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Effect of Common Vetch (*Vicia sativa* L.) Green Manure on the Yield of Corn in Crop Rotation System

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Abstract: Regenerative farming systems are gaining increasing attention in crop production worldwide. The challenge of the future is to find and apply farming methods that not only reduce the carbon footprint of cultivation, but also produce sustainably through an optimal choice of inputs. We set up our crop rotation experiment in 2019 in order to evaluate the role of common vetch (*Vicia sativa* L.) as a green manure crop in a crop rotation system. The results were compared with nitrogen fertilizer (80 kg ha^{-1} N) and control (no green manure and no fertilizer) treatments. Based on the three years of results, it can be concluded that the biomass production capacity of common vetch sown in August is determined by the amount of precipitation in October under continental climatic conditions. In an optimum year for corn, common vetch as a forecrop was found to be equivalent to the effect of fertilizer application at all three applied seed rates, but under stress conditions in a drought year, significantly higher corn yields were obtained when common vetch green manure was applied. Our results suggest a justified role for the use of common vetch green manure in crop rotation systems.

Keywords: crop rotation; green manure; cover crop; common vetch; corn; biomass; yield

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Citation: Pál, V.; Zsombik, L. Effect of Common Vetch (*Vicia sativa* L.) Green Manure on the Yield of Corn in Crop Rotation System. *Agronomy* **2024**, *14*, 19. https://doi.org/10.3390/agronomy14010019

Academic Editor: Joji Muramoto

Received: 20 November 2023
Revised: 18 December 2023
Accepted: 19 December 2023
Published: 21 December 2023

1. Introduction

Diversified crop rotation (DCR) greatly improves crop production efficiency [1,2]. The use of crop rotation improves soil conditions and increases the productivity of the crop production system. Improvements in soil properties, such as increased soil water absorption and storage capacity, and increased numbers of beneficial soil organisms can ameliorate the negative effects of drought and other stressful conditions on yields in different crop rotations [3]. Crop rotation-based management systems can influence the type, rate and severity of soil degradation by affecting organic carbon stocks, soil structure and water and nutrient management properties, as well as nitrate leaching [4–7]. The different crops in a rotation can also reduce the effects of unfavourable weather. Increased yields in crop rotation are due to the mitigation of negative stressors compared to monoculture cropping systems [8]. The benefits of crop rotation and the goals of low-input, sustainable agriculture are similar in most respects. The use of crop rotation is essential for farmers to adopt low-input, sustainable farming practices. Crop rotation and sustainable agriculture are long-standing agricultural practices. In the mid-twentieth century, agriculture began a transition to an intensive monoculture farming system on large areas of land, using high levels of fossil fuel-based technology. Farmers believed that the benefits of crop rotations were being replaced by new, rapidly developing technology and monoculture cropping systems. Changes in agriculture, environmental concerns and analyses based on time-series experimental results require a new and thorough examination of crop rotation systems [9].

The use of different modifications in plant cultivation is justified in order to diversify the crop rotations of the production system based mainly on monoculture or a very small number of plant species, in which the use of different green manure plants can be a solution to replace the summer fallow period. The basic purpose of summer fallowing is to preserve the moisture content of the soil, which is essential for effective crop production; however, this procedure results in a low utilization efficiency of natural resources. Another disadvantage of summer fallowing is the weak water storage capacity, depending on the soil type, and the increased exposure to soil erosion [10–12], which threatens the sustainability of production in the case of degradation of fertilized soil. The application of green manure is an alternative method of sustainable management of agro-ecosystems [13].

Several authors recommend the use of green manuring with N-fixing plant species instead of fallowing as an alternative to improving degraded soils [14–16]. The benefits of using leguminous green manures include the ability to enrich the soil with N [17], maintain soil fertility and biological activity [18] and reduce the amount of N fertilizer that needs to be applied for the subsequent crop [19]. According to [20], green manure increases soil organic carbon content, aggregate stability, improves infiltration coefficients and hydraulic conductivity, and can reduce soil compaction. It can affect the distribution of soil pore sizes, reduce soil erosion susceptibility and slow the formation of surface compact layers, thereby maintaining optimum infiltration factors and reducing the likelihood of runoff, thus increasing soil moisture content [21–24]. The root systems of green manures significantly improve soil structure and biological activity [25]. Studies by the authors of [26] show that the application of green manures of any type is more effective for recycling N, maintaining soil fertility and increasing soil organic matter than rotation systems without green manure application.

In intensively cultivated areas with a high proportion of cereals in crop rotation or in areas where high amount of N fertilization is applied, the integration of leguminous crops can reduce energy demand, global warming potential and the ecological footprint of cultivation. Given that the next crop will have lower N fertilizer requirements, it offers the possibility of crop rotation diversification, which can reduce the proliferation of certain weed and pathogen species, thereby reducing the amount of pesticides applied [27]. One of the limitations of the spread of green manure plants is the limited sowing time interval [28]. For sowing green manure crops, early sowing (August–September) is recommended in order to achieve higher biomass, N uptake and soil coverage [5]. The biomass weight of green manure crops is greatly influenced by the time of sowing; for overwintering green manure crops, late sowing increases the risk of freezing, especially for legumes [29]. A late sowing time greatly compromises diversity in green manure mixtures [30]. It is not always possible for the farmer to sow early; this depends on the harvest time of the crop preceding the green manure crop and the prevailing weather during the sowing period. In semi-arid conditions, it is common that the time of sowing is linked to the larger amount of autumn precipitation, but this precipitation can be delayed [31]. The positive effects of green manure plants on the ecosystem are site-specific, and the effectiveness of these plants in regions with variable rainfall conditions is not always obvious [32]. Quantitative models were used to analyse the temporal dynamics of 11 ecosystem services and economic metrics in a 3-year crop rotation (soybean (*Glycine max*)—winter wheat (*Triticum aestivum*)—corn (*Zea mays*)), when green manure was applied between different crops in a typical mid-Atlantic climate. They estimate that green manures can enhance 8 of 11 ecosystem services without negatively affecting crop yields. When measuring ecosystem services, cumulative assessments can be misleading due to the in situ nature of some services and the time sensitivity of treatments. For example, nutrient retention benefits occurred primarily during the growing season of green manures, weed control benefits occurred during the growing season of the main crop, and soil carbon dioxide content increased over decades. The differences in production costs with and without green manures have increased threefold in the last 10 years, largely due to changes in fertilizer prices, so green manure use becomes more economical as fertilizer prices increase [33].

Different green manure crops (GM) were investigated in corn–soybean rotations and researchers found that under appropriate growing conditions, some GM species can significantly reduce GHG emissions, reduce soil NO_3-content and have no negative effect on yield [34]. The use of crop rotation and green manures in no-tillage systems increases corn and soybean yields in most cases compared to winter fallow and no-tillage systems, respectively. The use of green manures did not reduce yields of dry beans, corn, and soybean in no-till compared to conventional tillage [35]. Significant yield increases were also reported for sweetcorn yields when fabaceous green manure crops, including common vetch, were used [36]. Overwintering poaceae green manure crops had no effect on corn yield regardless of the amount of N fertilizer applied. Application of fabaceous green manures increased corn yield even without N fertilizer [37].

Leguminous green manure crops can provide all or most of the N required for the subsequent crop, if the biomass weight of the green manure is adequate. N is one of the most important nutrients for corn growth and yield formation, contributing 30–50% to grain yield increase [38]. The leguminous green manures examined in the experiment (alfalfa and hairy vetch) were able to fully or largely replace the N-fertilizer required for cultivation in sweetcorn grown in the following year; the fertilizer replacement value (FRV) was 58–156 kg N ha^{-1}. These leguminous green manures represent a real alternative N source, greatly reducing or eliminating N fertilizer application [39]. The value of leguminous green manure is the most effective, given their C:N ratio (10–15), which enables faster mineralization, and the plant residues turned into the soil contain a larger amount of N bound by the plant [40]. In the study of Pan et al. [41], the effects of common vetch (*Vicia sativa* L.), hairy vetch (*Vicia villosa* Roth.) and lathyrus (*Lathyrus quinquenervius* (Miq.) Litv.) on the physical and chemical properties of the soil were investigated. The authors found that compared to the soil of the control treatment, the organic carbon content increased from 1.6% to 6.2%, and the amount of mineral N increased significantly. Ammonium-N was the dominant form between days 0 and 20, but nitrate-N became dominant between days 30 and 70. The highest potassium and phosphorus content was observed in the treatment of common vetch.

According to numerous studies, one of the plants that can be used most effectively among the leguminous green manure plants is the common vetch (*Vicia sativa* L.), which is an annual plant, one of the alternative fabaceae forage plants that represent a small proportion of the domestic sowing structure. By sequestering atmospheric N, common vetch reduces the use of N-fertilizers, and with its good weed-suppressing ability in mixed crops, it makes the use of herbicides redundant, so it can be part of environmentally friendly farming [42]. When grown as a green manure plant, vetch species quickly provide ground cover in the case of a high seed density, demonstrating their ability to suppress weeds [43]. Six common vetch cultivars were sown at two seed rates (S1 = 100 kg ha^{-1} and S2 = 180 kg ha^{-1}) in the study of Tigka et al. They detected the highest biomass decomposition value (62.6%) after six months of application, when soil N content was 50 kg ha^{-1} in case of S1 [44]. The use of common vetch as a green manure plant and its incorporation into the soil significantly influenced the yield of corn, the number of seeds per cob and the chlorophyll content of the leaf. Compared to the control, common vetch yielded 46.30, 21.95, and 8.52% higher yield, number of seeds per cob, and chlorophyll content. In order to achieve optimal results, the use of green manures should be supplemented with N fertilizer [45]. The benefits of green manures (GM) and their use in crop rotations may be limited by the short period until the next crop is planted. In field experiments in central Spain, the pre-crop value of different green manure species, among them common vetch, was assessed in case of irrigated corn (*Zea mays* L.), and fallowing was used as a control treatment. In terms of ground cover, the common vetch (*Vicia sativa* L.) was the best performing species, along with the yellow sweet clover (*Melilotus officinalis* L.) and the perennial ryegrass (*Lolium multiflorum* L.). None of the tested species reduced corn yield or quality, but green manure plants reduced the possibility of N leaching. The results confirm the suitability of the green manure plants used in the summer season for corn, as well as the additional advantages of using them in crop rotation [46]. Nitrogen (N), phosphorus (P) and potassium (K) uptake, aboveground biomass weight and soil nutrient content of 47 vetch genotypes were investigated during the early flowering stage of common vetch under field conditions [47]. Biomass weight ranged from 21.33 to 47.31 t ha^{-1}, plant N content from 100.34 to 212.51 kg ha^{-1}, P content from 10.31 to 25.25 kg ha^{-1} and K content from 63.89 to 140.41 kg ha^{-1}, supporting the importance of common vetch as a green manure in replenishing soil nutrients.

In our research, we aimed to determine whether common vetch (*Vicia sativa* L.) leguminous green manure sown at different seed rates can achieve the nutrient replenishment effect of 80 kg N ha^{-1} fertilization during the cultivation of corn, and whether the soil moisture content is affected during the growing season of the main crop by the green manure treatments.

2. Materials and Methods

2.1. Experimental Site Description

Our experiment was set up in Hungary at the UD IAREF Research Institute of Nyíregyháza (Figure 1) to investigate the nutrient and forecrop value of common vetch (*Vicia sativa cv. Emma*), as a leguminous green manure plant, in a crop rotation system.

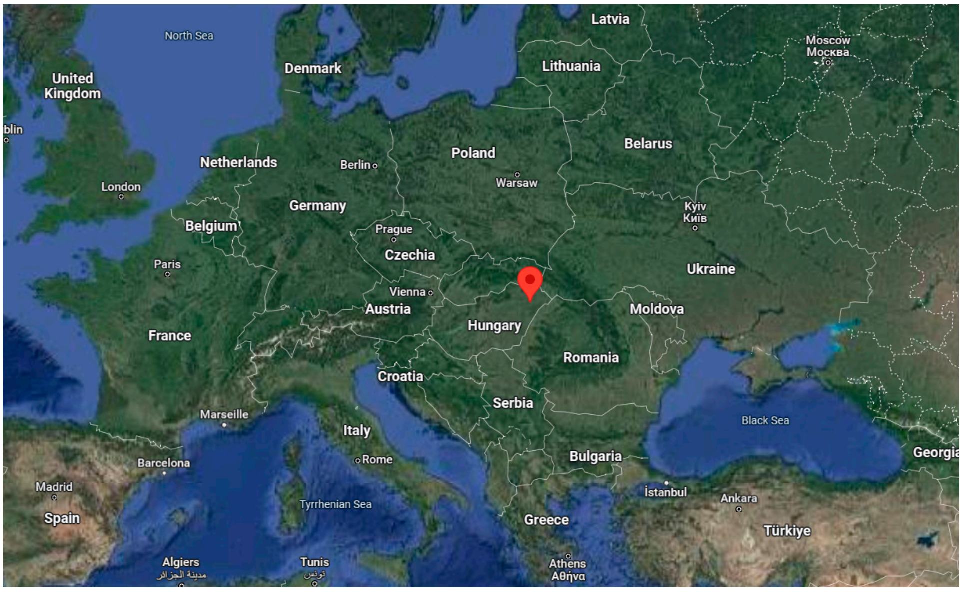


Figure 1. Location of the trial.

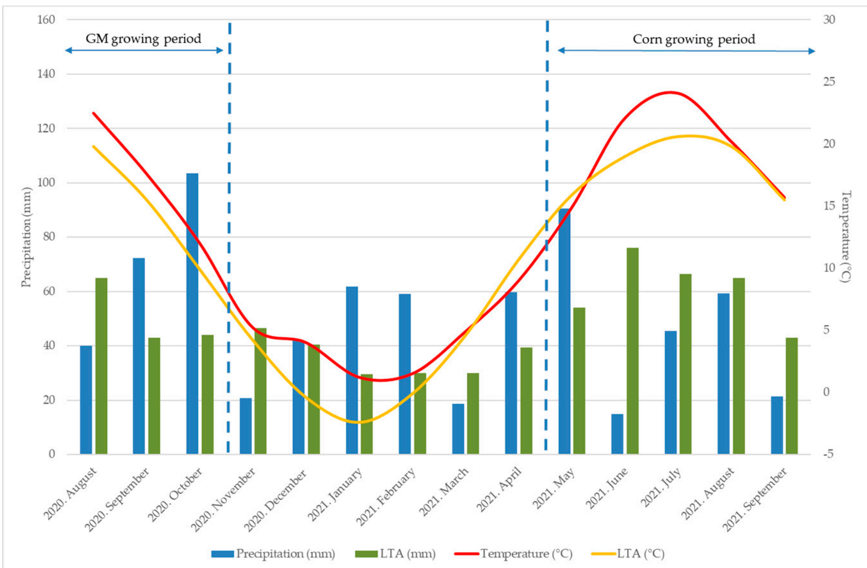
The soil type of the experimental area is humic sandy soil with neutral pH (pH 7.4), with organic matter content ranging between 1.36 and 1.43 [m/m] %. The Arany-type plasticity index is 31. Sub-samples from the soil were collected from each plot; the results represented the whole research area. The samples were analysed in an accredited soil laboratory. The soil has good phosphorus and potassium supply, the soil condition is favourable and the cultivation techniques can be applied in good quality (Table 1).

Table 1. Soil properties of the experimental area (Nyíregyháza, 2021).

Soil Depth	0–25 cm	25–50 cm
pH (KCl 1:2.5) [-]	7.4	7.4
Arany-type plasticity index [K_A]	31	31
Total soluble salt content [m/m%]	<0.02	<0.02
Carbonated lime content [m/m%]	1.65	2.90
Organic matter content [m/m%]	1.43	1.30
Nitrogen–nitrite + nitrate (KCl soluble) [mg/kg d.m.]	4.1	4.0
Potassium-oxide (AL-soluble) [mg/kg d.m.]	293	234
Phosphorus-pentoxide (AL-soluble) [mg/kg d.m.]	263	214

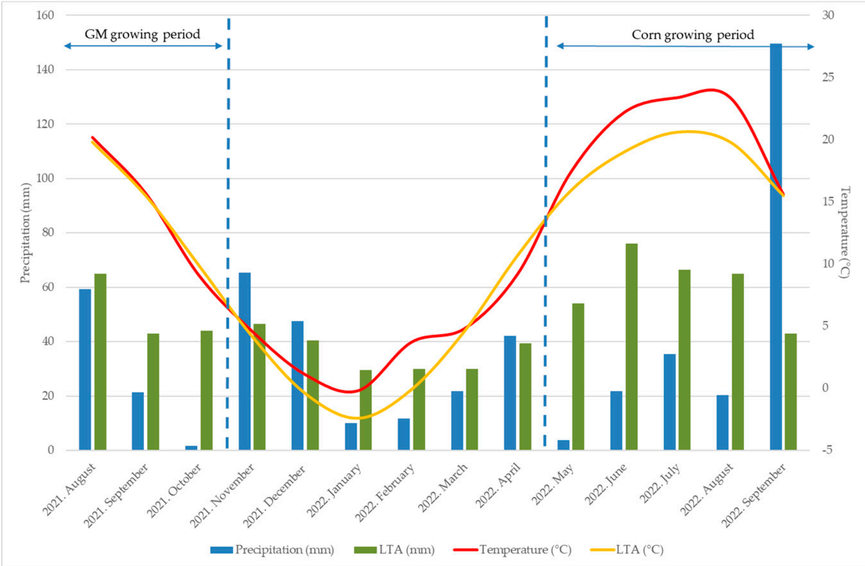
2.2. Characteristics of Precipitation and Temperature during the Research Period

Meteorological data (precipitation, temperature) were measured with µMETOS by Pessl instruments. Figure 2 demonstrates the precipitation and temperature conditions for the studied years, with averages over the last 30 years (LTA), and indicates the growing period of common vetch green manure (GM) and the growing period of corn. The autumn period of 2020 favoured the vegetative development of the common vetch GM. Although the August rainfall was below the LTA, the rainfall in October provided optimal conditions for the development of sufficient biomass, with 197.3 mm of rainfall during the growing period of common vetch. In 2021, sufficient rainfall was recorded in the region during the sowing period of corn and during the initial development period, exceeding the multiannual average by 20.2 mm in April and 36.6 mm in May. On the contrary, the amount of precipitation in June was low, totalling 14.9 mm, 61.1 mm below the LTA, after which the rainfall for the rest of the growing period was also below the LTA. The autumn of 2021 was also characterised by very low rainfall, with 44.5 mm of precipitation during the growing season of GM, of which only 1.7 mm fell in October. In 2022, corn received 237.7 mm of precipitation during the growing period, but only 81.5 mm precipitation fell during the sensitive phenophases of corn. These phenophases of corn were characterised by extreme drought, with rainfall from May to September 180 mm below the LTA. In 2022, 182.8 mm of precipitation fell during the growing period of the GM, but the distribution of precipitation was very uneven, with 82% of the rainfall falling in September. The year 2023 was considered optimal for corn, with a good distribution of rainfall in the growing season, 7.1 mm different from the LTA. In 2020, the average temperatures of August, September and October during the GM growing period were all higher than the LTA, a trend that was observed in all three studied years except October 2021. For the corn growing season, average monthly temperatures exceeded the multi-year averages in all three studied years (2021, 2022, 2023) except May 2021. The highest monthly average temperature was recorded in July 2021 (24.1 °C), with 12 average daily temperatures above 25.0 °C. The monthly average temperatures in July and August 2022 were also well above the LTA, with low precipitation. July and August had 10 and 5 heat days (daily average temperatures above 25 °C), respectively. In 2023, the average temperatures in July and August were lower than in 2022, with 4 and 7 heat days in July and August, respectively.



(**A**)

Figure 2. *Cont.*



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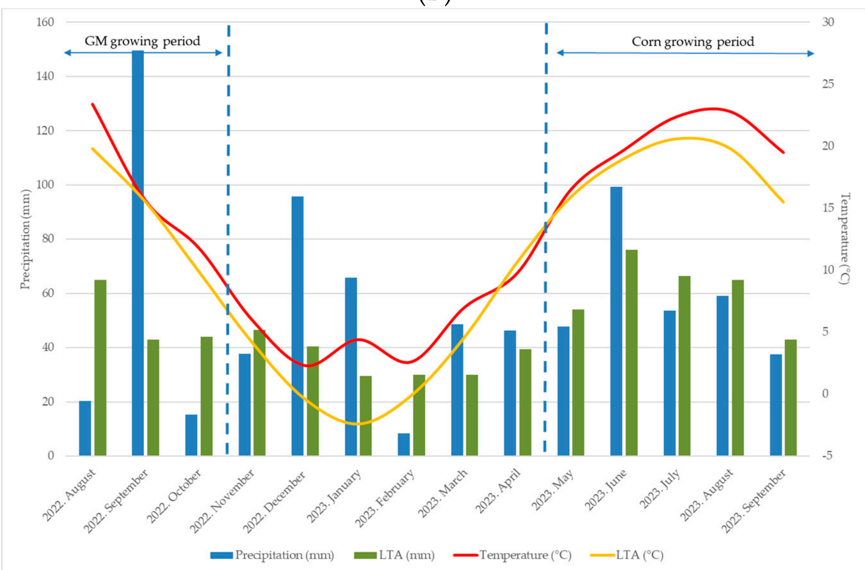

(**C**)

Figure 2. Long-term average (LTA) and total monthly precipitation and average monthly air temperature for years (**A**) 2020–2021, (**B**) 2021–2022, and (**C**) 2022–2023. Bars and left *y*–axis represent precipitation, and right *y*–axis and lines represent temperature data. GM: Green manure.

2.3. Experimental Design

The experiment was set up in 2019 to study the efficiency of different green manure treatments in a crop rotation system. In the experiment, we investigated the biomass yield of common vetch green manure with different seed rates and the forecrop value on corn over three crop seasons (2021, 2022 and 2023). Common vetch was sown at three different seed rates, rates (2 million germs ha^{-1}; 2.5 million germs ha^{-1}; 3 million germs ha^{-1}), and in addition to the green manure treatments, fertilized (80 kg ha^{-1} N) and control treatments were applied, where no green manure treatment has been carried out. Control treatments and fertilized treatments during the GM period resulted in black fallow, without herbicide spraying. For the green manured treatments, no fertilizer was used at all during the growing period of either the green manure or the main crop. The treatments were set up in a randomized block design with 4 replicates (Figure 3).

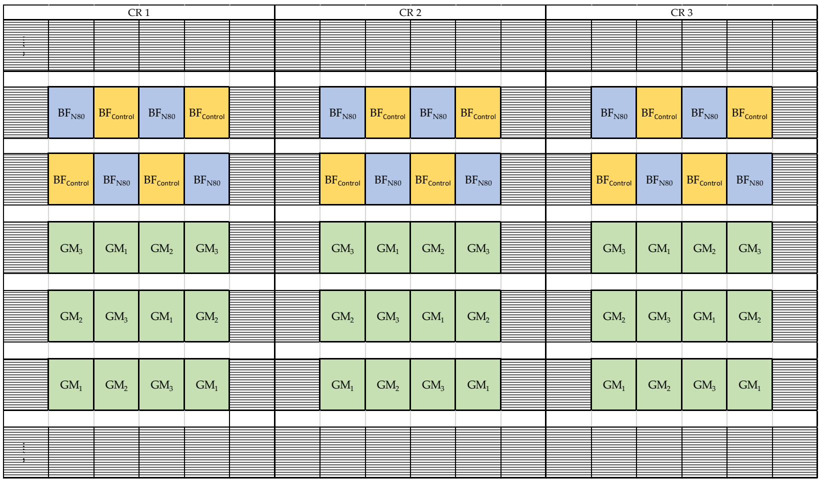

Figure 3. Construction of the experiment. CR: Crop Rotation; BF_{N80}: Bare Fallow with fertilizer application during main crop growing period; $BF_{Control}$: Bare Fallow without fertilization and green manuring; GM_1: Green Manure, seed dose 2 million germs ha^{-1}; GM_2: Green Manure, seed dose 2.5 million germs ha^{-1}; GM_3: Green Manure, seed dose 3 million germs ha^{-1}.

The crop rotations (CR) are illustrated in Table 2. For all CR, green manuring was applied after triticale or oat harvesting; hence, corn yields were evaluated over three years for the different treatments.

Table 2. Plant order of the crop rotations of the experiment.

Year/Period	CR 1	CR 2	CR 3
2020—CCP	Triticale	Oat	Triticale
2020—GMP	Green manure—Common vetch	Green manure—Common vetch	Green manure—Common vetch
2021—CCP	Corn	Triticale	Oat
2021—GMP	Fallow	Green manure—Common vetch	Green manure—Common vetch
2022—CCP	Triticale	Corn	Triticale
2022—GMP	Green manure—Common vetch	Fallow	Green manure—Common vetch
2023—CCP	Oat	Triticale	Corn

CR: Crop Rotation; CCP: Cash Crop Period referring to the growing period of main crops. GMP: Green Manure Period referring to the vegetation period time of the green manures.

For crop rotation one (CR 1), after triticale and a green manure period, we evaluated the corn yield as a result of the different treatments in 2021. In the case of the second crop rotation (CR 2) in 2022, corn yields were analysed after oat and triticale production and two periods of green manuring. In crop rotation 3 (CR 3), corn yields were evaluated after three poaceae plants and three green manuring periods. In the experiment, each treatment was applied at the same location each year, so that treatment effects cumulated year by year.

The size of the experimental plots was gross 1.7 × 10 m, net 1.7 × 9.2 m. The soil preparation and plant protectional works were carried out in a conventional plant production system. The green manure plants were incorporated into the soil at a depth of 30 cm with a plough after the plants had been crushed. The green manure plants were sown with a Wintersteiger Plot Spider plot seeder (Wintersteiger Seedmech GmbH, Ried im Innkreis, Austria), and the cash crops were harvested with a Zürn SE 130 plot combine (Zürn Harvesting GmbH & Co. KG, Waldenburg, Germany).

2.4. Agrotechnical Datas and Measurements

The seed densities used for the common vetch green manure were 2 million germs ha^{-1}, 2.5 million germs ha^{-1} and 3 million germs ha^{-1}, respectively. The 1000 seed weight of the seeds varied between 31.5 and 46.5 g. Green manure treatments were sown between 3 and 12 August each year and terminated after intensive vegetative development, before flowering, between 27 and 28 October. The green manure was crushed above the soil surface during termination and then ploughed into the soil.

An assessment of the above-ground biomass yield of the green manures was carried out before the terminal at the end of October. The determination was carried out using a 50 × 50 cm frame in replicates, during which the above-ground green yield was harvested from a 0.25 m^2 area and its weight was measured.

Soil samples were collected in the growing period of corn in order to determine the long-term effect of green manuring on soil moisture content. Soil samples were collected in 2021 and 2022 in the middle of May, in a corn growing period in the BBCH 16 stage in 2021 and BBCH 12 stage in 2022. Soil samples were taken with a hammer system soil sampler in four measurement ranges (0–25 cm, 25–50 cm, 50–75 cm, 75–100 cm), up to 1 m depth with a 5 cm diameter sampling tube in 3 replicates per treatment. The moisture content of the soil samples was determined gravimetrically and expressed as a weight percentage.

The corn (*Zea mays* cv. DKC 4316) was sown following soil preparation between 15 April and 3 May at a seed density of 65 thousand germs ha^{-1}. The fertilizer (80 kg ha^{-1} N) was applied at the time of inter row cultivation between 30 May and 15 June in case of the fertilized treatments. Corn harvesting was carried out between 5 and 14 October (Table 3).

Table 3. Time of the main field operations during the experimental time.

Operation/Year	2020/2021	2021/2022	2022/2023
Green manure sowing	11 August	12 August	3 August
Green manure sampling	27 October	27 October	26 October
Green manure termination	28 October	28 October	27 October
Corn sowing	15 April	3 May	3 May
Soil sampling	19 May	16 May	-
Fertilization (80 kg ha^{-1} N)	30 May	1 June	15 June
Corn harvest	12 October	14 October	5 October

2.5. Statistical Analysis

SPSS software (ver. 26, IBM, Armonk, NY, USA) was run to compare the means and analyse the variance among treatments, followed by Tukey's post hoc analysis to indicate the significant differences where applicable and for regression analyses. Pearson correlations among parameters were calculated using SPSS software and were used to interpret relationships among precipitation, biomass yield and corn grain yield variables.

3. Results

3.1. Effect of Different Seed Densities and Amount of Precipitation on Above-Ground Biomass Production of Common Vetch

Figure 4 illustrates the above-ground biomass yield of common vetch in the studied years at different seed rates. In 2020, the highest values of the three years were observed, with the highest precipitation of 197.3 mm during the growing season of the green manure. No significant difference was detected between the results of the three different seed rates; the highest value was observed in case of the highest seed rate of 3 million germs ha^{-1} (12.82 t ha^{-1}). The values measured in 2021 were significantly lower than the values for 2020. The total rainfall during the growing season of the green manure was 44.5 mm for this year. No significant difference was observed between the different seed rates; the highest value in this year was obtained with the lowest seed rate (0.82 t ha^{-1}). In 2022, there was no significant difference between the measured values. The highest biomass yield was measured in case of the highest seed rate (3.31 t ha^{-1}), but yields were low in this year, as in the previous year. The amount of precipitation during the growing period of common vetch green manure was 182.8 mm, but after the summer drought period, rainfall was a limiting factor during the emergence and initial development of the green manure plant. Although rainfall in September was well above the LTA (149.6 mm), in October it amounted to 30% of the average (15.4 mm), which hindered the intensive vegetative development of the plants.

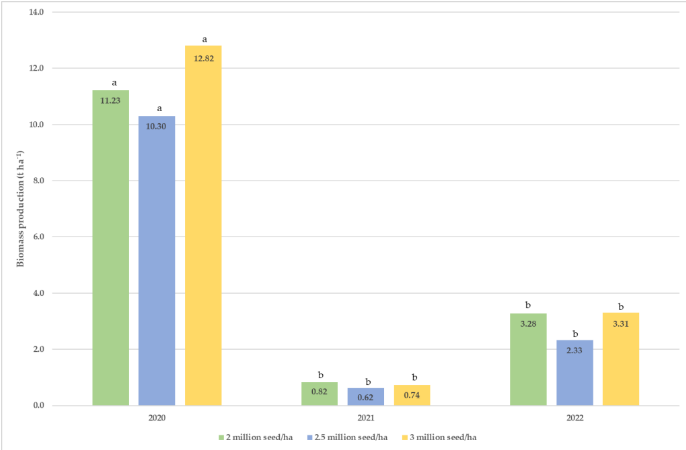

Figure 4. Above-ground biomass production of common vetch in case of different seed densities and crop years. Values with different letters are significantly different at the 95% confidence level obtained using Tukey's test.

Examining the correlation between the amount of rainfall during the growing season of the green manure plant and the biomass yield developed, the Pearson's correlation value was 0.865; however, the highest correlation value was observed for the amount of rainfall with the biomass yield in the month of October. In this case, Pearson's correlation value was 0.987, which is significant at the 0.01 level. Based on the obtained result, it can be concluded that the amount of rainfall in October had the greatest effect on the vegetative biomass yield of common vetch sown for green manure in early August under Hungarian climatic conditions, with an r^2 value of 0.895 (Figure 5).

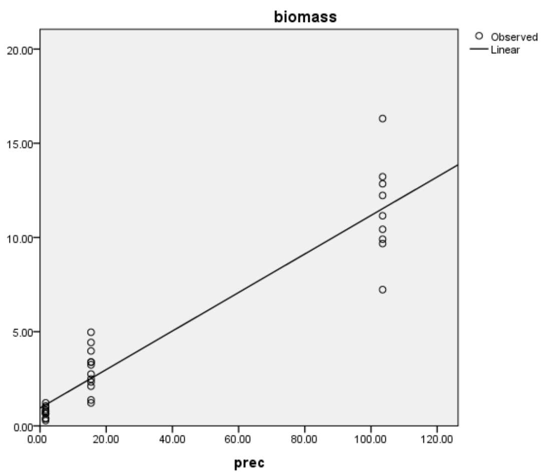

Figure 5. Regression analysis of the biomass weight of common vetch and the amount of precipitation in October in 2020, 2021 and 2022, Nyíregyháza.

3.2. Effect of Green Manuring on Soil Moisture Content in the Growing Period of Corn

In the year 2021, 89.9 mm of precipitation was recorded between the sowing of corn and the time of soil sampling; thus, drainage was an important factor for the soil. No significant difference in soil moisture was observed between the 0–25 cm and 25–50 cm depths, but at the 50–75 cm depth, the soil moisture of the control area was found to be significantly lower than that of the green manured treatments. At a depth of 75–100 cm, the soil moisture content of both the fertilised and control treatments was significantly lower than the green manured ones. The green manure treatments allowed precipitation to infiltrate deeper into the soil and reduced the risk of erosion.

The year 2022 was characterised by extreme drought, with 2 mm of precipitation from the sowing of corn to the time of soil sampling. No significant differences in soil moisture values were observed in the 0–25 cm soil layer. A tendency towards deeper layers was observed, where the soil moisture content of the green manured plots was higher than that of the control treatments. At depths of 50–75 and 75–100 cm, significantly higher moisture values were measured for the green manure treated plots, while the lowest values were observed for the fertilized plots (Table 4).

Table 4. Effect of green manuring, fertilization and control treatments on soil moisture content (m/m %) in corn stand at BBCH 16 stage in 2021 and BBCH 12 stage in 2022.

Crop Year	Treatment	Depth (cm)			
		0–25	25–50	50–75	75–100
2021	GM	19.79 [a]	19.22 [a]	18.64 [b]	18.08 [b]
	N_{80}	20.10 [a]	19.61 [a]	18.86 [b]	15.07 [a]
	Control	20.51 [a]	20.25 [a]	16.65 [a]	15.58 [a]
2022	GM	15.72 [a]	15.47 [b]	16.15 [b]	14.10 [c]
	N_{80}	14.40 [a]	16.28 [b]	13.15 [a]	8.35 [a]
	Control	15.11 [a]	13.56 [a]	13.81 [a]	12.16 [b]

GM: Green Manure treatments; N_{80}: Fertilized (80 kg N ha^{-1}) treatments; Control: Treatments without GM and fertilizer application. Values with different letters are significantly different at the 95% confidence level according to Tukey's test.

3.3. *Effect of Common Vetch Green Manure on Corn Yield in Different Crop Years*

3.3.1. Effect of Common Vetch Green Manure on Corn Yield in 2021

Figure 6 illustrates corn yields in 2021 in case of green manure treatments of common vetch at different seed densities, compared to the effect of fertilizer and control treatments. No significant differences were observed between the different green manure doses. All of these treatments significantly outperformed the results of control treatment. The effect of the fertilized treatment was non-significantly lower than that of the green manured treatments at all three seed densities. The effect of both N fertilized and green manured treatments significantly exceeded the yield results of the control treatment.

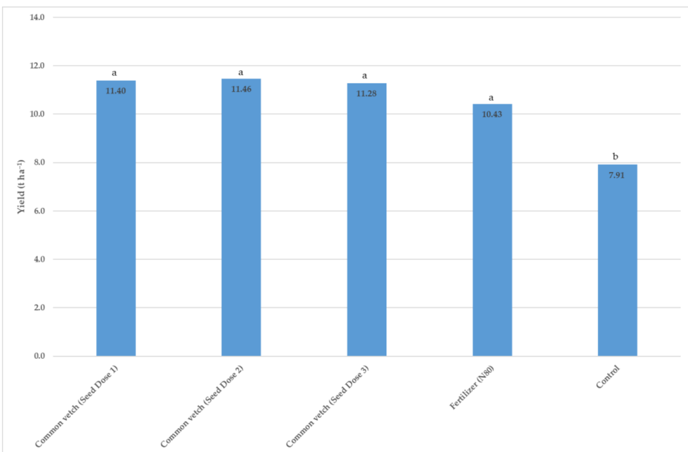

Figure 6. Corn yields as a result of green manuring with different seed doses, fertilization and control treatments in CR 1 in 2021. Values with different letters are significantly different at the 95% confidence level according to Tukey's test.

3.3.2. Effect of Common Vetch Green Manure on Corn Yield in 2022

The summer of 2022 was characterised by an extreme drought, with 3.9 mm of precipitation in May following the sowing of corn and a total of 81.5 mm at the critical phenophases of the crop, resulting in significantly lower yields than average. Under these conditions, the moisture-holding and providing capacity of the soil, which are decisive factors for the vegetative and generative development of the plant, have become extremely important. The results of the green manured treatments significantly outperformed the fertilized and control treatments (Figure 7) in case of all three seed densities applied. It is important to note that the green manured plots in the studied crop rotations had not had any fertilizer application for 3 years, only green manuring. Strong evidence of the long-term impact of green manuring is that, although a very low biomass yield was achieved in 2021, the positive effects were realised even under very stressful conditions, thanks to the two periods of green manuring (2020 and 2021).

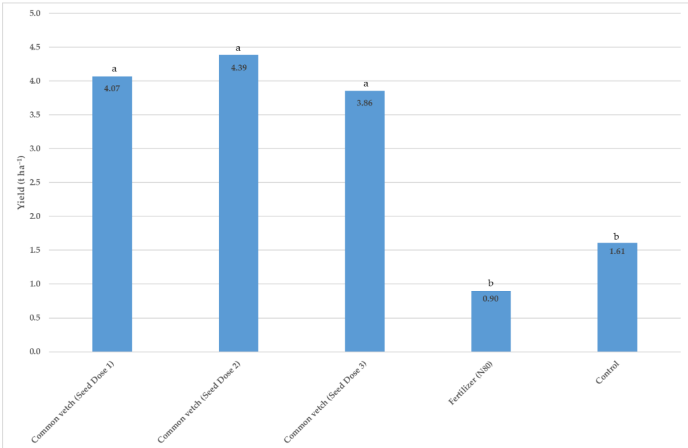

Figure 7. Corn yields as a result of green manuring with different seed doses, fertilization and control treatments in CR 2 in 2022. Values with different letters are significantly different at the 95% confidence level according to Tukey's test.

3.3.3. Effect of Common Vetch Green Manure on Corn Yield in 2023

The year 2023 has been considered optimal for corn in terms of precipitation. During the growing season, the crop received 297.4 mm of precipitation, with a favourable distribution. No significant difference was observed between treatments in corn yield results for this crop year. The highest yield (12.11 t ha^{-1}) was observed in case of GM treatment at a seed density of 3 million germs ha^{-1} (Figure 8). In this case, in CR 3, the green manured areas had not been fertilized for 4 years and had been treated with common vetch green manure for 3 consecutive years. The results confirm that green manuring with legumes can maintain the effect of N fertilization at 80 kg ha^{-1} in an optimal year and could be more successful than fertilization under increased stress conditions.

3.4. Correlation between the Examined Parameters

Both triticale and corn yields were influenced by the amount of precipitation during their growing seasons (r = 0.960 and r = 0.941, $p < 0.01$) (Table 5). Based on the results of the three years studied, a strong correlation was also found between the biomass of the green manure (Biomass GM) and the precipitation during green manure vegetation period (PGMVP) (r = 0.865, $p < 0.01$). The crop order of the rotation studied is triticale—green manure—corn. The amount of precipitation during the growing season of triticale (PTVP) also shows a positive correlation (r = 0.554, $p < 0.01$) with Biomass GM. A similarly strong positive correlation was observed between corn yield and PGMVP (r = 0.870, $p < 0.01$), and a strong correlation was also observed between the amount of Biomass GM and Corn Yield (r = 0.562, $p < 0.01$).

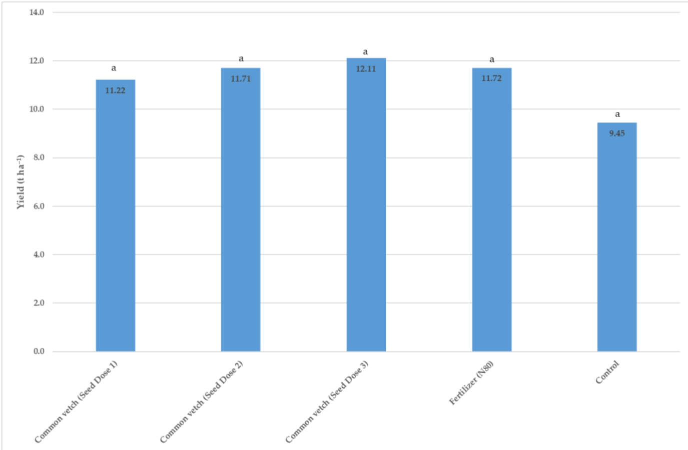

Figure 8. Corn yields as a result of green manuring with different seed doses, fertilization and control treatments in CR 3 in 2023. Values with different letters are significantly different at the 95% confidence level according to Tukey's test.

Table 5. Pearson correlation coefficients for green manure biomass, corn yield, precipitation during green manure vegetation period (PGMVP), precipitation during corn vegetation period (PCVP), triticale yield and precipitation during triticale vegetation period (PTVP) for the field of study (n = 33).

	$\text{Biomass}_{\text{GM}}$	$\text{Yield}_{\text{CORN}}$	PGMVP	PCVP	$\text{Yield}_{\text{TRITICALE}}$	PTVP
$\text{Biomass}_{\text{GM}}$	1					
$\text{Yield}_{\text{CORN}}$	0.562 **	1				
PGMVP	0.865 **	0.870 **	1			
PCVP	0.411 *	0.941 **	0.767 **	1		
$\text{Yield}_{\text{TRITICALE}}$	0.383 *	−0.430 *	−0.001	−0.629 **	1	
PTVP	0.554 **	−0.248	0.195	−0.480 **	0.960 **	1

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

4. Discussion

4.1. Effects of Precipitation and Different Seed Densities on the Biomass Weight of Green Manure

The biomass yield of common vetch green manure is largely determined by the weather conditions in a given year. Our studies show that precipitation during the growing season is the most important determinant of biomass, which is in agreement with Talgre's [48] finding that the biomass formation and nutrient uptake of leguminous green manure plants, including common vetch, in continental climates is highly dependent on climatic conditions and the length of the growing season. Rainfall during the growing season not only had a significant effect on the biomass yield of green manure, but also influenced corn yield in the years studied [49]. Based on the correlation analyses carried out, it is evident that within the autumn precipitation, the rainfall in October had the greatest influence on the biomass yield. In addition to the amount of precipitation, the distribution is also determinant, as the biomass yield is determined by the amount of precipitation in the second half of the growing season of the green manure. In our studies, the different green manure seed rates had no significant effect on the biomass yield, but [50] found that the biomass yield of vetch sown in a mixture with oats was significantly influenced by the seed density in addition to the crop year, suggesting that in pure seeding, the number of plants is not a determining factor, but that when vetch is grown in combination with oats, the number of plants used determines its green manure value.

4.2. Effects of Green Manuring on Soil Moisture Content during the Main Crop Growing Period

In terms of soil moisture, the moisture content of the soil in the top 0–25 cm and 25–50 cm layers of the green manured plots did not differ significantly from the fertilized and control plots when tested after sowing corn. However, significantly higher moisture contents were detected in the deeper soil layers (50–75 and 75–100 cm), suggesting that the green manure treatments allowed moisture to infiltrate into the deeper soil layers, indicating a long-term beneficial effect of green manuring. Studies on the cultivation of vetch (*Vicia sativa* L.) as a green manure have shown that the deep root system of vetch GM improves soil porosity due to the root remaining in the soil [51]. In the case of the use of leguminous GM crops, after harvesting wheat, the moisture content of the soil in the 0–100 cm layer was replenished to 81%, while in the case of fallow, it was only 68%. Replacing fallow with legumes increases soil moisture and reduces the risk of nutrient leaching and erosion [52]. A similar trend was observed by Mikó [53], who found that a more favourable soil condition developed 2–3 months after the incorporation of GMs, as the beneficial effects of GMs take longer to develop after incorporation, and therefore the cultivation of spring-sown crops is recommended after GMs. In terms of the effect of green manuring on soil moisture, the leguminous GMs used had a neutral effect in the upper layers of the soil and a positive effect in the deeper layers. Termination and incorporation at flowering time had a positive effect on soil moisture [54], but other observations have shown that the gravimetric water content of soil decreased as a result of GM treatment [55]. In the upper cultivated layer of soil, moisture content is mainly influenced by rainfall, and below the cultivated layer it is mainly influenced by soil porosity.

4.3. Comparison of the Effects of Green Manuring and Fertilization on the Yield of Corn

In our studies, based on the three-year averages, after common vetch GM treatments sown with different plant numbers, the average yield of corn increased by 43.2% compared to the yield of the control treatment. A similarly favourable effect on yield is reported by [55], according to whom the yield of corn increased significantly by 11% as a result of leguminous GM, but at the same time, the effect of GM on the yield of wheat and potatoes was not conclusive. Different GM seed densities had no significant effect on the yield of corn in any of the examined years. The highest green manure effect was observed in the extreme drought year 2022, when common vetch GM resulted in a 155% increase in yield compared to the control treatment (1.61 t ha^{-1}). The positive effect of legume GM on corn yield is due to the N fixed by the leguminous plant, with N fertilizer replacement values ranging from 70–184 kg ha^{-1} N active ingredient [56]. Stute and Posner [57] have a similar opinion; in their experiments with hairy vetch and red clover, they found that half of the N content of the plants had been released four weeks after incorporation in the soil, and that ten weeks after incorporation, a great amount of N (about 80%) had been released, so that corn grown as a main crop had a potential N source from the use of leguminous GM. The importance of N form is shown by the fact that the application of N fertilizer at 80 kg ha^{-1} active ingredient in the extreme drought year resulted in a 50.27% yield reduction compared to the control, indicating the beneficial effect of organic forms of N fertilization when applied regularly. The N uptake rates of common vetch and Egyptian clover were 60 and 100 kg N ha^{-1}, respectively, depending on the amount of precipitation in different years. Weather conditions and soil moisture content were crucial during germination and early plant development, which may explain the different N uptake rates [58]. In years with favourable precipitation for corn (2021 and 2023), yield differences between GM and fertilizer treatments were not significant, but under increased stress conditions (2022), green manuring with common vetch proved to be significantly more effective than fertilizer treatments. In studies by Tao et al. [59], common vetch was found to be the most effective of four different green manuring methods in terms of its effect on corn yield, increasing yield by 31.3%.

Based on our results, the common vetch green manuring provided equivalent or more favourable results than the fertilization with 80 kg ha^{-1} N active ingredient in all three years studied; thus, its application in crop rotation systems is justified. An additional advantage is that the amount of fertiliser replaced by GM in crop rotation systems reduces the input requirements of production, greenhouse gas emissions and the ecological footprint of production, especially considering that the largest contribution to the ecological footprint of production is the use of N fertilizers [60].

5. Conclusions

Our results demonstrated that common vetch green manure (GM) treatments are equivalent to the application of 80 kg ha^{-1} of N in terms of their effect on corn yield. Based on the 3-year results, no significant difference was observed between the effect of the applied different GM seed densities (2.0, 2.5 and 3.0 million germs ha^{-1}) on the corn yield, which suggests that the applied doses are the upper part of the effective common vetch seed dose. The biomass weight of common vetch GM was significantly influenced by the amount of precipitation in the autumn period, but even more by its distribution. In terms of the distribution of precipitation during the vegetation period of GM, the amount of precipitation that fell in October was the most decisive. This trend is valid in the continental climate of Hungary, which is the location of the study. One of the reasons for the favourable effect of the investigated GM treatments is that a larger amount of moisture content was available in the lower layers of the soil (50–100 cm layer) for the subsequent cash crop in the investigated years. The beneficial effect of the common vetch GM was most pronounced in the extreme drought year 2022, where the previously mentioned beneficial effects took effect to a greater extent. The examined years varied widely, so we had the opportunity to interpret the results from this perspective. In an average year, we observed an equivalent but not significantly higher GM effect than 80 kg N ha^{-1} fertilization. In an extreme drought year, a great and significant yield enhancing effect of GM application was observed compared to both the control and the 80 kg ha^{-1} N application. Based on our studies, under continental climatic conditions, common vetch GM can be an excellent tool with which to achieve the objectives of regenerative agriculture, can save significant amounts of inputs and is a potential option for improving soil nutrient supply under ecological conditions. However, this effect is only achieved if the GM is applied in a crop rotation system.

Author Contributions: Conceptualization, L.Z.; methodology, V.P.; investigation, V.P.; writing—original draft preparation, V.P.; writing—review and editing, V.P. and L.Z.; visualization, V.P.; funding acquisition, V.P. and L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: Project no. [KDP-4-3/PALY-2021] has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the [KDP-2020] funding scheme.

Data Availability Statement: Data are contained within the article.

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

References

1. Liu, C.; Plaza-Bonilla, D.; Coulter, J.A.; Kutcher, H.R.; Beckie, H.J.; Wang, L.; Floch, J.B.; Hamel, C.; Siddique, K.H.M.; Li, L.; et al. Diversifying crop rotations enhances agroecosystem services and resilience. *Adv. Agron.* **2022**, *173*, 299–335. [CrossRef]
2. Zotarelli, L.; Zatorre, N.P.; Boddey, R.M.; Urquiaga, S.; Jantalia, C.P.; Franchini, J.C.; Alves, B.J. Influence of no-tillage and frequency of a green manure legume in crop rotations for balancing N outputs and preserving soil organic C stocks. *Field Crops Res.* **2012**, *132*, 185–195. [CrossRef]
3. Shah, K.K.; Modi, B.; Pandey, H.P.; Subedi, A.; Aryal, G.; Pandey, M.; Shrestha, J. Diversified Crop Rotation: An Approach for Sustainable Agriculture Production. *Adv. Agric.* **2021**, *2021*, 8924087. [CrossRef]
4. Lal, R. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability* **2015**, *7*, 5875–5895. [CrossRef]
5. Lawson, A.; Cogger, C.; Bary, A.; Fortuna, A.-M. Influence of Seeding Ratio, Planting Date, and Termination Date on Rye-Hairy Vetch Cover Crop Mixture Performance under Organic Management. *PLoS ONE* **2015**, *10*, e0129597. [CrossRef]

6. Dinnes, D.L.; Karlen, D.L.; Jaynes, D.B.; Kaspar, T.C.; Hatfield, J.L.; Colvin, T.S.; Cambardella, C.A. Nitrogen Management Strategies to Reduce Nitrate Leaching in Tile-Drained Midwestern Soils. *Agron. J.* **2002**, *94*, 153–171. [CrossRef]
7. De Baets, S.; Poesen, J.; Meersmans, J.; Serlet, L. Cover crops and their erosion-reducing effects during concentrated flow erosion. *Catena.* **2011**, *85*, 237–244. [CrossRef]
8. Zeng, Z.-H.; Lu, Z.-H.; Jiang, Y.; Zhang, K.; Yang, Y.-D.; Zhao, P.-Y. Legume-cereal crop rotation systems in China. In *Crop Rotation*; Nova Science Publishers Inc.: Hauppauge, NY, USA, 2016; pp. 51–69.
9. Higgs, R.L.; Peterson, A.E.; Paulson, W.H. Crop rotations sustainable and profitable. *J. Soil Water Conserv.* **1990**, *45*, 68–70.
10. Tanaka, D.L.; Aase, J.K. Fallow method influuences on soil water and precipitation storage effciency. *Soil Tillage Res.* **1987**, *9*, 307–316. [CrossRef]
11. Black, A.L.; Bauer, A. Strategies for storing and conserving soil water in the northern Great Plains. In *Challenges in Dryland Agriculture: A Global Perspective, Proceedings of the International Conference on Dryland Agriculture, Amarillo, TX, USA, 15–19 August 1988*; Unger, P.W., Jordan, W.R., Sneed, T.V., Eds.; Texas Agric. Exp. Stn.: College Station, TX, USA, 1988; pp. 137–139.
12. Steiner, J.L. Simulation of evaporation and water use effciency of fallow-based cropping systems. In *Challenges in Dryland Agriculture: A Global Perspective, Proceedings of the International Conference on Dryland Agriculture, Amarillo, TX, USA, 15–19 August 1988*; Unger, P.W., Jordan, W.R., Sneed, T.V., Eds.; Texas Agric. Exp. Stn.: College Station, TX, USA, 1988; pp. 176–178.
13. Cherr, C.M.; Scholberg, J.M.S.; McSorley, R. Green manure approaches to crop production: A synthesis. *Agron. J.* **2006**, *98*, 302–319. [CrossRef]
14. Biederbeck, V.O. Sustainable crop production in the Canadian Prairies. *Conserv. Tillage. Proc. Great Plains Conserv. Tillage Symp. Great Plains Agric. Counc. Bull.* **1990**, *131*, 291–305.
15. Wright, A.T. Yield effect of pulses on subsequent cereal crops in the northern prairies. *Can. J. Plant Sci.* **1990**, *70*, 1023–1032. [CrossRef]
16. Campbell, C.A.; Schnitzer, M.; Lafond, G.P.; Zentner, R.P.; Knipfel, J.E. Thirty-year crop rotations and management practices effects on soil and amino nitrogen. *Soil Sci. Soc. Am. J.* **1991**, *55*, 739–745. [CrossRef]
17. Walley, F.L.; Clayton, G.W.; Miller, P.R.; Carr, P.M.; Lafond, G.P. Nitrogen economy of pulse crop production in the Northern Great Plains. *Agron. J.* **2007**, *99*, 1710–1718. [CrossRef]
18. Larkin, R.P. Relative effects of biological amendments and crop rotations on soil microbial communities and soil borne diseases of potato. *Soil Biol. Biochem.* **2008**, *40*, 1341–1351. [CrossRef]
19. Yu, Y.L.; Xue, L.H.; Yang, L.Z. Winter legumes in rice crop rotations reduces nitrogen loss, and improves rice yield and soil nitrogen supply. *Agron. Sustain. Dev.* **2013**, *34*, 633–640. [CrossRef]
20. Martens, D.A.; Frankenberger, W.T., Jr. Modification of infiltration rates in an organic-amended irrigated soil. *Agron. J.* **1992**, *84*, 707–717. [CrossRef]
21. Bresson, L.M.; Koch, C.; Le Bissonnais, Y.; Barriuso, E.; Lecomte, V. Soil surface structure stabilization by municipal waste compost application. *Soil Sci. Soc. Am. J.* **2001**, *65*, 1804–1811. [CrossRef]
22. Edmeades, D.C. The long-term effects of manures and fertilisers on soil productivity and quality: A review. *Nutr. Cycl. Agroecosyst.* **2003**, *66*, 165–180. [CrossRef]
23. Haynes, R.J.; Naidu, R. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. *Nutr. Cycl. Agroecosyst.* **1998**, *51*, 123–137. [CrossRef]
24. Hababi, A.; Javanmard, A.; Mosavi, S.B.; Rezaei, M.; Sabaghina, N. Effect of green manure on some soil physicochemical characteristics. *Int. J. Agron. Plant Prod.* **2013**, *4*, 3089–3095.
25. Nyiraneza, J. Nitrogen Recovery and Nitrogen Balance with ^{15}N in Potato Systems Amended with Cover Crops and Manure. Master's Thesis, Michigan State University, East Lansing, MI, USA, 2003.
26. Couëdel, A.; Alletto, L.; Tribouillois, H.; Justes, É. Cover crop crucifer-legume mixtures provide eddefctive nitrate catch crop and nitrogen green manure ecosystem services. *Agric. Ecosyst. Environ.* **2018**, *254*, 50–59. [CrossRef]
27. Nemecek, T.; von Richthofen, J.S.; Dubois, G.; Casta, P.; Charles, R.; Pahl, H. Environmental impacts of introducing grain legumes into European crop rotations. *Eur. J. Agron.* **2008**, *28*, 380–393. [CrossRef]
28. Roesch-McNally, G.E.; Basche, A.D.; Arbuckle, J.G.; Tyndall, J.C.; Miguez, E.F.; Bowman, T.; Clay, R. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renew. Agric. Food Syst.* **2017**, *33*, 322–333. [CrossRef]
29. Brandsæter, L.O.; Heggen, H.; Riley, H.; Stubhaug, E.; Trond, E.; Henriksen, M. Winter survival, biomass accumulation and N mineralization of winter annual and biennial legumes sown at various times of year in Northern Temperate Regions. *Eur. J. Agron.* **2008**, *28*, 437–448. [CrossRef]
30. Murrell, E.G.; Schipanski, M.E.; Finney, D.M.; Hunter, M.C.; Burgess, M.; LaChance, J.C.; Baraibar, B.; White, C.M.; Mortensen, D.A.; Kaye, J.P. Achieving Diverse Cover Crop Mixtures: Effects of Planting Date and Seeding Rate. *Agron. J.* **2017**, *109*, 259–271. [CrossRef]
31. Gabriel, J.L.; Quemada, M. Replacing bare fallow with cover crops in a maize cropping system: Yield, N uptake and fertiliser fate. *Eur. J. Agron.* **2011**, *34*, 133–143. [CrossRef]
32. Blanco-Canqui, H.; Shaver, T.H.; Lindquist, J.L.; Shapiro, C.A.; Elmore, R.W.; Francis, C.A.; Hergert, G.W. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. *Agron. J.* **2015**, *107*, 2449–2474. [CrossRef]

33. Schipanski, M.E.; Barbercheck, M.; Douglas, M.R.; Finney, M.D.; Haider, K.; Kaye, J.P.; Kemanian, A.R.; Mortensen, D.A.; Ryan, M.R.; Tooker, J.; et al. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric. Syst.* **2014**, *125*, 12–22. [CrossRef]
34. Behnke, G.D.; Villamil, M.B. Cover crop rotations affect greenhouse gas emissions and crop production in Illinois, USA. *Field Crops Res.* **2019**, *241*, 107580. [CrossRef]
35. Forte, C.T.; Beutler, A.N.; Galon, L.; Castoldi, C.T.; Winter, F.L.; Holz, C.M.; Bianchessi, F.; Concenço, G.; Chechi, L.; Ferreira, M.M.; et al. Soil Physical Properties and Grain Yield Influenced by Cover Crops and Crop Rotation. *Am. J. Plant Sci.* **2014**, *9*, 584. [CrossRef]
36. Turgut, I.; Bilgili, U.; Duman, A.; Acikgoz, E. Effect of green manuring on the yield of sweet corn. *Agron. Sustain. Dev.* **2005**, *25*, 433–438. [CrossRef]
37. Miguez, F.E.; Bollero, G.A. Review of Corn Yield Response under Winter Cover Cropping Systems Using Meta-Analytic Methods. *Crop Sci.* **2005**, *45*, 2318–2329. [CrossRef]
38. Erisman, J.W.; Sutton, M.A.; Galloway, J.; Klimont, Z.; Winiwarter, W. How a century of ammonia synthesis changed the world. *Nat. Geosci.* **2008**, *1*, 636–639. [CrossRef]
39. Griffin, T.; Liebman, M.; Jemison, J. Cover Crops for Sweet Corn Production in a Short-Season Environment. *Agron. J.* **2000**, *92*, 144–151. [CrossRef]
40. Tonitto, C.; David, M.B.; Drinkwater, L.E. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. *Agric. Ecosyst. Environ.* **2006**, *112*, 58–72. [CrossRef]
41. Pan, F.; Lu, J.; Liu, W.; Geng, M.; Li, X.; Cao, W. Effect of different green manure application on soil fertility. *J. Plant Nutr. Fertil.* **2011**, *17*, 1359–1364. [CrossRef]
42. Szabóné, C.K. Tavaszi bükköny (*Vicia sativa* L.). In *Az Alternatív Növények Szerepe az Észak-alföldi Régióban*; Gondola, I., Ed.; DE Agrár- és Műszaki Tudományok Centrum Kutató központja: Nyíregyháza, Hungary, 2010; pp. 48–49.
43. Uzun, A.; Bilgili, U.; Sinicik, M.; Acikgoz, E. Effects of seeding rates on yield and yield components of Hungarian vetch (*Vicia pannonica* Crantz.). *Turk. J. Agric. For.* **2004**, *28*, 179–182.
44. Tigka, E.; Beslemes, D.; Kakabouki, I.; Pankou, C.; Bilalis, D.; Tokatlidis, I.; Vlachostergios, D.N. Seed Rate and Cultivar Effect on Contribution of *Vicia sativa* L. Green Manure to Soil Amendment under Mediterranean Conditions. *Agriculture* **2021**, *11*, 733. [CrossRef]
45. Mohammadi, G.R.; Ghobad, M.E. The effects of different autumn-seeded cover crops on subsequent irrigated corn response to nitrogen fertilizer. *Sci. Res.* **2010**, *1*, 148–153. [CrossRef]
46. Alonso-Ayuso, M.; Gabriel, J.L.; Pancorbo, J.L.; Quemada, M. Interseeding cover crops into maize: Characterization of species performance under Mediterranean conditions. *Field Crops Res.* **2020**, *249*, 107762. [CrossRef]
47. Chen, Z.; Chang, D.; Han, M.; Li, Z.; Yan, Q.; Zhang, J.; Zhou, G.; Sun, X.; Cao, W. Capability evaluation of 47 Common vetch cultivars (lines) as autumn green manure in Qinghai Province, Northwest China. *Acta Prataculturae Sin.* **2022**, *31*, 39–51.
48. Talgre, L. Biomass Production of Different Green Manure Crops and Their Effect on the Succeeding Crops Yield. Ph.D. Thesis, Estonian University of Life Sciences, Tartu, Estonia, 2013.
49. Vojnov, B.; Jačimovič, G.; Seremešič, S.; Pezo, L.; Lončar, B.; Krstić, Ð.; Vujič, S.; Čupina, B. The Effects of Winter Cover Crops on Maize Yield and Crop Performance in Semiarid Conditions—Artificial Neural Network Approach. *Agronomy* **2022**, *12*, 2670. [CrossRef]
50. Jannink, J.-L.; Liebman, M.; Merrick, L.C. Biomass Production and Nitrogen Accumulation in Pea, Oat, and Vetch Green Manure Mixtures. *Agron. J.* **1996**, *88*, 231–240. [CrossRef]
51. Ambartsumova, K.A. Prospects for the Cultivation of *Vicia sativa* L. in Mixed Crops on Green Manure in Novgorod Region. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *852*, 012004. [CrossRef]
52. Biederbeck, V.O.; Bouman, O. Water use by annual green manure legumes in dryland cropping systems. *Agron. J.* **1994**, *86*, 543–549. [CrossRef]
53. Mikó, P. Examining the Effects of Green Manuring on Soil Conditions and Subsequent Crops. Ph.D. Thesis, Szent István University, Gödöllő, Hungary, 2009; pp. 1–163.
54. O'Dea, J.K.; Miller, P.R.; Jones, C.A. Greening summer fallow with legume green manures: On-farm assessment in north-central Montana. *J. Soil Water Conserv.* **2013**, *68*, 270–282. [CrossRef]
55. Ma, D.; Yin, L.; Ju, W.; Li, X.; Liu, X.; Deng, X.; Wang, S. Meta-analysis of green manure effects on soil properties and crop yield in northern China. *Field Crops Res.* **2021**, *266*, 108–146. [CrossRef]
56. Liebman, M.; Graef, R.L.; Nettleton, D.; Cambardella, A.C. Use of legume green manures as nitrogen sources for corn production. *Renew. Agric. Food Syst.* **2011**, *27*, 180–191. [CrossRef]
57. Stute, J.K.; Posner, J.L. Synchrony between legume nitrogen relase and corn demand in the upper Midwest. *Agron. J.* **1995**, *87*, 1063–1069. [CrossRef]
58. Mueller, T.; Thorup-Kristensen, K. N-Fixation of Selected Green Manure Plants in an Organic Crop Rotation. *Biol. Agric. Hortic.* **2001**, *18*, 345–363. [CrossRef]

59. Tao, J.; Liu, X.; Liang, Y.; Niu, J.; Xiao, Y.; Gu, Y.; Ma, L.; Meng, D.; Zhang, Y.; Huang, W.; et al. Maize growth responses to soil microbes and soil properties after fertilization with different green manures. *Appl. Microbiol. Biotechnol.* **2017**, *101*, 1289–1299. [CrossRef] [PubMed]
60. Snyder, C.S.; Bruulsema, T.W.; Jensen, T.L.; Fixen, P.E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* **2009**, *133*, 247–266. [CrossRef]