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PRODUCTIVITY OF SHORT-ROTATION CROP ROTATIONS WITH DIFFERENT SOYBEAN SATURATION DEPENDING ON THE FERTILIZATION SYSTEM

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Crop yield, as well as crop rotation productivity in general, is an integral indicator of soil fertility, and its level is determined by a complex combination of soil, biological, and weather factors, the crop fertilization system, and the set and scheme of crop rotation. Among the components of agricultural management systems, a leading role is played by the crop rotation system, which is based on scientific principles. The effectiveness of various crop rotations depends on the saturation with grain, technical, and fodder crops.

Ecological fertilization systems, such as plant residues, micronutrients, humus, and microbiological fertilizers, involve adherence to natural biological laws, including the accumulation of organic matter, enhancement of microbiological activity, and increased availability of nutrients for agricultural crops.

Recently, there has been a need to provide the population with protein. Significant attention has been focused on soybean cultivation. It is a high-yielding crop, and its yield potential largely depends on the choice of predecessor. Research on soybean cultivation in monocultures and the possibility of different degrees of saturation of crop rotations with this crop in our region has not been conducted.

Therefore, there is a need to develop new schemes that differ from previous ones in terms of higher saturation of crop rotations with high-yielding crops, a wide range of doses and ratios of essential nutrients in the fertilization system of intensive grain crop rotations with short rotations. A real and effective way to halt the degradation of chernozem soils is the purposeful use of by-products of crop production (straw from cereal and leguminous crops, corn and sunflower stalks) as fertilizers, combined with other intensification factors.

The results of our research have shown that under dry vegetation conditions, especially for late-maturing crops, the fertilization system had the most significant impact on crop rotation productivity. The most significant increases in grain units yield, feed units, and digestible protein were observed using the organic-mineral fertilization system. Higher rainfall and moderate air temperatures neutralized the effect of fertilizers and increased the influence of the crop rotation factor on productivity.

Among the studied crop rotation models, the highest productivity for grain units (5.45 t/ha), feed units (5.85 t/ha), and digestible protein (0.74 t/ha) was observed in the variant using the organic-mineral fertilization system in a grain-fallow-row crop rotation with up to 20 % soybean saturation.

Key words: *soybean saturation in crop rotation, productivity, fertilization systems, short rotation crop rotations, crop rotation factor.*

Соколовська І.М., Мащенко Ю.В. Продуктивність коротко-ротаційних сівозмін з різним насиченням соєю залежно від системи удобрення

Урожайність сільськогосподарських культур, як і продуктивність сівозміни в цілому, виступає інтегральним показником ефективної родючості ґрунту, а її рівень визначається складним поєднанням цілого комплексу ґрунтових, біологічних і погодних факторів, системою удобрення культур, набором та схемою чергування їх у сівозміні. Серед складових систем ведення сільського господарства чільне місце займає система землеробства, головною ланкою якої є науково обґрунтована сівозміна. Ефективність різноротаційних сівозмін залежить від насичення зерновими, технічними та кормовими культурами.

Екологізовані системи удобрення: рослинні рештки, мікродобрива, гумусні і мікробіологічні добрива, передбачають дотримання природних біологічних законів, а саме нагромадження органічної речовини, посилення мікробіологічної активності, підвищення доступності елементів живлення для сільськогосподарських культур.

В останній час виникла потреба у забезпеченні населення білком. Велика увага господарств зосереджена на вирощуванні сої. Це високоприбуткова культура, її потенціал урожаю в значній мірі залежить від вибору попередника. Дослідження стосовно вирощування сої у беззмінних посівах та можливості різного ступеню насичення сівозмін даною культурою в нашому регіоні не проводили.

Отже, виникає потреба розробки нових схем, які відрізняються від попередніх більш високим ступенем насичення сівозмін високопродуктивними культурами, широким діапазоном доз і співвідношень основних елементів живлення в системі удобрення інтенсивної зернової сівозміни з короткою ротацією. Реальний і ефективний шлях призупинення деградації чорноземів – цілеспрямоване використання в якості добрив побічної продукції рослинництва (солома злакових і бобових культур, стебла кукурудзи та соняшнику) та сидератів у поєднанні з іншими чинниками інтенсифікації.

За результатами проведених досліджень встановлено, що в посушливих умовах періоду вегетації, особливо пізньостиглих культур, найбільш істотно на продуктивність сівозмін впливала система удобрення. Більшими прибавки врожаю зернових, кормових одиниць та перетравного протеїну були за органо-мінеральної системи удобрення. Більша кількість опадів та помірні температури повітря нівелювали дію добрив та збільшили вплив сівозмінного фактору на продуктивність сівозмін.

Серед досліджуваних моделей сівозмін вища продуктивність за зерновими одиницями (5,45 т/га), кормовими одиницями (5,85 т/га) та перетравним протеїном (0,74 т/га) була у варіанті за органо-мінеральної системи удобрення у зерно-паро-просапній сівозміні з насиченням соєю до 20 %.

Ключові слова: *насичення сівозміни соєю, продуктивність, системи удобрення, сівозміни короткої ротації, сівозмінний фактор.*

Problem statement. The basis of the modern farming system is crop rotation. When it is properly applied, it optimally utilizes land, fertilizers, and new varieties and hybrids better realize their genetic potential, reduces weediness, decreases the impact of pests and diseases with minimal use of chemical agents. Rational use of natural and agrotechnical resources positively affects the environment, allows for increased agricultural production, and reduces costs [8].

In the conditions of intensive and competitive agriculture, there is a need to reduce the rotation period of crops in crop rotations. More and more producers are growing crops in repeated plantings and enriching short-rotation crop rotations with economically advantageous crops, reducing their list in the structure of crop rotation. Therefore, it is important to implement scientifically grounded crop rotations with the saturation of grain, leguminous, and oilseed crops, including corn, soybeans, wheat, and sunflowers, taking into account organizational and natural-climatic conditions in farming today.

Analysis of recent research and publications. The reduction of the range of cultivated crops, the creation of smaller farms, and the narrowing of farm specialization do not allow for diverse crop rotations. Therefore, short-rotation crop rotations are relevant today. Moreover, with the advent of new technologies, modern equipment, varieties and hybrids, fertilizers, and plant protection products, the negative impact of continuous cropping can be significantly reduced [13, 15].

The introduction of short-rotation crop rotations does not compromise the agronomic effectiveness of crop rotation factors and may even enhance economic measures such as variety renewal, changes in soil cultivation technologies, and so on. The structure of short-rotation crop rotations is determined by farm specialization, zonal soil-climatic conditions, and market conditions [2, 15, 16].

According to many researchers, the saturation of crop rotations with leguminous crops, particularly soybeans, ensures increased crop yield and improved quality.

Furthermore, these crops contribute to the improvement of biological processes in the soil due to the activity of nitrogen-fixing bacteria and crop residues. This allows subsequent crops in the rotation to utilize less soluble nutrients such as phosphorus and potassium [4, 5, 6, 9, 10, 14].

The implementation of short-rotation soybean crop rotations and the use of crop residues as fertilizer in combination with mineral fertilizers are important issues in agriculture.

The value of individual agricultural crops is usually assessed based on their yield and economic value, but it is crucial to evaluate the entire crop rotation cycle based on the included crops to demonstrate the productivity and economic efficiency of crop rotation [3].

To realize the yield potential and productivity of agricultural crops, it is necessary to consider their biological characteristics, cultivation technology requirements, and their relationship within the crop rotation to ensure maximum yield digestible protein, grain units, feed units, and to maintain or even improve soil fertility [12].

The value of soybeans as a preceding crop lies in their biological nitrogen fixation from the air at a level of up to 90-120 kg/ha. A certain portion of biologically fixed nitrogen from soybeans remains in the soil. Therefore, this crop is a good precursor for most cereal crops. In short-rotation crop rotations, given the agronomic and economic role of soybeans, priority should be given to this grain legume. Properly planned crop rotation has many advantages, one of which is increased field productivity. Additionally, crop rotation is a very important and effective tool for comprehensive pest and disease control. By interrupting the life cycles of pests and diseases, we can prevent the accumulation of certain diseases characteristic of soybeans and reduce the number of soybean-specific weeds [1, 7, 9, 17].

Furthermore, including high-biomass agricultural crops in crop rotations and increasing their productivity can help reduce organic carbon losses and increase soil fertility. The effectiveness of crop rotation in preventing soil degradation can also be assessed directly by determining changes in soil properties over time.

Thus, the transition from long-rotation to short-rotation crop rotations in each specific case needs to be addressed primarily based on soil-ecological factors. Real, stable increases in agricultural production, guaranteed food supply, and creating the best living conditions for people can only be achieved through reliable soil protection and preservation and improvement of its fertility.

The aim of the research. To investigate the impact of crop rotation factors and fertilization systems on the productivity of short-rotation crop rotations and monoculture cultivation of agricultural crops in the conditions of the northern Steppe of Ukraine.

Research methodology. The main method of research is field and laboratory-field studies. Field studies were conducted during 2019-2023 in the fields of the Institute of Agriculture of the Steppe NAAS. The experiment was conducted using the method of randomized block design, with each crop rotation being a separate block.

A stationary experiment was established in 2005 on plots with uniform natural fertility and relief after spring barley. The degree of soil contamination, where the field studies were conducted, is high, corresponding to the conditions of the northern part of the Ukrainian Steppe.

The technology of growing agricultural crops in crop rotations is generally accepted for the zone, except for the methods under study.

Factor A is the crop rotation: 1. Saturation of crop rotation with soy (Zlatoslava variety) at 100 %. 2. Grain-row crop rotation, soybean saturation up to 60 %, crop alternation: soybean (Zlatoslava variety); winter wheat (Oranta Odessa variety); soybean

(Zlatoslava variety); corn for grain (DK Veles hybrid); soybean (Zlatoslava variety). 3. Grain-row crop rotation, soybean saturation at 40 %, crop alternation: soybean (Zlatoslava variety); winter wheat (Oranta Odessa variety); soybean (Zlatoslava variety); corn for grain (DK Veles hybrid); buckwheat (Yaroslavna variety). 4. Grain-fallow-row crop rotation, saturated with soybean at 20 %, crop alternation: fallow and cultivated fallow; winter wheat (Oranta Odessa variety); soybean (Zlatoslava variety); corn for grain (DK Veles hybrid); sunflower (LG 50510). Peas are sown in the cultivated fallow.

Factor B. Fertilization systems: 1. Without fertilizers; 2. Mineral fertilization system (fertilizer rates calculated according to the fertilization system for each crop and field in the crop rotation); 3. Organic-mineral (mineral fertilizers according to the fertilization system and by-products of the predecessor). The fertilization system was designed so that on average for each crop in the fertilizer treatments, $N_{40}P_{40}K_{40}$ was applied, without violating the recommended fertilizer rates for the research area.

The climatic conditions of the Institute of Agriculture of the Steppe NAAS are typical for the northern Ukrainian Steppe with a moderate continental climate.

The formation of agricultural crop productivity during 2019-2020 occurred under dry conditions. The hydrothermal coefficient from May to September 2019 was 0.67, and in 2020 – 0.75. However, due to very uneven rainfall distribution in the summer months, the hydrothermal coefficient in 2019 fluctuated within 0.26-0.84, and due to a more severe summer drought in 2020 – 0.13-0.52. The average air temperature exceeded the norm by 4.2°, reaching 21.8°C, and the sum of effective air temperatures above +10°C was 1802°C, with a sum of active (above +10°C) temperatures – 3332°C, which is 637°C higher than the norm.

The most favorable weather conditions (by the hydrothermal coefficient) were in 2021. In May and June, GTC was 1.68, in August – 1.18, in September – 1.59. Over the period from May to September, it was 1.37, which is 0.37 higher than normal.

The hydrothermal coefficient for late spring crops in 2022 was 0.84 (normal is 1.0). The weather conditions in 2023 were generally dry and not sufficiently favorable for achieving high yield and productivity

Thus, the weather conditions during the years of research were not sufficiently favorable for achieving high indicators of crop rotation productivity

The presentation of the main material of the research. The results of the five-year study focused on the productivity indicators of crop rotations that were formed in the conditions of 2019. This year was characterized as moderately dry, but due to the uneven distribution of precipitation in the spring and especially in the summer months, spring of late cultures plants had the opportunity to actively use soil moisture and lay the potential for productivity.

The complex of weather-climatic and soil conditions in 2019 leveled the effect of the crop rotation factor over the years of the study. The difference in yield grain units in different crop rotations averaged 0.04-0.64 t/ha, with slightly higher values in the crop rotation with 20 % soybean saturation (Fig. 1).

The fertilization system had a more significant impact on crop rotation productivity in 2019. Moreover, it should be noted that its effectiveness differed in crop rotations depending on their structure. In monoculture and with 60 % soybean saturation, under the mineral fertilization system, the yield of grain units was almost the same, 5.06 t/ha and 5.09 t/ha. Mineral fertilizers most effectively contributed to increasing crop rotation productivity with a 40 % soybean share, +0.71 t/ha (4.78 t/ha) grain units, although the highest indicator was in the crop rotation with 20% crop saturation, 5.31 t/ha, but the yield increment was only 0.46 t/ha.

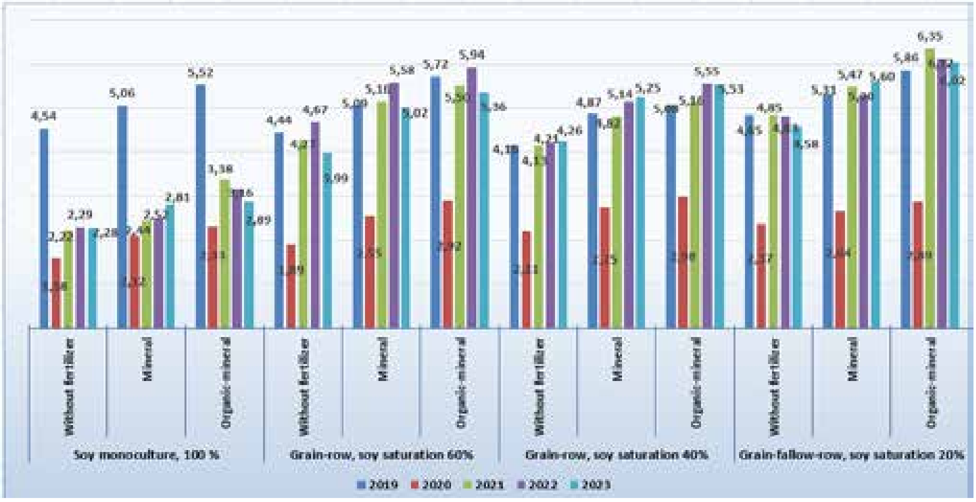

Fig. 1. Yield grain units in different crop rotations over the years of the study, t/ha

The highest grain unit yield in this year was obtained under the organic-mineral fertilization system in all crop rotations we studied. The highest indicator was in the crop rotation with 20 % soybean saturation, 5.86 t/ha. An increase in the soybean share in the crop rotation structure led to a decrease in crop rotation productivity in terms of grain unit yield and the lowest yield was in the crop rotation with 40 % crop saturation, 5.08 t/ha.

The weather conditions in 2020 were most critical, especially for late grain crops. The grain unit yield in crop rotations ranged from 1.50-2.98 t/ha, the lowest over the five years of the study. This year, there was a continuation of trends observed regarding the factors we studied. The crop rotation factor had a smaller impact on productivity compared to the previous year, with a yield increase of 0.02-0.44 t/ha depending on the crop rotation. For soybean cultivation in monoculture, it averaged 2.01 t/ha, while with 60 % saturation – 2.45 t/ha, 40 % – 2.65 t/ha, and 20 % – 2.63 t/ha grain unit. The most significant difference was between the productivity indicators of monoculture and crop rotation with 60 % soybean saturation, 0.44 t/ha, and between crop rotations with 60 %, 40 %, and 20 % saturation – 0.20 t/ha and 0.02 t/ha, respectively.

The highest grain unit yield in crop rotations with different soybean saturation levels was obtained under the organic-mineral fertilization system, 2.33-2.89 t/ha. The yield increment was 0.92-1.28 t/ha.

Under more favorable weather conditions in 2021-2023, the effect of the crop rotation factor increased, and the impact of the fertilization system decreased. There was a very clear trend towards increasing grain yield with a decrease in the soybean share in the crop rotation structure. The most significant difference between these indicators was between monoculture and crop rotation with 60 % soybean saturation, 2.3 t/ha. However, with further decreasing soybean share in the crop rotation, the difference between grain yield indicators became less significant, and the highest productivity was characterized by a crop rotation with 20 % crop saturation, 5.56 t/ha, 5.42 t/ha, and 5.40 t/ha in 2021, 2022, and 2023 respectively.

The yield increment of grain units due to the fertilization system factor was lower than that due to the crop rotation factor, ranging from 0.22-1.50 t/ha. The organic-mineral fertilization system had a more significant impact on crop rotation productivity; increment the yield of grain units was 1.03-1.50 t/ha, and with a decrease in the soybean share in the crop rotation, grain unit yield increased. The highest indicators were obtained in a crop rotation with a 20% crop saturation; 6.35 t/ha, 6.12 t/ha, and 6.02 t/ha in 2021, 2022, and 2023 respectively.

According to the results of five years of research, we observed the same trend in terms of feed unit formation. In 2019, the feed unit yield in soybean monoculture was lower by only 0.50 t/ha (average indicator of crop rotation 5.04 t/ha) compared to crop rotations with less crop saturation (Figure 2).

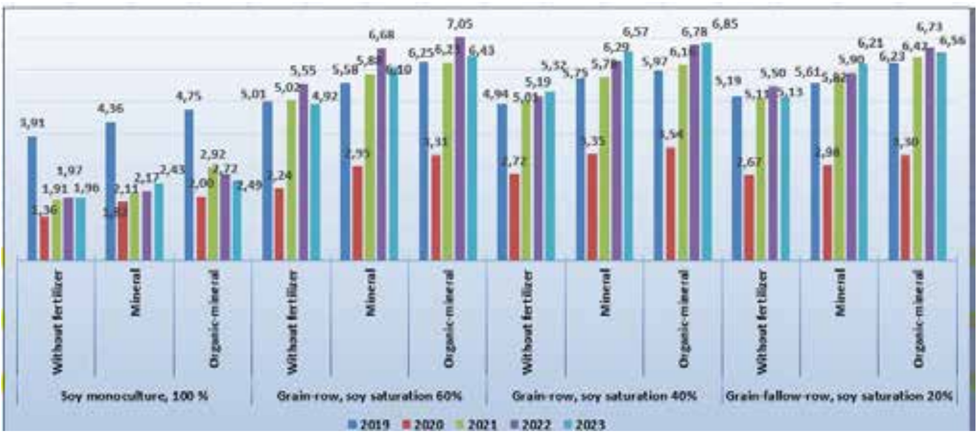

Fig. 2. Feed units yield in different crop rotations over the years of research, t/ha

The difference between the productivity indicators of crop rotations, where soybean made up 60 %, 40 %, and 20 %, was only 0.06-0.13 t/ha. Without fertilization, feed unit yields were 4.54 t/ha, 5.01 t/ha, 5.61 t/ha, and 5.19 t/ha in crop rotations with 100 %, 60 %, 40 %, and 20 % soybean saturation, respectively

In the conditions of 2020, the feed units yield ranged from 1.36 to 3.30 t/ha, the lowest for all years of our research. In this year, the factor that had the greatest influence on feed units yield was the fertilization system. Under the mineral-fertilization system in crop rotations with 100 %, 60 %, 40 %, and 20 % saturation with soy, yields of 2.00 t/ha, 3.31 t/ha, 3.54 t/ha, and 3.30 t/ha were obtained, respectively. The most productive crop rotation was where soybean made up 40 %, but the yield increase due to the fertilization system was highest in the crop rotation with 60 % crop saturation, +1.07 t/ha.

Under the mineral fertilization system, the feed units yield was slightly lower at 1.82 t/ha, 2.95 t/ha, 3.35 t/ha, and 2.98 t/ha in crop rotations with 100 %, 60 %, 40 %, and 20 % soybean saturation, respectively. Due to the crop rotation factor, the most significant difference in feed units yield was between crop rotations with 100 % and 60 % soybean saturation, at 0.66 t/ha. Further reduction in the share of the crop in the crop rotation resulted in changes in this indicator within the range of 0.05-0.48 t/ha.

More favorable conditions for crop vegetation in 2021-2023 increased the impact of the crop rotation factor. The largest difference in feed units yield was also between crop rotations with 100 % and 60 % soybean saturation, at 3.11 t/ha. As the share of soybean in the crop rotation structure decreased to 40 % and 20 %, the increase in crop rotation productivity was within the range of 0.06-0.69 t/ha. The most productive crop rotation in 2021 was with 20 % soybean saturation, yielding 5.11 t/ha; in 2022 – 60 %, yielding 5.55 t/ha; and in 2023 – 40 %, yielding 5.32 t/ha.

Higher feed units yield was obtained under the organo-mineral fertilization system, and in 2021, the highest indicator was in the crop rotation with 20 % soybean saturation (6.42 t/ha), in 2022 – 60 % (7.05 t/ha), and in 2023 – 40 % (6.85 t/ha).

It should be noted that the highest yield digestible protein units over the years of research was obtained in monoculture soybeans in 2019, at 0.85 t/ha. The difference between fertilization systems in this variant was 0.09-0.16 t/ha, with the highest indicator under the organo-mineral system, at 0.93 t/ha. A decrease in the share of soybeans in the crop rotation structure led to a decrease in their productivity, with the lowest yield digestible protein units being in crop rotations with 40 % soybean saturation, at 0.52 t/ha.

The application of mineral fertilizers contributed to an increase in protein yield by 0.09-0.19 t/ha. However, as the share of soybeans decreased in the crop rotation, the productivity of crop rotations also decreased under the influence of mineral fertilizers; in crop rotations with 100 % crop saturation, yield digestible protein units amounted to 0.86 t/ha, while for 60 % it was 0.70 t/ha, for 40 % – 0.61 t/ha, and for 20 % – 0.74 t/ha (Figure 3).

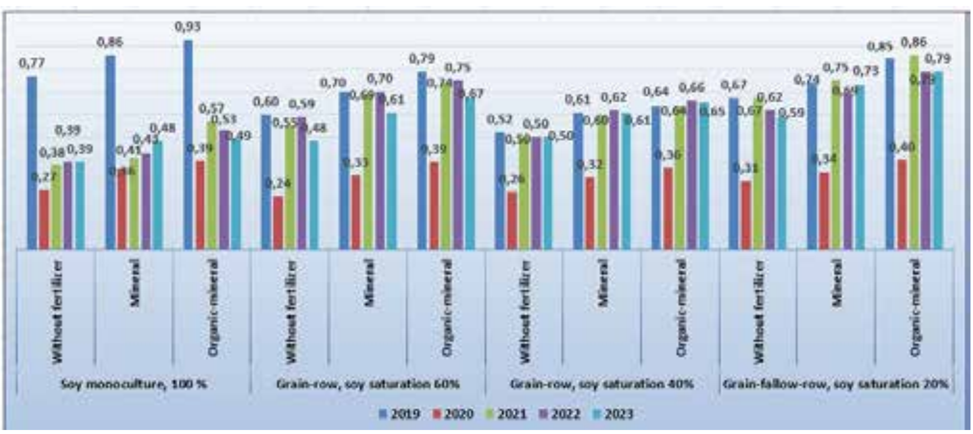

Fig. 3. Yield digestible protein units in different crop rotations over the years of research, t/ha

The highest yield digestible protein units in 2019 was obtained under the organo-mineral fertilization system, at 0.93 t/ha for soybean cultivation in monoculture. In crop rotations where the share of the crop decreased from 60 % to 20 %, the application of mineral fertilizers with organic residues from the previous crop led to a decrease in crop rotation productivity; with 60 % saturation, 0.79 t/ha was obtained, with 40 % – 0.64 t/ha, and with 20 % – 0.85 t/ha of crude protein.

In 2020, the indicators of crop rotation productivity for protein yield were the lowest in the years of research, at 0.27-0.40 t/ha, but crop rotations with 60 % (0.24 t/ha) and 40 % (0.26 t/ha) soybean saturation also yielded less than monoculture soybean, which produced 0.27 t/ha of protein. Only the crop rotation in which soybean occupied one field out of five exceeded other crop rotations in this indicator, at 0.31 t/ha of crude protein.

The use of mineral fertilization systems increased the yield digestible protein units in crop rotations compared to the variant without fertilizers by 0.4-0.9 t/ha, and the least effective mineral fertilizers were used by crops in crop rotation with 20 % soy saturation. However, reducing the share of soybeans in the crop rotations structure neutralized the effect of mineral fertilizers, leading to a decrease in protein yield: 0.36 t/ha was obtained in monoculture, and in crop rotations with 60% saturation – 0.33 t/ha, 40 % – 0.32 t/ha, and 20 % – 0.34 t/ha.

Under the organo-mineral fertilization system, the highest digestible protein yield was obtained, at 0.36-0.40 t/ha, with the highest indicator in a crop rotation with 20 % soybean saturation.

In other years of research, which were wetter with moderate temperatures, there was a tendency towards increased crop rotation productivity in terms of yield digestible protein units with a decrease in the share of soybeans in their structure, and the crop rotation factor was also enhanced.

The highest protein yield without the use of fertilizers was in a crop rotation with 20 % soybean saturation, in 2021 – 0.67 t/ha, 2022 – 0.62 t/ha, and 2023 – 0.59 t/ha. The increase in protein yield due to the crop rotation factor was 0.17-0.29 t/ha.

Under the mineral fertilization system, the increase in crop rotation productivity ranged from 0.03-0.10 t/ha, and in 2022 and 2023, the most productive crop rotations were those with 40 % soybean saturation, yielding 6.78 t/ha and 6.85 t/ha of protein, respectively. In 2021, the highest protein yield was obtained in a crop rotation where soybeans accounted for 60 % of the structure, at 5.88 t/ha.

The highest productivity of the crop rotations we studied in 2021-2023 was under the organo-mineral fertilization system. In 2021, the highest yield digestible protein units was obtained in a crop rotation with 20 % soybean saturation – 0.42 t/ha, in 2022 – 60 %, 7.05 t/ha, and in 2023 – 6.85 t/ha.

On average, over five years of our research, the most significant effect of crop rotation on crop productivity was demonstrated. Although the highest productivity indicators were achieved using the organic-mineral fertilization system, the yield increases in grain units, feed units, and digestible protein were most significant due to the effect of crop rotation.

For example, reducing the proportion of soybeans in the crop rotation structure increased the productivity of the crop rotation in terms of grain unit's yield. If a monoculture yielded 2.58 t/ha, then removing one, two, or three soybean fields from the crop rotation increased this figure to 4.30 tons/ha. The increase grain units was 1.27 t/ha (49.2 %), 1.21 t/ha (46.9 %), and 1.71 t/ha (66.4 %) for soybean saturation of 60 %, 40 %, and 20 %, respectively.

It should be noted that the greatest effect of crop rotation was observed when one field with a 20 % soybean share was used in the crop rotation (Table 1).

Furthermore, a crop rotation with 40 % soybean saturation (3.79 t/ha) slightly lagged behind in grain units yield compared to the crop rotation with 60 % soybean saturation (3.85 t/ha). Despite the insignificant difference, the crop rotation with 60 % soybean saturation was more productive.

The application of mineral fertilizers increased the productivity of crop rotations in terms of grain units yield with the highest yield achieved in the crop rotation with 20 % soybean saturation, at 4.86 t/ha. However, the most effective was the mineral fertilization system in crop rotations with 60 % and 40 % soybean saturation structures, resulting in a yield increase of +0.83 tons/ha (21.5 %) and 0.77 t/ha (20.3 %), respectively, LSD_{05} = 0,30 t/ha.

Table 1

Productivity indicators for grain units yield of different short-rotational crop rotations depending on fertilization systems

Crop rotation, factor A	Fertilizer system, factor B	Average for 2019-2023	Difference factor A		Difference factor B	
			t/ha	%	t/ha	%
Soy monoculture, 100 %	Without fertilizer	2,58	–	–	–	–
	Mineral	2,99	–	–	0,41	15,8
	Organic-mineral	3,46	–	–	0,87	33,8
Grain-row, soy saturation 60%	Without fertilizer	3,85	1,27	49,2	–	–
	Mineral	4,68	1,69	56,6	0,83	21,5
	Organic-mineral	5,09	1,63	47,3	1,24	32,1
Grain-row, soy saturation 40%	Without fertilizer	3,79	1,21	46,9	–	–
	Mineral	4,57	1,58	52,7	0,77	20,3
	Organic-mineral	4,86	1,41	40,7	1,07	28,1
Grain-fallow-row, soy saturation 20%	Without fertilizer	4,30	1,71	66,4	–	–
	Mineral	4,86	1,88	62,7	0,57	13,3
	Organic-mineral	5,45	1,99	57,7	1,15	26,8
LSD_{05}: Factor A = 0,32; Factor B = 0,28; Factors AB = 0,63						

The highest grain units yield collection was obtained by applying mineral fertilizers in combination with the residues of the previous crop, with the highest indicator observed in the crop rotation with 20 % soybean saturation, at 5.45 t/ha. The yield increases due to the action of the organic-mineral fertilization system ranged 0.87-1.24 t/ha (33.8-26.8 %). However, as the proportion of soybeans in the crop rotation structure decreased, the effectiveness of this fertilization system decreased, resulting in the highest yield increase in soybean monoculture, +33.8 %.

Reducing the proportion of soybeans in the crop rotation structure also had a positive effect on yield of feed units. The most significant difference in this indicator was observed between soybean monoculture (2.22 t/ha) and other crop rotations (4.55 t/ha – 60 % soybeans, 4.64 t/ha – 40 % soybeans, 4.72 t/ha – 20 % soybeans) – a difference of 2.33-2.20 t/ha, while among crop rotations with less saturated cultures, the difference was within the significant range – 0.08-0.09 t/ha, LSD_{05} = 0,34 t/ha (Table 2).

The use of mineral fertilization systems increased feed units yield from the crop rotations we studied. The highest indicator was observed in crop rotations with 40 % soybean saturation (5.55 tons/ha) and 60 % (5.44 tons/ha), resulting in a yield increase of 0.91 tons/ha (19.7 %) and 0.89 tons/ha (19.6 %), respectively, without significant differences between the productivity of these crop rotations. The least effective action of the mineral fertilization system was observed in the crop rotation with 20 % soybean saturation, resulting in a +12.4 % yield increase.

The highest feed units yield was obtained by using the organic-mineral fertilization system in all crop rotations. However, it was interesting to note that the productivity of feed units in crop rotations with 60 %, 40 %, and 20 % soybean saturation was the same, at 5.85-5.86 t/ha, which was twice as much as the productivity of soybean monoculture, where 2.98 t/ha were obtained. Nevertheless, despite this fact, the most effective use of organic-mineral fertilization was in soybean monoculture, with a 34.0 % increase in feed unit yield, while in other crop rotations, this indicator was lower at 23.9-28.7 % with a decrease in the proportion of soybeans in the rotation structure.

Table 2

Productivity indicators for feed units yield of different short-rotational crop rotations depending on fertilization systems

Crop rotation, factor A	Fertilizer system, factor B	Average for 2019-2023	Difference factor A		Difference factor B	
			t/ha	%	т/га	t/ha
Soy monoculture, 100 %	Without fertilizer	2,22	–	–	–	–
	Mineral	2,58	–	–	0,36	16,0
	Organic-mineral	2,98	–	–	0,75	34,0
Grain-row, soy saturation 60%	Without fertilizer	4,55	2,33	104,6	–	–
	Mineral	5,44	2,86	110,9	0,89	19,6
	Organic-mineral	5,85	2,88	96,7	1,31	28,7
Grain-row, soy saturation 40%	Without fertilizer	4,64	2,41	108,7	–	–
	Mineral	5,55	2,97	115,2	0,91	19,7
	Organic-mineral	5,86	2,88	96,8	1,22	26,4
Grain-fallow-row, soy saturation 20%	Without fertilizer	4,72	2,50	112,4	–	–
	Mineral	5,30	2,72	105,7	0,58	12,4
	Organic-mineral	5,85	2,87	96,4	1,13	23,9
LSD_{05}: Factor A = 0,34; Factor B = 0,30; Factors AB = 0,68						

There was no significant difference found in yield digestible protein digestible protein between soybean monoculture (0.44 t/ha) and crop rotations with 40 % soybean saturation (0.46 t/ha), and rotations with 60 % (0.49 t/ha) and 40 % (0.46 t/ha). The highest yield and increase digestible protein were obtained in the crop rotation with 20 % soybean saturation, at 0.57 t/ha (Table 3).

The application of mineral fertilizers to crop rotations increased their productivity, with the highest yield digestible protein observed in the crop rotation with 20 % soybean saturation, at 0.65 t/ha. However, the most effective action of fertilizers was observed in the crop rotation with 60 % soybean saturation, resulting in a yield increase of 0.12 t/ha (19.36 t/ha) for protein. Growing soybeans in monoculture through the application of mineral fertilizers resulted in a protein yield of 0.51 t/ha, an increase of 0.07 t/ha compared to the variant without fertilizer application.

The organic-mineral fertilization system provided the highest yield digestible protein in our studies. Using organic fertilizers together with the nutrient residues, soybean monoculture and crop rotation with 40 % crop saturation formed an equal protein yield of 0.58 t/ha and 0.59 t/ha, with no significant difference found. A higher figure was obtained in the crop rotation where one field was occupied by soybeans, at 0.74 t/ha. However, this fertilization system was most effective in the crop rotation with 60 % soybean saturation, resulting in an increase of 0.18 t/ha protein (26.9 %).

Table 3

Productivity indicators for yield digestible protein of different short-rotational crop rotations depending on fertilization systems

Crop rotation, factor A	Fertilizer system, factor B	Average for 2019-2023	Difference factor A		Difference factor B	
			t/ha	%	т/га	t/ha
Soy monoculture, 100 %	Without fertilizer	0,44	–	–	–	–
	Mineral	0,51	–	–	0,07	13,7
	Organic-mineral	0,58	–	–	0,14	24,1
Grain-row, soy saturation 60%	Without fertilizer	0,49	0,05	10,2	–	–
	Mineral	0,61	0,10	16,4	0,12	19,7
	Organic-mineral	0,67	0,09	13,4	0,18	26,9
Grain-row, soy saturation 40%	Without fertilizer	0,46	0,02	4,4	–	–
	Mineral	0,55	0,04	7,3	0,09	16,4
	Organic-mineral	0,59	0,01	1,7	0,13	22,0
Grain-fallow-row, soy saturation 20%	Without fertilizer	0,57	0,13	22,8	–	–
	Mineral	0,65	0,14	21,5	0,08	12,3
	Organic-mineral	0,74	0,16	21,6	0,17	23,0
LSD_{05}: Factor A = 0,04; Factor B = 0,04; Factors AB = 0,09						

Conclusions. Thus, under dry vegetation conditions, especially for late-repining crops, the fertilization system had the most significant impact on crop rotation productivity. The most significant increases in grain units, fed units, and digestible protein were observed using the organic-mineral fertilization system.

Higher rainfall and moderate air temperatures neutralized the effect of fertilizers and increased the influence of the crop rotation factor on productivity.

Among the studied crop rotation models, the highest productivity for grain units (5.45 tons/ha), feed units (5.85 tons/ha), and digestible protein (0.74 tons/ha) was observed in the variant using the organic-mineral fertilization system in a grain-fallow-row crop rotation with up to 20 % soybean saturation.

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