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Comprehensive Assessment of the Multi-Cropping Effect on the Agroecosystems

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Abstract: Multi-cropping is becoming an increasingly popular approach in agriculture to tackle major and complex agroecosystem problems such as biodiversity and soil fertility losses, erosion and degradation, increased greenhouse gas emissions, etc. Comprehensive assessment of the impact of multi-cropping intensity on the agroecosystem is a new and still under-researched approach that provides a better understanding of the impact of the individual indicators studied on the overall functioning of the biodiversed agroecosystems. Data from a stationary field experiment with multi-cropping at the Vytautas Magnus University, Experimental Station between 2020 and 2022 were used to achieve this objective. The study included maize, hemp and faba bean as single, binary, and ternary crops. A complex assessment approach (CEI value) was used to determine the impact of these diversified crops on the agroecosystem, the interrelationships between the main indicators and the strength of their effects. It was found that the most positive effect on agroecosystem had ternary maize-hemp-faba bean crop. The effectiveness of other crops was from 2 to 35% less. The lowest one was calculated for the maize-faba bean crop.

Keywords: maize; hemp; faba bean; multifunctional crop; complex analysis; CEI

1. Introduction

Intensive farming is still popular worldwide and in Lithuania, requiring large investments without considering environmental pollution problems to maximize yields and profits [1]. Multi-crops allow for the development of sustainable agriculture, where high yields can be achieved with less investment in terms of money and time, and, with the right choice of crops, on less fertile soils. For example, in Latin America, 70–90% of faba beans are grown as cover crops in maize or potato crops [2].

Multi-cropping can consist of several agricultural crops that are grown in the same field, but differ in their biological and agrotechnical characteristics, as well as in their length of growing season [3]. Studies have shown that mixed cropping systems in agriculture have a higher yield potential than when grown individually [4]. Maize is a major source of human food and livestock feed in many developing countries [5]. As the climate warms, maize will be increasingly grown in Lithuania to produce not only grain yields but also green biomass [6]. Hemp is mostly grown for fiber or seeds, which are rich in starch, protein, and oil [7]. Hemp produces a sufficiently high biomass and can therefore be used for energy purposes [8]. Faba beans are a source of protein, and their nutritional and feed value is therefore of particular importance [9]. One of the most important functions of these crops is to fix atmospheric nitrogen, which helps maintain soil fertility. Faba beans can adapt to a wide range of climatic conditions, as shown by their worldwide distribution [10].

Most multi-crops are annuals, which have clear advantages over perennials, for example, annual crops, due to their short growing season, enable farmers to produce more crops to meet market demands [11]. In addition to their main production, these crops also produce by-products, such as harvesting residues that can be used for energy purposes or in animal husbandry.

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Growing multi-crops on the same field at the same time can lead to more sustainable agricultural systems, where it is possible to increase biodiversity, reduce damage from diseases, pests, and weeds, reduce the need for mineral fertilizers, and maintain the fertility and quality of the soil [12]. Purpose-grown multi-cropping systems (agroecosystems) offer the potential to increase organic carbon, nutrient content, soil bioactivity, etc. [13].

Multi-crops are a valuable tool for nutrient management in crop rotations, as nutrients taken up by one plant, such as nitrogen, can then be utilized by other plants in the multi-cropping system. It has been shown that more root biomass is produced by multi-cropping compared to single-cropping. This is due to interspecific synergy between plants [14].

Multi-crops also stabilize and restore soil fertility by reducing nutrient leaching into deeper soil layers and protect the soil from wind and water erosion [13]. Multi-crops affect the whole soil biota by increasing the abundance, diversity, and activity of soil microorganisms [15]. When growing a multi-crop, plants compete and use solar energy more efficiently [16]. Some authors suggest that under good conditions (cultivated, optimally fertilized soil, where perennial and short-lived weeds have been eradicated and weed seeds are low), agricultural crops are able to outcompete weeds by themselves, if they are grown in a sufficiently dense crop with the right choice of varieties [17].

In our study, in multi-functional maize-hemp-faba bean agroecosystem maize plays the role of a producer of abundant biomass, hemp - the role of a producer of biomass and a protector against diseases and pests, and faba bean - the role of a provider of ecological services in the agroecosystem. The question arises as to which of the agroecosystems - single, binary, or ternary - is the most efficient in different aspects.

The aim of these study was to perform a comprehensive assessment to reveal the impact of crop diversification intensity on agroecosystems, the interrelationships between the indicators assessed, and to ascertain which indices have had the greatest impact on the agroecosystem or in which agroecosystem's level.

2. Materials and Methods

2.1. Site Description

The field experiment was carried out in 2020–2022 at the Experimental Station of Vytautas Magnus University, Agriculture Academy (coordinates: 54°53′7.5″N 23°50′18.11″ E). The soil of the experimental field is a deeper gleyic saturated loam (45.6% sand, 41.7% silt, 12.7% clay) Planosol (*Endohypogleyic-Eutric Planosol-Ple-gln-w*) [18]. The microrelief is levelled and the water regime is regulated by closed drainage.

In 2020, the average daily air temperature and precipitation during the vegetative season were close to the long–term average (since 1974). In 2021, the air temperature was high, and the distribution of precipitation was very uneven, as there was too little moisture in the middle of the crop's vegetative season and not enough at the end. In 2022, the end of the vegetative season was unusually dry with high temperatures (Tables 1–2).

Table 1. The average air temperature (° C) during multi-crops vegetative period. Kaunas Meteorological Station.

Month / Year	2020	2021	2022	Long-term average
March	3.3	1.6	1.5	2.1
April	6.9	6.2	6.2	6.4
May	10.5	11.4	11.0	11.0
June	19.0	19.5	17.7	18.7
July	17.4	22.6	17.9	19.3
August	18.7	16.5	20.9	18.7
September	14.8	11.4	10.6	12.3

Table 2. Precipitation rate (mm) during multi-crops vegetative period. Kaunas Meteorological Station.

Month / Year	2020	2021	2022	Long-term average
March	21.0	1.9	49.3	24.1
April	4.0	33.7	38.4	25.4
May	94.4	121.6	84.0	100.0
June	99.3	40.3	77.6	72.4
July	60.5	48.4	100.5	69.8
August	92.8	122.2	38.7	84.6
September	30.0	48.0	44.0	40.7

2.2. Experimental Design and Agricultural Practice

The experimental treatments were 7: a single crop of maize (1), hemp (2) and faba bean (3), a binary crop of maize and hemp (4), maize and faba bean (5), hemp and faba bean (6), and a ternary crop of maize, hemp and faba bean (7). A total of 21 plots were investigated in the experiment. Table 3 shows the grouping of crops, the treatments, and their abbreviations.

Table 3. Experimental treatments.

Biodiversity level	Crops	Abbreviation and number of treatments
Single crop	Maize, hemp, faba bean (sole crops)	M (1), H (2), FB (3)
Binary crop	Maize + hemp	M+H (4)
	Maize + faba bean	M+FB (5)
	Hemp + faba bean	H+FB (6)
Ternary crop	Maize + hemp + faba bean	M+H+FB (7)

According to the sowing idea, a 50 cm row spacing was maintained when sowing a single row of maize, hemp or faba bean. Before the experiment was set up, sown oats (*Avena sativa*) were grown on the site. In the spring of each year of the experiment, when the soil reached physical maturity, it was cultivated to a depth of 3–4 cm with a compound cultivator. Subsequently, the experimental plots were formed and fertilized with NPK 15:15:15 (200 kg ha^{-1}) in the first year and NPK 5:15:30 + 5S (200 kg ha^{-1}) in the second and third years of the experiment. Maize (*Zea mays* L.) (Pioneer hybrid P8105), hemp (*Cannabis sativa* L.) (variety Austa SK) and faba bean (*Vicia faba* L.) (variety Vertigo) were sown manually in a continuous manner in the experimental fields as single, binary, and ternary crops according to a predetermined sowing scheme. After the weeds had germinated in abundance, the crop row spacing was loosened twice. Synthetic pesticides were not used in the agro-technics of the experiment. The agro-technics of the experiment are well described in Balandaitė [19].

2.3. Methods and Analysis

2.3.1. Soil Agrochemical Properties

The samples of agrochemical properties of the soil were taken in each vegetative season after harvesting from the 0–25 cm layer of the soil. Laboratory analyses were used to determine the levels of the main macro–elements (N, P, K, Mg) and the pH of the soil. The analyses were carried out in the Agrochemical Research Laboratory of the Lithuanian Agricultural and Forestry Science Centre in Kaunas.

Soil structure and its stability. Soil samples were collected with a shovel after sowing the crop, before inter–row loosening from 0–25 cm soil layer. A Retsch sieving apparatus (Retsch Lab Equipment, VERDER Group, Netherlands) and a set of sieves were used for the determination of the soil structure. The water-stability (wet sieving) of the soil aggregates was determined by the Retsch

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wet sieving device only from a previously dry sieved soil fraction of 1–2 mm. The results of the tests are expressed as a percentage [20].

CO_2 concentration and emissions. Determined by IRGA (InfraRed Gas Analyzer). A portable soil respiration system LI-8100A with camera 8100–103 was used. A 20 cm diameter ring was hammered into each plot in the spring and 3 measurements were taken. The measurements were taken 3 times: at the beginning, in the middle and at the end of the crop vegetative season.

Photosynthetically active radiation (PAR). Tests were carried out during the vegetative season, at the beginning of faba bean flowering. Photosynthetically active radiation (PAR) was measured with an HD 9021 RAD/PAR radiometer (FAR E m^{-2}, 400–700 nm). The PAR was measured in different arcs of the crop: at the ground surface, at 1/2 agal height and above the crop (background). The indicator is expressed as a percentage of the background irradiance [19].

Crop density. At the end of the vegetative season, crop density was evaluated by determining the productivity of multi-crops. Density was evaluated at a minimum of 5 locations in the plot, in a 0.5 m longitudinal row. An average sample was taken. The density of the crop was converted to m^2.

Crop development indicators. They were determined in the second half of the vegetative season by assessing chlorophyll index and leaf assimilative area. The leaf assimilative area (cm^2) of the crops was determined using a Win Dias leaf area meter (Delta-T Devices Lts, UK). The chlorophyll index of the crop leaves was measured with a chlorophyll meter CCM-200 plus.

Crop biometric and productivity indices. They were carried out at harvest time, assessing crop height and dried biomass. A total of 36 spots were generated for the study. The biomass samples were dried in a thermostat at 105 °C to constant weight [21].

Weed flora. Determined by assessing the number of weeds at the end of the crop vegetative season. The number of weeds in units m^{-2} at the end of the vegetative season and the dried biomass (g m^{-2}) at the end of the vegetative season were studied. Weeds were uprooted, dried to air-dry biomass, and weighed, and a botanical analysis of species composition was performed [22].

The variation in the indices (variables) observed above and the units of measure-ments are presented in Table 4.

Table 4. Tested variables and their variation.

Indices	Variation	Units	Indices	Variation	Units
Total dried crop biomass (at the end of vegetative season)	1.28-4.30	g m^{-2}	CO_2 e-flux rate (in the middle of vegetative season)	2.12-5.98	μmol m^{-2} s^{-1}
PAR at the soil surface	1.61-6.06	%	Change in total nitrogen	2.89-7.55	mg kg^{-1}
Total crop density (at the end of vegetative season)	1.67-6.30	units m^{-2}	Change in mobile phosphorus	3.50-7.54	mg kg^{-1}
Average crop hight (at the end of vegetative season)	1.73-7.12	cm	Change in mobile potassium	4.06-6.81	mg kg^{-1}
Average leaf chlorophyll index (in the second half of the crop vegetative season)	2.49-8.83	-	Change in mobile magnesium	4.65-6.48	mg kg^{-1}
Average leaf assimilative area (in the middle of vegetative season)	2.85-7.11	cm^{-2}	Dried biomass of total weeds (at the end of vegetative season)	2.65-5.16	g m^{-2}
Soil megastructure content (at the beginning of vegetative season)	2.06-6.66	%	Total number of weeds (at the end of vegetative season)	2.93-5.1	units m^{-2}
Soil macrostructure content (at the beginning of vegetative season)	3.30-8.18	%	Average daily air temperature	1.24-7.75	° C

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Soil microstructure content (at the beginning of vegetative season)	3.33-5.67	%	Precipitation rate	2.47-7.52	mm
Soil aggregate stability (at the beginning of vegetative season)	3.53-6.66	%	-	-	-

2.3.2. Statistical Analysis

Correlation and regression analyses of the data were carried out using STAT and SIGMA PLOT. A comprehensive evaluation of the multi-cropping effect on agroecosystem was carried out based on the methodologies of G. Lohmann [23] and K. U. Heyland [24]. An example of the CEI calculations is well shown in Supplementary Materials, Table S1 [25].

3. Results and Discussion

To produce as much crop biomass per area unit as possible with minimal damage to nature, many authors recommend the use of multi-crops. To achieve maximum results, it is necessary to take advantage of the strengths of each crop grown in a multifunctional crop. To do this, appropriate combinations, placement, and proportions of crop species are selected [26]. In Figure 1, a comprehensive multi-crops agroecosystem evaluation model is presented.

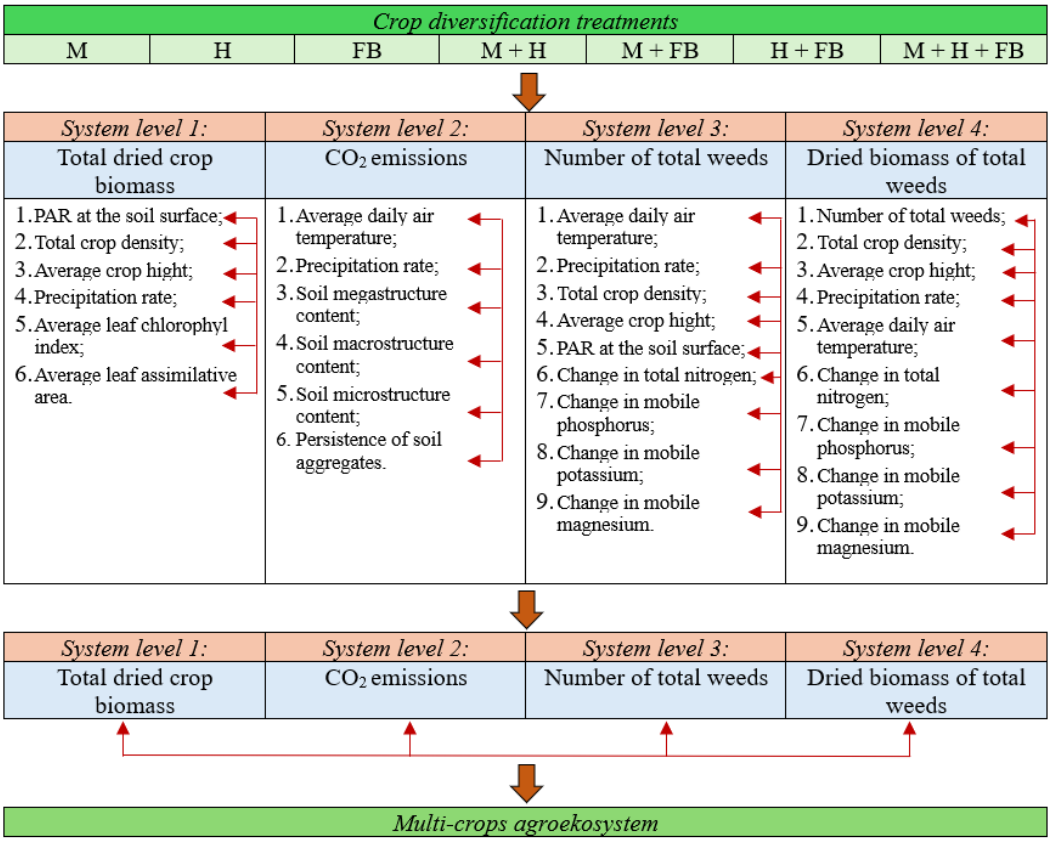

Figure 1. A model for the comprehensive assessment of the impact of multi-croping on the agroecosystem [according to [25]].

3.1. Level 1: Crops Total Dried Biomass

The total crop dried biomass (system level 1) scores did not reach the assessment threshold. Nevertheless, the highest score was obtained for a ternary crop of maize, hemp and faba bean. There was also a marked advantage in dried biomass scores for binary crops over single crops (Figure 2).

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The results showed that the dried biomass of faba bean decreased at higher temperatures (r = –0.47; $p > 0.05$) because faba bean is moderate climate crop [19].

Crop productivity in any types of cropping system implemented relies primarily on the interception of photosynthetically active radiation (PAR) of crop canopy and conversion of intercepted radiation into biomass or known as radiation use efficiency (RUE) [27]. Photosynthetically active radiation scores at the soil surface rose above the assessment threshold for hemp in a single crop and in a binary crop with maize. The assessment scores for the maize single crop and the faba bean single crop did not reach the assessment threshold but were close to it.

The highest total crop density scores at the end of the vegetative season were obtained in the maize-faba bean binary crop, the hemp-bean binary crop and the ternary crop.

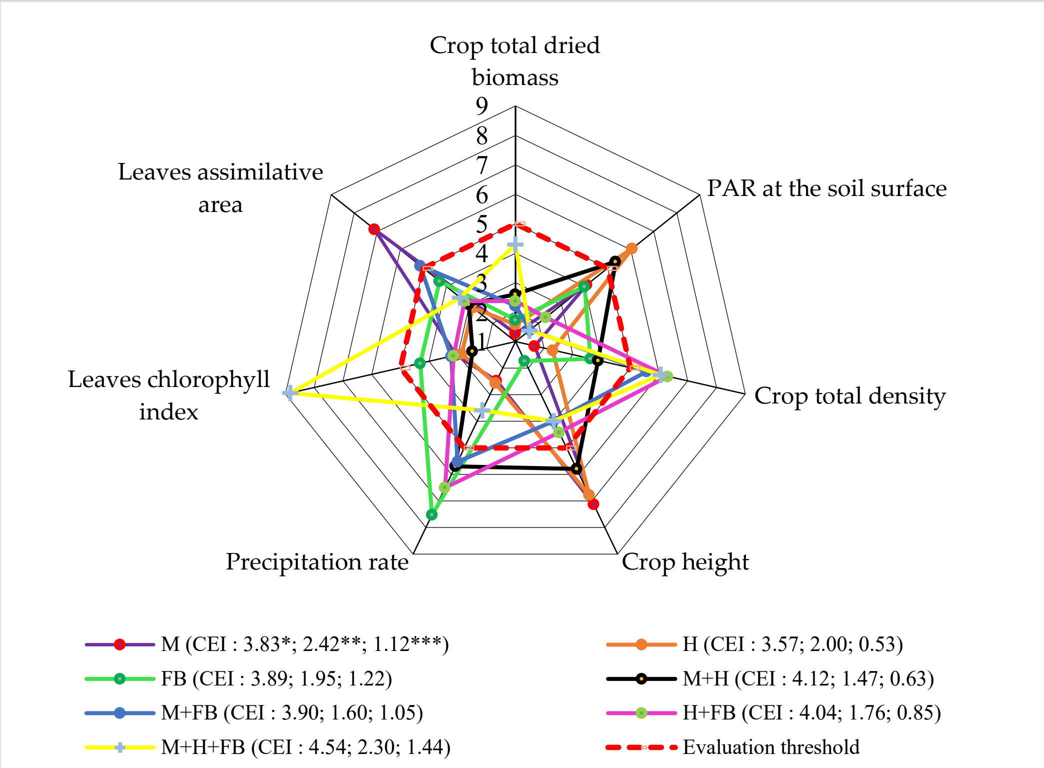

Figure 2. Comprehensive assessment of crop diversification in terms of crops total dried biomass (system level 1), 2020–2022. Note: M–maize single crop, H–hemp single crop, FB–faba bean single crop, M+H–binary maize and hemp crop, M+FB–binary maize and faba bean crop, H+FB–binary hemp and faba bean crop, M+H+FB–ternary maize, hemp and faba bean crop. CEI–complex evaluation index, * –average of evaluation points (EPs), ** –standard deviation of EPs, *** –standard deviation of the average of the evaluation points below the evaluation threshold.

The average crop height was highly affected by the cultivation of single-crops, as the scores for single-crops of maize and hemp were well above the assessment threshold, except for the single faba bean crop, which scored significantly lower than the assessment threshold (Figure 2).

According to Litvinova et al. [28], correlation analysis revealed a significant effect of maize height on green biomass yield. It was found that as maize height increases, the cob biomass decreases, which significantly decreases the total green biomass.

The precipitation assessment scores were below the assessment threshold for single-cropping of maize and hemp and for the ternary crop. According to Birthal et al. [29], multi-cropping had a positive effect on the distribution of precipitation over the soil surface, thus retaining soil moisture for longer.

The scores for the crop development indicators were unevenly distributed. The leaf chlorophyll index scores rose above the assessment threshold due to the influence of the ternary crop. In the case of single and binary crops, the leaf chlorophyll index scores were below the assessment threshold.

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The leaf assimilated area scores for the ternary and binary crops did not rise above the assessment threshold, except for the binary maize and faba bean crop, where the scores were higher and above the assessment threshold.

At system level 1, the highest CEI values were observed by the ternary crop, which proved the highest impact of ternary crop on the canopy dried biomass (Figure 2).

3.2. Level 2: CO_2 Emission from the Soil

Soil respiration is a good proxy for soil biological activity, as it releases carbon dioxide (CO_2) to the atmosphere because of the decomposition of soil organic matter [30]. Increased CO_2 concentrations increase photosynthesis and thus crop biomass [31].

In our experiment, in terms of the agrobiological characteristics of the soil under multi-cropping, the hemp single crop and the maize-hemp binary crop had the greatest influence on this characteristic. The assessment scores for these crops were above the assessment threshold. The CO_2 score of the single maize crop was very close to the assessment threshold but did not exceed it (Figure 3). Hu et al. [32] found that maize-wheat binary crop integrated with non-arable agriculture can effectively increase crop yields while reducing CO_2 emissions from the soil and improving water use efficiency in arid areas. Our tested binary crops with faba bean did not reach the assessment threshold. In the study of Lupwayi et al. [33], due to the ability of faba bean to fix atmospheric nitrogen, lower greenhouse gas emissions from the soil compared to single-cropping or diversified crops without faba bean crops were found.

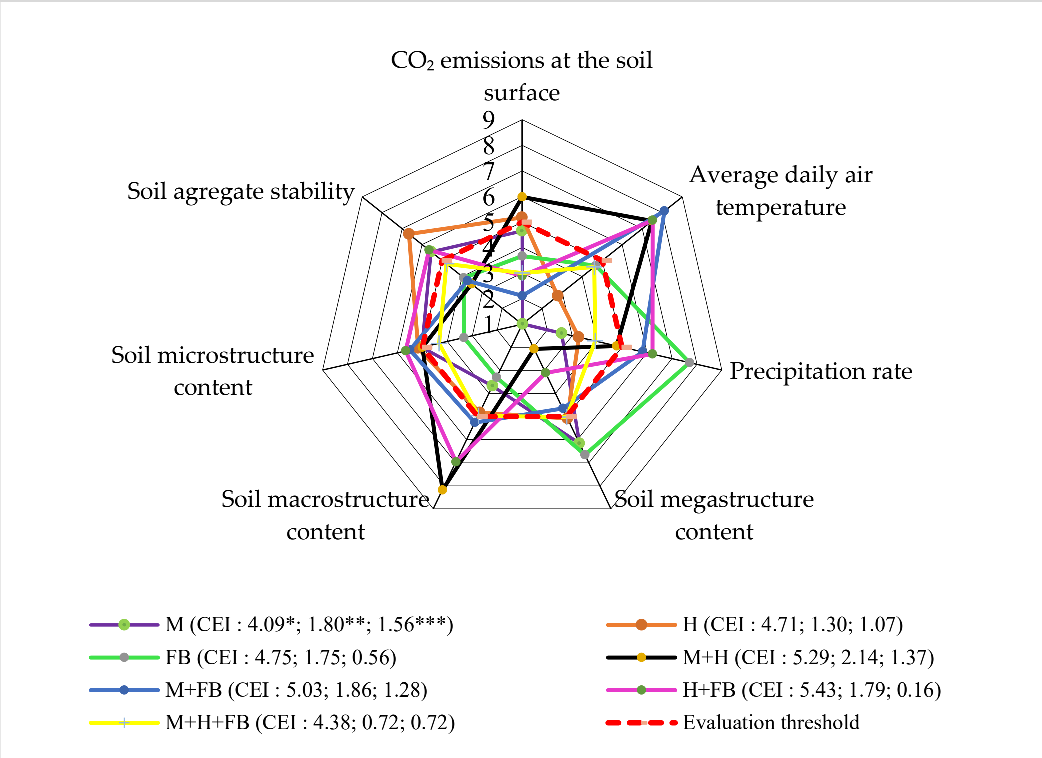

Figure 3. Comprehensive assessment of crop diversification in terms of CO_2 respiration from the soil (system level 2), 2020–2022. Note: M–maize single crop, H–hemp single crop, FB–faba bean single crop, M+H–binary maize and hemp crop, M+FB–binary maize and faba bean crop, H+FB–binary hemp and faba bean crop, M+H+FB–ternary maize, hemp and faba bean crop. CEI–complex evaluation index, * –average of evaluation points (EPs), ** –standard deviation of EPs, *** –standard deviation of the average of the evaluation points below the evaluation threshold.

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In terms of the effect of average daily air temperature, the assessment scores for the binary crops rose above the assessment threshold. The highest precipitation effect scores were obtained for the faba bean single binary crops with faba bean (Figure 3).

The cultivation of binary crops had a higher effect on the agrophysical properties of the soil. The highest soil megastructure content scores were obtained with faba bean single crop and ternary crop, which were well above the assessment threshold. Soil macrostructure scores rose above the assessment threshold in the case of the maize-hemp binary crop. However, it should be noted that the macrostructure score for the ternary crop was also very close to the assessment threshold. Similar results were obtained by Rudinskienė, who reports that the macroaggregate content was positively affected by growing caraway in binary and ternary crops. According to the integrated assessment system, the indicators of these crops rose above the assessment threshold [34,35]. In our experiment, the microstructure content score was also influenced by the cultivation of binary crops, but these scores were only slightly above the assessment threshold, and the binary crop of maize and hemp was equal to the assessment threshold. The lowest microstructure content score was obtained with a faba bean single crop. Li et al. [36] carried out a meta-analysis of 1924 observations and reported that, compared to single-cropping, multi-cropping led to the increase of soil macroaggregate content, while microaggregate content, on the contrary, decreases. In our experiment, it was found that increasing the amount of megastructure in the soil decreased the amount of microstructure ($r = -0.80$; $p < 0.01$), while increasing the amount of macrostructure in the soil influenced the microstructure increase ($r = 0.46$; $p < 0.05$) [19].

There was an uneven distribution of scores for soil aggregate stability. The highest soil aggregate stability scores were obtained in the single crops of maize and hemp and in the binary crop of hemp-faba bean. The influence of the ternary crop on the soil aggregate stability score was close to, but not above, the assessment threshold. More abundant and dense crops roots improve soil stability and Hauggaard-Nielsen et al. [15] argue that interactions between crops and interspecific competition promote crop rooting, and that the cultivation of multi-crops has a positive effect on the stability of soil structure.

CEI calculations showed that ternary crop was the most ineffective in terms of gasses' respiration, which means the possibilities to decrease the intensity of respiration in ternary crop.

3.3. Level 3: Total Number of Weeds at the End of the Vegetative Season

As well as increasing the productivity of the total crop biomass per unit area, the inter-crops protect the main crop from the spread of weeds, diseases, and pests as biodiversity increases. Cover or inter-crops are fast-growing and therefore able to compete well with weeds [37,38]. It should be noted that when assessing the weediness of a crop, the reverse principle of the comprehensive assessment system is at work, i.e., the highest value of the CEI takes on a negative meaning and indicates the highest weediness of the crop.

In our experiment, binary and ternary crops had the highest effect on the reduction of weed number. The lowest weed scores were observed in the binary crop of maize-hemp, maize-faba bean binary and ternary crop. The total weed score rose above the assessment threshold in the single maize crop and the weed score in the single crop of faba bean was very close to the assessment threshold (Figure 4).

The advantage of binary crops with faba beans was established by a comprehensive assessment of average daily air temperature. The assessment scores for the binary crops rose significantly above the assessment threshold. In the case of the single faba bean crop, the precipitation distribution score was the highest above the assessment threshold. Our pilot study showed that faba bean canopy height was mainly dependent on the precipitation rates ($r = 0.42$; $p > 0.05$), as precipitations were mostly scarce during the year of study [19].

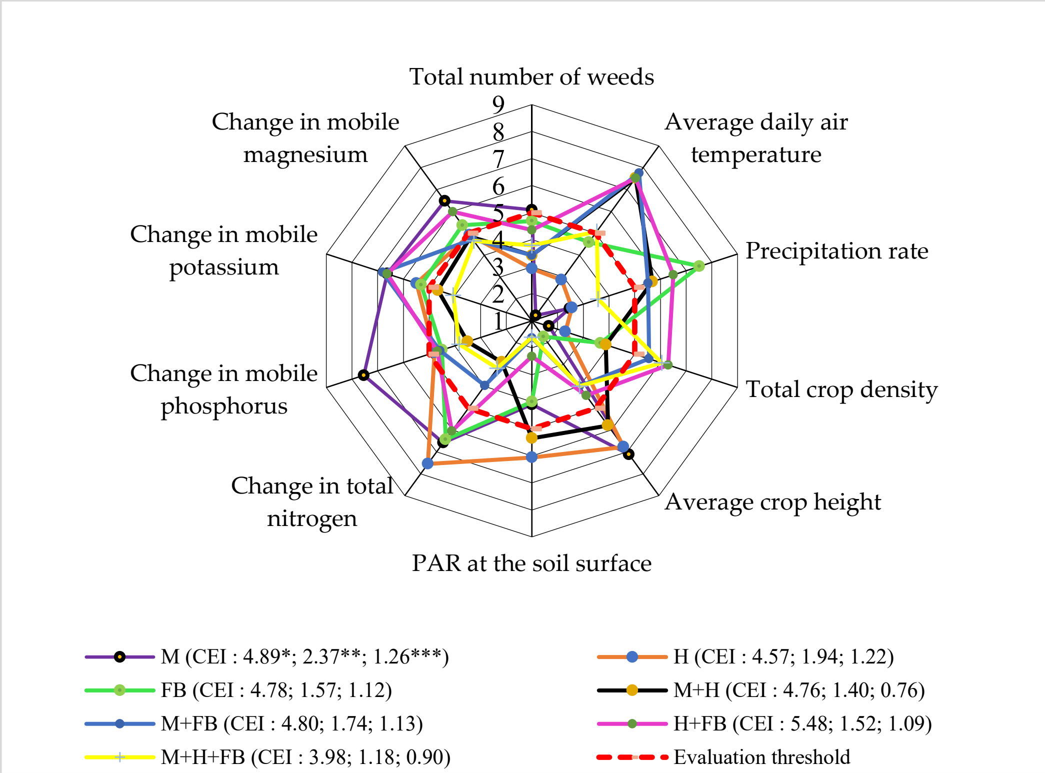

Figure 4. Comprehensive assessment of crop diversification in terms of the total number of weeds at the end of the vegetative season (system level 3), 2020–2022. Note: M–maize single crop, H–hemp single crop, FB–faba bean single crop, M+H–binary maize and hemp crop, M+FB–binary maize and faba bean crop, H+FB–binary hemp and faba bean crop, M+H+FB–ternary maize, hemp and faba bean crop. CEI–complex evaluation index, * –average of evaluation points (EPs), ** –standard deviation of EPs, *** –standard deviation of the average of the evaluation points below the evaluation threshold.

The highest crop density scores, which rose above the assessment threshold, were obtained in the case of the binary crop of hemp with faba bean and the ternary crop. The lowest crop density score was obtained in the single crop of maize. The greatest influence on the increase in crop height was due to the cultivation of single crop of maize and hemp and the cultivation of a binary maize and hemp crop. These crops had the highest evaluation scores and rose above the evaluation threshold. The lowest crop height assessment score was for the single faba bean crop. Livingstone et al. [39] reported that hemp sown at lower densities produced thicker and taller stems, which increased the overall green biomass of the crop. Similar results were obtained by Schafer et al. [40]. Results showed that a denser hemp crop leaded to stem elongation.

The scores for the assessment of radiation at the soil surface were not evenly distributed. For this indicator, the single crop had an advantage over ternary crops. The lowest radiation scores were obtained for the binary crop of maize and hemp with faba bean intercropping and the ternary crop. The highest scores were obtained with a single crop and with a binary crop of maize and hemp.

In terms of soil agrochemical properties, the scores were unevenly distributed, but there was a marked advantage of single crop over binary and ternary crops. The highest scores for total nitrogen change were found for every single crop and the binary crop of hemp and faba bean. The opposite results were obtained by Rudinskienė [34], who argues that the influence of binary and ternary crops led to a significant increase in total nitrogen scores above the assessment threshold. The scores for mobile phosphorus change were very similar in all single crops, in the binary and in the ternary crops, and the scores were very close to the assessment threshold, although not reaching it, except for the single crop of maize, which had scores well above the assessment threshold. The only exception was the maize single crop, where the score for mobile phosphorus change was much higher than the assessment threshold. The scores for the change in mobile potassium for all single, binary, and

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ternary crops were either above or very close to the assessment threshold. Similar trends were observed for the scores for the change in mobile magnesium.

As in previous level, ternary crop had the lowest effect on weed number. That means that ternary crop was an effective method to conservate weed spread in agroecosystem.

3.4. Level 4: Total Weed Dried Biomass at the End of the Vegetative Season

The scores for weed competition showed that the binary and ternary crops had an advantage over the single crops. In the case of dried biomass of weeds, the evaluation scores did not rise above the evaluation threshold, except for the single crop of faba bean. The decrease in dried biomass of weeds was positively influenced by the cultivation of the binary maize and hemp crop, the binary maize and faba bean crop and the single hemp crop, as these crops had the lowest evaluation scores. The cultivation of binary and ternary crops had a positive effect on the reduction of the weed score (Figure 5).

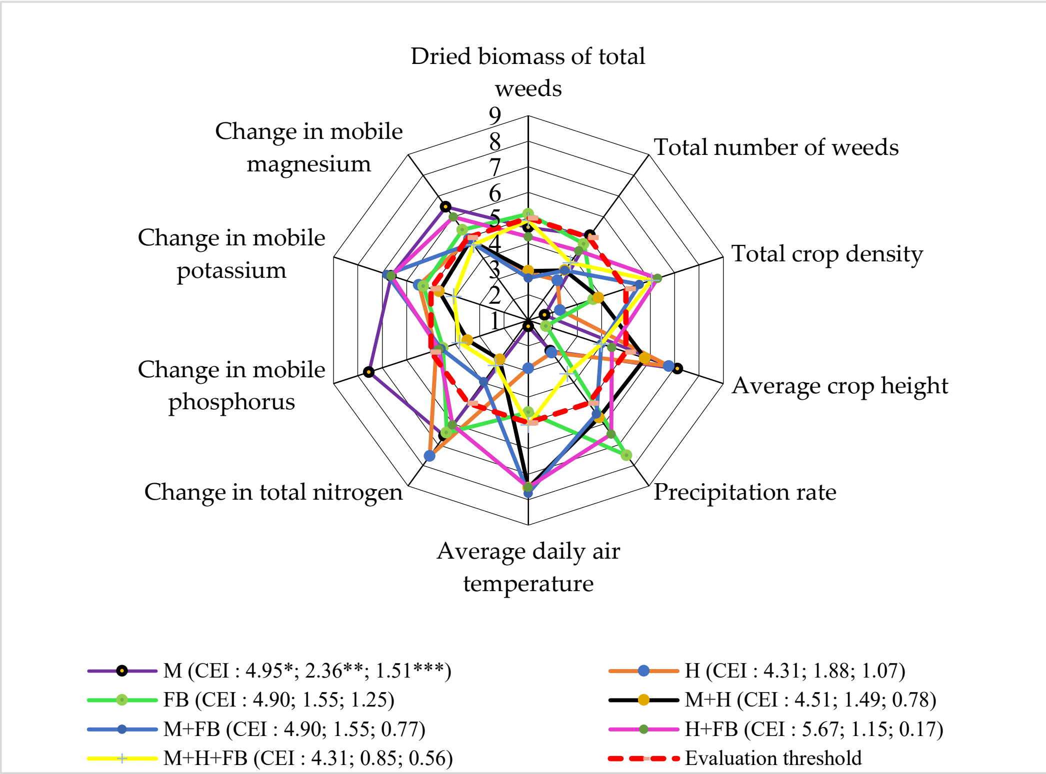

Figure 5. Comprehensive assessment of crop diversification in terms of total weed dried biomass at the end of the vegetative season (system level 4), 2020-2022. Note: M–maize single crop, H–hemp single crop, FB–faba bean single crop, M+H–binary maize and hemp crop, M+FB–binary maize and faba bean crop, H+FB–binary hemp and faba bean crop, M+H+FB–ternary maize, hemp and faba bean crop. CEI–complex evaluation index, * – average of evaluation points (EPs), ** –standard deviation of EPs, *** –standard deviation of the average of the evaluation points below the evaluation threshold.

The crop density scores rose above the assessment threshold for the binary crop of maize and hemp with faba bean intercropping and the ternary crop. The cultivation of maize and hemp single crops influenced the lowest crop density scores. The average height of the crop showed the opposite results, with the highest scores for single crops of maize and hemp. It was found that the maize grew lower at higher temperatures (r = –0.45; $p > 0.05$) [19].

The precipitation scores did not reach the assessment threshold in the maize and hemp single crops and in the ternary crop. Higher average daily air temperatures had a positive effect on the growth of all binary crops and the ternary crop.

When assessing the agrochemical properties of soils under multi-crops, the scores for total nitrogen, mobile phosphorus, potassium, and magnesium in single crops tend to be above the assessment thresholds and are higher compared to the scores in binary and ternary crops. Among the multi-crops, only the binary crop of hemp and faba bean stood out, with scores also above the assessment threshold or very close to it. The soil macro-nutrient scores of the ternary crop and the binary maize and hemp crop were below the assessment threshold.

According to the CEI value, the ternary crop had the lowest impact on the weed biomass increase or in other words, ternary crop stopped weed biomass growth.

3.5. Overall Comprehensive Assessment of All Four Levels

In the case of total dried biomass of crops, the scores were unevenly distributed and none of them reached the assessment threshold. The dried biomass assessment scores for the ternary crop, although not reaching the assessment threshold, were close to it. The dried biomass assessment scores for the binary crops ranged from 2.22 to 2.61, with the lowest dried biomass assessment scores for the single crop.

The highest CO_2 emission scores, which rose above the assessment threshold, were obtained in the single-crop of hemp and in the binary crop of maize and hemp. The assessment scores for the single maize crop were close to the assessment threshold (Figure 6).

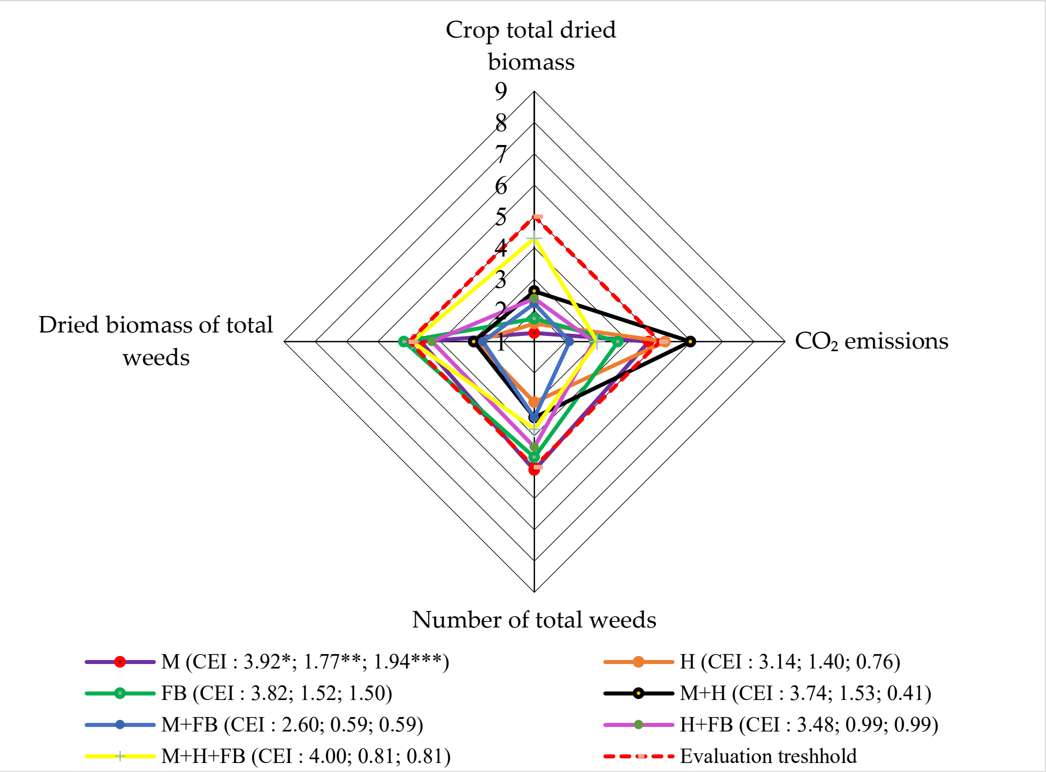

Figure 6. Comprehensive assessment of the impact of all four system levels on agroecosystem, 2020-2022. Note: M–maize single crop, H–hemp single crop, FB–faba bean single crop, M+H–binary maize and hemp crop, M+FB–binary maize and faba bean crop, H+FB–binary hemp and faba bean crop, M+H+FB–ternary maize, hemp and faba bean crop. CEI–complex evaluation index, * –average of evaluation points (EPs), ** –standard deviation of EPs, *** –standard deviation of the average of the evaluation points below the evaluation threshold.

The most positive effects on weed numbers and dried biomass were observed for the single hemp crop and for the binary maize-hemp and maize-faba bean crops. These crops received the lowest evaluation scores and were within the evaluation threshold. In terms of the number of weeds and their dried biomass, the highest scores, which were above or close to the assessment threshold,

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were obtained in the single crop of maize and faba bean. Slightly lower scores, but close to the assessment threshold, were also obtained in the ternary and binary crop of hemp and faba bean. Thus, the cultivation of these crops had a negative effect on their weediness.

Overall CEI value showed that a ternary crop was found to give the best results or the most effective one. The study showed that the choice to assess the impact of multi-cropping on the agroecosystem at four main levels provides a clearer understanding of the impact of the set of indicators on the overall functioning of the agroecosystem. Such an assessment framework can help decision-makers considering how best to implement multifunctional agriculture to maintain or increase yields and ecosystem service provision to consider alternative strategies for the development of new cropping systems [35].

4. Conclusions

A comprehensive assessment of the main indices (variables) in multi-crops agroecosystems showed that in terms of total dried biomass of the crop, the effects of ternary crop and binary crop of maize and hemp on the agroecosystem were found to be highest. The assessment of total weed numbers and dried weed biomass showed that the scores for the indices of the binary hemp and faba bean crop were significantly above the assessment threshold and had an advantage over the other single and multi-crops compared. The agroecosystem assessment in terms of CO_2 emissions showed that the binary crop has the highest impact on the agroecosystem.

The calculation of the CEI showed that ternary maize-hemp-faba bean crop had the lowest impact on the gasses emission and weed abundance raise (levels 2-4) and the highest effect on the total dried crops biomass capacity (level 1). Comprehensive assessment of the effect of all four system levels on agroecosystem showed the 2-35% higher effectiveness of ternary crop.

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