-based measurement systems. *Biogeochemistry* **2005**, *73*, 283–301. [CrossRef]
69. Mccormack, M.L.; Guo, D.; Iversen, C.M.; Chen, W.; Eissenstat, D.M.; Fernandez, C.W.; Li, L.; Ma, C.; Ma, Z.; Poorter, H.; et al. Building a better foundation: Improving root-trait measurements to understand and model plant and ecosystem processes. *New Phytol.* **2017**, *215*, 27–37. [CrossRef]
70. Chunderova, A.I. The Enzymatic Activity of Sod-Podzolic Soils of the North-Western Region. Doctoral Dissertation, Tallinn University, Tallinn, Estonia, 1973; p. 46.
71. Stancevičius, A. *Weed Inventory and Field Weed Mapping*; The Science: Vilnius, Lithuania, 1979; p. 37.
72. Lohmann, G. Entwicklung eines Bewertungsverfahrens für Anbausysteme mit Differenzierten Aufwandmengen Ertragssteigernder und Ertragssichernder Betriebsmittel. Ph.D. Thesis, University of Bonn, Bonn, Germany, 1994; p. 139. (In German)
73. Heyland, K.U. Zur Methodik einer integrierten Darstellung und Bewertung der Produktionsverfahren im Pflanzenbau. In *Pflanzenbauwissenschaften*; Verlag Eugen Ulmer GmbH & Co.: Stuttgart, Germany, 1998; Volume 2, pp. 145–159. (In German)
74. Sammama, H.; El Kaoua, M.; Hsissou, D.; Latique, S.; Selmaoui, K.; Alfeddy, M.N. The impact of wheat and faba bean intercrop on the competitive interactions, grain yield, biochemical parameters and mineral content of leaves. *Zemdirb.-Agric.* **2021**, *108*, 233–240. [CrossRef]
75. Andersen, M.K.; Hauggaard-Nielsen, H.; Ambus, P.; Jensen, E.S. Biomass production, symbiotic nitrogen fixation and inorganic N use in dual and tri-component annual intercrops. *Plant Soil* **2005**, *266*, 273–287. [CrossRef]
76. Hauggaard-Nielsen, H.; Andersen, M.K.; Joernsgaard, B.; Jensen, E.S. Density and relative frequency effects on competitive interactions and resource use in pea–barley intercrops. *Field Crops Res.* **2006**, *95*, 256–267. [CrossRef]
77. Rusinamhodzi, L.; Murwira, H.K.; Nyamangara, J. Cotton–cowpea intercropping and its N_2 fixation capacity improves yield of a subsequent maize crop under Zimbabwean rain-fed conditions. *Plant Soil* **2006**, *287*, 327–336. [CrossRef]
78. Thorsted, M.D.; Olesen, J.E.; Weiner, J. Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping. *Field Crops Res.* **2006**, *95*, 280–290. [CrossRef]
79. Hauggaard-Nielsen, H.; Jørnsgaard, B.; Kinane, J.; Jensen, E.S. Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. *Renew. Agric. Food Syst.* **2008**, *23*, 3–12. [CrossRef]
80. Iannetta, P.P.; Young, M.; Bachinger, J.; Bergkvist, G.; Doltra, J.; Lopez-Bellido, R.J.; Monti, M.; Pappa, V.A.; Reckling, M.; Topp, C.F.E.; et al. A comparative nitrogen balance and productivity analysis of legume and non-legume supported cropping systems: The potential role of biological nitrogen fixation. *Front. Plant Sci.* **2016**, *7*, 1700. [CrossRef] [PubMed]
81. Nasar, J.; Alam, A.; Nasar, A.; Khan, M.Z. Intercropping induce changes in above and below ground plant compartments in mixed cropping system. *Biomed. J. Sci. Tech. Res.* **2019**, *17*, 13043–13050. [CrossRef]
82. Eze, S.; Dougill, A.J.; Banwart, S.A.; Hermans, T.D.; Ligowe, I.S.; Thierfelder, C. Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. *Soil Tillage Res.* **2020**, *201*, 104639. [CrossRef]
83. Adamu, G.K.; Dawaki, M.U. Fertility Status of Soils under Irrigation along the Jakara Stream in Metropolitan Kano. *Bayero J. Pure Appl. Sci.* **2008**, *1*, 67–70.
84. Li, Z.; Gao, Q.; Liu, Y.; He, C.; Zhang, X.; Zhang, J. Overexpression of transcription factor ZmPTF1 improves low phosphate tolerance of maize by regulating carbon metabolism and root growth. *Planta* **2011**, *233*, 1129–1143. [CrossRef]
85. Li, L.; Tilman, D.; Lambers, H.; Zhang, F.S. Plant diversity and overyielding: Insights from belowground facilitation of intercropping in agriculture. *New Phytol.* **2014**, *203*, 63–69. [CrossRef]
86. Muofhe, M.L.; Dakora, F.D. Modification of rhizosphere pH by the symbiotic legume Aspalathus linearis growing in a sandy acidic soil. *Funct. Plant Biol.* **2000**, *27*, 1169–1173. [CrossRef]
87. Blaise, D.; Bonde, A.N.; Chaudhary, R.S. Nutrient uptake and balance of cotton+ pigeonpea strip intercropping on rainfed Vertisols of central India. *Nutr. Cycl. Agroecosyst.* **2005**, *73*, 135–145. [CrossRef]
88. Mondal, S.S.; Ghosh, A.; Acharya, D.; Maiti, D. Production potential and economics of different rainfed rice (Oryw sativa)-based utera cropping systems and its effect on fertility build up of soil. *Indian J. Agron.* **2004**, *49*, 6–9. [CrossRef]
89. Dotaniya, M.L.; Meena, V.D.; Basak, B.B.; Meena, R.S. Potassium uptake by crops as well as microorganisms. In *Potassium Solubilizing Microorganisms for Sustainable Agriculture*; Springer: New Delhi, India, 2016; pp. 267–280.

90. Xiao, X.; Cheng, Z.; Meng, H.; Liu, L.; Li, H.; Dong, Y. Intercropping of green garlic (*Allium sativum* L.) induces nutrient concentration changes in the soil and plants in continuously cropped cucumber (*Cucumis sativus* L.) in a plastic tunnel. *PLoS ONE* **2013**, *8*, e62173. [CrossRef]
91. Juchnevičienė, A.; Raudonius, S.; Avižienytė, D.; Romaneckas, K.; Bogužas, V. Effect of long-term reduced tillage and direct drilling on winter wheat yield. *Agric. Sci.* **2012**, *19*, 139–150.
92. Meng, S.; Zhao, G.; Yang, Y. Impact of plant root morphology on rooted-soil shear resistance using triaxial testing. *Adv. Civ. Eng.* **2020**, *2020*, 8825828. [CrossRef]
93. Alagöz, Z.; Yilmaz, E. Effects of different sources of organic matter on soil aggregate formation and stability: A laboratory study on a Lithic Rhodoxeralf from Turkey. *Soil Tillage Res.* **2009**, *103*, 419–424. [CrossRef]
94. Sarker, J.R.; Singh, B.P.; Cowie, A.L.; Fang, Y.; Collins, D.; Badgery, W.; Dalal, R.C. Agricultural management practices impacted carbon and nutrient concentrations in soil aggregates, with minimal influence on aggregate stability and total carbon and nutrient stocks in contrasting soils. *Soil Tillage Res.* **2018**, *178*, 209–223. [CrossRef]
95. Balesdent, J.; Chenu, C.; Balabane, M. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil Tillage Res.* **2000**, *53*, 215–230. [CrossRef]
96. Nasar, J.; Shao, Z.; Gao, Q.; Zhou, X.; Fahad, S.; Liu, S.; Li, C.; Banda, J.S.K.; Kgorutla, L.E.; Dawar, K.M. Maize-alfalfa intercropping induced changes in plant and soil nutrient status under nitrogen application. *Arch. Agron. Soil Sci.* **2022**, *68*, 151–165. [CrossRef]
97. Bellostas, N.; Hauggaard-Nielsen, H.; Andersen, M.K.; Jensen, E.S. Early interference dynamics in intercrops of pea, barley and oilseed rape. *Biol. Agric. Hortic.* **2003**, *21*, 337–348. [CrossRef]
98. Saha, S.; Prakash, V.; Kundu, S.; Kumar, N.; Mina, B.L. Soil enzymatic activity as affected by long term application of farm yard manure and mineral fertilizer under a rainfed soybean–wheat system in NW Himalaya. *Eur. J. Soil Biol.* **2008**, *44*, 309–315. [CrossRef]
99. Cui, T.; Fang, L.; Wang, M.; Jiang, M.; Shen, G. Intercropping of gramineous pasture ryegrass (*Lolium perenne* L.) and leguminous forage alfalfa (*Medicago sativa* L.) increases the resistance of plants to heavy metals. *J. Chem.* **2018**, *2018*, 7803408. [CrossRef]
100. Liu, E.; Teclemariam, S.G.; Yan, C.; Yu, J.; Gu, R.; Liu, S.; He, W.; Liu, Q. Long-term effects of no-tillage management practice on soil organic carbon and its fractions in the northern China. *Geoderma* **2014**, *213*, 379–384. [CrossRef]
101. Lupwayi, N.Z.; Kennedy, A.C. Grain legumes in Northern Great Plains: Impacts on selected biological soil processes. *J. Agron.* **2007**, *99*, 1700–1709. [CrossRef]
102. Rochette, P.; Janzen, H.H. Towards a revised coefficient for estimating N2O emissions from legumes. *Nutr. Cycl. Agroecosyst.* **2005**, *73*, 171–179. [CrossRef]
103. Ibrahim, H.; Hatira, A.; Pansu, M. Modelling the functional role of microorganisms in the daily exchanges of carbon between atmosphere, plants and soil. *Procedia Environ. Sci.* **2013**, *19*, 96–105. [CrossRef]
104. Yan, J.J.; Yan, L.F.; Yang, J. Pang effects of soybean and cotton growth on soil respiration. *Acta Sci. Agron.* **2010**, *36*, 1559–1567.
105. Mennan, H.; Jabran, K.; Zandstra, B.H.; Pala, F. Non-chemical weed management in vegetables by using cover crops: A review. *Agronomy* **2020**, *10*, 257. [CrossRef]
106. Sturm, D.J.; Peteinatos, G.; Gerhards, R. Contribution of allelopathic effects to the overall weed suppression by different cover crops. *Weed Res.* **2018**, *58*, 331–337. [CrossRef]
107. Szumigalski, A.; Acker, R.V. Weed suppression and crop production in annual intercrops. *Weed Res.* **2005**, *53*, 813–825. [CrossRef]
108. Cheriere, T.; Lorin, M.; Corre-Hellou, G. Species choice and spatial arrangement in soybean-based intercropping: Levers that drive yield and weed control. *Field Crops Res.* **2020**, *256*, 107923. [CrossRef]
109. Gu, C.; Bastiaans, L.; Anten, N.P.; Makowski, D.; Werf, W.V.D. Annual intercropping suppresses weeds: A meta-analysis. *Agric. Ecosyst. Environ.* **2021**, *322*, 107658. [CrossRef]
110. Golijan, J.; Marković, D. The benefits of organic production of medicinal and aromatic plants in intercropping system. *Acta Agric. Serb.* **2018**, *23*, 61–76. [CrossRef]