Thesis of Doctoral (Ph.D.) Dissertation

Evaluation of the production biology of green manures and their effect on soil

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1. BACKGROUND AND OBJECTIVES OF THE DOCTORAL DISSERTATION

The increase in productivity efficiency seen in recent decades places a significant pressure on the agricultural environment. In order to protect the environmental potential, the concept of sustainability has become more important, and the spread of regenerative farming practices is becoming more widespread both internationally and domestically. Adapting to the different environmental conditions caused by climate change is a constant challenge in crop cultivation. The increasingly hectic distribution of the annual rainfall and the increase in the number of hot days in the summer period make the inclusion of new practices increasingly urgent. A typical trend is that most of the annual precipitation falls in the winter period, so the water storage capacity of our soils is crucial. In 2019, the European Union adopted the resolution declaring a climate emergency, and as a result, the legislative and budget proposals must be in line with the objectives of the Paris Climate Agreement, creating the draft program for a climate-neutral Europe. In the European Union, the agricultural sector is responsible for more than 10% of greenhouse gas emissions, however, unlike other sectors, agriculture has a huge potential in terms of sequestering atmospheric CO_2, given the possibility of storing it in organic form in the soil.

One of the main components of sustainable farming is the environmentally-oriented management of the soil, which includes the reasonable use of water and nutrient resources, as well as the preservation and possible increase of organic matter resources. Different green manuring methods serve this latter aspect. The domestic agricultural support system also relies on the incorporation of the application of green manures or cover crops. The use of green manure plants is not a new practice in plant cultivation, however, it can be concluded from domestic plant cultivation in general that the utilization of the potential inherent in the use of green manure plants is low due to the unreasonable application. Green manuring, as one of the fundamental elements of sustainable farming methods, also contains risk factors, however, numerous researches support that the practice of green manuring applied correctly in the crop rotation can bring benefits both in the short and long term, also in terms of the yield of the subsequent crop and the soil condition. Green manure application is also one of the most effective elements of regenerative management tools. The basic goals of using green manure plants are to increase biodiversity and reduce CO_2 emissions directly and indirectly. The soil surface covered with vegetation sequesters carbon dioxide, and by turning the produced organic matter into the soil, the need for fertilizer for the next crop can be reduced. The practice of green manuring in Hungary is largely based on foreign results and experiences. At the same time, the specific ecological and production conditions of our country, as well as the unique crop rotation structure, require the validation of the application technology. In many cases, the currently applied green manure strategies are schematic, so the positive effect of the applied green manure plants does not come into effect.

In our experiment, among the plant species that can be used in green manuring, we examined the biomass yield of lupin, common vetch, oil radish, and buckwheat as green manure plants, as well as their effect on the soil, its nutrient content, and the subsequent crop. Given the limited number of the literature and cultivation technology database related to the seed production of green manure plants, due to the different ecological sensitivities of these plant species, their cultivation technology validation based on domestic conditions is reasonable. In the seed production module of the experiment, the seed production parameters (quantitative and qualitative) of the mentioned plant species were examined by applying and changing different agrotechnical elements. The results obtained from tests carried out under field conditions over four years gave us the opportunity to develop effective cultivation technology proposals in our domestic ecological conditions, which are suitable for a significant reduction of the environmental impact and the reduction of inputs.

Our research had the following objectives:

- Determining the effect of the previous crop and the crop year on the biomass yield of different green manure plant species
- Determining the short-term and long-term effects of green manure plants on soil moisture content, penetration resistance and nutrient content (organic matter content, nitrite + nitrate N content, available P and K content)
- Determining the forecrop value of green manure plants on different crop species with different sowing times
- Investigation of the reaction of the examined green manure plant species to different cultivation technological variables and cropyears in the case of seed cultivation in main sowing
- Determining the forecrop value of main-sown, seed-purpose green manure plants at different nutrient supply levels

2. MATERIAL AND METHOD

The two modules of the experiment are located in Szabolcs - Szatmár - Bereg county, in Nyíregyháza, on the area of the UD IAREF Research Institute of Nyíregyháza. The layout of the experiment is illustrated in *Figure 1* (A: green manuring module, B: seed production module).

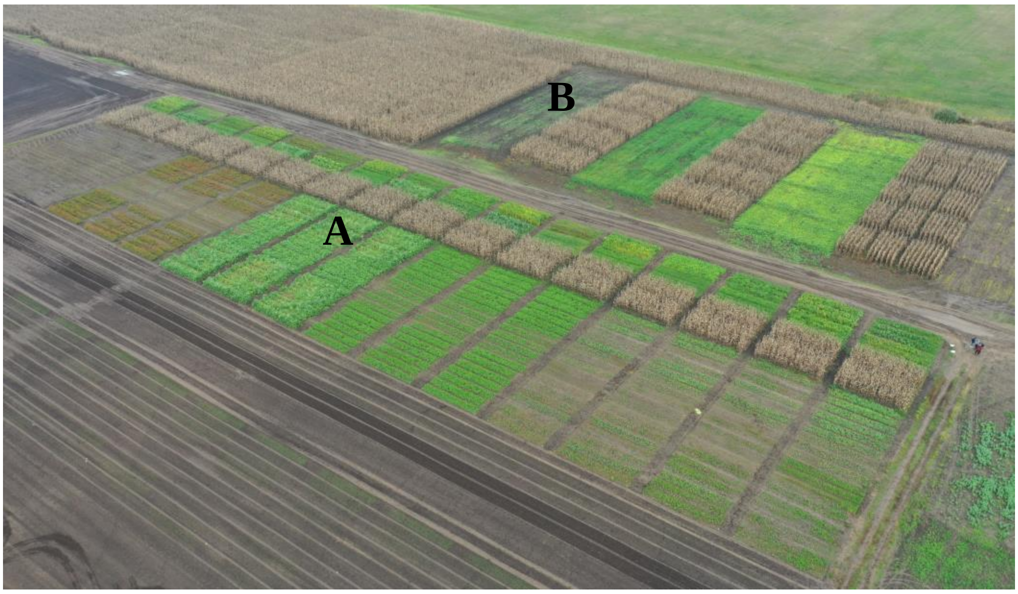

Figure 1. View of the green manuring module (A) and seed production module (B) in October (Nyíregyháza, 2020)

The soil type of the green mauring module is humic sandy soil, and its physical properties are classified as sandy loam according to the Arany-type plasticity index. The pH of the soils is around neutral. The total salinity of the soils examined is low. The organic matter content ranges from 1,37 to 2,07 % in the 0-25 cm layer and from 1,07 to 1,37 % in the 25-50 cm layer. The AL-soluble potassium content of the soils is very good. For AL-soluble phosphorus, the soils of the rotations are very well supplied in the 0-25 cm layer. At a depth of 25-50 cm, the soils of rotation I are well supplied with phosphorus, while the soils of rotations II, III and IV are moderately supplied.

In the seed production module of the experiment, the soils tested were classified as neutral to slightly alkaline in pH, sandy loam in physical properties according to the Arany-type plasticity index, and low in salinity. The soils are classified as medium calcareous on the basis of their carbonate lime content. The organic matter content ranges from 1,36 % to 1,89 % at a depth of 0-25 cm and from 1,24 % to 1,85 % at a depth of 25-50 cm. The AL-soluble potassium and phosphorus content of the soils is in the very good category.

The area of our research is the exterior of Nyíregyháza, with a continental climate. The average annual precipitation is 568 mm, the average annual mean temperature is 11.0 °C. During the investigated seasons the meteorological data (precipitation, temperature, evapotranspiration) were provided by the μMETOS by Pessl type meteorological station located on the territory of the research institute.

Precipitation in 2020 (661 mm) exceeded the 20-year average (568 mm) by 93 mm, but the distribution of precipitation was not evenly distributed. During the growing season of the green manure plants, 103.5 mm of precipitation fell in October, which provided favourable conditions for the development of the biomass.

In 2021, the annual rainfall was 22 mm below the 20-year average (546 mm). In January and February, the rainfall was above average, while the rainfall in March was below average. April and May were months with good rainfall, which favoured the development of spring crops. However, the rainfall in June and July was well below average, with a total of 14.9 mm in June, which had a negative impact on the optimal development of corn. Rainfall in September and October was also below average. The rainfall was 21.5 mm in September and 1.7 mm in October, which created unfavourable conditions for the development of green manure crops. In terms of temperatures, the averages for June and July were above the long-term average, combined with low rainfall.

The 2022 cropyear was considered to be very extreme in terms of precipitation. The annual rainfall was 102 mm below the 20-year average, and its distribution was also highly uneven. From January to August, with the exception of April, monthly rainfall was below average, resulting in a water deficit of 233.3 mm. In September, 149.6 mm of rainfall was recorded, 100.1 mm above the average. For green manure plants, the rainfall in September supported vegetative development, but the rainfall deficit accumulated during the year was not replenished in the soil. In terms of temperatures, the months of June, July and August were 1.6 to 1.9 °C above average, in combination with a lack of rainfall.

Precipitation in 2023 was 590 mm, 22 mm above the 20-year average. The rainfall was evenly distributed, with rainfall in the spring and summer months being around average values, but the precipitation made up for the deficits in the previous months. Temperatures in August, September and October were all above average, which, with sufficient rainfall, provided optimum conditions for the development of green manure plants.

The experiment set up for the purpose of evaluating the role of the green manure plant species sown as a second crop (lupin, common vetch, oil radish, buckwheat) in the crop rotation includes 4 crop rotations, in which we evaluated the forecrop value of the green manure plants in a complex system on three cash crop species (triticale, oats, corn) (*Table 1*). In addition to the green manure treatments, only fertilized and control plots were included as comparison plots, and green manure crops were applied at three seeding densities per crop species (*Table 2*). Fertilizer treatments were applied during the growing season of the indicator crops at an active rate of 80 kg ha^{-1} N in the form of lime-ammonium-salt (Pétiso) at the time of tillering in triticale and oat stands and at the time of inter-row cultivation in corn stands at the 4-6 leaf stage. The fertilizer-treated plots were used as uncovered stubble during the growing period of the green manure crops. In the control treatments, no green manure was applied, the soil remained uncovered after harvest until the next crop was sown, and no fertilizer was applied during the growing period of the cash crops. The treatments were applied in a randomized block design with four replicates, and the treated plots were bounded by border plots. The experimental plots were sown with a Wintersteiger Plot Spider plot seeder for cereals and green manure crops, with a plot size of 10 m x 1.7 m gross and 9.2 m x 1.7 m net. Harvesting of the experiments was done by a Zürn 130SE plot combine for cereals and corn was harvested by hand.

Table 1. Plant sequences of the crop rotation systems used in the greening module in the investigated years

Year	**Crop rotation I.**	**Crop rotation II.**	**Crop rotation III.**	**Crop rotation IV.**
2020	Triticale	Oat	Triticale	Corn
	Green manure	Green manure	Green manure	Stubble
2021	Corn	Triticale	Oat	Triticale
	Stubble	Green manure	Green manure	Green manure
2022	Triticale	Corn	Triticale	Oat
	Green manure	Stubble	Green manure	Green manure
2023	Oat	Triticale	Corn	Triticale
	Green manure	Green manure	Stubble	Green manure

Table 2. Seed doses used in the crop rotation experiment of the greening module

Species	Dose 1	Dose 2	Dose 3
	million seeds ha^{-1}	million seeds ha^{-1}	million seeds ha^{-1}
Lupin (*Lupinus albus cv. Nelly*)	0.3	0.5	0.65
Common vetch (*Vicia sativa cv. Emma*)	2	2.5	3
Oil radish (*Raphanus sativus cv. Litinia*)	0.8	1.5	2
Buckwheat (*Fagopyrum esculentum cv. Hajnalka*)	2.3	3	3.8
Triticale (*x Triticale cv. Szabolcs*)	4		
Oat (*Avena sativa cv. Lota*)	4		
Corn (*Zea mays cv. DKC 4943*)	0.065		

In module 2, two sowing densities (*Table 3*) and three nutrient supply levels were applied to all four green manure crop species in case of cultivation for seed production, and the forecrop value of the species was tested on corn. The three nutrient supply levels were applied equally to the plots during both the main-seeded green manure crop growing season and the corn growing season, so that their effects were cumulative over the years. The applied nutrient supply levels were the control, 80 kg ha^{-1} N and 80:96:96 kg ha^{-1} NPK active substances. The phosphorus and potassium active ingredients and 40% of the nitrogen were applied to the complex fertilizer-treated plots before sowing, the remaining nitrogen was applied in spring as top dressing. In the 80 kg N ha^{-1} treatment, the fertiliser was also applied in the spring as a top dressing. The fertiliser treatments were carried out with a plot seeder before sowing and applied by hand as top dressing to the plots. The treatments were applied in a randomized block design in four replicates. The experiment consists of 8 blocks, within which corn and main-seeded green manure species are grown in rotation.

Table 3. Seed doses and row spacings used in the seed production module for the different green manure plant species and corn

Species	1	2	Row spaing
	million seeds ha^{-1}	million seeds ha^{-1}	cm
Lupin (*Lupinus albus cv. Nelly*)	0.25	0.4	40
Common vetch (*Vicia sativa cv. Emma*) +	1.8	2.3	12
Oat (*Avena sativa cv. Lota*)	1.5		
Oil radish (*Raphanus sativus var. oleiferus cv. Litinia*)	0.5	0.8	24
Buckwheat (*Fagopyrum esculentum cv. Hajnalka*)	2	3	12
Corn (*Zea mays cv. DKC 4943*)	0.065		75

In the greening module, soil compaction was determined by measuring penetration resistance to a depth of 1 m with a PEN 100M500 mechanical penetrometer. The instrument records the soil resistance in kP every centimetre down to a depth of 1 m. Soil resistance measurements were measured in the second replicate of each treatment, in three replicates per plot, on the same plots throughout the duration of the experiment. Statistical evaluation of the results was performed on the basis of the mean values of the 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm layers.

In the greening module, soil samples were collected for the determination of soil moisture content and for laboratory testing of soil nutrient supply values. Sampling was carried out for gravimetric determination of moisture content at depths of 0-25, 25-50, 50-75 and 75-100 cm using a 5 cm diameter sampling tube with a percussor hammer system. Soil was sampled from the same plot for the duration of the experiment. To test soil nutrient supply, samples were collected from the 0-25 cm and 25-50 cm soil layers and analysed in an accredited laboratory.

Above-ground plant samples were collected from the plots of green manure plants to determine the above-ground biomass yield using a 50x50 cm frame at the time before the green manure plants were incorporated into the soil. The samples were stored in a watertight storage bag until the fresh weight was measured. After fresh weight measurement, the samples were spread out to dry to a constant weight, after which the weight of the plant samples was measured. From the values we determined the green biomass yield per hectare, the moisture content of the samples and the dry matter content.

In the seed production module, the yield components of lupin, common vetch, oil radish and buckwheat were investigated under different nutrient supply levels and seeding densities. In the experimental plots of these crop species, 10 plant samples per plot were collected prior to harvesting to determine the parameters (number of pods per plant; number of seeds per pod; seed weight per plant; thousand seed weight). Based on the collected plant samples, the parameters were evaluated in 40 plants per treatment. After harvesting, seed lots were cleaned using a Kamas-type laboratory sieve.

The collected data were processed using Microsoft Excel program for data management, data organization and graphing. Statistical analysis of data was performed using IBM SPSS version 23.0 statistical analysis software. Results were evaluated using one-way ANOVA at $P<0.05$ significance level. After analysis of variance, Tukey-B test was applied to form statistically homogeneous groups among post hoc tests. Correlation tests were performed using *Pearson's* correlation tests.

3. RESULTS AND DISCUSSION

3.1. Complex evaluation of crop rotation systems based on the use of green manure plants

3.1.1. Evaluation of aboveground biomass yield of green manure plants

For the green manure crops, above-ground biomass yields were evaluated on a plot-by-plot basis for different seed densities and different previous crops. Statistical analysis of the results showed that the different seed densities did not cause significant differences in above-ground biomass yield for any of the green manure crop species studied, so that in the following, green manure crop treatments will be evaluated as an average of the different densities, and the evaluation of the factor as a separate variable is not relevant due to the absence of significance.

In 2020, 213.7 mm of rainfall fell during the growing season of the green manure crops (11 August - 16 November), which provided optimal conditions for vegetative development of the crops. The green manure crops were sown after the harvest of triticale in rotations I and III and after the harvest of oats in rotation II. The different previous crops resulted in significant differences in above-ground biomass yields for common vetch and buckwheat, while lupin and oil radish also tended to have lower biomass yields following oat production.

In 2021, the growing season of the green manure crops (12 August - 28 October) received very low rainfall of 44.5 mm, of which only 1.7 mm fell in October. Due to the low and unfavourable rainfall distribution, vegetative development was critically weak. Green manure crops were sown in rotation II after triticale, in rotation III after oats for the second time in the period under study and in rotation IV after triticale for the first time in the period under study. In the case of common vetch, oil radish and buckwheat, the amount of biomass produced in rotation IV was significantly higher than in the other two rotations.

In 2022, following the drought year, 185.3 mm of rainfall fell during the growing season of the green manure crops (3 August - 2 November), of which 80 % was in September. In August, 20.3 mm of rainfall was recorded, which had a negative impact on the germination and initial development of the plants. No significant differences in biomass yield were observed between the rotations studied for lupins and oil radish. For lupin, the highest biomass yield was measured in rotation IV, after oats, and for oil radish in rotation III, after triticale. In the case of common vetch and buckwheat, significantly highest green yields were measured in rotation IV after oats.

In 2023, 152.3 mm of precipitation fell during the growing season of the green manures (9 August - 8 November), with an even distribution of rainfall, providing good conditions for vegetative development of the plants. For all four crop species, significantly the lowest biomass yields were measured in rotation I, following oat.

In the case of green manure application after triticale, the significantly lowest above-ground biomass yields were measured in 2021 and 2022 for all four green manure species. The highest biomass yield values were observed in 2020 and 2023.

Above-ground biomass yields of lupin, common vetch and buckwheat green manure following oat showed the highest values in 2022. In 2022, the precipitation in September accounted for 80.7 % of the precipitation in the growing season, compared to 33.8 % in 2020, 48.3 % in 2021 and 35.1 % in 2023. The highest biomass yield values for oil radish green manure were observed in 2020 and 2022.

Pearson correlation analysis was used to analyze the effect of precipitation and its distribution on the biomass yield of the green manure crop species studied after triticale and oat, and to evaluate the relationship between the yield of the main crop harvested and the subsequent biomass yield of the green manure crop. Based on the results of the four years studied, after triticale forecrop, the biomass weight of the green manures was significantly affected by the amount of precipitation in August and October ($r=0.813^{**}$- 0.937^{**}). For triticale, no significant effect was observed between the amount of seed harvested and the subsequent biomass yield produced by the green manure crops. In case of oat forecrop, the amount of precipitation in September had a significant effect on the green yield of green manures ($r=0.848^{**}$- 0.964^{**}). A negative, strong correlation was observed between oat yield and biomass yield of green manure crops in case of lupin, common vetch and buckwheat green manures ($r=-0.818^{**}$- -0.911^{**}).

3.1.2. Effect of green manure crops in crop rotation on soil moisture content in different cropyears

In all four soil layers tested (0-25, 25-50, 50-75, 75-100 cm) on 10 August 2020, before sowing the green manure crops, the moisture content values after oat harvest were significantly lower than those after triticale harvest. After triticale, the available water content was optimal up to the 0-75 cm soil layer, but after oat harvesting, moderate water deficits were observed in the 0-25 cm soil layer, and increased and extreme water deficits in the deeper layers.

In 2020, during the growing season of the green manure crops, the soil moisture content was highest for the fertilized control treatment in rotations I and III in the case of triticale forecrop, with significant differences up to the top 50 cm in rotation I and only up to the top 25 cm in rotation III. However, in the 75-100 cm layer, the moisture content of the green manured plots in rotation III showed significantly higher values than the control plots. In the case of oat forecrop, no significant differences were observed in the upper layers of rotation II, while the moisture content of the soils of the fertilized control plots was significantly lower at the 50-75 and 75-100 cm depths.

In May 2021, in corn stand (I), the soil moisture content of the 50-75 cm soil depth of the plots treated with lupin green manure was significantly higher than that of the control plots and the plots treated with oil radish and buckwheat green manure. In the triticale stand (II), soil moisture content was significantly higher in the 25-50 cm depth of the lupin green manured plots than in the oil radish green manured plots and in the fertilized control and control plots. At depths of 50-75 cm, moisture content was significantly higher in soils green-manured with lupin, common vetch and oil radish than in the fertilized control treatment, where water deficit was moderate to increased (*Figure 2*).

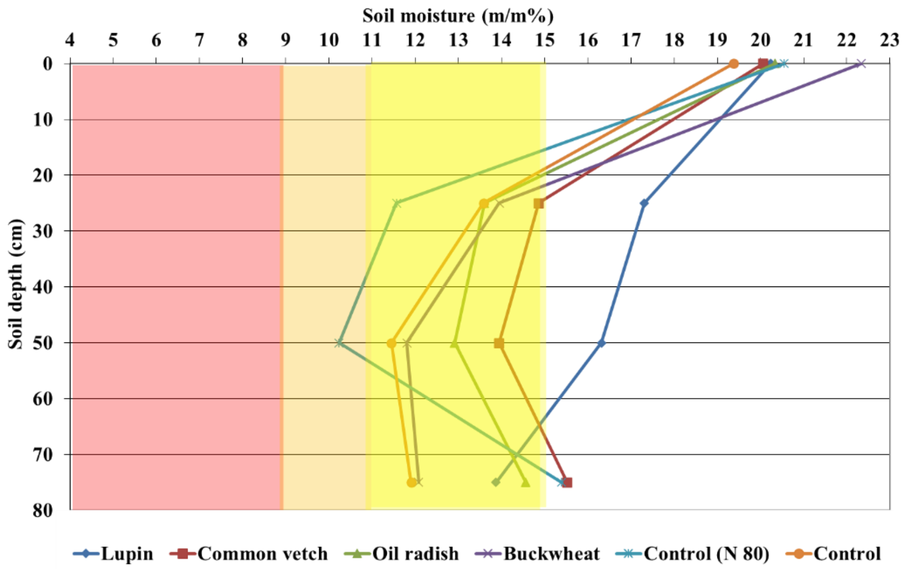

Figure 2. Soil moisture content values in triticale stand in crop rotation II in case of different green manure treatments (Nyíregyháza, 2021.05.19)

At the sampling on 19 May, the highest moisture contents in oat stand (III) at the depths of 0-25, 25-50 and 50-75 cm were measured in the soils of the lupin green-manured and fertilized control plots, where the soil moisture conditions were optimal at the whole depth studied. The lowest moisture content was found in the soils of the green-manured plots with buckwheat in all four measurement ranges.

The summer period of 2021 started with low precipitation combined with above-average temperatures. In triticale stands (II), the highest moisture content was measured in the soil of the plots treated with lupin green manure at the whole studied depth, with significantly higher values in the 25-100 cm layers than in the fertilized control and untreated control plots, furthermore, all four green manure treatments had higher moisture values in the 25-100 cm range than the fertilized control and untreated control plots, but the soils of the plots were characterised by extreme water deficit, except for the lupin green manure treatments.

The results of the sampling in July in the oat stand (III) showed that the application of lupin green manure significantly resulted in the highest moisture values over the whole depth range studied, with significant differences in the 0-50 cm depth compared to the other treatments. Soil moisture values in the common vetch green manure treated areas were significantly higher at depths of 25-75 cm compared to the untreated control areas. The lowest moisture content values were found in the soils of the areas treated with buckwheat green manure and in the control treatment at a depth of 50-100 cm.

Tests in August, following triticale (II) showed that soil moisture content was lowest in the 25-100 cm layer in case of the fertilized control and untreated control plots, while the highest values were measured in the lupin and common vetch green manured stands. Following oat, the lowest moisture content in the 50-100 cm depth was measured in the untreated control plots, while in the 0-50 cm layer the values measured in the fertilized control and untreated control plots exceeded those measured in the green manure stands of buckwheat and oil radish.

In May 2022, extremely low rainfall was recorded, 2 mm up to the time of soil sampling (16 May). In rotation I, the forecrop of triticale was corn, green manure was applied in 2020, but significant differences were observed in the green manured treatments. In the 0-50 cm depth, all four green manured plots had significantly higher moisture values compared to the control treatment. In the plots of rotation III, where green manuring was applied immediately before sowing triticale, the moisture content in the 0-25 cm soil layer of the green manured plots was significantly higher than that of the two control treatments (fertilized and unfertilized), and the lowest values were recorded in the total depth studied in the fertilized control and untreated control plots. In the oat stand of 16 May (IV), the lowest soil moisture values were found in the 0-25 cm layer in the oil radish green manure-treated plots, but no significant differences in soil moisture were observed in the deeper layers, with the lowest values in the 50-75 cm layer in the control plots and the highest values in the 50-100 cm layer in the lupin green manure-treated and unfertilized control plots.

In the 2023 season, optimal rainfall was received, so that the right amount of moisture was available when the green manure was sown. At the measurement on 9 August, following the harvest of oat (I), the soil moisture content was lowest in the untreated control plots at a depth of 0-50 cm before sowing the green manure. After triticale (II), the lowest moisture content in the 0-25 cm soil layer was measured in plots green manured with oil radish, and the highest moisture content was measured in plots green manured with lupin. At a depth of 25-50 cm, the highest moisture content was found in the soils of plots treated with oil radish green manure, with significantly the lowest values in the soils of untreated control plots. On 9 August, in corn stands, soil moisture values were highest in the 0-25 cm depth in untreated control plots, but in the deeper layer (25-50 cm), soil moisture values in green manure treated plots were significantly higher than in fertilized control plots, in the case of lupin green manure treatment, higher than in untreated control plots.

3.1.3. The effect of green manure plants on the development of soil penetration resistance values in a crop rotation system

The tests were carried out in triticale stand (II.) on November 24, 2020 after a green manuring period. The highest soil resistance value was measured in the case of the fertilized control soil at a depth of 0-10 cm, and in the case of oil radish green manure at a depth of 20-30 cm.

In 2021, during the measurement on May 19, we did not observe any significant differences in the corn stand (I.) in the 10-50 cm layer, in the 0-10 cm depth the highest soil resistance value was after common vetch green manure treatment, and the lowest value was following buckwheat green manure treatment. In triticale stand (II.), we did not observe any significant difference between the treatments in the upper 20 cm layer of the soil, in the 20-40 cm layer the lowest value was in the case of lupin green manuring, in the 20-50 cm layer the highest soil resistance value was after the oil radish green manure. Based on the measurements made in the oat stand (III.), the highest soil resistance value was measured at a depth of 10-30 cm in the case of the untreated control plots. At a depth of 20-40 cm, the plots treated with buckwheat green manure showed the highest values, while the lowest resistance values were measured in the plots treated with lupin green manure in the entire tested depth. Based on measurements of penetration resistance in the stands of green manure plants and in the control areas, after triticale (II.) on August 26, the highest values were measured in the fertilized control and untreated control areas at a depth of 10-50 cm in the soil, and the lowest soil resistance values were measured on the soils of plots green-manured with lupin and common vetch. Based on the August measurement after the oat harvest (III.), the control plots had the highest soil resistance values in the deeper layers, which were already reached the upper measurement limit (100 kP) at a depth of 10-20 cm in the case of the control, and at a depth of 20-30 cm in the case of the fertilized control. The smallest soil resistance values up to a depth of 30 cm were measured in the plots of green manure stands of lupin, common vetch and oil radish, which trend remained in the deeper layers in the case of lupin and common vetch treatments.

Tests carried out on May 16, 2022, in the corn stand (II) did not show a large difference between the effects of the treatments, the highest values were measured in the case of the fertilized control plots. Based on tests carried out in the triticale stand (III), the significantly highest soil resistance values were measured in the fertilized control plots, where the soil resistance value reached the upper measurement limit at a depth of 10-20 cm. The lowest soil resistance values were measured on plots fertilized with buckwheat and lupin. In the oat stand (I), the soil was characterized by an extremely compact layer in the 10-20 cm layer. The upper measurement limit was reached in all treatments, except for the areas green-manured with lupin, at a depth of 20-30 cm and 30-40 cm, respectively. Based on the measurements made after green manuring in the triticale stand (IV) in November, the highest soil resistance values were measured in the plots green-manured with lupin and common vetch at a depth of 10-30 cm. Up to 30-50 cm in the plots green-manured with common vetch and oil radish, the highest soil resistance was detectable, the smallest values were measured in the control plots.

In 2023 August, after oat (I), the highest soil resistance values were measured at the depth of 0-20 cm in the plots green-manured with lupin, based on the measurements taken when the green manure plants were sown, the highest resistance values below the 20 cm depth were in the control plots. After triticale (IV), the significantly highest soil resistance values were measured in the untreated control plots at a depth of 10-40 cm. In the corn stand (III), during the measurement in August, the highest soil resistance values in the soil depth of 10-50 cm were shown in the fertilized control and control areas. The smallest soil resistance values were measured on the plots treated with green manure of oil radish and common vetch. The tests carried out in November in the triticale stand (I) showed the highest soil resistance values at the depth of 10-30 cm in the case of the fertilized control and control plots, at the depths of 0-10 cm and 30-50 cm we did not experience significant differences.

3.1.4. Development of the seed yield of cash crops in green manured crop rotation systems in the investigated years

Table 4 shows the total yields for the cash crops in case of the green manure, fertiliser and control treatments in the years studied. The table shows the yields of rotations for each crop species where green manure was applied prior to the main crop.

In the case of **triticale**, in the first year of the study (2021), the effect of green manuring of common vetch and oil radish was found to be equivalent to that of fertilisation, but in the second and third years of the study (2022 and 2023), the effect of fertilisation was found to be significantly better than green manuring in terms of grain yield. Among the green manure treatments, lupin and common vetch were the best performers in 2022 and 2023 in terms of triticale seed yield, but neither year performed significantly better than the control treatment.

In the case of **oats**, in the first year (2021), common vetch green manure treatments resulted in significantly higher yields than fertilizer treatments. Furthermore, lupin and oil radish green manure treatments also resulted in higher yields than fertilizer-treated plots, but the difference was not significant. In 2022, no significant difference between treatments was observed, with the highest yields still being harvested from plots green manured with common vetch, lupin and oil radish. In 2023, the yield of the fertilized areas was statistically the highest, with common vetch being the most efficient among the green manure treatments, followed by lupin and oil radish green manure in terms of impact on oat yield.

In the case of **corn**, the highest yields in 2021 were harvested from plots green-manured with common vetch, and the yields from plots green-manured with lupin and oil radish were equivalent to those from plots treated with fertilizer, with no statistical difference. In 2022, the yields of all four green manure treatments were significantly higher than those of the fertilizer treatments, with the highest yields in the lupin and common vetch green manure treatments. In 2023, the yields of the lupin, common vetch and oil radish green manure treatments were not significantly different from the fertilized plots and remained significantly higher than the control plots.

Table 4. Evolution of yields of triticale, oats and corn in the studied years in the case of different green manure treatments, and fertilizer and control treatments (Nyíregyháza, 2020-2023)

Triticale yield (t ha^{-1})				
Treatment / Year	*2020*	*2021*	*2022*	*2023*
Lupin green manure	-	$4,4^{bc}$	$\mathbf{2,47^{b}}$	$3,99^{b}$
Common vetch green manure	-	$4,94^{ab}$	$2,36^{b}$	$\mathbf{4,25^{b}}$
Oil radish green manure	-	$\mathbf{5,22^{a}}$	$1,96^{a}$	$4,23^{b}$
Buckwheat green manure	-	$3,67^{cd}$	$1,87^{a}$	$2,93^{a}$
Fertilizer (N 80)	$4,5^{a}$	$\mathbf{5,41^{a}}$	$\mathbf{3,52^{c}}$	$\mathbf{5,51^{c}}$
Control	$5,1^{a}$	$3,62^{d}$	$2,4^{b}$	$3,77^{b}$
Oat yield (t ha^{-1})				
Treatment / Year	*2020*	*2021*	*2022*	*2023*
Lupin green manure	-	$3,92^{b}$	$2,64^{a}$	$3,63^{bc}$
Common vetch green manure	-	$\mathbf{5,18^{c}}$	$\mathbf{2,75^{a}}$	$\mathbf{3,79^{c}}$
Oil radish green manure	-	$3,94^{b}$	$2,45^{a}$	$3,46^{abc}$
Buckwheat green manure	-	$2,61^{a}$	$2,39^{a}$	$3,19^{ab}$
Fertilizer (N 80)	$3,2^{a}$	$3,3^{ab}$	$2,42^{a}$	$\mathbf{4,44^{d}}$
Control	$3,2^{a}$	$2,57^{a}$	$2,4^{a}$	$3,07^{a}$
Corn yield (t ha^{-1})				
Treatment / Year	*2020*	*2021*	*2022*	*2023*
Lupin green manure	-	$10,62^{bc}$	$\mathbf{4,21^{c}}$	$10,87^{ab}$
Common vetch green manure	-	$\mathbf{11,38^{c}}$	$4,11^{c}$	$\mathbf{11,68^{b}}$
Oil radish green manure	-	$9,94^{b}$	$2,23^{b}$	$11,53^{b}$
Buckwheat green manure	-	$8,24^{a}$	$2,52^{b}$	$9,45^{a}$
Fertilizer (N 80)	$14,2^{a}$	$10,42^{bc}$	$0,90^{a}$	$\mathbf{11,71^{b}}$
Control	$13,1^{a}$	$7,91^{a}$	$1,61^{ab}$	$9,45^{a}$

Different letters indicate significant difference based on the Tukey-B test at the $p<0.05$ level. The markings are to be interpreted by year within certain plant species.

3.1.5. Changes in the soil nutrient content and organic matter content of crop rotation systems based on green manuring in the 0-25 and 25-50 cm depth of the soil

The organic matter content of the soil showed an increase in all treatments in the examined crop rotations by the end of the 4-year study period. During the sampling in May, the organic matter content in the 0-25 cm layer of the soil after the 4-year period increased by 0.30-0.50% compared to the initial values. The largest change was observed in the fertilized (0.50 %) and lupin green manured (0.46 %) plots, the smallest change (0.30 %) was detected in the control treatment. A similar change was detected in the 25-50 cm depth of the soil, the organic matter content of the soil increased by 0.27-0.46%, the largest increase was in the control treatment and the plots green-manured with common vetch (0.45 and 0.46%), the smallest change resulted from the green manured treatment with oil radish and buckwheat (0.27%). Based on sampling in November after the incorporation of the green manure plants into the soil, the organic matter content of the plots treated with green manure plants increased to a lower extent (0.11 - 0.23 %) in the 0-25 cm layer of the soil than the fertilized control and the control treatment (0. 36 and 0.25%, respectively). However, in the 25-50 cm layer of the soil, the largest change resulted from treatments green-manured with lupin and common vetch (0.36 and 0.35 %), following the value of the fertilized treatment (0.37 %) (*Table 5*).

Regarding the change in the nitrite+nitrate nitrogen content during the sampling in May, the rate of change in the 0-25 cm depth was between 1.17 and 1.92 mg/kg in the case of the green-manured treatments. During the 4 years of the experiment, the nitrite+nitrate N content of the soil increased without the application of fertilizers, the greatest change was measured in the treatments green-manured with common vetch and oil radish (1.92 and 1.86 mg/kg increase). In the soil depth of 25-50 cm, the largest change was detected in the case of the green-manured treatments, the nitrite + nitrate nitrogen content of the soil increased by 1.67 and 1.31 mg/kg in the case of lupin and oil radish green manuring, while the fertilized and control treatments, we experienced an increase of 0.86 and 0.81 mg/kg. During the sampling in November, the values of the green manured areas (0.08 - 1.83 mg/kg increase) were lower than the values of the control treatment (3.07 mg/kg increase) regarding the change in the nitrite+nitrate nitrogen content in the 0-25 cm layer of the soil. In the 25-50 cm layer of the soil, we observed a different degree of change in the green-manured areas, in the areas treated with common vetch and oil radish, the nitrite + nitrate nitrogen content increased by 3.51 and 2.22 mg/kg, in the areas treated with lupin and buckwheat the rate of change was 0.66 and 1.10 mg/kg, which did not reach the value of the fertilized (2.71 mg/kg) and control (1.85 mg/kg) treatments (*Table 5*).

Table 5. Changes in soil organic matter content (%) and in nitrite + nitrate N content (mg/kg) in the average of the examined crop rotations compared to the initial values of the experiment during the measurements in May and November in green-manured crop rotation systems, at the 0-25 cm and 25-50 cm soil depth (Nyíregyháza, 2020-2023)

Measured parameter	Change in organic matter content compared to the initial value (%)		Change in nitrite + nitrate N content compared to the initial value (mg/kg)	
Time of measurement	**May**	**November**	**May**	**November**
Treatment / Depth (cm)	**0-25 cm**			
Lupin green manure	+0,46	+0,17	+1,48	+0,58
Common vetch green manure	+0,40	+0,23	+1,92	+1,78
Oil radish green manure	+0,39	+0,11	+1,86	+1,83
Buckwheat green manure	+0,34	+0,15	+1,17	+0,08
Fertilizer (N 80)	+0,50	+0,36	+1,46	+1,48
Control	+0,30	+0,25	+1,42	+3,07
Treatment / Depth (cm)	**25-50 cm**			
Lupin green manure	+0,41	+0,36	+1,67	+0,66
Common vetch green manure	+0,46	+0,35	+1,26	+3,51
Oil radish green manure	+0,27	+0,18	+1,31	+2,22
Buckwheat green manure	+0,27	+0,22	+1,03	+1,10
Fertilizer (N 80)	+0,39	+0,37	+0,86	+2,71
Control	+0,45	+0,30	+0,81	+1,85

Note: The highest values are marked in green.

In the case where sufficient precipitation fell during the growing season of the green manure crops and a higher biomass weight developed, the nitrite+nitrate nitrogen content of the green manured areas exceeded the nitrogen content of the fertilized areas in May of the following year (crop rotations I and III, 2021 and 2023), if corn was grown on the area. In the case where autumn cereals were grown after green manuring, the green manure crops did not have sufficient time to decompose in the soil. In the case of spring cereals after green manuring, soil nitrite+nitrate nitrogen levels were close to those of the fertilized treatment in May, but did not increase as much as in the same year when corn was sown.

In the crop rotations, neither the green manured nor the fertilized areas were treated with P fertilizer during the 4-year duration of the experiment. In case of the sampling in May, the available phosphorus content of the soil at a depth of 0-25 cm increased by 27.6 mg/kg in the nitrogen-fertilized treatment, and decreased by 29.80 mg/kg in the control treatment. Among the green manure treatments, an increase of 14.51, 5.52, and 9.52 mg/kg was observed in the areas green-manured with lupin, common vetch, and buckwheat, and a decrease of 1.41 mg/kg was measured in the soils green-manured with oil radish. At the depth of 25-50 cm, we showed a small increase in the available phosphorus content of the soil (9.88 and 24.4 mg/kg) in the case of the treatments green-manured with common vetch and nitrogen-fertilized (9.88 and 24.4 mg/kg), the values of the control areas showed the greatest decrease (-36.60 mg/kg). Based on the results of the sampling date in November, we experienced a small decrease in the available phosphorus content of the soil at the depth of 0-25 cm. However, in the 25-50 cm layer of the soil, an increase in the available phosphorus content was detected both in the case of the green manured treatments (9.74 - 22.58 mg/kg), which values exceed those of the fertilized (6.28 mg/kg) and values of the control treatment (-22.80 mg/kg) (*Table 6*).

No potassium fertilizer was applied during the 4-year duration of the experiment. During the sampling in May, we observed an increase in the available K content in the 0-25 cm soil layer in the case of green manure treatment of lupins, oil radishes and buckwheat (23.47, 1.63 and 1.58 mg/kg), while the fertilized and control treatments showed a decrease (-16.40 and -20.30 mg/kg). In the 25-50 cm layer of the soil, the largest increase was shown by treatments green-maanured with lupin and common vetch (42.70 and 16.74 mg/kg), while a decrease was observed in the control treatment (-22.1 mg/kg) in the available potassium content of the soil. During the sampling in November, we observed a decrease in the available potassium content of the soil in both treatments in the upper layer of the soil (0-25 cm), the control treatment resulted in the largest decrease (-37.9 mg/kg). However, in the 25-50 cm layer, the green-manured treatments both showed an increase in the available potassium content of the soil, the values of the green-manured treatments with lupin and common vetch increased the most (56.88 and 19.03 mg/kg). In the case of nitrogen-fertilized and control treatments, we experienced a decrease (-12.90 and -7.85 mg/kg) in the available potassium content of the soil during the 4 years of the experiment (*Table 6*).

Table 6. Changes in the available phosphorus and potassium content (mg/kg) of the soil in the average of the examined crop rotations compared to the initial values of the experiment during the measurements in May and November in green-manured crop rotation systems, at the 0-25 cm and 25-50 cm soil depth (Nyíregyháza, 2020-2023)

Measured parameter	Change in available P content compared to the initial value (mg/kg)		Change in available K content compared to the initial value (mg/kg)	
Time of measurement	**May**	**November**	**May**	**November**
Treatment / Depth (cm)	**0-25 cm**			
Lupin green manure	+14,51	-29,40	+23,47	-6,79
Common vetch green manure	+5,52	-18,20	-12,10	-9,16
Oil radish green manure	-1,41	-9,75	+1,63	-15,00
Buckwheat green manure	+9,52	-2,13	+1,58	-19,80
Fertilizer (N 80)	+27,60	-13,50	-16,40	-21,00
Control	-29,80	-20,00	-20,30	-37,90
Treatment / Depth (cm)	**25-50 cm**			
Lupin green manure	-15,40	+22,58	+42,70	+56,88
Common vetch green manure	+9,88	+14,76	+16,74	+19,03
Oil radish green manure	-11,60	+17,11	-0,86	+15,02
Buckwheat green manure	-3,75	+9,74	+5,20	+10,75
Fertilizer (N 80)	+24,40	+6,28	+0,79	-12,90
Control	-36,60	-22,80	-22,10	-7,86

Note: The highest, positive values are marked in green, the lowest, negative values are marked in red.

3.2. Evaluation of the effect of different cultivation technologies on the seed yield of green manure plants in main sowing and their forecrop effect

3.2.1. Evaluation of yield-forming elements and seed yield of lupin using different seed densities and nutrient supply levels

In terms of the number of pods per plant in the seed production of Nelly white-flowered sweet lupin, the highest values were observed in all four years studied for the stands sown at the lower seed rate (0.25 million germs ha^{-1}), with significant differences in 2022 and 2023. In all four years, the best results were obtained with the 80 kg ha^{-1} N fertilizer treatment for the 0.25 million germs ha^{-1} sowing rate. For the seed rate of 0.4 million germs ha^{-1}, the control treatment, except 2021, had the highest values. The trend for the number of seeds per plant is the same as for the number of pods per plant. Significantly, the highest values in 2021, 2022 and 2023 were obtained in the treatment with the lower number of seeds, fertilized with N 80 kg ha^{-1}. Also for seed weight per plant, higher values were observed with the lower number of seeds, with the highest values obtained with the nitrogen fertilizer treatment. In terms of thousand seed weight, the higher values were observed at a seed density of 0.4 million germs ha^{-1}, except for the 2023 crop year. At lower seed densities, the highest nutrient application (80:96:96 kg ha^{-1} NPK) resulted in the highest values (except 2023), while at higher seed densities, the treatment with only 80 kg ha^{-1} N fertilizer resulted in the highest values.

Pearson's correlation values show a strong correlation between the number of pods and number of seeds per plant and the amount of rainfall during the growing season (r=0.743** and 0.691**), with the amount of rainfall in June being the most relevant correlation value (r=0.706** and 0.728**) for the two values. The evolution of seed weight values was most influenced by rainfall during the growing season (r=0.695**). No strong correlation was observed between the parameters studied for the thousand seed weight, suggesting genetic determinism of the value.

No significant differences between treatments were observed for lupin seed yield, except for 2021. With the exception of the extreme dry year 2022, higher seed yields were observed for the crop sown with a higher germination rate (0.4 million germs ha^{-1}), but the differences were not statistically verifiable (*Table 7*). Yields are positively correlated with the amount of rainfall during the growing season (r=0.518**) and negatively correlated with the average temperature in June (r=-0.560**).

Table 7. Evolution of the seed yield of main-sown lupins when using different seed densities and nutrient supply levels, in different cropyears (Nyíregyháza, 2020-2023)

Treatment		Yield (kg ha^{-1})			
Seed density	**Nutrient level**	**2020**	**2021**	**2022**	**2023**
0,25 million seed ha^{-1}	**Control**	630,4^{a}	413,6^{a}	277,2^{a}	1478,6^{a}
	80 kg ha^{-1} N	947,3^{a}	252,1^{a}	496,0^{a}	2006,1^{a}
	80:96:96 kg ha^{-1} NPK	604,3^{a}	553,6^{ab}	206,7^{a}	1398,7^{a}
0,4 million seed ha^{-1}	**Control**	1207,5^{a}	463,4^{a}	463,0^{a}	2381,7^{a}
	80 kg ha^{-1} N	794,0^{a}	329,4^{a}	417,1^{a}	1726,3^{a}
	80:96:96 kg ha^{-1} NPK	920,6^{a}	797,2^{b}	382,0^{a}	2301,8^{a}

Note: The highest values according to the lower seed rate are marked in green, the highest values according to the higher seed rate are marked in yellow.

3.2.2. Evaluation of yield-forming elements and seed yield of common vetch in case of mono and mixed sowing and different nutrient supply levels

Among the yield parameters, the number of pods per plant was higher in the years with better rainfall (2020 and 2023) when grown with the oat support plant in the common vetch cultivar Emma for seed production, but the difference was significant only in 2020. In the years with lower rainfall (2021 and 2022), the number of pods per plant was higher in the years with no fertilizer, and in the years with higher rainfall (2020 and 2023), the number of pods per plant was higher in the N80 treatment. In pure sowing, significant differences were only observed in the year 2022, with the highest number of pods per plant being obtained with the highest fertilizer level ($N_{80}P_{96}K_{96}$). The values of the number of seeds per plant when growing with oat support crops were highest in the control treatment in the years with higher rainfall (2020 and 2023) and in the years with lower rainfall (2021 and 2022) when 80 kg ha^{-1} N treatment was applied. In years with low rainfall, the number of seeds per plant decreased significantly with the highest nutrient supply level ($N_{80}P_{96}K_{96}$) when common vetch was sown with a supporting crop.

The trend in seed weight per plant is the same as the trend in seed number per plant. In terms of thousand seed weight, significantly higher values were observed in 2020 for the mono seeded plots, with the highest values in 2021 for the mono seeded plots with N_{80} treatment and in 2022 and 2023 for the plots with support crops, with $N_{80}P_{96}K_{96}$ and N_{80} treatments, respectively. *Pearson's* correlation values showed a strong positive correlation between rainfall during the growing season and the values of number of pods per plant ($r=0.913^{**}$), number of seeds per plant ($r=0.896^{**}$), seed weight per plant ($r=0.895^{**}$) and thousand seed weight ($r=0.932^{**}$) when growing with oats as a supporting crop. For all four parameters studied, the correlation values were dominated by the amount of rainfall in June, with correlation values $r=0.610\text{-}0.685^{*}$. For the values of seed number and seed weight per plant, a negative correlation was observed with the average temperature in May ($r=-0.668^{*}$ and -0.646^{*}). In mono seeding, similar to the support crop seeding, a strong positive correlation was observed between the rainfall during the growing season and the values of pod number ($r=0.917^{**}$), seed number ($r=0.902^{**}$), seed weight ($r=0.946^{**}$) and thousand seed weight ($r=0.910^{**}$) per plant. A negative correlation was found between the average temperature in May and the evolution of the thousand kernel weight ($r=-0.781^{**}$).

For common vetch seed yield, no significant differences were observed between the effects of treatments on yields, except for the 2022 crop year, where significantly higher seed yields were obtained with mono seeding, but no statistically significant treatment effect was observed between fertilizer levels (*Table 8*). There was a strong correlation between yield and rainfall during the growing season in the case of the production with support crop with r=0.961**, but the average temperature during the growing season was the most important factor for yield in the case of the pure stand production (r=-0.836**).

Table 8. Evolution of the yield results of common vetch sown as a main crop mixed with a supporting plant, or in the case of pure sowing with different levels of nutrient supply, in different cropyears (Nyíregyháza, 2020-2023)

Treatment		Yield (kg ha^{-1})			
Cropping method	**Nutrient level**	**2020**	**2021**	**2022**	**2023**
Mixed sowing with oat	**Kontroll**	797,5^a	628,7^a	64,9^a	992,6^a
	80 kg ha^{-1} N	740,0^a	453,7^a	56,0^a	818,4^a
	80:96:96 kg ha^{-1} NPK	802,5^a	407,7^a	16,9^a	784,8^a
Pure sowing	**Kontroll**	525,0^a	387,9^a	467,0^b	1182,9^a
	80 kg ha^{-1} N	447,5^a	401,2^a	395,5^b	1037,4^a
	80:96:96 kg ha^{-1} NPK	537,5^a	305,4^a	462,5^b	906,3^a

Note: The highest values in case of mixed sowing are marked in green, and the highest values of pure sowing are marked in yellow.

3.2.3. Evaluation of yield-forming elements and seed yield of oil radish using different seed densities and nutrient supply levels

In the case of the Litinia oil radish cultivar grown for seed, the number of pod per plant was higher in all four years studied at the lower seed density, the difference being significant in 2021. At the lower number of seed densities (0.5 million germs ha^{-1}), the highest nutrient supply level ($N_{80}P_{96}K_{96}$) in 2020, 2021 and 2022, and the N80 treatment in 2023 resulted the highest value. No significant difference was observed between the two fertilizer doses in either year, but the $N_{80}P_{96}K_{96}$ treatment significantly outperformed the control treatment. At a seed density of 0.8 million seeds ha^{-1}, no significant differences in the number of pods were observed in 2020, 2021 and 2023, while in 2022, the values of both fertilizer treatments exceeded the values of the control treatment. For the seed number per plant values, the lower seed density resulted higher values in all four years, with significant differences in 2021 and 2022. Seed weight per plant values were higher in all four years for plots with lower germination numbers. No clear treatment effect was observed in terms of the evolution of thousand seed weight.

Pearson's correlation values showed a negative correlation between July rainfall and the number of pods per plant (r=-0.616**), number of seeds (r=-0.657**), seed weight (r=-0.796**) and thousand seed weight (r=-0.804**). For seed number, seed weight and thousand seed weight, a positive correlation was observed with the rainfall during the growing season (r=0.460*; 0.570** and 0.715**), where the rainfall in April and May was found to be the most significant.

Oil radish seed yields were highest at the highest nutrient supply level ($N_{80}P_{96}K_{96}$) in all four years at a dose of 0.5 million germs ha^{-1}, but differences between nutrient supply levels were not statistically verified. In terms of seed densities, higher yields were measured in all four years at the seed rate of 0.8 million germs ha^{-1}, but the differences were not statistically verifiable (*Table 9*). The correlation values show a positive correlation between seed yield and rainfall during the growing season (r=0.701**). In terms of rainfall distribution, a positive correlation of medium strength was observed for March and April rainfall (r=0.582** and 0.401), while July rainfall showed a negative correlation with seed yield (r=-0.605**).

Table 9. Evolution of the seed yield of main-sown oil radish when using different seed densities and nutrient supply levels, in different cropyears (Nyíregyháza, 2020-2023)

Treatment		Yield (kg ha^{-1})			
Seed density	**Nutrient level**	**2020**	**2021**	**2022**	**2023**
0,5 million seed ha^{-1}	**Control**	282,5^{ab}	170,0^{a}	40,4^{a}	1031,0^{a}
	80 kg ha^{-1} N	302,5^{ab}	466,0^{ab}	64,2^{a}	1310,7^{a}
	80:96:96 kg ha^{-1} NPK	355,0^{ab}	651,8^{b}	70,2^{a}	1374,7^{a}
0,8 million seed ha^{-1}	**Control**	245,0^{a}	613,0^{b}	32,4^{a}	1342,7^{a}
	80 kg ha^{-1} N	337,5^{ab}	652,0^{b}	74,3^{a}	1478,6^{a}
	80:96:96 kg ha^{-1} NPK	407,5^{b}	574,0^{b}	79,2^{a}	1518,5^{a}

Note: The highest values according to the lower seed rate are marked in green, the highest values according to the higher seed rate are marked in yellow.

3.2.4. Evaluation of yield-forming elements and seed yield of buckwheat using different seed densities and nutrient supply levels

For the seed production of the variety Hajnalka buckwheat, the highest seed number per plant and seed weight per plant for both seed densities were in the control treatment in 2020, 2021 and 2022, respectively. Seed number per plant and seed weight were higher at the lower seed density, (2 million germs ha^{-1}) in the years studied, but the difference was not significant. There was no consistent effect of seed density and nutrient supply on thousand seed weights.

Pearson's correlation values showed positive correlations between rainfall during the growing season and seed number, seed weight and thousand seed weight per plant ($r=0.838^{**}$; 0.631^{**} and 0.668^{**}), with June rainfall being the most relevant correlation. A strong negative correlation was observed for the thousand seed weight values with the evolution of the average temperature during the growing season ($r=-0.800^{**}$). The yield of buckwheat was higher in 2020, 2021 and 2022 for the lower germination number (2 million germs ha^{-1}), but the differences were not statistically verifiable. In 2020, the highest nutrient supply level ($N_{80}P_{96}K_{96}$) resulted in the highest yield at the lower germination rate, in the remaining years the control treatment had the highest yield, but the differences were not significant (*Table 10*). *Pearson*'s correlation tests showed that rainfall during the growing season ($r=0.786^{**}$) and rainfall in June ($r=0.709^{**}$) were correlated with seed yield, but showed a negative correlation with June temperature ($r=-0.612^{**}$).

Table 10. Evolution of the seed yield of main-sown buckwheat when using different seed densities and nutrient supply levels, in different cropyears (Nyíregyháza, 2020-2023)

Treatment		Yield (kg ha^{-1})			
Seed density	**Nutrient level**	**2020**	**2021**	**2022**	**2023**
2 million seed ha^{-1}	**Control**	390,0^{ab}	190,9^{a}	73,7^{a}	479,5^{a}
	80 kg ha^{-1} N	320,0^{a}	96,0^{a}	16,2^{a}	415,6^{a}
	80:96:96 kg ha^{-1} NPK	530,0^{b}	109,8^{a}	45,3^{a}	423,6^{a}
3 million seed ha^{-1}	**Control**	410,0^{ab}	123,8^{a}	33,5^{a}	503,5^{a}
	80 kg ha^{-1} N	440,0^{ab}	76,2^{a}	48,8^{a}	487,5^{a}
	80:96:96 kg ha^{-1} NPK	450,0^{ab}	57,2^{a}	36,8^{a}	359,7^{a}

Note: The highest values according to the lower seed rate are marked in green, the highest values according to the higher seed rate are marked in yellow.

3.2.5. Evaluation of the forecrop value of green manure crops sown as a main crop on corn with different nutrient supply levels

In case of the main-sown green manure crops, we evaluated their forecrop value on corn, where the effect of nutrient supply, or lack of it, was evaluated cumulatively from year to year. Based on our four-year results, there was no significant effect of fertilizer treatment (80 kg ha^{-1} N; 80:96:96 kg ha^{-1} NPK) on corn yield, and the results of the unfertilized control treatment were not statistically significantly different from the fertilized treatments when the forecrop of corn was lupin, common vetch, or oil radish (*Figure 3*).

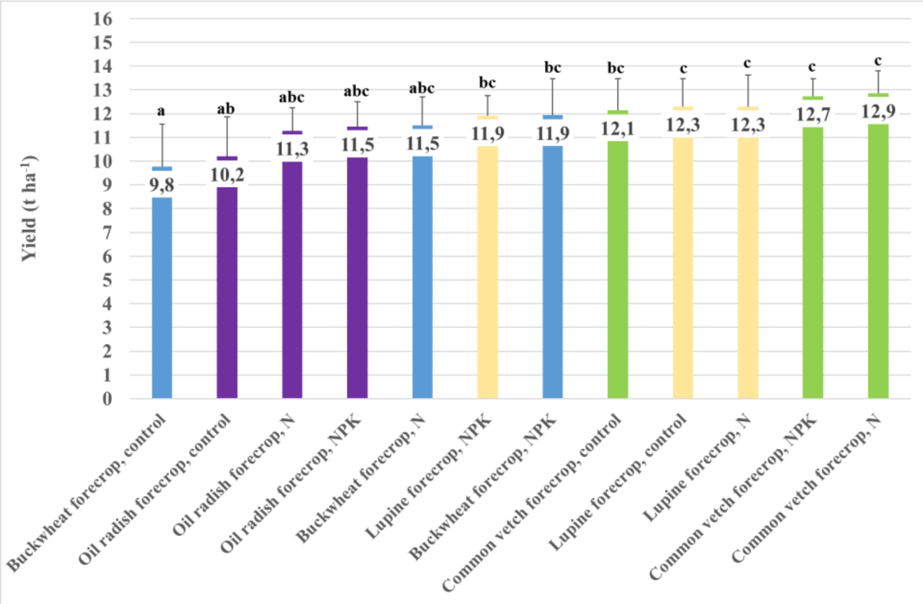

Figure 3. Effect of different forecrops and nutrient supply levels on corn yield (Nyíregyháza, 2023)

4. NEW SCIENTIFIC RESULTS

1. In the case of the use of **lupin and common vetch green manure plants** in the growing season of the following plant culture, we showed **a significantly higher moisture content** in the soil at a depth of 25-75 cm **compared to the control treatment** in May (on average +4.38; +2.10 m/m %), July (on average +3.00; +1.60 m/m%) and August (on average +3.07; +1.93 m/m%).

2. The **forecrop had a significant effect on the biomass yield** produced by the green manure plants. A strong **negative correlation** relationship was found between **seed yield of oats and biomass yield of lupin, common vetch and buckwheat green manure crops.**

3. In the **dry season, leguminous green manure** applied (lupin 2.47 t ha^{-1}, common vetch 2.36 t ha^{-1}) **before winter cereal** (triticale) **did not reach the effect of the fertilized treatment** (3.52 t ha^{-1}) in case of seed yield, while **in case of oil radish and buckwheat** green manure application (1.96 t ha^{-1} and 1.87 t ha^{-1}), a **yield reduction was observed** compared to the control treatment (2.40 t ha^{-1}).

4. For **corn**, in years with **average rainfall**, the effect **of green manuring with lupin, common vetch and oil radish** (8.57 t ha^{-1}; 9.06 t ha^{-1}; 7.90 t ha^{-1}) was **equivalent to the yield increase effect of fertilisation** with 80 kg ha^{-1} N (7.68 t ha^{-1}). In an **extreme dry season**, the application of **green manure crops** (2.52-4.21 t ha^{-1}) **significantly exceeded the results of fertilization** (0.90 t ha^{-1}) in terms of seed yield.

5. The increase in the organic matter content of the crop rotation systems was also observed **independently of the use of green manure crops**. The effect of the green manure treatments on **soil nitrate N content** was **apparent in May** of the year following green manure application when the green manure crops produced sufficient biomass. The **nitrate N content** of the soils treated **with leguminous green manure** (7.6-10.5 mg/kg) exceeded the nitrate N content of the soils of the fertilized and control treatments (3.1 and 2.5 mg/kg). In the case of the **control treatments,** we experienced a **decrease in the available P** (-27.3 mg/kg) **and K** (-22.0 mg/kg) content of the soil. As a result of the application **of green manure plants, the available P and K content of the soil increased** (16.1 mg/kg, and 25.4 mg/kg), which was detectable in the **deeper layers** of the soil (25-50 cm) in the autumn period.

6. Under the investiated ecological conditions, four years of results showed that the **number of pods per plant of lupins** grown for seed was **determined by temperature conditions at flowering in May** and **rainfall conditions in June**. In the case of **common vetch**, the **amount of rainfall during the growing season** was the determinant of the **number of pods per plant**, the **yield** was influenced by the **amount of rainfall** during the growing season in the case of **mixed sowing** and by the **temperature conditions** during the growing season in the case of **pure sowing**.

5. RESULTS THAT CAN BE USED IN PRACTICE

1. The amount of rainfall in the second half of the growing season has proved to be decisive for the biomass production of green manure crops, which means that their earlier termination (before October) is not recommended under our domestic ecological conditions.

2. In the case of green manuring before winter cereals in dry seasons, there are no suitable conditions for the establishment of an optimum seedbed, and yield depression is expected, mainly due to weaker tillering.

3. In case of spring-sown cereals, green manuring with common vetch can be equivalent to the yield-enhancing effect of fertilising with 80 kg ha^{-1} N.

4. In the case of lupin seed production, the use of intensive nutrient supply levels is not justified at the higher germination rate (0.4 million germs ha^{-1}).

5. In the case of common vetch seed production, mixed with oat in a year with poor rainfall, fertiliser supplementation will have a yield-reducing effect on common vetch seed yields due to the more intensive habit of oats.

6. In the case of oil radish cultivation for seed, a clear fertilizer reaction was shown, intensive fertilizer use (80:96:96 kg ha^{-1} NPK) is justified.

7. Contrary to the traditional and accepted approach, based on our test results, the species previously classified as extensive cultivable plants can be cultivated successfully with more intensive species-specific cultivation technology based on their ecological and technological sensitivity.

6. PUBLICATIONS ON THE SUBJECT OF THE DISSERTATION

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List of publications related to the dissertation

Hungarian book chapters (1)

1. **Pál, V.**, Erdős, Z., Henzsel, I., Zsombik, L.: A zöldítés szerepe a talajdegradáció elleni védelemben homoktalajon.
   In: A talajok multifunkcionalitásának megőrzéséhez szükséges ismeretek átadása az agrárkörnyezet fenntarthatósága céljából. Szerk.: Ladislav Kovac, Jana Jakubová, Aranyos Tibor József, Makádi Marianna, NPPC-Vyskumny ústav agroekológie Michalovce, Piestany, 220-230, 2021. ISBN: 9788097356521

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