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*ORIGINAL ARTICLE*

# Ecological and economic indicators of short crop rotations on drained soils in the conditions of climate change

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**Aim:** To establish the influence of a complex of factors on productivity of short crop rotations with the cultivation of commercially attractive crops, the reproduction of soil fertility is based on optimized agrochemical supply by replacing litter manure with by-products in the conditions of low moisture supply drained sod-podzolic soils. **Methods:** Field, statistical, laboratory methods. **Results.** We found that the productivity of crop rotations depends on their saturation with corn, which, on average, in 2016–2020, at the recommended ($N_{60}P_{60}K_{60}$) and increased rates of mineral fertilizers ($N_{90}P_{90}K_{90}$) on the background of manure or by-products of precedents, had a grain yield levels of 6.04–7.66 t/ha. The highest yield of grain from 1 ha of crop rotation area was obtained in the three-field crop rotation (soybean–corn–corn) from 66.6% of corn–from 3.14 tons for control, to 6.05 tons–at high rates of mineral fertilizers ($N_{62}P_{86}K_{90}$+by-product). Productivity of three-field (field pea-oats–winter triticale–corn) and four-field (lupine–winter rape–winter rye–corn) crop rotations with a share of corn of 33.3% and 25%, ranged from 2.43 tons to 4.52 tons of grain, respectively. Crop rotation without corn (soybeans–winter wheat–sunflower–buckwheat) had overall productivity of 50% less. **Conclusions:** Combining the recommended $N_{42}P_{57}K_{60}$ and the increased $N_{62}P_{86}K_{90}$ norm of mineral fertilizers with by-products in all crop rotations promotes the formation of expanded reproduction of humus in the soil. Deficient nitrogen balance was manifested only with the introduction of $N_{42}P_{57}K_{60}$ against the background of 10 tons of manure per 1 ha of crop rotation area. The most effective in all crop rotations is the organo-mineral fertilizer system $N_{42}P_{57}K_{60}$ on the background of by-products, which provided a 27.9–36.5% profitability level. Each crop rotation is dynamic and can be recommended for production, depending on the farm's market conditions and economic capacity. As for the choice of feed system with mineral fertilizers, each in itself may be acceptable. In the absence of livestock farms, an alternative to manure is using by-products of all crops, which does not reduce crop productivity, profitability and increases soil fertility.

**Keywords:** Sod-podzolic soil, moisture supply, crop rotations, market crops, fertilizer system, soil fertility, profitability.

## Introduction

At the present stage of agricultural production in Ukraine, radical social and economic transformations have taken place, market production relations have been formed, which are based on commodity-money circulation to obtain maximum profit, without considering environmentally friendly principles of land use. Large investment companies have switched to a chemical-intensive system of agricultural intensification, imposing the belief that the use of crop rotations is inherent only in the extensive management of agriculture. This approach meets market conditions rather than the scientific and environmental justification of land use. The consequences of these transformations have led to disturbances in the ecological balance in the natural environment (Kaminskyi, 2015). At the same time, there is also neglect of the introduction of scientifically sound crop rotations in agricultural production. The negative effect of non-compliance with crop rotation is proven. In particular, there is an accumulation of toxic substances in the soil, which causes the manifestation of allelopathy, which is one of the reasons for the need for proper crop rotation (Boiko et al., 2018; Acharya et al., 2020). Ignoring the principles of crop rotation leads to reduced yields and deterioration of product quality, unproductive use of land, and other means of production. Repeated and unchanging crops develop plant-specific and harmful fungal microflora, bacteria, pests, specific weeds, which reduces arable land productivity and soil fertility (Yeshchenko, 2015; Ojiambo et al., 2017). Decreased soil fertility in monoculture is associated with the release into the soil of specific plant species growth inhibitors. This is due to "soil fatigue", which is not observed in natural biogeocenoses (Boiko and Kovalenko, 2003). According to FAO estimates, the "soil fatigue" currently covers about 1,250 million hectares of agricultural land and remains the leading cause of almost 25% of the world's harvest losses. In the European Union, 100% of cultivated land is used in crop rotations, and in the United States–85% (Reddy, 2017; HE DC et al., 2016; Li et al., 2018). Adherence to scientifically sound crop rotations is essential for efficient agricultural production, ensuring the rational use and protection of land, creating a favorable ecological environment in agricultural landscapes. In modern agriculture, crop rotations are the basis of the high productivity of crops, as they provide an average of 20–30% more yields than permanent crops (Kaminskyi et al., 2015).

The determining factor in agriculture in modern conditions is climate change, which is already an objective reality all around the world and, together with the anthropogenic load on agricultural land, poses a significant threat to soils, which negatively affects the productivity of the agroecosystems (Dubey et al., 2019; Savchuk, Olympics, 2018). In climate change, the limiting factor that determines the productivity of the crop is their moisture supply (Nash et al., 2015; Awale et al., 2015). This is especially true of drained soils, their degree of gleying, and particle size distribution. In particular, in the Polissia area in recent years, the climate has changed from excellent with increased rainfall to warmer and drier ones (Tarariko et al., 2016) that allowed to grow highly productive, not typical for the zone, heat-loving commercially attractive crops: corn for grain, soybeans, winter rape, sunflower, winter wheat. To realize the biological potential of modern hybrids, varieties of these crops are possible only with an optimized fertilizer system in dynamic crop rotations.

In general, farms have switched to short crop rotations, mainly with narrow specialization in the cultivation of cereals and oilseeds (Savchuk et al., 2020). Technologies for growing these crops require improvement and development of short dynamic crop rotations to adapt to regional sod-podzolic soils. It is crucial to put crops in crop rotations, which would increase their productivity, stabilize soil fertility, disturb the ecology of the environment, and meet market needs (Haruna and Nkongolo, 2019; Savchuk et al., 2005). In the absence of livestock farms, to address nitrogen deficiency in sod-podzolic soils, it is necessary to saturate crop rotations with legumes, using their by-products as organic fertilizers and sow green manure (Hiel et al., 2018). In addition to the traditional field peas and lupines for the Polissia region, soybeans are currently one of the main legumes, a good precedent, and producer of the cheapest vegetable protein (Melnychuk et al., 2018). Corn for grain in Polissia has become the main fodder and energy crop, with high yield potential. Expansion of its areas in crop rotations makes it possible to increase grain production without significantly reducing the yield of other cereals (Artemenko, 2017). To obtain a high yield of corn, the composition of the precedents is also essential. The best precedents for it (in short crop rotations) are legumes, especially soybeans; the satisfactory ones are early spring cereals and corn. Maize tolerates repeated crops satisfactorily for 3–4 years. In the structure of crops, corn for grain should occupy at least 20–25% of the total sown area. The share of corn in the grain group can increase up to 40–50%. The level of saturation of short crop rotations with grain crops is significant (33–66% – cereals and 25–50 – legumes), which makes it possible to widely implement such crop rotations with the appropriate set of crops. Winter rape is an economically attractive crop in Polissia, but its cultivation is risky due to the freezing of crops, so large arrays of rape in the structure of sown areas are impractical (Rudyk et al., 2015).

Thus, it is essential to study the productivity of short crop rotations with different proportions of corn and other commercially attractive crops, ensuring the preservation of fertility of sod-podzolic soil, stable yields, and profitability of growing crops under different fertilization systems.

## Materials and Methods

The research was conducted at the Institute for Agriculture of Polissia NAAS (Hrozyne village, Korosten district, Zhytomyr region) during 2016–2020 on pottery-podzolic sandy soil drained pottery drainage with unilateral regulation of water-air regime. Agrochemical parameters of soil are humus content–1.27%, total nitrogen–0.063%, mobile phosphorus–84, metabolic potassium–101 mg/kg soil, $pH_{salt}$–5.0, hydrolytic acidity–2.25 mg.-equivalent per 100 g of soil.

The scheme of the experiment is developed in 14 fields, which includes four crop rotations–two three-field and two four-field rotations with a share of corn 33.3; 66.6 and 25% and with its absence. The sown area is 48 $m^2$, the accounting area is 28 $m^2$. Repetition is three times. The primary method of tillage is plowing.

The fertilizer system provides: control (without fertilizers); by-products; recommended fertilizer rate per 1 ha of crop rotation area ($N_{42}P_{57}K_{60}$+10 tons of manure); alternative ($N_{42}P_{57}K_{60}$+by-products); increased 1.5 times ($N_{62}P_{86}K_{90}$+by-products). The recommended for the zone and 1.5 times higher rates of mineral fertilizers were used for crops: winter cereals and corn–$N_{60}P_{60}K_{60}$ and $N_{90}P_{90}K_{90}$; winter rape–$N_{60}P_{60}K_{80}$ and $N_{90}P_{90}K_{120}$; field pea-oat–$P_{45}K_{60}$ and $P_{70}K_{90}$; lupines–$P_{45}K_{45}$ and $P_{70}K_{70}$; soybeans–$P_{60}K_{60}$ and $P_{90}K_{90}$; sunflower–$N_{60}P_{60}K_{90}$, $N_{90}P_{90}K_{135}$, buckwheat–$N_{45}P_{45}K_{45}$ and $N_{70}P_{70}K_{70}$, respectively. Litter manure was applied in one crop rotation field (corn and sunflower) at 30 t/ha in three-field and 40 t/ha in four-field crop rotation, at the rate of 10 tons per 1 ha of the crop rotation area.

Soil moisture reserves were determined each year of research monthly during the growing season by the thermostatic-weight method. In the plant samples, it was determined the following: dry matter content by thermostatic-weight method; in soil samples: humus–according to Tyurin's method (State Standard of Ukraine 4289: 2004); soil pH–by the method of direct potentiometry using ion-selective electrodes according to the method of CINAO (State Standard of Ukraine 26483-85); easily hydrolyzed nitrogen by Cornfield's method; phosphorus and potassium–according to Kirsanov's method (State Standard of Ukraine 4405-2005); hydrolytic acidity – (State Standard of Ukraine 26212-91); the number of absorbent bases – by Kappen's method (State Standard of Ukraine

27821-88). According to the "Method of analysis of variance" (Dospehov, 1985) and Statistica software, generalization of materials and analysis of research results were performed. Varieties of crops grown in crop rotations are winter wheat–Myronivska yuvileina, winter rye–Final, winter triticale–Amur, soybean–Vorskla, sunflower–Yason, corn–Garant, buckwheat–Gloriya, lupine–Peremozhets, field pea–Zvyagilska.

## Results and Discussion

One of the essential conditions that ensure stable yields of crops is the optimal provision of soil moisture during the growing season (Romashchenko and Tarariko, 2017). Observations of the dynamics of soil moisture showed an increase in moisture deficit by early summer. If at the beginning of spring fieldwork the moisture reserves in the 1-meter layer of soil were 120–200 mm, then in the summer, they decreased to 60–80 mm, i.e., to the critical level (Fig. 1).

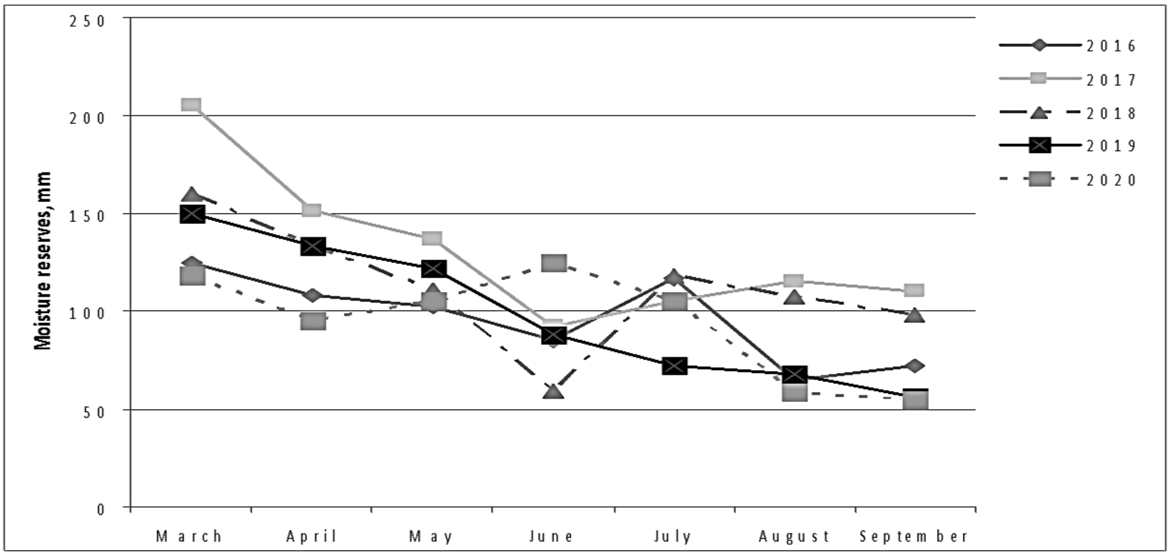


**Fig. 1**. Moisture reserves in sod-podzolic soil (0–100 cm layer) during the vegetation period of 2016–2020.

According to Alpatyev A.M. (1954, 1966), if on sod-podzolic soils in a 1-meter layer the reserves of productive moisture are less than 60 mm, this condition is critical. At the same time, the decrease in precipitation against the background of high air temperature led to a decrease in the groundwater level to 2.0–3.0 m (depth of drainage was 1.1 m).

Soil and air drought and frequent differences in night and day temperatures that occurred each year during the growing season significantly negatively affected the growth, development, and yield of traditional Polissia crops, particularly legumes, field pea, and lupines. The yield of these crops on fertilized backgrounds ranged from 1.4 to 2.2 t/ha. Adverse weather conditions were also for soybeans and buckwheat, which affected the productivity of their seeds.

Winter cereals suffered less from summer drought due to spring moisture; they managed to form a relatively high grain yield. The exception was 2020, when the plants came out of hibernation in a weak state during the snowless winter and dry spring, but the rains that passed in the second half of April somewhat improved their situation. Grains were placed in crop rotations after leguminous precedents, the by-products of which, as organic fertilizers, contributed to grain growth, on average over the years of research, by 12.9–15.9% compared to the control variant. The highest yield of winter cereals was observed on an elevated background ($N_{90}P_{90}K_{90}$) in combination with by-products, for which, on average, over the years of research, the grain yield was 4.02–4.23 t/ha (Table 1).

| **Crop Rotation** | **Rotation Crop** | **Fertilizer system (per 1 ha of crop rotation area)** | | | | | **HIP$_{05}$** |
|---|---|---|---|---|---|---|---|
| | | **Without Fertilizers** | **By-products** | **Litter Manure 10 t+$N_{42}P_{57}K_{60}$** | **By-products+$N_{42}P_{57}K_{60}$** | **By-products+$N_{62}P_{86}K_{90}$** | |
| | 1. Field pea-oat | 1.61 | 1.74 | 2.03 | 2.04 | 2.20 | 0.16 |
| I | 2. Winter triticale | 2.32 | 2.69 | 3.72 | 3.71 | 4.23 | 0.27 |
| | 3. Corn | 3.36 | 4.03 | 7.23 | 6.14 | 7.12 | 0.61 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Harvesting of grain, t/ha of crop rotation area | **2.43** | **2.82** | **4.32** | **3.96** | **4.52** | |
| II | 1. Soybean | 1.18 | 1.25 | 1.42 | 1.44 | 1.64 | 0.13 |
| | 2. Corn | 3.74 | 4.51 | 7.67 | 6.58 | 7.66 | 0.54 |
| | 3. Corn | 3.56 | 4.33 | 6.98 | 6.24 | 7.22 | 0.51 |
| | Harvesting of grain, t/ha of crop rotation area | **3.14** | **3.78** | **5.86** | **5.23** | **6.05** | |
| III | 1. Lupine | 1.09 | 1.15 | 1.26 | 1.36 | 1.42 | 0.14 |
| | 2. Winter rape | 1.41 | 1.53 | 1.69 | 1.64 | 1.92 | 0.13 |
| | 3. Winter wheat | 2.47 | 2.79 | 3.75 | 3.69 | 4.06 | 0.29 |
| | 4. Corn | 3.46 | 4.13 | 7.13 | 6.04 | 7.12 | 0.49 |
| | Harvesting of grain, t/ha of crop rotation area | **2.57** | **2.9** | **4.0** | **3.73** | **4.23** | |
| IV | 1. Soybean | 1.20 | 1.35 | 1.48 | 1.48 | 1.60 | 0.11 |
| | 2. Winter wheat | 2.44 | 2.82 | 3.53 | 3.7 | 4.02 | 0.25 |
| | 3. Sunflower | 1.50 | 1.75 | 2.30 | 2.23 | 2.40 | 0.20 |
| | 4. Buckwheat | 1.19 | 1.22 | 1.54 | 1.45 | 1.61 | 0.10 |
| | Harvesting of grain, t/ha of crop rotation area | **2.11** | **2.33** | **2.98** | **2.92** | **3.20** | |

**Table 1.** Influence of sown area structure and fertilizer system on crop productivity (t/ha) and crop rotations (tons of grain units per 1 ha of crop rotation area), the average for 2016–2020.

Corn reacted the least to moisture deficiency. On average, over five years of research, the grain yield of corn ranged from 3.36 t/ha on absolute control to 7.67 t/ha with 40 t/ha and the recommended rate of mineral fertilizers $N_{60}P_{60}K_{60}$. Grain yield was stable, except for 2018, when the soil-air drought before the ejection of the panicle harmed the development of generative organs, which led to a decrease in grain productivity by 25–38%. The combination of 30–40 t/ha of manure with $N_{60}P_{60}K_{60}$ showed a significant advantage over by-products+$N_{60}P_{60}K_{60}$–by 11.8–18.0%. The increased rate of $N_{90}P_{90}K_{90}$ fertilizers compatible with straw and the recommended $N_{60}P_{60}K_{60}$ on the background of manure, on the impact on the yield of corn, were equivalent (the increase was within the error of the experiment). In addition, it should be noted that corn after soybean in the first field (crop rotation 2) had a grain yield of 5.0–9.8% higher than in re-sowing.

Sunflower also reacted little to drought during the growing season. During all years of research, seed yield was almost stable: from 1.32–1.65 t/ha in control to 2.12–2.72 t/ha with an increased dose of mineral fertilizers combined with the by-products of the forecrop. Using the recommended fertilizer rate ($N_{60}P_{60}K_{90}$) combined with winter wheat straw, 2.1 t/ha of seeds were obtained. A significant increase in productivity was observed by introducing $N_{60}P_{60}K_{90}$ with 40 t/ha of manure–2.3 t/ha. That is, the efficiency of manure had an advantage over by-products. The increased rate of $N_{90}P_{90}K_{135}$ fertilizers compatible with straw and the recommended $N_{60}P_{60}K_{90}$ with manure, in terms of impact on seed yield, were equivalent (increase within the error of the experiment). During the 2016–2020 studies, winter oilseed rape was absent in crop rotation in 2017 and 2020. The reason was the lack of moisture in the autumn of 2016 and 2019 when due to prolonged drought received liquid rapeseed seedlings, the plants could not form sufficient vegetative mass and thickness of the root collar, so the crops could not withstand overwintering, and the field was replanted with spring oilseed radish. During the remaining three years, rapeseed crops overwintered satisfactorily, yielding an average of 1.41–1.92 t/ha of seeds. Oil radish, sown for two years instead of winter rape, had a reasonably high seed yield (up to 2.4 t/ha), which indicates that this crop is adapted to changing weather conditions in the Polissia zone.

The results of the obtained research showed that the total productivity of crop rotations depended on the share of corn as the most productive crop, which affected the final yield. The highest yield of grain from 1 ha of crop rotation area was obtained in the three-field crop rotation with 66.6% of corn–from 3.14 tons in control to 6.05 tons–at 1.5 times higher than the rate of mineral fertilizers ($N_{62}P_{86}K_{90}$). On the biological variant (by-products) 3.78 tons of grain were obtained, which is 20.4% more than the control variant. With the introduction of the recommended norm $N_{60}P_{60}K_{60}$ under the crop with 10 tons of manure (per 1 ha of arable land), crop rotation productivity increased by 10% compared to the introduction of $N_{60}P_{60}K_{60}$ into the soil and by-products.

Productivity of three-field and four-field crop rotations with one field of corn (33% and 25%, respectively) was close: from 2.43 and 2.57 on control to 4.52 and 4.23 tons of grain on an elevated background. With the obtained yields, the total productivity of crop rotation without corn with a share of winter wheat and sunflower of 25% was relatively low. The largest harvest was observed on an elevated background ($N_{62}P_{84}K_{96}$+by-products)–3.20 tons of grain, which is 7.4% more than with 10 tons of manure+$N_{41}P_{56}K_{64}$. The total productivity of this crop rotation is, on average, 50% less than other crop rotations with corn. In addition, the low yield of this crop rotation was influenced by the low yield of soybean seeds.

Analysis of crop rotation productivity showed the priority of corn as the most productive grain crop on sod-podzolic soils of Polissia. Thus, the total productivity of all crop rotations when applying the recommended rates of mineral fertilizers ($N_{41}P_{56}K_{64}$) under the condition of replacing manure with by-products decreased by 6–10%. With a 1.5-fold increase in the rate of mineral fertilizers ($N_{62}P_{84}K_{96}$) in combination with by-products, the yield of grain per 1 ha of crop rotation area increased by 5–7%, compared with the application of manure on the background of $N_{41}P_{56}K_{64}$. An alternative to manure is by-products–subject to a 50% increase in the rate of mineral fertilizers.

Along with optimizing the nutrient regime, one of the most important soil protection functions of crop rotation and conditions of its consistently high productivity is creating a deficit-free balance of humus and nutrients (Şeker et al., 2017; Raphael et al., 2016). Therefore, one of our research tasks was to study the conditions for maintaining soil fertility by replacing manure with local organic materials in combination with moderate doses of mineral fertilizers. The accumulation of humus depends on the set of crops in crop rotation and their characteristics to accumulate minor and root mass, resulting from transformation into organic matter. According to Lykov A. M. (Lykov, 1979), the positive balance of humus should be at the level of 300–800 kg/ha. This increase provides enhanced reproduction and increased soil fertility.

Our analysis of the humus balance showed that there is a sharp decrease in soil fertility in all crop rotations on an unfertilized background: humus losses are 430–630 kg/ha per year (Fig. 2). Plowing of all by-products contributed to a deficit-free balance of humus at the level of 20–90 kg/ha, with a combination of 10 tons of manure and the recommended rate of $N_{42}P_{57}K_{60}$ mineral fertilizers (per 1 ha of crop rotation area) there was an accumulation of humus at 50–100 kg, a significant increase in humus (220 kg/ha) on this variant is noted in the first crop rotation (field pea–triticale–corn). Replacement of litter manure with alternative sources of local organic matter (by-products of cereals, legumes, and oilseeds), with the introduction of $N_{42}P_{57}K_{60}$ per hectare of crop rotation area, contributed to the more active synthesis of humus in the soil–310–480 kg/ha. The increased rate of $N_{62}P_{86}K_{90}$ increased the yield of biomass and the inflow of organic plant residues into the soil; respectively, the annual accumulation of humus increased to 350–630 kg, which provided expanded reproduction and increased soil fertility.

Most of the organic matter is synthesized in crop rotations, in the structure of which corn occupies 33 and 66%, and the fertilizer system, which provides for the use of by-products against the background of the recommended and increased rates of mineral fertilizers.

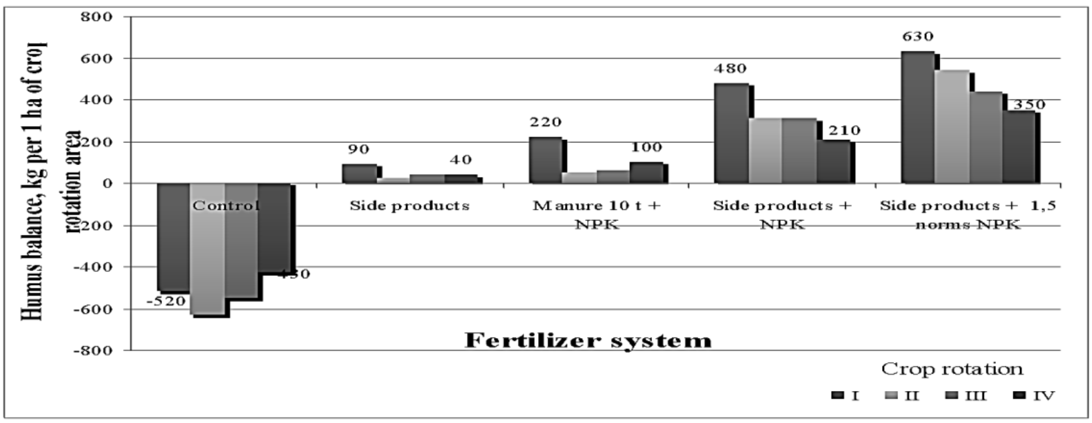


**Fig. 2.** Humus balance in short crop rotations for different fertilizer systems, kg per 1 ha of crop rotation area (average for 2016–2020).

We evaluated the effect of crop rotation factor and fertilizer system on the balance of the essential nutrients–nitrogen, phosphorus, and potassium. However, the amount of nutrients carried out by the harvest characterizes its economic removal, which in all cases is less than biological. This is because part of the nutrients contained in the root-post-harvest residues are not considered in determining the economic removal, as it remains in the soil as part of the specified organic mass. We calculated the economic balance of nitrogen exclusively, i.e., the balance in the plant-fertilizer system, taking into account the nitrogen fixation coefficients of legumes and not considering changes in total nitrogen content in the soil, which is determined in a long cycle of observations.

In addition to alienation with crops, gaseous losses of nitrogen from mineral and organic fertilizers, leaching outside the soil profile by downstream water flows were considered. The revenue part included revenues from organic and mineral fertilizers, biological nitrogen recorded by legumes from the atmosphere, and revenues from precipitation and seeds. According to the literature, to create an active-positive balance of nutrients and significantly increase the fertility of sod-podzolic soils of Polissia, it is necessary to return to the soil concerning the total costs: nitrogen–105-110%, phosphorus–200-260%, potassium–120–150% (Lykov, 1979). As a result, almost all variants had a negative nitrogen balance: in control, it was 48–75 kg (Table 2).

| S.No of Crop Rotation | Fertilizer system (per 1 ha of crop rotation area) | | | | |
|---|---|---|---|---|---|
| | **Control** | **By-products*** | **$N_{42}P_{57}K_{60}$+litter manure 10 t** | **$N_{42}P_{57}K_{60}$+by-products** | **$N_{62}P_{86}K_{90}$+by-products** |
| | nitrogen balance | | | | |
| I | -50 | -13 | 10 | -3 | 0 |
| II | -75 | -39 | 4 | -30 | -25 |
| III | -50 | -23 | 16 | -2 | 0 |
| IV | -48 | -28 | 27 | -7 | 6 |
| | phosphorus balance | | | | |
| I | -20 | -15 | 51 | 33 | 58 |
| II | -27 | -27 | 47 | 27 | 31 |
| III | -20 | -18 | 53 | 32 | 57 |
| IV | -20 | -16 | 56 | 36 | 72 |
| | potassium balance | | | | |
| I | -53 | -1 | 95 | 46 | 74 |
| II | -82 | -20 | 80 | 32 | 58 |
| III | -66 | -12 | 88 | 37 | 67 |
| IV | -58 | -11 | 97 | 47 | 75 |

**Note:** *in the first and third crop rotations with by-products, Serradella green manure was used.

**Table 2.** Influence of fertilizer system on the balance of nutrients in crop rotations, kg per 1 ha of crop rotation area (average for 2016–2020).

In the variants with by-products, the deficit is twice smaller. A positive balance was observed with the introduction of $N_{42}P_{57}K_{60}$ with 10 tons of manure–the annual surplus is 4–27 kg per 1 ha of arable land with a balanced intensity of 102–122%, which is close to the norm. The structure of sown areas and crop rotation schemes are based on two main principles–the nature of the soil cover and the availability of livestock in farms. In the absence of livestock on the farm, manure deficiency encourages crop rotation to ensure a positive balance of humus–it is mandatory to use a straw and intermediate crops as fertilizer. The structure of sown areas and crop rotation schemes are based on two main principles–the nature of the soil cover and the availability of livestock in farms. By the absence of livestock on the farm, manure deficiency encourages crop rotation to ensure a positive balance of humus–it is mandatory to use a straw and intermediate crops as fertilizer.

The supply of nitrogen with straw with the recommended NPK rate did not compensate for its removal with the harvest of the main product. In the first and third crop rotations with by-products and the recommended rate of mineral fertilizers, green manure was used, which was sown in early spring in winter rye and triticale crops. The yield of green mass, on average, was at the level of 8.0 t/ha, which contributed to an additional yield of 37–39 kg/ha of biological nitrogen. The use of green manure contributed to the establishment of a deficit-free nitrogen balance (-2 and -3 kg/ha can be considered balanced). The 1.5-fold increase in the rate of mineral fertilizers combined with straw ensured a deficit-free balance under crops, except for crop rotation 2 (from 66% of corn), which had an annual nitrogen deficit of 25 kg.

As for phosphorus and potassium, their deficiency was 20–27 and 53–82 kg, respectively. The use of by-products did not compensate for their removal. A positive balance of these elements is noted on all mineral backgrounds. Mineral fertilizers, manure, and by-products fully compensate for removing phosphorus and potassium from the crop. Under these conditions, the intensity of the phosphorus balance is 195–254%, which is within the established norm. As for potassium, in the variant with manure, the revenue exceeds its consumption by 80–97 kg per 1 ha of crop rotation area. Increased intensity (more than 190%) indicates an imbalance of this element with nitrogen and phosphorus. Therefore, it is possible to recommend reducing the dose of potassium for production conditions, provided the use of traditional organic fertilizers.

The conducted comparative assessment of crop rotations requires additional economic justification of the decisions made. In general, it can be argued that economic analysis determines relatively net income, the level of profitability of products separately for each crop, and crop rotations. However, such an analysis is significantly determined by time limits, as it requires annual accounting of prices for fertilizers, seeds, pesticides, and fuels due to their instability. The level of economic activity of growing crops is the main criterion for the effectiveness of research. We calculated economic efficiency to determine the most optimal fertilizer system for crops and crop rotations in general in terms of economic feasibility. According to the price situation for seeds, fuel, fertilizers, these indicators were determined in October 2020. The performed calculations of economic evaluation of short crop rotations show that significant differences between indicators of economic efficiency are not observed (Table 3).

| **Indicator** | **Fertilizer system (per 1 ha of crop rotation area)** | | | | |
|---|---|---|---|---|---|
| | **Control** | **By-products** | **$N_{42}P_{57}K_{60}$+litter manure 10 t** | **$N_{42}P_{57}K_{60}$+by-products** | **$N_{62}P_{86}K_{90}$+by-products** |
| Crop rotation I: field pea-oat–winter triticale–corn | | | | | |
| Costs, UAH | 9552 | 9495 | 15289 | 14002 | 15951 |
| Conditionally net profit, UAH | 2254 | 4016 | 4260 | 4221 | 4684 |
| Profitability, % | 23.6 | 42.3 | 27.9 | 30.1 | 29.4 |
| Crop rotation II: soybean–corn–corn | | | | | |
| Costs, UAH | 9570 | 9686 | 16367 | 14851 | 16767 |
| Conditionally net profit, UAH | 2091 | 3832 | 4160 | 4137 | 4950 |
| Profitability, % | 21.9 | 39.6 | 25.4 | 27.9 | 29.8 |
| Crop rotation III: lupine–winter rape–winter rye–corn | | | | | |
| Costs, UAH | 8255 | 8150 | 13780 | 12871 | 14682 |
| Conditionally net profit, UAH | 3798 | 5316 | 4231 | 4223 | 4554 |
| Profitability, % | 46.0 | 65.2 | 30.7 | 32.8 | 31.0 |
| Crop rotation IV: soybean–winter wheat–sunflower–buckwheat | | | | | |
| Costs, UAH | 7972 | 7744 | 13221 | 12383 | 10792 |
| Conditionally net profit, UAH | 4540 | 5916 | 3792 | 4526 | 3344 |
| Profitability, % | 57.0 | 76.4 | 28.7 | 36.5 | 31.0 |

**Table 3.** Economic efficiency of crop rotations per 1 ha of crop rotation area.

The costs incurred for growing crops in three-field crop rotations with 33.3 and 66.6% saturation with corn are almost the same: in the control version, they amount to 9.5 thousand UAH to use mineral fertilizers–14.0–16.7 thousand UAH per 1 ha of crop rotation area. The most significant expenditures were noted in option 2 using 10 tons of litter manure (in combination with the recommended NRC)–15.3–16.4 thousand UAH and with the increased rates of mineral fertilizers in combination with by-products–15.9–16.8 thousand UAH. The latter received the largest relatively net profit–4.6–4.9 thousand UAH.

In four-field crop rotations, costs are reduced by 10–15%, and the most considerable profit is obtained on the biological option–provided that the straw is wrapped without mineral fertilizers: 5.3 thousand UAH with crop rotation saturation of 25% corn and 5.9 thousand UAH in crop rotation with 25% sunflower.

Based on these indicators, in four-field crop rotations at lower costs, respectively, there is a higher level of profitability. When using the recommended and increased NRC rate in combination with by-products, the level of profitability is 27.9–36.5%, the highest in the fourth crop rotation with sunflower. All these crop rotations have the highest profitability in the biological variant, 42.3%, 39.6, 65.2% and 76.4%, respectively. When using mineral fertilizers, this figure is reduced to 27.9–36.5%. The increase in crop yields does not recoup the costs incurred for the purchase and application of mineral fertilizers. When applying the recommended and increased rate of mineral fertilizers under soybeans and the yield obtained at the level of 1.4 and 1.6 t/ha, respectively, its cultivation is unprofitable. Therefore, in the second and fourth crop rotations with soybeans, total profits are reduced.

It should be noted that the use of litter manure in the amount of 10 tons per 1 ha of crop rotation area gives a profit of 3.8–4.2 thousand UAH if there is livestock on the farm. If organic fertilizers are purchased from other farms, it was evident that growing crops will be unprofitable if they are applied.

The analysis results (Table 4) allow for an objective assessment of these crop rotations, and if necessary, to determine one of them according to specific criteria.

| **Indicator** | **Fertilizer System (per 1 ha of crop rotation area)** | | | | |
|---|---|---|---|---|---|
| | **Control** | **By-products** | **$N_{42}P_{57}K_{60}$+litter manure 10 t** | **$N_{42}P_{57}K_{60}$+by-products** | **$N_{62}P_{86}K_{90}$+by-products** |
| Crop rotation I: field pea-oat–winter triticale–corn | | | | | |
| Grain harvesting, t/ha | 2.43 | 2.82 | 4.32 | 3.96 | 4.52 |
| Humus balance, kg/ha | -520 | 90 | 220 | 480 | 630 |
| Nitrogen balance, kg/ha | -50 | -13 | 10 | -3 | 0 |
| Profitability, % | 23.6 | 42.3 | 27.9 | 30.1 | 29.4 |
| Crop rotation II: soybean–corn–corn | | | | | |
| Grain harvesting, t/ha | 3.14 | 3.78 | 5.76 | 5.23 | 6.05 |
| Humus balance, kg/ha | -830 | 20 | 50 | 310 | 540 |
| Nitrogen balance, kg/ha | -75 | -39 | 4 | -30 | -25 |
| Profitability, % | 21.9 | 39.6 | 25.4 | 27.9 | 29.8 |
| Crop rotation III: lupine–winter rape–winter rye–corn | | | | | |
| Grain harvesting, t/ha | 2.57 | 2.3 | 4.0 | 3.73 | 4.23 |
| Humus balance, kg/ha | -550 | 40 | 60 | 310 | 440 |
| Nitrogen balance, kg/ha | -50 | -23 | 16 | -2 | 0 |
| Profitability, % | 46.0 | 65.2 | 30.7 | 32.8 | 31.0 |
| Crop rotation IV: soybean–winter wheat–sunflower–buckwheat | | | | | |
| Grain harvesting, t/ha | 2.11 | 2.33 | 2.98 | 2.92 | 3.2 |

| | | | | | |
|---|---|---|---|---|---|
| Humus balance, kg/ha | -430 | 40 | 100 | 210 | 350 |
| Nitrogen balance, kg/ha | -48 | -28 | 27 | -7 | 6 |
| Profitability, % | 57.0 | 76.4 | 28.7 | 36.5 | 31.0 |

**Table 4.** Generalized indicators of ecological and economic assessment of crop rotations.

From the obtained data, according to the productivity of 1 ha of crop rotation area, the best indicators are usually observed in the second crop rotation: soybean–corn–corn–up to 6.05 t/ha of grain.

In terms of the ability to accumulate humus, or in terms of environmental friendliness, the best indicators are characterized by the first crop rotation: field pea-oats–winter triticale–corn, under crops which, subject to wrapping by-products against mineral fertilizers, most synthesized humus (480–630 kg/ha), which provides enhanced reproduction and increases soil fertility.

Regarding the balance of nutrients, in particular nitrogen (as it is the main limiting element in the Polissia area), it was found that using the recommended NRC against litter manure under crops of all crop rotations, a positive balance is ensured. Under the condition of wrapping straw in crop rotation 2, a negative balance of nitrogen at the level of 25–30 kg per 1 ha of crop rotation area is created from 66.6% of corn. In the other three crop rotations, the application of an increased rate of mineral fertilizers contributed to a deficit-free or balanced nitrogen balance, and at the recommended rate–a slight deficit (-2-7 kg/ha).

The highest level of profitability in all crop rotations was observed for using by-products without mineral fertilizers (39.6–76.4%), but without mineral nutrition, the soil fertility decreases, and we get a low shaft of products (on average by 50%). The most effective is the fertilization system, which replaces the traditional organo-mineral system of manure fertilization with other adaptive sources of organic matter, including by-products of the precedent, and provides profitability of growing crops at 27.9–36.5%.

The choice of fertilizer system depends on the direction of specialization of the farm. In the absence of livestock farms, an alternative to manure is using by-products of all crops, which does not significantly reduce crop productivity, profitability and increase soil fertility.

Therefore, it is impossible to single out any crop rotation that would be the best by all defined criteria. Therefore, their dynamics are explained, i.e., the possibility of replacing a culture that has lost its competitiveness with another single-crop one, which is most in-demand in the market. Replacing one crop with another that has not violated the basic principle of crop rotation is not a violation of crop rotations. It is also possible to introduce a specific crop rotation during one rotation and the second–a change to another crop rotation, usually considering their phytosanitary function, the laws of crop rotation, and soil fertility.

## Conclusion

Based on the research, we state that in conditions of low moisture supply, short-rotation crop rotations with a small set of market-oriented crops with different biological features provide reproduction of fertility of drained sod-podzolic soil and high yields of crops. The highest yield of grain (6.05 tons) from 1 ha of crop rotation area was obtained in the three-field crop rotation (soybean–corn–corn) with 66.6% of corn for the combination of by-products with an increased rate of mineral fertilizers ($N_{62}P_{86}K_{90}$). Reducing the share of corn from 33.3% in the three-field (field pie-oats–winter triticale–corn) to 25% in the four-field (lupine–winter rape–winter rye–corn) crop rotation under a similar fertilizer system led to a decrease in productivity–up to 4.5 and 4.23 tons of grain, respectively. Crop rotation without corn (soybeans–winter wheat–sunflower–buckwheat) reduced grain harvest by an average of 50%.

As for the choice of feed system with mineral fertilizers, each in itself can be recommended for production. In livestock on the farm, it is necessary to apply mineral fertilizers in the norm $N_{42}P_{57}K_{60}$ with manure in the amount of 10 tons per 1 ha of crop rotation area, which provides profitability of crop rotations 25.4–30.7% and simple reproduction of soil fertility. In the field of crop specialization, an alternative to bedding manure is the use of by-products of all crops by its combination with the recommended rates of mineral fertilizers ($N_{42}P_{57}K_{60}$), which does not significantly reduce crop rotation productivity, provides expanded reproduction of soil fertility, and profitability at 27.9–36.5%.

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