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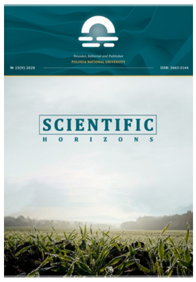

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Restoration of war-damaged soil fertility to ensure sustainable agricultural production, food security and global recognition of Ukraine

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Abstract. The introduces new agrotechnological crop rotations is relevant in the context of environmental protection. The study aims to investigate the effectiveness of introducing two crop rotations on degraded lands in the Mykolaiv region, where active military operations were conducted. The study determined that the introduction of new crop rotations led to a 1.3-fold increase in gross output compared to previous data. In a five-field crop rotation, growing perennial grasses for green fodder together with annual grasses for silage restored soil fertility and increased yields by 30 c/ha compared to existing economic indicators. Oat yields with perennial grasses increased by 18 c/ha. Growing corn for silage and green fodder provided an additional 100 cwt/ha. An increase in the yield of fodder roots and annual grasses for green fodder by 110 c/ha demonstrated the effectiveness of the new crop rotations. In a seven-season

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crop rotation, the introduction of perennial grasses increased soil fertility reduced soil erosion, and increased yields of winter wheat and sugar beet. Sugar beet yields increased by 25 c/ha, while potatoes and grain corn yields increased by 55 c/ha. The introduction of annual grasses, pulses and buckwheat helped to increase yields by 28 c/ha. The results of the study can be used by local communities to develop and implement environmental measures and programmes aimed at restoring the structure and fertility of damaged lands and preserving their quality

Keywords: crop rotation; plants; compaction; dunder molasses; organic fertilisers; phytoremediation

INTRODUCTION

The topic of the study needs to be explored, as one of the main environmental problems in Ukraine is the problem of soil degradation damaged by military operations. This problem exists because military operations are often accompanied by intense bombing, explosions and the use of chemicals that affect soil quality and fertility. Heavy metal contamination can harm agriculture through reduced yields, as well as loss of food quality and safety (Shaforost *et al.*, 2024).

One of the challenges of sustainable production of S. Shahini *et al.* (2023) notes a decrease in yields due to excessive application of inorganic fertilisers. According to the results of their study, the balanced application of organic nitrogen fertilisers not only contributed to an increase in yields but also supported the environmental sustainability of agricultural ecosystems. The impact of different types of organic fertilisers on the biodiversity of soil microorganisms and macroorganisms, such as biological nitrogen sources, composts, mulch, etc., should be further studied. The problem of low soil fertility and winter wheat yields is noted by A. Panfilova (2021). According to the findings, the use of the stubble biodestructor led to an increase in winter wheat yields, especially after spring barley and peas. The gap that needed to be addressed was to test the effect of stubble biodegradation on other soil and plant parameters, such as microelement balance, resistance to pathogens, or the impact on soil biodiversity.

The problem of the lack of optimal technologies for soil restoration is noted by O.O. Efremova and D.V. Repetskyi (2023). Based on the results of the study, it was recommended to introduce crop rotation, phytoremediation, chemical reclamation, reclamation and the application of organic fertilisers such as phosphate rock, phosphorus and potash fertiliser. A systematic assessment of the state of land resources aimed at monitoring soils and crops is needed. The problem of soil contamination with radionuclides, heavy metals, pesticides, oil and oil products is discussed by I. Boretska *et al.* (2021). According to the results of their research, energy crops such as miscanthus, willow, poplar, switchgrass, sorghum, sainfoin, red clover, and sweet clover are recommended for cultivation. The disadvantage of the study is that it did not consider the economic aspects of growing energy crops for phytoremediation.

The problem of soil contamination with cadmium was studied by H. Haller *et al.* (2023). The results of their work showed that *Amaranthus hypochondriacus* could be effectively used for the remediation of cadmium-contaminated sites due to its ability to hyperaccumulate this metal from the soil. To fully assess the potential of using *Amaranthus hypochondriacus* for remediation of cadmium-contaminated soils, additional research is needed, including on the impact of this process on the ecosystem. The problem of the heterogeneous distribution of elements titanium (Ti), iron (Fe) and copper (Cu), arsenic (As), strontium (Sr) and manganese (Mn) in plants and soil was investigated by V. Pidlisnyuk *et al.* (2020). Their study revealed that the high potential of miscanthus phytoremediation can be an effective tool for soil remediation. Further experiments and comparisons of laboratory and field conditions are needed to better understand the effectiveness of principal component analysis and general linear model approaches and their potential benefits for the ecological restoration of degraded ecosystems.

The need to study the problem of increasing nitrate concentration in soil contaminated with diesel fuel during the growing season was pointed out by V.O. Khomenchuk *et al.* (2023). As a result of the study, they determined that the application of biochar contributed to the enrichment of the soil with nitrates. The study can be supplemented by developing recommendations for the optimal use of biochar and other fertilisers for balanced nitrogen nutrition of plants. The problem of heavy metal contamination of soil, water and air because of military operations was noted by D. Papusha *et al.* (2023). As a result of their research, they recommended the introduction of optimal crop rotations with a variety of plant species, as well as the use of genetic engineering to create plants with an increased ability to cleanse the soil of contaminants. The paper does not fully cover all the possible consequences of heavy metal contamination of soil and water, such as the impact on human health and biodiversity.

The problem of reducing the sown areas of legumes and perennial grasses was noted by V. Gamajunova *et al.* (2021). Based on the results of their work, they recommended the use of farm manure and the incorporation of straw and stubble. The study's shortcoming was that it did not consider the possibility of secondary pollution of soil and water resources as a result of the use of commercial biodegraders. The need to create more productive and adapted varieties of giant miscanthus was noted by C. Wang *et al.* (2020). After conducting a scientific study, they found that the root system of miscanthus can effectively increase the distribution and transformation of various heavy metals such as lead, cadmium, and copper. The shortcomings of the scientific work include the limited number of studies on the impact of miscanthus on biodiversity and ecosystem processes.

The purpose of the study is to assess the effectiveness of introducing new crop rotations on the territory of the private rental company (PRC) "Victoria". Objectives: to develop a methodology for introducing new agricultural-technological crop rotations on degraded lands; to conduct an experimental study of the effectiveness of introducing two crop rotations: five- and seven-manure.

MATERIALS AND METHODS

In conducting the scientific work, research methods were used to analyse agrotechnical measures, and assess the yield and value of crop production, established by Law of Ukraine No. 962-IV (2003) and Resolution of the Cabinet of the Ministers of Ukraine No. 164-2010-p (2010). The study applied the method of crop rotation to increase soil fertility and preserve moisture. The method of characteristic (key) plots to determine the yield of the plant under study over large areas of germination of this plant. A method for determining field soil moisture is to measure soil weight before and after drying. The research was carried out during 2022-2023 on the arable land of PRC "Victoria", located in Mykolaiv region, Bashtanka district, Stantsiynske village. The soil cover is represented by the southern black soil of the Steppe zone of Ukraine.

The study of field moisture dynamics in sod-podzolic soils of the Mykolaiv region and the impact of molasses bards and mineral fertilisers on this process was conducted at the experimental field of the Educational and Research Centre of Mykolaiv National Agrarian University. The project envisages the introduction of two new crop rotations on the arable land of PRC "Victoria" with a total area of 759.0 ha. A fodder five-field crop rotation of 149.6 ha with an average field size of 29.9 ha and crop rotation was introduced near the main areas of existing fodder lands: 1 field – perennial grasses for green fodder and annual grasses for silage; 2 field – oats; 3 field – corn for silage and corn for green fodder; 4 field – fodder roots and annual grasses for green fodder; 5 field – oats with perennial grasses. On the remaining arable land, a seven-field crop rotation was designed for 609.4 hectares with an average field size of 87.1 hectares and the following crop rotation: 1 field – perennial grasses; 2 field – perennial grasses; 3 field – winter wheat; 4 field – sugar beet; 5 field – potatoes and corn for grain; 6 field – annual grasses, legumes and buckwheat; 7 field – spring barley with perennial grasses.

When designing the fields, one of the requirements was that the fields should be equal in size. Fields of the same size are more convenient for planning arable farming, controlling product accounting, etc. When designing fields, small paths to the fields should be avoided, while maintaining the integrity of existing arrays. In difficult conditions, deviations from the average field size of ± 10% or even more are allowed when placing fields. The characteristics of the designed fields by equilibrium are presented in Table 1.

Table 1. *Characteristics of fields by equilibrium*

Fields	Field area, ha	Average field size, ha	Deviation from the average field size (+/-)	
			ha	%
		Forage crop rotation		
I	25.1	29.9	-4.8	-3.2
II	29.9		-	-
III	29.9		-	-
IV	35		5.1	3.4
V	29.7		-0.2	-0.1
Total	149.6			
		Field crop rotation		
I	87.1	87.1	-	-
II	87.1		-	-
III	88.1		1.0	0.2
IV	87.1		-	-
V	87.1		-	-
VI	85.4		-1.7	-0.3
VII	87.5		0.4	0.1
Total	609.4			

Source: *compiled by the authors*

At PRC "Victoria", the crop rotation fields are designed to be equal in area, and rectangular in shape (length to width 3:1), with deviations from the average field size within the permissible range of ± 10%.

RESULTS

The hostilities caused both physical deterioration of the soil and chemical contamination. This was due to direct hits from shells, fires and the destruction of burnt military equipment that could contain oil products and other hazardous substances. The study by B. Biyashev *et al.* (2023) found that the content of various toxic substances in the combat zone exceeded the permissible limits several times, and the acidity of the soil was elevated. The consequence of this pollution was the spread of potentially toxic elements such as heavy metals and explosives. Crop rotation is a scientifically based alternation of crops in space and time, or only in time. Since crop rotation is the main element of agriculture, the crop rotation envisaged in it must be maintained all the time (in rotation). Crop rotation helps to reduce the number of weeds, pests and diseases. For some of the crop rotation fields, the design was based on a set of existing contours and therefore consisted of several small working plots (Table 2).

Table 2. *Explication of land by crop rotation fields*

Name of crop rotations	Average field size, ha	General area, ha	Including crop rotation fields						
			1 field	2 field	3 field	4 field	5 field	6 field	7 field
Forage crop rotation	29.2	149.6	25.1	29.9	29.9	35	29.7		
Field crop rotation	87.1	609.4	87.1	87.1	88.1	87.1	87.1	85.4	87.5

Source: *compiled by the authors*

In fodder rotation, the average field size is smaller (29.2 ha) compared to field rotation (87.1 ha). The increased average size of field crop rotation fields may indicate a larger scale of production and the possibility of more intensive use of land for field crops. The location of crops and their structure after the introduction of two crop rotations in the PRC "Victoria" are shown in Table 3. Perennial grasses for hay account for 23.1% of the total acreage, sugar beet – 11.5%, winter wheat and spring barley – 11.2%. The calculation of the value of gross crop production for the future compared to the actual situation is presented in Table 4.

Table 3. *Placement of crops in crop rotations*

Cultures	General area		Including crop rotations, ha		Total in crop rotation, ha	Deviation, ha
	ha	Option 1 Seven-season field crop rotation %	Option 2 Fodder five-field crop rotation			
Winter wheat	85	11.2	87		87	2
Spring barley	85	11.2	87		87	2
Oats	63.4	8.3		59.8	59.8	-3.6
Pulses	30.3	4	30.3		30.3	-
Buckwheat	30	4	25.7		25.7	-4.3
Sugar beets	87	11.5	87		87	-
Potatoes	60	7.9	60		60	-
Grain corn	17.9	2.4	27.1		27.1	+9.2
Silage corn	23	3		20	20	-3
Annual grasses for silage	39	5.1	31.1	7.9	39	-
Fodder root crops	10.4	1.4		10.4	10.4	-
Annual grasses for green fodder	20	2.6		19.5	19.5	-0.5
Perennial grasses for green fodder	22	2.9		22	22	-
Corn for green fodder	10.3	1.4		10	10	-0.3
Perennial grass hay	175.7	23.1	174.2		174.2	-1.5
Total crops	759	100	609.4	149.6	759	0

Source: *compiled by the authors*

Table 4. *Calculation of gross crop production under the project after the introduction of new crop rotations in the PRC "Victoria"*

Cultures	Area		Yields, hwt/ha	Gross yield	Conversion factor to conventional grain	Product yield in terms of conventional grain
	ha	%				
Winter wheat	87	11.2	37	3,219	1	3,219
Spring barley	87	11.2	38	3,306	0.8	2,644.8
Oats	59.8	2.4	38	2,272.4	0.7	1,590.7
Pulses	30.3	8.4	30	909	1.4	1,272.6
Buckwheat	25.7	4	19	488.3	1.4	683.6
Sugar beet	87	11.5	345	30,015	0.26	7,803.9
Potatoes	60	7.9	170	10,200	0.3	3,060
Grain corn	27.1	4	29	785.9	1.2	943.1
Silage corn	20.1	3	230	4,623	0.2	924.6
Annual grasses for silage	39	5.1	120	4,680	0.12	561.6
Fodder root crops	10.4	1.4	450	4,680	0.13	608.4
Annual grasses for green fodder	19.5	2.6	120	2,340	0.12	280.8
Perennial grasses for green fodder	22	2.9	150	3,300	0.15	495
Corn for green fodder	10	1.4	230	2,300	0.2	460
Perennial grass for hay	174.2	23.1	45	7,839	0.5	3,919.5
Total crops	759	100				28,467.6
Including per 1 ha of arable land						37.5

Note: *to calculate the output in terms of conditional grain per 1 ha of arable land, it is proposed to multiply 37.5 by 180 UAH (realised price of winter wheat) = 6,750 UAH*
Source: *compiled by the authors*

From the calculations, it can be concluded that the value of gross production in the PRC "Victoria" per 1 ha of arable land was 6,750 UAH, which indicated an increase in the value of gross production by 1.3 times compared to the existing state. For the soils damaged by the hostilities, the introduction of a five-field fodder crop rotation and a seven-field field crop rotation helped restore their fertility and increase crop yields.

In a five-field crop rotation, the cultivation of perennial grasses for green fodder and annual grasses for silage (total yields of 150 cwt/ha + 120 cwt/ha = 270 cwt/ha) generally led to a 30 cwt/ha increase in yield compared to the existing economic indicators (130 cwt/ha + 110 cwt/ha = 240 cwt/ha). Comparison of oat yields showed an increase of 18 centners per hectare. The cultivation of corn for silage and corn for green fodder resulted in a total yield of 460 cwt/ha (230 cwt/ha + 230 cwt/ha = 460 cwt/ha, respectively), which is 100 cwt/ha more than the previous crop rotation (170 cwt/ha + 190 cwt/ha = 360 cwt/ha). As a result, the yield of fodder roots and annual grasses for green fodder increased by 110 c/ha (450 c/ha + 120 c/ha = 570 c/ha) compared to the previous crop rotation (350 c/ha + 110 c/ha = 460 c/ha). Oats with perennial grasses increased soil fertility and restored soil structure.

In a seven-season crop rotation, the introduction of perennial grasses increased fertility and improved soil structure, reducing erosion. Winter wheat cultivation ensured efficient use of moisture and higher yields by 9 cwt/ha compared to the previous crop rotation, while sugar beet yields increased by 25 cwt/ha. Potato and grain corn yields increased by 55 c/ha (170 c/ha + 29 c/ha = 199 c/ha) compared to the previous year (120 c/ha + 24 c/ha = 144 c/ha). The introduction of annual grasses, legumes and buckwheat helped to provide the soil layer with organic residues, increase the biological nitrogen content and the development of soil microflora, and increase their yield by 28 c/ha (120 c/ha + 30 c/ha + 19 c/ha = 169 c/ha) compared to the previous figures (110 c/ha + 18 c/ha + 13 c/ha = 141 c/ha). A summary of the results of the design decisions is presented in Table 5.

Table 5. *Technical and economic indicators of the project*

	Indicators	Measurement unit	At the time of drafting	By the project
1	Total area of the village council	ha	1,063.3	1,063.3

Table 5. Continued

	Indicators	Measurement unit	At the time of drafting	By the project
2	PRC "Victoria Square"	ha	871	871
	including agricultural land	ha	858.8	858.8
	of them arable land	a	759	759
	pastures	ha	99.8	99.8
3	Number of crop rotations	pcs.	-	2
	including the aft five-point	ha	-	149.6
	field seven-point No. 1	ha	-	609.4
4	Crop production, per 1 ha of arable land	UAH	5,364	6,750

Source: *compiled by the authors*

Thus, the cost of crop production under the implemented project increased by 1,386 UAH compared to the economic indicators of the previous crop rotation, which indicated an increase in production costs and improved product quality. In addition to crop rotation planning, additional soil remediation methods such as phytoremediation to reduce heavy metals and organic fertilisation to combat soil compaction should be considered for the land in the Mykolaiv region that has been affected by the war. The hostilities in Mykolaiv region have contaminated almost 100,000 m^2 of soil (Tkach, 2023). Chemical contamination results from the leakage of fuel, combustion products that can settle on the ground from the air, and toxins from explosives in shells. However, ammunition explosions can cause not only chemical contamination but also mechanical contamination. The blast wave can lead to erosion and soil compaction in the area of agricultural land. Due to the effects of the blast wave, the fertile soil layer can be removed, its structure and composition can be altered, and vegetation and microorganisms that ensure its fertility can be destroyed. This can cause serious soil depreciation and make it difficult to restore the soil.

To reduce the concentration of mobile forms of heavy metals (cadmium, lead, copper, zinc, chromium, nickel), it is proposed to use a special fertilisation system by applying molasses dunder, which can detoxify heavy metals. Molasses dunder can be useful for combating soil over-compaction and heavy metal contamination of soils. It contains organic substances such as nitrogen, phosphorus and potassium, which nourish the soil, maintain its fertility, stimulate plant growth and can reduce heavy metal concentrations in the soil through phytoextraction or phytoremediation processes. The results of the study identified patterns and trends in the change of field moisture under the influence of various factors. Soil moisture plays a crucial role in the physiological processes and development of plants. Ensuring optimal moisture levels is critical for plant organogenesis and growth. The dynamics of field moisture in sod-podzolic soils of Mykolaiv region was studied and the effect of molasses bards and mineral fertilisers on this process was investigated.

In 2023, warm January and February were recorded, which facilitated fieldwork in April and May. July was the period with the highest air temperature (+20.7°C), but in general, the year was marked by predominantly dry weather with precipitation of 352 mm. Table 6 shows the results of the study of the effect of molasses dunder on changes in field moisture and density of soddy-loamy soil.

Table 6. *Influence of molasses dunder on the dynamics of changes in field moisture and density of soddy-loamy soil*

Variant	Soil layer, cm	May		June		July		August	
		P	W	P	W	P	W	P	W
Control (without fertilizer)	0-20	1.51	23.71	1.5	23.92	1.52	24.13	1.52	26.73
	21-40	1.56	23.5	1.6	23.92	1.63	24.02	1.55	25.75
Dunder – 10 t/ha	0-20	1.55	23.75	1.54	24.13	1.57	24.19	1.51	31.83
	21-40	1.53	23.52	1.71	24.76	1.71	24.78	1.83	27.71
Dunder – 20 t/ha	0-20	1.69	24.11	1.73	24.56	1.75	24.59	1.74	33.89
	21-40	1.7	24.03	1.84	24.34	1.85	24.35	1.75	21.9
Dunder – 30 t/ha	0-20	1.61	24.08	1.62	24.66	1.63	24.71	2.15	35.62
	21-40	1.64	24.32	1.69	23.98	1.71	24	1.49	31.29
$N_{90}P_{70}K_{170}$ – equivalent to 10 t/ha	0-20	1.63	24.06	1.58	24.32	1.59	24.29	1.93	26.18
	21-40	1.65	24.01	1.85	24.32	1.84	24.31	1.89	24.21

Note: *P – soil density, mg/cm^3; W – field humidity, %*
Source: *compiled by the authors*

The application of molasses dunder in different doses had a significant effect on the density of soil composition. In June, the variant with 10 t/ha of dunder was marked by an increase in field moisture by 0.04% compared to the control. In July and August, the application of dunder proved to be more effective, contributing to an increase in field moisture to 24.71%, providing additional soil moisture. In May, the application of 20 t/ha of dunder showed a decrease in the density of soddy-weak podzolic soil by 0.18 mg/cm^3 compared to the control. When applying 30 t/ha of dunder, the results showed a decrease in density by 0.08 mg/cm^3 compared to the control. A comparison with N90P70K170 mineral fertiliser in an equivalent dose showed the latter to be superior in terms of soil density. The study showed an important influence of molasses dunder on the dynamics of field moisture and soil density in sod-podzolic soils of southern Ukraine. The application of dunder has proven effective in increasing field moisture and reducing soil density, making it more suitable for crops. Measures to overcome the negative effects of chemical pollution should be aimed at restoring the fertility of damaged arable soils. The cultivation of giant miscanthus (*Miscanthus giganteus*) on reclaimed soils is recommended, which cleanses and improves soil structure and fertility, as well as reduces pollution or restores natural ecosystems after pollution. *Miscanthus giganteus* is used to remediate marginal and contaminated land.

Such a drought-resistant energy crop as miscanthus giganteus does not require annual ploughing for 25-28 years on the soils of the Ukrainian Forest-Steppe and grows without the use of plant protection products and fertilisers. The study noted that the plant can provide relatively cheap energy raw materials in the amount of 17-25 t/ha of dry weight already in the third year of cultivation (Damaged fields will…, 2022). A promising way to improve soil fertility is to apply organic fertiliser made from molasses dunder, a waste product of sugar production at sugar factories. Its composition is rich in organic substances that contribute to the accumulation of nitrogen, phosphorus, potassium, and important trace elements in the soil and restore soil fertility. Dunder molasses also has a positive effect on soil deoxidation. Thus, the choice of a strategy for remediation of contaminated soil using miscanthus giganteus culture and organic fertiliser in the context of chemical contamination is a promising solution for soil clean-up. Miscanthus giganteus is known for its ability to perform phytoremediation, meaning that it can absorb toxic substances from the soil through its roots and destroy them or accumulate them in its tissues. The use of organic fertilisers can promote plant growth and health by improving their phytoremediation ability and providing the necessary nutrients for their development.

DISCUSSION

Analysing the results of the study, it can be concluded that soil pollution as a result of hostilities has harmed natural ecosystems. The ecocide carried out by the aggressor state has destroyed the top fertile soil layer, which has been formed over centuries. Soils lose their fertility due to changes in physical, chemical and physicochemical properties.

This study determined that soil compaction caused by the movement of heavy machinery and vehicles had damaged its structure and degraded the soil environment. A similar issue was addressed by M.R. Shaheb *et al.* (2021). They obtained results that showed that soil compaction increased its bulk density and strength, decreased soil porosity and hydraulic properties, slowed the growth of crop roots, and reduced yields by up to 50% or more, depending on the amount and degree of soil compaction. The statement of the researchers is noteworthy, as delayed root growth reduces the efficiency of plant nutrients and water uptake, which in turn leads to lower crop yields.

The study determined that the introduction of annual grasses, legumes and buckwheat increased the content of nitrogen and organic matter in the soil. A similar problem was addressed by B.G. Jothilakshmi and J. Sivanantha (2024). Their study determined that the use of a legume crop rotation significantly improved soil conservation and increased nitrogen availability for other plants. This statement is noteworthy, as legumes are indeed able to enrich the soil with atmospheric nitrogen through symbiosis with nitrogen-fixing bacteria of the genus Rhizobium, thereby improving soil fertility for subsequent crops (Dymytrov *et al.*, 2023).

The study determined that the introduction of molasses dunder contributed to the increase of soil fertility, as molasses contained a significant amount of nutrients such as nitrogen, phosphorus, potassium, and trace elements. A similar issue was addressed by W. Hua *et al.* (2020). Their study found that the use of organic fertilisers increased the efficiency of nitrogen use, contributing to improved fertility and higher yields. This statement is noteworthy, as the use of organic fertilisers increases the number and diversity of microorganisms in the soil, which improves its structure and contributes to better moisture and nutrient retention (Yerzhanova *et al.*, 2021).

The study determined that the diversification of potato crop rotation with corn for grain had a positive impact on the restoration of soil damaged by the war. A similar issue was studied by M. Zong *et al.* (2024). Their study found that diversification of maize with winter rye halved nitrate leaching, increased soil carbon and nitrogen stocks, and improved the stability and productivity of maize yields compared to monoculture. Similar results were obtained in this study, which showed that potato and corn yields increased by 55 cwt/ha compared to the previous crop rotation.

As determined, corn for grain was an excellent precursor for the growth of legumes. A similar issue was raised by J. Hirzel *et al.* (2023). Their study shows that maize was the best previous crop to increase the yield of rapeseed and beans. In this study, similar conclusions were obtained, according to which a significant increase in the yield of legumes (beans) was found, which amounted to 30 c/ha under the condition of preliminary cultivation of corn. As noted, the use of crop rotation with legumes increased the content of biological nitrogen and improved soil fertility (Poliovyi *et al.*, 2023). A similar issue was studied by Á. Carrascosa-Robles *et al.* (2023). According to the results of their research, four legume cultivation systems with crop rotation and their combination with intercropping increased purslane production and soil enzymatic activity. The conclusions of the researchers are noteworthy, as this system contributes to improving soil structure, increasing the content of organic matter and microorganisms that restore soil fertility.

As demonstrated, potatoes and winter wheat used as previous crops were more productive than a legume crop such as peas (Vinyukov *et al.*, 2022). The study was conducted by P.A. Ooro *et al.* (2020). Their study results recommended the use of hyacinth beans *Dolichos lablab* (*L. purpureum*) and green peas as previous crops, as they proved to be more productive than potatoes or wheat. The results obtained in the present study contradict the findings of the researchers, which may be due to differences in agronomic practices such as sowing dates, crop density, pest and disease control methods, and the use of fertilisers and irrigation.

As recorded, when sugar beet and winter wheat are grown in a crop rotation, higher yields are obtained compared to grain corn. This issue was addressed by B. Boincean and D. Deny (2019). They determined that the yields of winter wheat and sugar beet in crop rotation were higher than those of corn and sunflower grown in continuous sowing. Similar conclusions were reached in this study, as it showed a high yield of sugar beet (345 c/ha), which is 316 c/ha more than corn.

The study determined that the introduction of winter wheat, spring barley and oats into the crop rotation had a positive effect on the yield of corn for silage. A similar issue was studied by E. Dube *et al.* (2023). The results of their work revealed that the inclusion of winter cover crops in maize production systems significantly improved soil organic matter content. The statements of the researchers are noteworthy, as winter crops have a strong root system that helps to store carbon and other organic matter in the soil, increasing its fertility.

The study determined that the use of phytoremediation technologies and the use of the giant miscanthus plant is important for improving the environment and human health. H. Haller *et al.* (2023). Their study revealed that the amaranth plant (*Amaranthus hypochondriacus*) can effectively extract cadmium (Cd) from the substrate even at low Cd concentrations (2 mg Cd kg per 1 kg dry weight), accumulating a significant amount of this metal in its aboveground biomass, in particular in stems and leaves. This statement is noteworthy since amaranth is indeed a well-known "hyperaccumulator" capable of actively absorbing heavy metals and partially accumulating them in its underground and aboveground parts.

To remediate the contaminated soil, it was decided to use the giant miscanthus culture and organic fertiliser (Donchak & Shkvaruk, 2024). A similar issue was studied by A. Tennakoon *et al.* (2024). Their study revealed the following reduced levels of heavy metal contamination in soil and water, which indicated the success of phytoremediation technologies. The results of the study by the researchers are noteworthy, as the use of green plants can help maintain soil cover, reducing the risk of erosion and loss of soil fertility. The study determined that the strategy of phytoremediation, and particularly the cultivation of giant miscanthus, was effective in reducing soil contamination with heavy metals. This problem was addressed by F.U. Rasool *et al.* (2023). Their research has shown that species of hyperaccumulator plants from the *Brassicaceae* family can actively accumulate heavy metals from the soil in their tissues. While agreeing with this statement, it should be noted that the opinion of the researchers is correct, as species of the *Brassicaceae* family, such as rutabagas and various types of mustard, can indeed demonstrate a high capacity for heavy metal accumulation.

As determined, the use of miscanthus in conditions of chemical contamination was an effective solution for soil purification. This issue was investigated by L. Wechtler *et al.* (2024). They present the results, according to which the joint cultivation of miscanthus and white clover increased the microbial biomass, and fungal density and stimulated the degradation of the bacterial population. The results of a study by the researchers are noteworthy, as an increase in microbial biomass and fungal density may indicate changes in the soil ecosystem that may be favourable for plant growth and soil nutrients.

As determined, the use of the giant miscanthus culture and the organic fertiliser under molasses contributed to the retention of soil moisture. This issue was studied by Z. Zgorelec *et al.* (2020). Their study determined that miscanthus is suitable for phytostabilisation and biomass production on soils contaminated with cadmium and mercury. This formulation of the researchers' conclusions is noteworthy, as the use of this plant can be useful for cleaning up contaminated soils, as well as for producing biomass that can be used as a source of energy or biofuel.

The study established that the use of miscanthus culture is effective for growing on damaged soils of the forest-steppe of Ukraine. This topic was studied by R.A. Newton *et al.* (2024). According to the results of the research, miscanthus biomass had high potential as an energy crop for reclaiming marginal lands and as an alternative energy source for climate change mitigation. The opinion of the researchers is noteworthy because miscanthus can be grown without the use of chemical fertilisers, and this plant can absorb carbon during its growth, helping to reduce greenhouse gas emissions.

As determined, phytoremediation technology contributed to the restoration of soil fertility. R. Thakur *et al.* (2022) addressed this issue. Their work demonstrated that the use of phytoremediation reduced the concentration of heavy metals in the soil by restoring their biologically active states. The conclusions of the researchers are noteworthy, as an important advantage of this remediation strategy is that this process is natural and contributes to the restoration of ecological stability and soil system functions without active interference with the natural landscape.

The study determined that the application of molasses dunder is effective in increasing field moisture and reducing soil density. This issue was addressed by S. Assefa and S. Tadesse (2019). Their research showed that organic fertilisers are superior to synthetic fertilisers, so they recommend the use of natural or combined fertilisers. The recommendations of the researchers are that the use of organic fertilisers helps to preserve soil properties and increase its fertility. As determined, the combination of giant miscanthus culture and organic fertiliser was an effective solution for cleaning the soil from heavy metal contamination. A similar topic was studied by E. D'Amours *et al.* (2021). The results of their research showed that the inclusion of a perennial cereal-legume forage mixture in a crop rotation with barley led to the accumulation of significantly higher nitrogen reserves in the soil in the 0-50 cm profile compared to a cereal monoculture. The results of my study did not coincide with the findings of the researchers, as they analysed the impact of molasses bards and mineral fertilisers on the process of changing field moisture in sod-podzolic soils.

The study found that the nitrogen, phosphorus and potassium contained in the molasses dunder are favourable substances for soil fertilisation. A similar topic was studied by M.J. Hawkesford and S. Griffiths (2019). Their study showed that genetic variation can improve the ability of plants to assimilate nitrogen from the environment, which leads to increased yields and reduced nitrogen losses. The conclusions of the researchers are noteworthy, as improving the ability of plants to assimilate nitrogen can indeed be achieved through the selection and development of plant varieties or hybrids with improved genetic properties. This section reviewed the literature and considered studies on soil compaction caused by heavy machinery and vehicles, and the impact of various agronomic practices, such as crop rotation, organic fertilisation, and phytoremediation technologies on soil fertility and crop yields.

CONCLUSIONS

The study found that in active military operations in the Mykolaiv region, the implementation of the project to introduce new crop rotations at PRC "Victoria" contributed to improving soil quality and increasing crop yields. The cost of crop production per 1 ha of arable land in the previous crop rotation was 5,364 UAH, while according to the new project, it was 6,750 UAH. Thus, the cost of crop production under the project increased by 1,386 UAH per hectare of arable land, which indicated positive changes in economic indicators and increased production efficiency.

As a result of analysing the impact of molasses dunder on the dynamics of field moisture and soil density in sod-podzolic soils of southern Ukraine, it was found that the application of molasses dunder is effective in increasing field moisture and reducing soil density. In particular, the application of molasses dunder in July and August contributed to an increase in field moisture by 24.71% compared to the control. The composition of the molasses dunder is rich in organic matter, which resulted in the accumulation of nitrogen, phosphorus, potassium, and important trace elements in the soil and the restoration of soil fertility. To improve soil fertility in the Mykolaiv region, it is recommended to grow giant miscanthus and apply organic fertiliser under molasses in conditions of chemical pollution. In the review of studies of chemical contamination with heavy metals in the Mykolaiv region, it should be noted that some data on crop yields are not available for analysis or that it is impossible to collect data due to hostilities.

Further research into the factors that affect soil quality and crop yields in the Mykolaiv region could include a detailed study of the impact of new crop rotations and organic fertilisers on the region's ecosystems, an analysis of the impact of different climatic conditions on the productivity of growing miscanthus giganteus and other crops, and the development of recommendations for optimal agronomic measures to maintain and restore soil fertility in the area of active hostilities and after their completion.

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CONFLICT OF INTEREST

None.

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Відновлення родючості ґрунтів, ушкоджених війною, для забезпечення сталого агровиробництва, продовольчої безпеки та світового визнання України

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Анотація. Дослідження необхідності впровадження нових агротехнологічних сівозмін являється актуальним в контексті охорони навколишнього середовища. Метою дослідження є вивчення ефективності введення двох рослинницьких сівозмін на деградованих землях в Миколаївській області, де проводились активні воєнні дії. По результатам дослідження виявлено, що впровадження нових сівозмін призвело до збільшення валової продукції в 1,3 рази порівняно з попередніми даними. У п'ятипільній сівозміні вирощування багаторічних трав на зелений корм разом з однорічними травами на силос відновило родючість ґрунту та збільшило врожайність на 30 ц/га порівняно з існуючими економічними показниками. Врожайність вівса з підсівом багаторічних трав зросла на 18 ц/га. Вирощування кукурудзи на силос та на зелений корм забезпечило додаткові 100 ц/га. Збільшення врожайності кормових коренеплодів та однорічних трав на зелений корм на 110 ц/га свідчило про ефективність нових сівозмін. У семипільній сівозміні введення багаторічних трав збільшило родючість та зменшило ерозію ґрунту, а також підвищило врожайність озимої пшениці та цукрового буряка. Врожайність цукрового буряка збільшилась на 25 ц/га, картоплі та кукурудзи на зерно зросла на 55 ц/га. Введення однорічних трав, зернобобових та гречки сприяло підвищенню врожайності на 28 ц/га. Результати дослідження можуть бути використані місцевими громадами з метою розробки та впровадження екологічних заходів та програм, спрямованих на відновлення структури та родючості пошкоджених земель та збереження їх якості

Ключові слова: сівозміна; рослини; ущільнення; барда мелясна; органічні добрива; фіторемедіація