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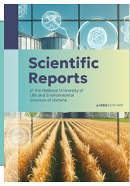

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Efficient winter wheat cultivation in high-productivity different-field crop rotations under the conditions of unstable moisture in the Forest-Steppe zone of Ukraine

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Abstract. The application of modern technologies for cultivating winter wheat in scientifically grounded crop rotations is increasingly important in the context of climate change. Such practices enhance its yield and production volumes, ensuring domestic market demands and the stable export of Ukrainian grain products. The study aimed to identify, synthesise, and systematise scientifically

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validated measures for effectively cultivating winter wheat in high-productivity five-field and ten-field crop rotations with varying levels of cereal saturation under unstable moisture conditions in the Left-Bank Forest-Steppe zone of Ukraine. To achieve this goal, a comprehensive system of general scientific and specialised research methods was employed, including field, laboratory-field, comparative-calculation, mathematical-statistical, and abstract-logical approaches. It was established that, on average, during the research period of 2021-2023, the highest winter wheat yield of 6.64 t/ha was achieved following peas in a five-field crop rotation with 60% cereal saturation and the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land. In five-field crop rotations, the yield of winter wheat following peas increased by 7.1-18.1% compared with perennial grasses, spring barley, and spring wheat. A high winter wheat yield of 6.44 t/ha was achieved following peas in a ten-field crop rotation with 80% cereal saturation and the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land. In ten-field crop rotations, the yield increase of winter wheat following peas compared with annual grasses (vetchoat), soybean, perennial grasses, spring barley, oilseed radish, and silage maize ranged from 7.5% to 24.4%. The yield increase attributable to mineral fertiliser application at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land was 39-60% after peas, 43% after perennial grasses, and 36-42% after silage maize. The most economically viable option was identified as the five-field crop rotation with 60% cereal saturation and mineral fertiliser application at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land, yielding the highest net profit of 26.93 thousand UAH/ha and a profitability level of 151%

Keywords: five-field and ten-field crop rotations; cereal saturation; predecessors; mineral fertilisation; productivity; economic efficiency

Introduction

Winter wheat plays a crucial role in addressing the grain production challenge, serving as one of the best predecessors in crop rotations for key agricultural crops such as sugar beet, maize, sunflower, peas, soybean, rapeseed, and potatoes. Consequently, significant attention is directed towards employing modern cultivation technologies for winter wheat within scientifically validated crop rotations. These efforts aim to enhance its yield and production volumes, increase overall food reserves and seed security stocks, and meet the demands of the domestic market while supporting the stable export of Ukrainian grain products.

Comprehensive research into an integrated scientific and technological approach – combining scientifically grounded measures for cultivating high-productivity winter wheat varieties within different-field crop rotations under unstable moisture conditions – has not yet been fully undertaken. At the same time, individual agronomic practices highlighted in scientific publications require optimal coordination. Notably, a series of studies by Ukrainian researchers provide valuable insights into the effective cultivation of cereal crops within short-field crop rotations, which merits further attention.

For instance, Ye. Yurkevych *et al.* (2021) investigated the impact of organic and mineral fertilisers on the yield and quality of cereal crops, including under the conditions of unstable moisture in Ukraine. The authors highlighted the effectiveness of combining organic fertilisers (such as compost and manure) with mineral fertilisers (nitrogen, phosphorus, and potassium), which enhances crop productivity amidst climate change and supports the sustainable development of agriculture. Similarly, V. Ivanina & T. Prokopiuk (2024) underscored the significance of mineral fertilisers and micronutrients (manganese and silicon) in improving soil fertility and increasing grain yield and quality, emphasising their advantages for the sustainable management of soil resources.

The research conducted by B. Mazurenko *et al.* (2021) focused on the post-sowing application of compound fertilisers in the cultivation technologies of soft winter wheat. Compound fertilisers, which contain essential macro- and microelements, were shown to improve yields, grain quality, and disease resistance, demonstrating their efficacy in enhancing winter wheat productivity. In a monograph, O. Demydenko *et al.* (2019) analysed the effects of crop rotations systems and the use of plant residues on the fertility of chernozem soils in the Left-Bank Forest-Steppe zone of Ukraine. The use of crop residues and green manure crops, such as alfalfa and peas, was found to enrich the soil with nutrients, promoting its sustainable development and maintaining high productivity.

In her study, N. Kovalenko (2024) examined innovative technologies for the effective cultivation of cereal crops, focusing on green manure and the use of plant residues. The author emphasised the importance of incorporating green manure crops, which improve soil structure and enrich it with nutrients, thereby enhancing crop yields under diverse climatic conditions in Ukraine.

These findings underscore that the use of organic, mineral, and compound fertilisers, alongside the utilisation of plant residues and green manure crops, represents effective strategies for improving soil fertility and crop productivity in contemporary agricultural systems.

Romanian researchers I. Sulea & F. Sala (2022) highlighted the significance of combined applications of biodynamic preparations for improving the physiological parameters and productivity of winter wheat. Their study demonstrated the effectiveness of such approaches in alternative cultivation systems, enhancing plant growth and yield under challenging agro-climatic conditions. Similarly, C. Iordan *et al.* (2022) investigated plant protection systems against diseases and pests in Romania and other European countries. They confirmed that the integrated application of protection measures is essential for maintaining high yields, particularly in the context of increasing pathogen pressure. Soil tillage methods are another critical aspect for improving winter wheat cultivation efficiency. Research by I. Prymak *et al.* (2023) in Ukraine and M. Nankova & S. Doneva (2024) in Bulgaria demonstrated the effectiveness of both conventional and no-till systems in preserving soil structure and enhancing productivity. These methods ensure better soil preparation for sowing and contribute to higher yields by reducing the adverse effects of erosion and improving conditions for plant root systems.

However, the specific features of integrating fertilisation systems and crop predecessors for the efficient cultivation of winter wheat in high-productivity different-field crop rotations under the unstable moisture conditions of the Left-Bank Forest-Steppe zone of Ukraine require further investigation and analysis.

The study aimed to identify, synthesise, and systematise scientifically grounded measures for the efficient cultivation of winter wheat in high-productivity five-field and ten-field crop rotations with varying levels of cereal saturation under the unstable moisture conditions of the Left-Bank ForestSteppe zone of Ukraine.

Materials and Methods

The research was conducted as part of long-term stationary experiments at the Cherkasy State Agricultural Research Station of the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine". This station is located in the Left-Bank Forest-Steppe zone of Ukraine, characterised by unstable moisture conditions, and is situated on typical low-humus, medium loamy chernozem soils. The study adhered to ethical standards outlined in the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992). Between 2021 and 2023, the research evaluated the efficiency of cultivating winter wheat in high-productivity five-field and ten-field crop rotations with 60-100%

cereal saturation, including 20-40% winter wheat and 10-20% spring wheat, depending on their arrangement and proportion. This analysis incorporated various predecessors and the application of mineral fertilisers (Table 1, 2). The total research area was 27 hectares, with a plot size of 230 m² for sowing and 100 m² for accounting, and each trial was conducted in triplicate.

Table 1. *Structure of sown areas of five-field crop rotations*

Variant No.	Structure of sown areas, %											
	Cereals (total)	Including:					Row crops (total)	Including:		Spring rapeseed	Annual and perennial grasses	Oilseed radish
		Winter and spring wheat	Spring barley	Oats	Maize for grain	Legumes		Maize for silage	Sunflower			
Application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land												
1	80	40	20	-	-	20	-	-	-	20	-	-
2	80	40	-	20	-	20	-	-	-	20	-	-
3	80	20	-	-	20	40	-	-	-	20	-	-
4	80	20	-	-	40	20	-	-	-	-	-	20
5	60	60	-	-	-	-	-	-	-	-	20	20
6	60	40	-	-	20	-	-	-	-	-	20	20
Application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land												
7	100	40	-	-	20	40	-	-	-	-	-	-
8	100	40	20	-	20	20	-	-	-	-	-	-
9	60	40	-	-	-	20	40	20	20	-	-	-
10	80	40	-	-	20	20	-	-	-	-	20	-
11	100	40	-	-	-	60	-	-	-	-	-	-
12	80	20	20	-	20	20	40	20	-	-	20	-

Source: developed by the authors

Table 2. *Structure of sown areas of ten-field crop rotations*

Variant No.	Structure of sown areas, %										
	Cereals (total)	Including:				Row crops (total)	Including:			Annual and perennial grasses	Oilseed radish
		Winter and spring wheat	Spring barley	Maize for grain	Legumes		Maize for silage	Sugar beet	Sunflower		
Without fertiliser application											
1	70	30	10	10	20	20	10	10	-	10	-
Application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land											
2	80	30	-	20	30	20	10	-	10	-	-
3	60	30	20	-	10	20	10	-	10	10	10
4	90	40	-	20	30	10	-	-	10	-	-
5	70	20	-	30	20	10	-	-	10	-	10
6	70	30	10	10	20	20	10	10	-	10	-
7	60	20	10	10	20	10	10	-	-	20	10
8	100	30	10	30	30	-	-	-	-	-	-
9	70	30	-	10	30	30	10	-	20	-	-

Source: developed by the authors

The weather conditions during the years of the study were generally favourable for the growth and development of winter wheat plants. However, the 2020/2021 and 2021/2022 growing seasons were characterised by uneven precipitation distribution and excessive drought, which adversely affected winter wheat yield formation.

The study utilised regionally adapted varieties and hybrids of agricultural crops listed in the State Register of Plant Varieties Suitable for Distribution in Ukraine (2024). To achieve the research objectives, a combination of general scientific and specialised methods was employed: field and laboratory-field methods were applied to obtain experimental data on the impact of scientifically justified measures on the efficiency of cultivating winter wheat in high-productivity fivefield and ten-field crop rotations with varying cereal saturation; comparative and computational methods were used to determine winter wheat yield, as well as the quantitative indicators of productivity and the economic efficiency of five-field and ten-field crop rotations; mathematical and statistical methods were employed to assess the reliability of the research results; the abstractlogical method facilitated the formulation of conclusions and the development of a series of scientifically substantiated measures for the efficient cultivation of winter wheat in high-productivity crop rotations under conditions of unstable moisture to ensure Ukraine's food security.

Results and Discussion

Over the 2021-2023 study period, it was determined that in five-field crop rotations, pea was the most effective preceding crop for winter wheat, yielding the highest productivity of this key strategic crop (Table 3). Specifically, the maximum yield of 6.64 t/ha was observed with the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land in crop rotations with 60% cereal saturation, including 20% winter wheat and 20% spring wheat (Variant 9). The application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land in crop rotations with 80% cereal saturation, also with 20% winter wheat and 20% spring wheat, resulted in high yields of 6.33-6.43 t/ha (Variants 2, 4). Other preceding crops ranked in descending order of effectiveness were annual grasses (vetch-oat mixture), spring barley, and spring wheat. Winter wheat yields following pea cultivation were 7.1-18.1% higher compared to these alternatives.

Table 3. *Winter wheat yield in five-field crop rotations depending on preceding crops, t/ha, average for 2021-2023*

Variant No.	Preceding crop	Yield, t/ha			
		2021	2022	2023	Average
Application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land					
1	Pea	6.52	5.22	6.80	6.18
	Spring barley	6.48	4.24	6.42	5.71
2	Pea	6.64	5.60	6.76	6.33
3	Pea	6.19	5.43	6.62	6.08
4	Pea	6.28	5.24	7.78	6.43
5	Annual grasses (vetch-oat)	6.00	5.10	6.74	5.95
	Spring wheat	5.97	4.70	5.64	5.44
6	Annual grasses (vetch-oat)	5.80	4.90	6.30	5.67
Application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land					
7	Pea	6.42	5.38	6.65	6.15
8	Pea	6.38	5.30	8.11	6.59
9	Pea	6.63	5.30	8.00	6.64
10	Annual grasses (vetch-oat)	6.09	5.02	7.40	6.17
11	Spring wheat	6.70	5.58	7.12	6.47

Table 3. *Continued*

Variant No.	Preceding crop	Yield, t/ha			
		2021	2022	2023	Average
12	Annual grasses (vetch-oat)	5.90	4.67	6.03	5.53
	LSD_{05}	0.16	0.15	0.17	-

Source: compiled by the authors based on research findings

On average, from 2021 to 2023, the highest yield of winter wheat in ten-field crop rotations was obtained following pea cultivation with the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land (Table 4). Specifically, the maximum yield of 6.44 t/ha was recorded in a crop rotation with 80% cereal saturation, including 30% winter wheat (Variant 2). Other preceding crops can be ranked in descending order of effectiveness as follows: annual grasses (vetch-oat), soybeans, perennial grasses, spring barley, oilseed radish, and silage maize. Winter wheat yields following pea cultivation were 7.5-24.4% higher compared to these alternatives. The yield increase for winter wheat resulting from the application of mineral fertilisers was as follows: after pea – 39-60%, after perennial grasses – 43%, and after maize for silage – 36-42% (Variants 1, 6).

Table 4. *Winter wheat yield in ten-field crop rotations depending on preceding crops, t/ha, average for 2021-2023*

Variant No.	Preceding crop	Yield, t/ha			
		2021	2022	2023	2021
Without fertiliser application					
1	Perennial grasses	3.60	3.44	4.63	3.89
	Pea	3.70	3.56	4.80	4.02
	Maize for silage	3.48	3.29	3.96	3.58
Application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land					
2	Pea	5.80	5.67	7.86	6.44
	Pea	5.68	5.13	5.95	5.59
	Maize for silage	5.00	4.60	5.51	5.04
3	Maize for silage	4.90	4.34	5.62	4.95
	Annual grasses (vetch-oat)	5.40	5.56	6.27	5.74
	Oilseed radish	5.50	4.78	5.48	5.25
4	Soybeans	5.73	5.29	6.34	5.77
	Pea	6.20	5.40	6.86	6.15
	Maize for silage	4.88	4.45	5.90	5.08
5	Annual grasses (vetch-oat)	5.75	5.20	6.94	5.96
	Soybeans	5.87	4.66	6.20	5.58
6	Perennial grasses	5.49	5.00	6.21	5.57
	Pea	5.90	5.34	7.04	5.79
	Maize for silage	4.80	4.28	5.52	4.87
7	Pea	6.40	5.80	7.02	6.41
	Maize for silage	5.10	4.30	5.46	4.95
8	Spring barley	5.54	4.90	5.80	5.41
	Pea	6.60	5.48	6.46	6.18
9	Pea	6.70	5.50	7.03	6.41
	Pea	6.38	5.20	7.02	6.20
	Maize for silage	4.97	4.64	5.40	5.01
	LSD_{05}	0.15	0.14	0.16	-

Source: compiled by the authors based on research findings

The differences in weather conditions during the growing season of winter wheat in the years of the study influenced its yield, both in five-field and ten-field crop rotations. The impact of uneven precipitation distribution and drought conditions in 2021 and 2022 led to a decrease in the yield of winter wheat following all preceding crops. The most unstable data were observed in 2022, when, in the five-field crop rotations, the lowest winter wheat yield was recorded with the application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land following spring barley – 4.24 t/ha. In the ten-field crop rotations, the lowest yield was observed with the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land following silage maize – 4.284.64 t/ha. Due to the lack of moisture in 2021, the combined effect of agronomic measures was generally significant, leading to an increase in the yield of winter wheat compared to 2022. In the favourable weather conditions of 2023, the yield of winter wheat was significantly higher compared to 2021. The greatest increase in yield was observed in all variants where peas were used as the preceding crop. Specifically, the highest yield of 8.11 t/ha was achieved by increasing the mineral fertiliser application rate to $N_{60}P_{64}K_{64}$ per hectare of arable land in a five-field crop rotation with 100% saturation of cereal crops, including 20% winter and spring wheat. With the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land in a ten-field crop rotation with 80% cereal crop saturation, including 30% winter wheat, the maximum yield of 7.86 t/ha was obtained. Therefore, the impact of preceding crops, the placement and ratio of cereal crops, and fertilisation in five-field and ten-field crop rotations with 60-100% cereal crop saturation, including 20-40% winter wheat and 10-20% spring wheat, on the yield of winter wheat is limited by both temperature and moisture conditions.

On average, from 2021 to 2023, the application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land in a five-field crop rotation with 80% cereal crop saturation, including 40% maize for grain, 20% winter wheat, 20% peas, and 20% oilseed radish (Variant 4), contributed to the highest productivity indicators: grain yield of 7.22 t/ha; grain harvest of 5.78 t/ha, including 4.49 t/ha of fodder; 10.47 t/ha of feed units; 0.77 t/ha of digestible protein, alongside high winter wheat yield of 6.43 t/ha (Fig. 1). This crop rotation resulted in a reduction of grain production costs to 3.36 thousand UAH/t; feed unit costs to 1.85 thousand UAH/t, while achieving a high net profit of 22.82 thousand UAH/ha and a profitability level of 123% (Fig. 2).

With the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land, the best results were observed in a five-field crop rotation with 80% cereal crop saturation, including 20% winter wheat, 20% spring wheat, 20% soybeans, 20% maize for grain, and 20% annual grasses (Variant 10). This crop rotation achieved the highest productivity indicators: grain yield of 6.69 t/ha; feed units of 8.71 t/ha; digestible protein of 0.75 t/ha, alongside a high winter wheat yield of 6.17 t/ha; grain harvest of 4.20 t/ha, including 2.13 t/ha of food-grade grain and 2.07 t/ha of fodder. This crop rotation ensured a high net profit of 21.92 thousand UAH/ha and a profitability level of 125%. The most economically advantageous crop rotation was one with 60% cereal crop saturation, including 20% winter wheat, 20% spring wheat, 20% peas, and 20% sunflowers and maize for silage, which resulted in the highest net profit of 26.93 thousand UAH/ha and a profitability level of 151% (Variant 9).

On average, between 2021 and 2023, the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land in a ten-field crop rotation with 70% cereal crop saturation, including 30% maize for grain, 20% winter wheat, 20% soybeans, and 10% sunflowers, oilseed radish, and annual grasses (Variant 5), contributed to achieving the highest productivity indicators: grain yield of 7.44 t/ha; digestible protein of 0.77 t/ha with a high winter wheat yield of 5.77 t/ha;

feed units of 8.54 t/ha; grain harvest of 3.92 t/ha, including 1.15 t/ha of food-grade grain and 2.77 t/ha of fodder (Fig. 3). This crop rotation resulted in a reduction in the cost of grain production to 4.99 thousand UAH/t; cost of feed unit to 2.29 thousand UAH/t, while ensuring a high net profit of 22.97 thousand UAH/ha and a profitability level of 124% (Fig. 4).

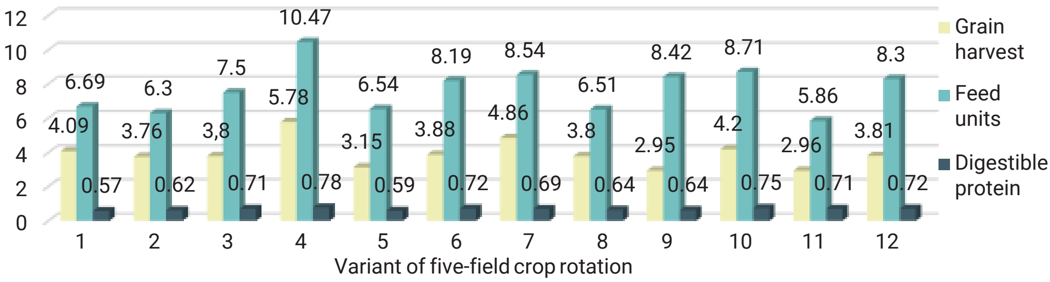

Figure 1. *Productivity of five-field crop rotations depending on cereal crop saturation, t/ha, average for 2021-2023*

Source: compiled by the authors based on research findings

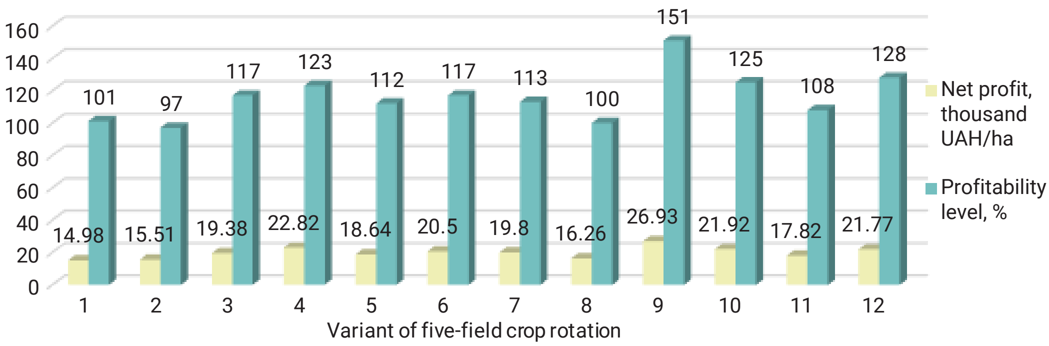

Figure 2. *Economic efficiency of five-field crop rotations depending on cereal crop saturation, average for 2021-2023*

Source: compiled by the authors based on research findings

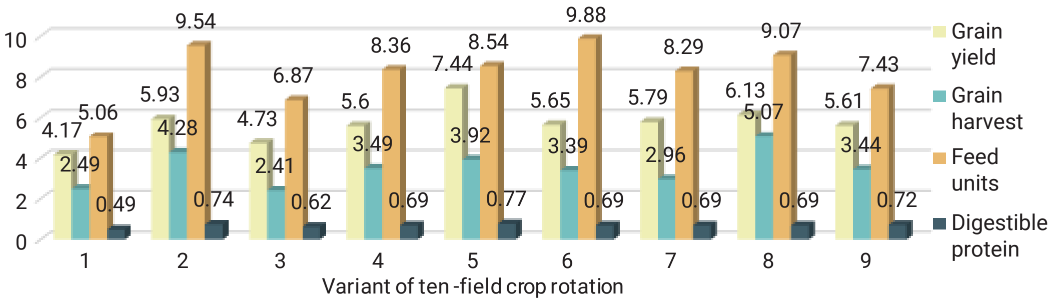

Figure 3. *Productivity of ten-field crop rotations depending on cereal crop saturation, t/ha, average for 2021-2023*

Source: compiled by the authors based on research findings

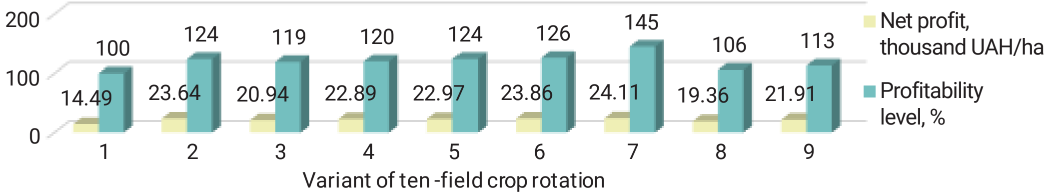

Figure 4. *Economic efficiency of ten-field crop rotations depending on cereal crop saturation, average for 2021-2023*

Source: compiled by the authors based on research findings

In a ten-field crop rotation with 60% cereal crop saturation, including 20% winter wheat, the use of two fields of perennial grasses and maize for silage resulted in the lowest cost of feed units – 2.01 thousand UAH/t, which provided the highest net profit of 24.11 thousand UAH/ha and a profitability level of 145% (Variant 7).

The increase in productivity and economic efficiency due to the application of mineral fertilisers was as follows: cereal crop yield – 26%; grain harvest – 27%, including food-grade grain – 30%, fodder – 23%; feed units – 49%; digestible protein – 29%; net profit – 39%; and profitability level – 26% (Variants 1, 6).

Based on the conducted research, it has been proven that the application of mineral fertilisers at rates of $N_{52-60}P_{56-64}K_{56-64}$ per hectare of arable land in five-field and ten-field crop rotations with 6080% cereal crop saturation ensures the highest winter wheat yield, productivity, and economic efficiency when using a leguminous predecessor.

Other researchers have also conducted similar studies. For instance, according to S. Kudria (2020), the effectiveness of using leguminous predecessors for winter wheat is fully confirmed, resulting in increased yields and productivity indicators in short-rotation four-field crop rotations. The results of the current research also align with the findings of I. Prymak *et al.* (2022), highlight the high productivity, economic, and energy efficiency of using organo-mineral fertilisers and differentiated soil cultivation when growing winter wheat after leguminous predecessors in short-field crop rotations. Specifically, the highest economic and energy efficiency indicators were achieved with the annual application of 12 tonnes of manure and $N_{95}P_{82}K_{72}$ per hectare of arable land. To improve biodiversity, the authors recommend including 20% white mustard as a green manure crop in five-field crop rotations.

Researchers M. Tkachenko *et al.* (2023) confirm the effectiveness of using leguminous predecessors for winter wheat in long-field crop rotations and the application of green manures and post-harvest residues alongside mineral fertilisers, as well as liming. They have demonstrated that the use of these technological practices contributes to an increase in productivity indicators of seven-field crop rotations by 1.2-2.5 t/ha annually. The effectiveness of growing winter wheat after leguminous crops in crop rotations with the application of mineral fertilisers and micronutrients (manganese and silicon) is examined by V. Ivanina & T. Prokopiuk (2024). The authors found that the highest yields and grain quality of winter wheat were achieved with the application of $P_{60}K_{60}$ before ploughing, ammonium sulphate N_{60} on frozen soil, and two foliar applications of urea in the phases of formation of the tube and earing ($N_{30} + N_{20}$), combined with manganese and silicon micronutrients.

Significant attention is devoted to the development and use of modern winter wheat varieties with high genetic productivity potential and resistance to adverse factors. These varieties, which have been obtained through genetic improvement and the implementation of innovative breeding methods, possess enhanced characteristics that enable them to be effectively cultivated under changing climatic conditions, ensuring stability and high-quality yields. For example, research conducted in Ukraine (Morhun *et al.*, 2022; Vakulenko *et al.*, 2024) confirms that modern Ukrainian varieties exhibit increased drought resistance and can withstand significant temperature fluctuations, which is particularly important in the context of climate change. They also demonstrate good resistance to diseases, particularly brown rust and fusarium head blight, which significantly reduces the need for chemical protection measures.

In Bulgaria, the research by E. Dimitrov *et al.* (2022) focuses on the adaptation of local varieties to the specific regional climate, particularly the drought conditions observed in recent years. The authors found that the new varieties demonstrate stable productivity, maintaining high grain quality even under reduced moisture conditions, making them attractive for dissemination in other regions with similar climatic conditions.

Egyptian scientists H. Elsayed *et al.* (2022) also studied the productivity of winter wheat varieties, taking into account the challenges posed by high temperatures and limited water resources. They noted that new varieties, characterised by increased drought tolerance and the ability to efficiently utilise moisture, show promise for large-scale implementation. This is particularly important for countries with arid climates, where the rational use of water resources is a key factor in ensuring food security.

Thus, modern winter wheat varieties that have been adapted to extreme weather conditions show great potential for further dissemination in global agriculture. Their use not only enhances productivity and grain quality but also reduces dependence on agrochemicals, contributing to the development of resilient and environmentally sustainable agroecosystems. These varieties are strategically important for ensuring food security in the context of climate change and the growing demand for food.

Overall, the findings of current research align with those of O. Tonkha *et al.* (2024), who established the effectiveness of mineral fertiliser application in winter wheat cultivation within short-rotation five-field crop rotations. Their study revealed that the highest winter wheat yield was achieved with optimal mineral fertiliser application at a rate of $N_{81}P_{54}K_{62}$ per hectare of arable land, which, alongside the residual effects of organic fertilisers, helped preserve soil resources and prevent potential soil contamination. Specifically, this organo-mineral fertilisation system ensured the maximum content of available phosphorus, which ranged from 4.8 to 8.5 mg/100 g of soil.

Key aspects of the issue, particularly the pre-sowing application of complex fertilisers to optimise the parameters for wheat yield and grain quality in winter wheat cultivated in a short-field crop rotation after a legume predecessor, were discussed by B. Mazurenko *et al.* (2021). The current study established the optimal parameters and patterns for the formation of yield structure components of winter wheat depending on the fertiliser formulation DuraSOP: the number of productive stems, grains per ear, grain weight per ear, and the 1,000-grain weight.

M. Nankova & S. Doneva (2024) determined that the yield and grain quality of winter wheat in short-field crop rotations are most influenced by the application of soil cultivation systems. Specifically, the highest yield of winter wheat in a four-field crop rotation was achieved with the implementation of a soil tillage system that included conventional deep ploughing at 24-26 cm for spring crops and disking at 10-12 cm for winter wheat, which showed a 6.4% increase compared to the continuous use of conventional deep ploughing. The current study revealed that interrupting annual conventional deep ploughing with disking or a No-till system for winter wheat in a four-field crop rotation resulted in the highest output of crude protein.

Thus, addressing the issue of effectively cultivating winter wheat in high-productivity crop rotations with varying cycles is both highly relevant and complex. The role of predecessors, fertilisation systems, and soil cultivation in increasing winter wheat yield is indisputable, but it is also crucial to establish the effectiveness of different placement and ratios of cereal crops in crop rotations concerning climate change. The conducted research revealed the impact of various predecessors and fertilisation systems on the yield of winter wheat, productivity, and economic efficiency in five-field and ten-field crop rotations with different levels of cereal crop saturation under conditions of unstable moisture.

Conclusions

It was found that, on average, from 2021 to 2023, the highest winter wheat yield was achieved after peas: in a five-field crop rotation with 60% cereal crop saturation, including 20% winter and spring wheat, and the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land – 6.64 t/ha; in a ten-field crop rotation with 80% cereal crop saturation, including 30% winter wheat, and the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land – 6.44 t/ha. The increase in winter wheat yield was: after peas, compared to other predecessors, in five-field crop rotations – 7.1-18.1%, in ten-field crop rotations – 7.5-24.4%; from the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land in ten-field crop rotations after peas – 39-60%, after perennial grasses – 43%, after maize for silage – 36-42%.

The highest productivity rates were achieved in five-field crop rotations with 80% cereal crop saturation: 40% maize for grain, 20% winter wheat and peas, and 20% oilseed radish, with the application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land; 20% winter and spring wheat, soybeans, and maize for grain, as well as 20% annual grasses, with the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land. In a ten-field crop rotation with 70% cereal crop saturation, including 30% maize for grain, 20% winter wheat and soybeans, and 10% sunflowers, oilseed radish, and annual grasses, the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land was optimal. The highest net profit – 26.93 thousand UAH/ha, and a profitability level of 151% were achieved in a five-field crop rotation with 60% cereal crop saturation, including 20% winter wheat, spring wheat, and peas, as well as 20% sunflowers and maize for silage, with the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land.

Further research should focus on determining the effectiveness of growing cereal crops in high-productivity different-field crop rotations, depending on fertilisation systems, soil treatment, and predecessors, based on the assessment of productivity, economic, and energy efficiency.

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None.

Conflict of Interest

None.

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Ефективне вирощування пшениці озимої у високопродуктивних різноротаційних сівозмінах в умовах нестійкого зволоження Лісостепу України

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Анотація. У зв'язку зі змінами клімату вагомого значення набуває застосування сучасних технологій вирощування пшениці озимої у науково обґрунтованих сівозмінах, що сприятиме підвищенню її урожайності та обсягів виробництва та забезпечуватиме потреби внутрішнього ринку і стабільного експорту української зернової продукції. Метою дослідження було встановлення, узагальнення та систематизація науково обґрунтованих заходів для ефективного вирощування пшениці озимої у високопродуктивних п'ятипільних та десятипільних сівозмінах з різним насиченням зерновими культурами в умовах нестійкого зволоження Лівобережного Лісостепу України. Для досягнення мети використовували систему загальнонаукових та спеціальних методів дослідження: польовий, лабораторно-польовий, порівняльно-розрахунковий, математично-статистичний та абстрактно-логічний. Встановлено, що у середньому за 2021-2023 рр. виконання досліджень, найвищу урожайність пшениці озимої, яка становила 6,64 т/га, отримали після гороху у п'ятипільній сівозміні з 60 % насиченням зерновими культурами та внесенням мінеральних добрив у нормі $N_{60}P_{64}K_{64}$ на 1 га ріллі. У п'ятипільних сівозмінах приріст урожайності пшениці озимої після гороху у порівнянні з травами багаторічними, ячменем ярим та пшеницею ярою становив 7,1-18,1 %. Високу урожайність пшениці озимої, яка становила 6,44 т/га, отримали після гороху в десятипільній сівозміні з 80 % насиченням зерновими культурами та внесенням мінеральних добрив у нормі $N_{60}P_{60}K_{60}$ на 1 га ріллі. У десятипільних сівозмінах приріст урожайності пшениці озимої після гороху у порівнянні з травами однорічними (вико-овес), соєю, травами багаторічними, ячменем ярим, редькою олійною, кукурудзою на силос становив 7,5-24,4 %; приріст урожайності пшениці озимої від внесення мінеральних добрив у нормі $N_{60}P_{60}K_{60}$ на 1 га ріллі склав: після гороху – 39-60 %, після трав багаторічних – 43 %, після кукурудзи на силос – 36-42 %. Найбільш економічно вигідною відзначено п'ятипільну сівозміну із 60 % насиченням зерновими культурами та внесенням мінеральних добрив у нормі $N_{60}P_{64}K_{64}$ на 1 га ріллі, де отримали найвищий умовно чистий прибуток – 26,93 тис. грн/га і рівень рентабельності – 151 %

Ключові слова: п'ятипільні та десятипільні сівозміни; насичення зерновими культурами; попередники; мінеральне удобрення; продуктивність; економічна ефективність