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GROWING WINTER WHEAT IN VARIOUS SHORT-ROTATION CROP ROTATION MODELS ADAPTED TO THE CONDITIONS OF THE STEPPE ZONE OF UKRAINE

Yuriy Mashchenko[1], Iryna Sokolovska[2]

[1] Institute of Agriculture of the Steppe, National Academy of Agrarian Sciences of Ukraine, Kropyvnytskyi, Ukraine
[2] Kherson State Agrarian and Economic University, Kropyvnytskyi, Ukraine

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Abstract

The need for developing new models of modern crop rotations is justified by the current conditions of agricultural and economic development. Research conducted in the conditions of the Northern Steppe of Ukraine confirmed the impact of crop rotation factors and fertilization on the yield, product quality, and economic efficiency of winter wheat cultivation. It was established that growing winter wheat in a grain-fallow-arable crop rotation model with 20 % soybean saturation contributed to achieving a higher yield level, with a difference compared to the grain-arable crop rotation model with 40 % soybean saturation – 0.59 t ha^{-1} or 9.0 %, and compared to model with 60 % soybean saturation – 0.81 t ha^{-1} or 12.7 %. Growing winter wheat in crop rotation model with 20 % soybean saturation under an organo-mineral biologized fertilization system contributed to achieving maximum yield at the level of 7.93 t ha^{-1}. The implementation of biologized mineral and organo-mineral fertilization systems in grain-arable crop rotation models (60 % and 40 % soybean saturation) ensured a yield formation at the level of 6.52–7.40 t ha^{-1} and 6.71–7.54 t ha^{-1}, respectively. The highest grain quality, corresponding to Class II, was also observed in the grain-fallow-arable crop rotation model, but under a mineral biologized fertilization system. In other crop rotation models and fertilization variants, the grain quality was lower and corresponded to Classes III and IV. The biologicalization of recommended crop rotations for the Ukrainian Steppe contributed to achieving significantly higher winter wheat grain yields regardless of their structure and soybean saturation. Higher economic efficiency was achieved by growing winter wheat in a grain-fallow-arable crop rotation with 20 % soybean saturation based on an organo-mineral fertilization system, which contributed to obtaining the highest conditional net profit at the level of 37 334 UAH ha^{-1} with a profitability of 156.2 %.

Keywords: biologized crop rotations, economic efficiency of winter wheat cultivation, fertilization systems, short-rotation crop rotation models, winter wheat grain quality, winter wheat grain yield

INTRODUCTION

The modern agricultural system does not ensure maximum productivity per unit area and stability of soil fertility. As a result, soil degradation is observed, its properties deteriorate, and the fields become increasingly weedy. Consequently, we face higher energy and economic costs with low productivity. Modern agricultural intensification is associated with the additional use of energy resources: fertilizers, pesticides, agricultural machinery, electricity, and labor. Therefore, the development of new and evaluation of existing agricultural systems, or their individual elements, should be based on the optimal ratio of the amount of energy used to the energy obtained from their functioning (Behera and France, 2022; Dixon *et al.*, 2023; Horton, 1986; Keating and McCown, 2001; Morris and Winter, 1999; Primak *et al.*, 2022; Ryaba, 2012; Vozhegova, 2020; Yeshchenko, 2015).

One of the directions to increase agricultural efficiency is the research and implementation of crop rotations with a short rotation period. The problem of developing short-rotation crop rotations and utilizing by-products of crop production is being addressed by many domestic and foreign scientists (Boyko *et al.*, 2014; Darguza and Gaile, 2023; Markovska, 2019; Nurbekov *et al.*, 2023; Sokolovska and Mashchenko, 2023a; Tsymbal *et al.*, 2022; Voitovyk, 2023a; Voitovyk *et al.*, 2023b).

In Ukrainian agriculture, most farms used crop rotations with 7 or 10 fields. These were necessary due to the development of diversified farms that had large areas of arable land and grew a wide range of crops (Boyko *et al.*, 2014). Long-term rotation crop rotations justified themselves and are still necessary in large farms today. However, under modern conditions, with the establishment of new forms of land relations, the number of farms with relatively small land use areas, a limited range of crops, and narrow specialization is increasing (Demydenko *et al.*, 2018).

Therefore, there is a current need for the development and implementation of narrowly specialized short-rotation crop rotations with a limited optimized set of crops. Typically, 4-5 field crop rotations are currently used. The transition from long-term crop rotations to short-rotation ones must be addressed in each specific case primarily based on soil-ecological factors. Real and stable increases in agricultural production, guaranteed food supply, and the creation of better living conditions for people can only be ensured through reliable protection of the soil cover and the preservation and enhancement of its fertility (Kudria, 2020; Pryma *et al.*, 2022; Shustik *et al.*, 2020).

In recent years there has been a growing trend towards the biologicalization of crop production in Europe, USA and Canada (starting from improving crop rotations that include grasses and legumes). If a crop rotation is too simplified and narrowly specialized, it maximally incorporates intermediate and sideral crops that improve crop rotation and phytosanitary conditions of the crops (Kropyvnytskyi *et al.*, 2020; Shakaliy *et al.*, 2020; Sokolovska and Maschenko, 2023b; Yastremska *et al.*, 2020).

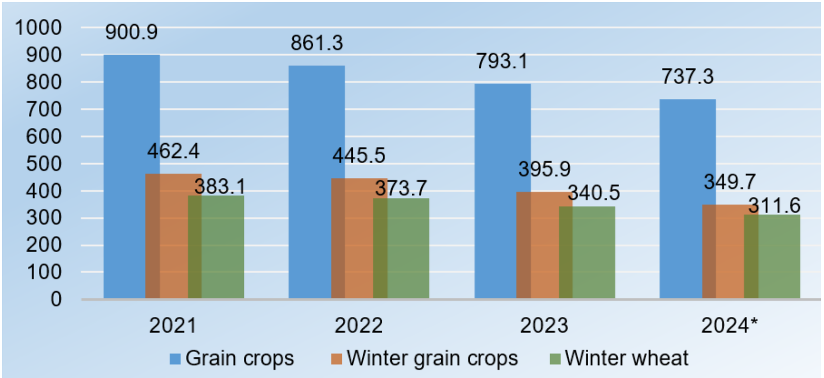
Some scientists argue that significant attention should be paid to the implementation of a biologized farming systems – utilizing secondary agricultural products, green manures, and non-chemical methods of plant protection. The importance of green manures in modern agriculture is determined by their role in the reproduction of organic matter, which is explained by their global impact on the complex agrochemical properties of the soil and the energetic significance of its fertility. The stocks of humus and nitrogen in the soils are primarily replenished through the application of fertilizers and significantly through organic substances that come in the form of plant residues (Azimbay and Anuar, 2023; Merfield, 2019; Rosa *et al.*, 2022).

Despite the fact that winter wheat is a key strategic crop in Ukraine, the area under its cultivation has been steadily decreasing over the past decades. Scientists and agrarians identify several reasons for the reduction of sown areas for winter crops, including winter wheat. The decrease in the total fund of usable land plots is a consequence of many factors – ranging from industrial development to global climate change and the negative impact of environmental pollution. Growing technical crops has become more economically attractive for farmers, with crops such as sunflower, rapeseed, and soybeans occupying increasingly larger areas in farms, while agrarians are more frequently introducing niche and less common crops into production.

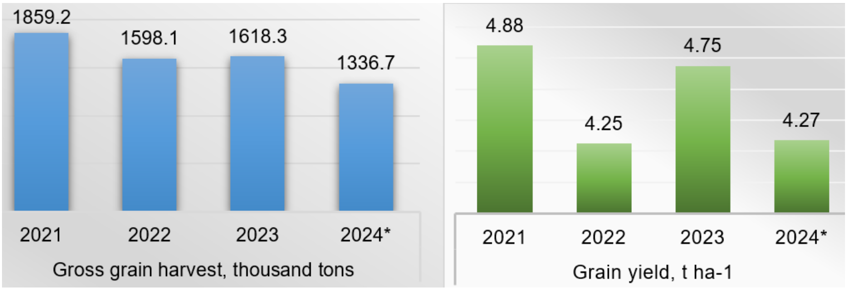
An analysis of the structure of sown areas in the Kirovohrad region indicates a trend towards a gradual reduction in sown areas for grain crops while simultaneously expanding the sown areas for technical group crops. In just the last three years, the area occupied by grain crops has decreased by 18.2 % from 900.9 thousand hectares to 793.1 thousand hectares. According to forecasts from the Department of Agricultural Production of the Kirovohrad Regional Administration, in 2024, the area under grain crops in the region will amount to 737.3 thousand hectares, which is 163.6 thousand hectares or 19.2 % less than in the pre-war year of 2021 (Fig. 1).

This transformation of sown areas for agricultural crops in the region affects changes in the structure of crop rotations. The area under sunflower continues to grow, which, according to preliminary forecasts, will once again reach a historical maximum in 2024, reaching 661 thousand hectares. In 2024, further expansion of soybean sowing is expected to reach 130.2 thousand hectares, which is 33.2 % more than in the previous year, as well as a reduction in sugar beet sowing to 11.6 thousand hectares. The areas under potatoes, vegetables, and melons have remained quite stable over the past 15 years. On average, they occupy 60 thousand hectares or 3.5 % of the total structure of sown areas in the region.

Since 2005, winter wheat has been the main grain crop in the region, occupying 94 % of the sown areas for winter crops. By 2024, its share is expected to decrease by 18.7 %; in 2023, winter wheat was sown on 340.5 thousand hectares, and for the next year, production volumes are expected to decrease to 311.6 thousand hectares. These changes in the structure of sown areas are associated not only with global changes in the use of fertile plots in the region but also in the country as a whole. The



1: *Sown areas of grain crops in Kirovohrad region, thousand ha*
Statistics by the Department of Agricultural Production of the Kirovohrad Regional State Administration. *Forecasted for 2024.



2: *Indicators of winter wheat production in Kirovohrad region*
Statistics by the Department of Agricultural Production of the Kirovohrad Regional State Administration. *Forecasted for 2024.

production volumes of spring barley and rapeseed are increasing, and the competitiveness of these crops' products has been rising in recent years.

In recent years, the yield of winter grain crops in the Kirovohrad region has shown a tendency to gradually increase. This is facilitated by the implementation of a range of scientifically grounded innovative measures in production, including the use of modern equipment. The index of average yield for winter wheat from 2021 to 2023 was 46.3, which represents an increase of 9.4 units compared to the period from 2011 to 2015. However, the rapid changes in climate, particularly observed in recent years in the Steppe zone of Ukraine, have become an even more limiting factor than in previous years, affecting plant growth and development processes and, consequently, crop productivity. This necessitates accelerated adaptation of agricultural crop cultivation technologies to a complex of natural components.

According to forecast data, in 2024, the gross harvest of winter wheat in the region is expected to be at the level of 1 336.7 thousand tons with an average yield of 4.27 t ha^{-1}, which may account for 6.6 % of the total grain production in Ukraine, projected at 52.4 million tons (Fig. 2).

Therefore, considering all of the above, there is a need to develop new models of modern crop rotations that differ from previous ones by a higher degree of saturation with high-yield and relevant crops, as well as a wide range of doses and ratios of essential nutrients in different fertilization systems. An effective and sufficiently realistic way to halt the degradation of chernozems while simultaneously increasing the production of quality agricultural products is to use by-products of crop production as fertilizers combined with biological elements.

MATERIALS AND METHODS

This article presents the results of studies conducted from 2020 to 2024 in a stationary field experiment at the fields of the Farming Laboratory of the Institute of Agriculture of the Steppe of NAAS of Ukraine. The soil-climatic conditions correspond to the northern Steppe region of Ukraine.

A two-factor experiment was set up in field conditions:

Factor A – crop rotation model with varying soybean saturation;

Factor B – fertilization systems.

Crop rotation models:

- grain-arable rotation with soybean saturation up to 60 % alternating crops: soybean, winter wheat, soybean, corn for grain, soybean;
- grain-arable rotation with soybean saturation at 40 %, including the following crop alternation: soybean, winter wheat, soybean, corn for grain, buckwheat;

- grain-fallow-arable rotation with soybean saturation up to 20 % consisted of the following fields: pure fallow (in the system without fertilizer application and in the mineral system) and occupied fallow (under the organic-mineral fertilization system), winter wheat, soybean, corn for grain, sunflower. In the occupied fallow, peas were sown, for which mineral fertilizers were applied at a rate of $N_{30}P_{30}K_{30}$.

Fertilization systems:

- natural soil fertility (without fertilizers);
- on the background of natural soil fertility, seeds were sown that were treated before sowing with the biopreparation Mycofriend;
- mineral fertilization system (in the rotation with 60 % soybean saturation – $N_{90}P_{60}K_{60}$; in the rotation with 40 % soybean saturation – $N_{70}P_{40}K_{40}$; in the rotation with 20 % soybean saturation – $N_{50}P_{20}K_{20}$);
- mineral fertilization system with seed treatment before sowing with Mycofriend biopreparation;
- organic-mineral fertilization system ($N_{60}P_{30}K_{30}$ + $N_{30}P_{30}K_{30}$ for the crop replacing fallow + by-products from the previous crop);
- organic-mineral fertilization system with seed treatment before sowing with Mycofriend biopreparation.

The sowing rate for winter wheat is 4.5 million ha^{-1}.

As an element of the biologicalization of fertilization systems in our experiments, we used Mycofriend (1.5 l t^{-1}), which is based on mycorrhizal fungi and phosphate-mobilizing bacteria and contains biologically active substances: phytohormones, vitamins, fungicidal substances, and amino acids. Seed inoculation with the preparation was carried out on the day of sowing.

The soil of the experimental plots is ordinary low-humus chernozem with a heavy clay texture. The arable layer of the soil contains an average of 3.70 % humus, easily hydrolyzable nitrogen – 117 mg, mobile phosphorus – 92 mg, and exchangeable potassium – 137 mg per 1 kg of soil, as well as mobile forms of manganese, zinc, and boron – 9.6, 0.65, and 1.51 mg per kilogram of soil, respectively. Ordinary chernozems typically have a neutral to near-neutral reaction of the soil solution and do not require chemical amelioration.

In the experiment, we cultivated the Oranta Odeska variety (winter wheat of Ukrainian selection, registered in 2017, recommended for cultivation in the Forest-Steppe, Polissia, and Steppe zones of Ukraine). This is a universal type variety, early-maturing, intended for grain production. The variety is highly resistant to lodging, shedding, and sprouting in the ear. It has a large, well-filled ear and high productive tillering.

The measurement of the gluten deformation index in conditional units was conducted using a gluten deformation meter.

The class of winter wheat grain was determined according to State Standards of Ukraine 3768:2019.

The weather conditions during the research periods of 2020, 2021, and 2024 were not sufficiently favorable for achieving high productivity indicators for winter wheat.

The weather conditions during the growing seasons of 2022 and 2023 for winter wheat were favorable, with moderate increases in air temperature and adequate moisture reserves in the soil during the spring and summer periods.

RESULTS

The analysis of the results of five years of research on winter wheat cultivation in the conditions of the Northern Steppe of Ukraine proved the variability of yield indicators depending on the crop rotation factor and fertilization system within 3.28 t ha^{-1}.

The model of short-rotation grain-fallow-arable crop rotation with soybean saturation up to 20 % ensured the formation of a higher level of winter wheat yield compared to other models, regardless of the fertilization system. When using a system that did not apply fertilizers, utilized the natural fertility of the soil, the yield of winter wheat increased by 1.51 t ha^{-1} compared to the crop rotation model with soybean saturation up to 60 %, reaching 6.15 t ha^{-1}. The increase in yield due to the effect of the crop rotation factor in this variant was the largest in the experiment (LSD05 for factor A = 0.21 t ha^{-1}). It should be noted that the application of other fertilization systems studied in our experiments neutralized the effect of the crop rotation factor. A trend was observed where the yield increase decreased with an increase in the number and variants of additional nutrients applied to the soil. Nevertheless, the highest yield indicator for winter wheat in the specified crop rotation model, and in the experiment as a whole, was achieved using an organo-mineral biologized crop fertilization system, 7.93 t ha^{-1}, corresponding to the highest variability indicator in our experiment (Tab. I).

The crop rotation model, in which the fallow field was replaced with a soybean field, provided somewhat lower yield indicators for winter wheat, ranging from 5.24 t ha^{-1} to 7.54 t ha^{-1}, than the previous model (with soybean saturation up to 20 %), but the influence of the fertilization system factor was similar. It is also worth noting that the yield increase due to the crop rotation factor in this model was significantly lower, at +0.59 t ha^{-1} (compared to the model with soybean saturation up to 60 % and the model with soybean saturation up to 20 %). Even more interesting was the fact that the application of various fertilization systems, except for the system without fertilizer application and the biologized system, did not ensure a significant increase in grain yield compared to the crop rotation model with 60 % soybean saturation (+ 0.05–0.20 t ha^{-1} at LSD05 = 0.21 t ha^{-1}). This means that the fertilization system factor in the crop rotation model with soybean saturation up to 40 %

I: *Yield of winter wheat depending on the crop rotation model and fertilization system*

Crop rotation model, factor A	Fertilization system, factor B	Average for 2020–2024	Difference factor A		Difference factor B	
			t ha^{-1}	%	t ha^{-1}	%
60 % soybean crop rotation saturation	Without fertilizer	4.65	–	–	–	–
	Biological	5.43	–	–	0.78	16.9
	Mineral	6.52	–	–	1.87	40.2
	Mineral biological	7.03	–	–	2.38	51.2
	Organic-mineral	7.10	–	–	2.45	52.8
	Organic-mineral biological	7.40	–	–	2.75	59.2
40 % soybean crop rotation saturation	Without fertilizer	5.24	0.59	12.7	–	–
	Biological	5.69	0.26	4.8	0.45	8.7
	Mineral	6.71	0.20	3.0	1.47	28.1
	Mineral biological	7.07	0.04	0.6	1.83	34.9
	Organic-mineral	7.15	0.05	0.6	1.91	36.4
	Organic-mineral biological	7.54	0.15	2.0	2.30	44.0
20 % soybean crop rotation saturation	Without fertilizer	6.15	1.51	32.4	–	–
	Biological	6.67	1.24	22.8	0.51	8.4
	Mineral	7.10	0.58	9.0	0.95	15.4
	Mineral biological	7.55	0.52	7.4	1.40	22.7
	Organic-mineral	7.56	0.46	6.5	1.40	22.8
	Organic-mineral biological	7.93	0.53	7.2	1.78	28.9
	LSD05: factor A = 0.21; factor B = 0.29; factors AB = 0.51					

*author's calculations

affects the increase in crop productivity only when using a biologized fertilization system.

The use of a crop rotation model with soybean saturation up to 60 % in the cultivation of winter wheat resulted in the lowest grain yield indicators in our experiment (4.65–7.40 t ha^{-1}). However, the application of mineral fertilizers in combination with the residues of the previous crop and a biologically active component allowed for achieving grain yields at the level of the crop rotation model with soybean saturation up to 40 %, reaching 7.40 t ha^{-1}. It should also be noted that the variability of yield indicators in this crop rotation model (up to 60 % soybean) was the highest in the experiment, amounting to 2.75 t ha^{-1}. This indicates that fertilizer systems had the most effective impact on increasing winter wheat yields specifically in the crop rotation model where three out of five fields were occupied by leguminous crops. The reaction limits of yield indicators depending on fertilizer application in the crop rotation model with soybean saturation up to 40 % was 2.30 t ha^{-1}, while in the grain–fallow–arable crop rotation where soybean was grown on one field, it was 1.78 t ha^{-1}.

The greatest yield increase due to the fertilizer system factor was also observed in the crop rotation model with soybean saturation up to 60 %, at +2.75 t ha^{-1}. The least effective was the impact of the biologized fertilizer system in the crop rotation model with soybean saturation up to 40 %, at +0.45 t ha^{-1}; however, considering the smallest significant difference in the influence of factor B (fertilizer system), the yield increase was still significant.

Thus, using a short-rotation grain–fallow–arable crop rotation model with soybean saturation up to 20 % when cultivating winter wheat provided the highest grain yield. The highest indicator, 7.93 t ha^{-1}, was achieved using an organo-mineral biologized fertilizer system. The biological enhancement of classical fertilization systems recommended for the Steppe zone of Ukraine contributed to a significant increase in winter wheat grain yield indicators across different crop rotation models, regardless of their structure and leguminous crop saturation.

According to the analysis of the chemical composition of winter wheat grain, it was established that the bulk density of the grain exceeded 775 g l^{-1} in most experimental variants, corresponding to Class I quality (State standard of Ukraine 3768:2019). It was found that the lower bulk density of winter wheat grain occurred in variants grown in a grain-arable crop rotation with soybean saturation up to 40 % using an organo-mineral biologized fertilizer system (774 g l^{-1}) and in a grain-fallow-arable crop rotation with soybean saturation up to 20 % under mineral fertilization (765 g l^{-1}) and mineral biologized fertilizer system (766 g l^{-1}), which relates to Class II quality of grain (Tab. II, III).

According to the quality indicators of gluten (measured in units of the gluten deformation meter), the grain of winter wheat of Class I was obtained regardless of the crop rotation factor and fertilization system. However, the mass fraction of raw gluten varied depending on the research variants. It was established that the highest quality of winter wheat grain in terms of raw gluten content was observed in the grain-fallow-arable crop rotation with soybean saturation up to 20 %, using both mineral and mineral biologized fertilization systems (25.2 % and 27.8 %, respectively), as well as in grain-arable crop rotations models (regardless of the proportion of soybean in the crop structure) under an organo-mineral biologized fertilization system (25.0 % and 24.7 %).

In crop rotations models with soybean saturation up to 20 % and up to 60 % using a mineral fertilization system and its combination with biologized systems, the raw gluten content did not exceed 27.8 % and was not less than 23.3 %, corresponding to Class II grain quality. The lowest mass fraction of raw gluten (Class IV) was found in variants of grain-arable crop rotation with soybean saturation up to 40 % without fertilizers and under a biologized fertilization system, amounting to 16.4 % and 16.6 %, respectively. In other research variants, this indicator ranged from 19.0 % for winter wheat grown in a grain-arable crop rotation with soybean saturation up to 60 % without fertilizers to 22.5 % in a grain-arable crop rotation with soybean saturation up to 40 % using a mineral fertilization system.

Our research established that in a grain-arable crop rotation with soybean saturation up to 40 %, the lowest protein content in winter wheat grain (Class IV) was obtained in variants without fertilizers and under a biologized fertilization system, amounting to 8.5 % and 9.1 %, respectively. Additionally, in the model where soybean fields occupied up to 60 % of the crop rotation, under a mineral biologized fertilization system, the protein content was somewhat higher at 10.9 %, but the grain quality still corresponded to Class IV. In the crop rotation models where the area occupied by soybeans was reduced to 40 % and then to 20 %, with the introduction of fallow fields, a similar trend was observed. In these variants, the protein content did not exceed 9.9 %, which corresponded to

II: *Quality indicators of winter wheat grain depending on the crop rotation factor and fertilizer system (average for 2020–2024)*

Crop rotation model, factor A	Fertilization system, factor B	Bulk density of the grain, g l^{-1}	Gluten quality, indicator of the device in conventional units	Mass fraction of raw gluten, %	Mass fraction of protein converted on dry matter, %
60 % soybean crop rotation saturation	Without fertilizer	784	87	19.9	9.4
	Biological	789	84	20.5	9.6
	Mineral	788	84	24.2	11.4
	Mineral biological	787	87	23.3	10.9
	Organic-mineral	783	84	24.1	11.6
	Organic-mineral biological	778	84	25.0	12.0
40 % soybean crop rotation saturation	Without fertilizer	781	88	16.4	8.5
	Biological	777	88	16.6	9.1
	Mineral	787	86	22.5	11.2
	Mineral biological	783	87	22.4	11.0
	Organic-mineral	782	86	23.6	11.5
	Organic-mineral biological	774	86	24.7	11.4
20 % soybean crop rotation saturation	Without fertilizer	783	86	19.0	9.7
	Biological	784	89	20.1	9.9
	Mineral	765	88	25.2	12.2
	Mineral biological	766	85	27.8	13.1
	Organic-mineral	777	86	21.7	11.1
	Organic-mineral biological	780	83	22.3	10.9

*author's calculations

III: *Economic efficiency of winter wheat cultivation depending on the crop rotation factor and fertilization system*

Crop rotation model, factor A	Fertilization system, factor B	Production costs, UAH ha^{-1}	Class of winter wheat grain	Price according to class, UAH t^{-1}	Cost of gross production, UAH ha^{-1}	Conditional net profit, UAH ha^{-1}
60 % soybean crop rotation saturation	Without fertilizer	14 849	IV	7 250	3 3713	18 863
	Biological	15 912	IV	7 250	3 9368	23 455
	Mineral	21 925	III	8 100	5 2812	30 887
	Mineral biological	22 082	IV	7 250	5 0968	28 886
	Organic-mineral	22 229	III	8 100	5 7510	35 281
	Organic-mineral biological	23 035	III	8 100	5 9940	36 905
40 % soybean crop rotation saturation	Without fertilizer	15 158	IV	7 250	3 7990	22 832
	Biological	16 012	IV	7 250	4 0745	24 733
	Mineral	25 862	III	8 100	5 4351	28 489
	Mineral biological	26 051	III	8 100	5 7267	31 216
	Organic-mineral	26 093	III	8 100	5 7915	31 822
	Organic-mineral biological	26 297	III	8100	61074	34 777
20 % soybean crop rotation saturation	Without fertilizer	16 977	IV	7250	44588	27 611
	Biological	17 855	IV	7250	48358	30 503
	Mineral	31 395	III	8100	57510	26 115
	Mineral biological	32 238	II	8400	63420	31 182
	Organic-mineral	23 902	III	8100	61236	37 334
	Organic-mineral biological	24 722	IV	7250	57493	32 770

*author's calculations

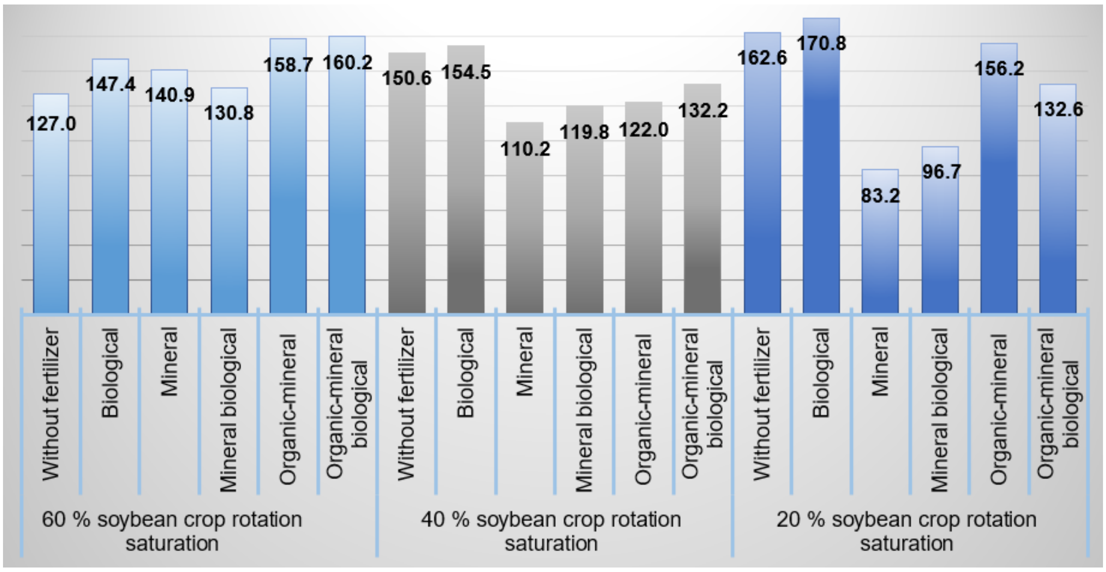
Class IV grain. The highest protein content in winter wheat grain was found under a mineral biologized fertilization system in a grain-fallow-arable crop rotation model with soybean saturation up to 20 %, with an indicator of 13.1 %, corresponding to Class II grain quality. In other research variants, the protein content of winter wheat grain corresponded to Class III quality.

Thus, based on the results of laboratory analysis of winter wheat grain conducted from 2020 to 2024, it was established that the highest quality, which met Class II standards, was achieved under conditions of growing winter wheat in a grain-fallow-arable crop rotation model with soybean saturation of up to 20 % using a mineral biologized fertilization system. Other studied variants showed a low level of protein and crude gluten accumulation in winter wheat grain, which in turn resulted in obtaining wheat of Classes III and IV quality. The established changes in the quality of winter wheat depended on the fertilization system and the use of biopreparations; additionally, the crop rotation factor also played an intermediate role in the content of quality indicators.

The main indicators affecting the structure of sown areas and the attractiveness of growing specific agricultural crops are economic efficiency. According to our calculations, it was established that at the prices prevailing in the third decade of June 2024 on the Ukrainian stock market, the lowest production costs were in the variants without fertilizers across all studied crop rotations. The increase in production costs in the variants without fertilizers ranged from 14 849 UAH ha^{-1} in a grain-arable crop rotation with 60 % soybean saturation to 15 158 UAH ha^{-1} in a grain-arable crop rotation with 40 % soybean saturation, and up to 16 977 UAH ha^{-1} in a grain-fallow-arable crop rotation with 20 % soybean saturation. This was a result of additional expenses for harvesting, transporting, and cleaning the grown products due to higher yields of winter wheat (Tab. III).

The highest costs were associated with the mineral biologized fertilization system in a grain-fallow-arable crop rotation with 20 % soybean saturation, amounting to 32 238 UAH ha^{-1}.

The highest value of produced products was observed in the variant with a mineral biologized fertilization system under conditions of growing winter wheat in a grain-fallow-arable crop rotation with soybean saturation of up to 20 %, amounting to 63 420 UAH ha^{-1}. This indicator is explained by the higher quality of the grown winter wheat grain, which met Class II standards and was priced at 300 UAH t^{-1} more than Class III wheat and 1 150 UAH t^{-1} more compared to Class IV. Thus, producers face the challenge of obtaining not only high yields but also ensuring that the grown



3: *Profitability of winter wheat production, %*
***author's calculations

products meet high-quality standards. This will contribute not only to increasing the volume of gross wheat harvests but also to providing the country with high-quality products.

The lowest conditional net profit of 18 863 UAH t^{-1} was obtained under conditions of growing winter wheat without fertilizers in a crop rotation with soybean saturation of up to 60 %. Such a low level of this indicator was caused by low yield and quality of winter wheat grain. The highest conditional net profit was achieved in variants with an organo-mineral biological fertilization system in a grain-arable crop rotation with soybean saturation of up to 60 %, amounting to 36 905 UAH t^{-1} (Class III grain quality), and with an organo-mineral fertilization system in a grain-fallow-grain crop rotation with soybean saturation of up to 20 % – 37 334 UAH t^{-1} (Class II grain quality).

Considering the high level of average yield of winter wheat variety Oranta Odeska, it was established that the level of profitability fluctuated between 127 % and 160.2 %, characterizing winter wheat cultivation as a highly profitable crop (Fig. 3).

The lowest profitability was observed under the mineral fertilization system in a grain-fallow-arable crop rotation with soybean saturation of up to 20 %, amounting to 83.2 %. This indicates high costs associated with using the full norm of mineral fertilizers, expenses for removing straw from the field, and low quality of the grown grain, which corresponded to Class IV.

The level of profitability of winter wheat cultivation was directly related to the conditional net profit in a grain-arable crop rotation with soybean saturation of up to 60 % under an organo-mineral fertilization system with the use of a biologized system, which had an indicator of 160.2 %. It should also be noted that in the grain-fallow-arable crop rotation with soybean saturation of up to 20 % under an organo-mineral fertilization system, the level of profitability was 156.2 %. The maximum value of profitability for winter wheat cultivation was achieved using a biologized fertilization system in a grain-fallow-arable crop rotation with soybean saturation of up to 20 %, which amounted to 170.8 %. This was facilitated by the placement following a better predecessor (fallow) and low production costs with a yield of 6.15 t ha^{-1}.

Thus, under conditions of growing winter wheat in various short-rotation biologized crop rotations, the greatest economic efficiency was provided by placing the crop in a grain-fallow-arable crop rotation with soybean saturation of up to 20 % against the background of an organo-mineral fertilization system, which contributed to obtaining the highest conditional net profit at the level of 37 334 UAH ha^{-1} with a profitability of 156.2 %.

DISCUSSION

The results of studies by many Ukrainian researchers confirm that crop rotation plays a significant role in providing plants with soil moisture and available forms of nutrients, and the alternating placement of different crops affects the activity of microorganisms, soil structure, etc. A scientifically justified structure of crop rotation can ensure an increase in the yield of individual crops and the productivity of the crop rotation as a whole by 20–25 % without significant material and energy costs (Mashchenko *et al.*, 2023).

In the zone of insufficient moisture in the Left Bank Forest-Steppe of Ukraine, higher yields of winter wheat grain were obtained at the level of 4.61 t ha^{-1} when using an organo-mineral fertilization system in a short-rotation crop rotation. In these experiments, for one hectare of arable land during the rotation of the crop rotation, 6.25 tons of manure and mineral fertilizers at a rate of $N_{33.8}P_{33.8}K_{33.8}$ were applied without straw and without tops (Filonenko and Tyshchenko, 2020). In the conditions of the Right Bank Forest-Steppe of Ukraine, the highest yield of winter wheat grain (6.5 t ha^{-1}) was obtained in a four-field crop rotation, while the lowest (4.7 t ha^{-1}) was observed with continuous cultivation (Rozhko and Makarenko, 2010). It should be noted that the use of short-rotation crop rotations when growing winter wheat significantly affected the main indicators of soil fertility. In particular, the four-field crop rotation provided the most favorable water-physical conditions, reduced weediness in crops, and created an optimal combination of ecological-trophic groups of microorganisms. This, in turn, led to higher yields of the crop and increased productivity of the studied crop rotations. The results of continuous winter wheat cultivation are confirmed by data from numerous researchers. Under such placement of the crop, water-physical indicators significantly decrease, weediness increases, and microbial activity in the soil deteriorates, leading to lower yields.

In our research, higher yields of winter wheat grain were obtained in a five-field grain-fallow-arable crop rotation with 20 % soybean saturation, ranging from 6.15 t ha^{-1} to 7.93 t ha^{-1}. Soybean, as a crop, utilizes hard-to-access nutrients from the lower soil horizons. On average, it leaves behind 70–100 kg ha^{-1} of available nitrogen, 20–25 kg ha^{-1} of phosphorus, and 30–40 kg ha^{-1} of potassium in the soil, which contributes to a yield increase of up to 15 %. The introduction of black or occupied pea fallow into the crop rotation improved the nutrition of the crops and had a positive impact on the biological regime of the soil, which contributed to an increase in the activity of soil microorganisms. Additionally, the use of mineral fertilizers, organic residues from previous crops, and the biologization of fertilization systems significantly increased the output per unit area when growing winter wheat: seed inoculation before sowing with a biologically active preparation containing mycorrhizal fungi and a complex of soil rhizosphere bacteria ensured a substantial increase in winter wheat yield regardless of the crop rotation model. Nevertheless, it should be noted that the highest yield increase was achieved in variants combining an organic-mineral fertilization system with a biological component. The organic residues that were plowed into the soil contributed to increased bacterial activity, resulting in plants receiving a greater amount of nutrients and forming a higher yield potential.

Obtaining winter wheat grain with high-quality baking characteristics has always been a pressing issue alongside its increasing production. To obtain grain with high quality indicators, a high agro background is necessary, which cannot be created today without controlled land use. The protein content in winter wheat grain depends on many factors of natural and agronomic origin. Growing high-quality wheat grain has been, is, and will remain one of the main tasks of agricultural production. Therefore, crop rotations and fertilization systems are of particular practical importance, as they can effectively influence the accumulation of protein in winter wheat grain. It is known that the main nitrogen-containing organic substances in wheat plants are proteins.

To enhance the quality of winter wheat grain, researchers suggest using foliar fertilization at the beginning of the booting phase in addition to a mineral fertilization system. In this case, the protein content and crude gluten increase to 13.9 % and 28.6 %, respectively (Kudriawytzka and Makarenko, 2023). In our experiments, higher quality indicators were achieved, with protein content at 13.1 % and crude gluten at 27.8 %, due to the application of a mineral biologized fertilization system and the cultivation of winter wheat in a grain-fallow-arable crop rotation with 20 % soybean saturation.

The overall quality indicators of the grain determine its class, which ultimately affects its market value. In our experiments, the bulk density of the grain was least dependent on the factors we investigated. In most variants, according to this quality indicator in accordance to State Standards of Ukraine 3768:2019, the product was classified as first class. Only when selecting a crop rotation model with 20 % soybean saturation and fallow land did the bulk density of the grain reach 765 g l^{-1} and 766 g l^{-1} when using mineral and mineral biologized fertilization systems, respectively, which ensured a second-class quality. The bulk density of the grain indirectly characterizes its quality indicators. In our experiments, the low bulk density of winter wheat grain in the aforementioned variants was associated with the peculiarities of early plant vegetation and weather conditions. The high agro background of this crop rotation model, along with mineral fertilizers and biological elements, contributed to a high tillering coefficient after the resumption of spring vegetation, increasing the number of productive stems and grains per ear. However, insufficient moisture supply in the Steppe region of Ukraine prevented the plants from utilizing their potential, resulting in underdeveloped grain under these growing conditions. Nevertheless, these conditions ensured a better chemical composition of the grain endosperm, allowing for protein and gluten content (13.1 % and 27.8 %, respectively) that enabled the product to be classified as second-class quality.

CONCLUSION

Based on the results of studying various crop rotation models adapted to the conditions of the Steppe zone of Ukraine, it was established that the highest yield of winter wheat grain was obtained in a short-rotation grain-fallow-arable crop rotation model with 20 % soybean saturation. The higher yield indicator was achieved using an organo-mineral biologized fertilization system, yielding 7.93 t ha^{-1}. The implementation of biologized mineral and organo-mineral fertilization systems in grain-arable crop rotation models, where soybean comprised 60 % and 40 %, respectively, ensured a yield formation at the level of 6.52–7.40 t ha^{-1} and 6.71–7.54 t ha^{-1}. However, no significant difference in yield was established between these models. The biologization of classical fertilization systems recommended for the Steppe zone of Ukraine contributed to a significant increase in the yield indicators of winter wheat grain in the crop rotation models we studied, regardless of their structure and saturation with high-protein leguminous crops.

The best grain quality, corresponding to Class II, was observed when growing winter wheat in a grain-fallow-arable crop rotation model with 20 % soybean saturation under a mineral biologized fertilization system. In other crop rotation models, regardless of the fertilization system, the grain quality corresponded to classes III and IV. The fertilization systems and the use of biological components in agricultural practices had a greater impact on the formation of grain quality, while the crop rotation factor occupied an intermediate position.

Higher economic efficiency was achieved by growing winter wheat in a grain-fallow-arable crop rotation with 20 % soybean saturation based on an organo-mineral fertilization system, which contributed to obtaining the highest conditional net profit at the level of 37 334 UAH ha^{-1} with a profitability of 156.2 %.

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Conflict of Interest

The authors declare that they have no conflict of interests.

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Contact information

Yuriy Mashchenko: mawenko2015@gmail.com, https://orcid.org/0000-0001-7965-0193

Iryna Sokolovska: marketing-kiapv@ukr.net, https://orcid.org/0000-0003-4256-8852 (corresponding author)