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Use of pre-sowing soil microbiological analysis to predict the spread of sugar beet root rot

Abstract. *Aphanomyces cochlioides* and *Rhizoctonia solani* are two of the main soil phytopathogens of sugar beet, which lead to substantial losses in yield and quality. Since disease control capabilities are complex and pathogen monitoring is important for predicting risks, it is of great importance in rural production to create available methods for preliminary field assessment. The purpose of the study was to introduce a predictive methodology for assessing the potential of soils for their suitability for growing sugar beet in the system of short-rotation crop rotations. As an indicator plant, sugar beet seeds were used, which are not characterised by genetic resistance against these diseases. The possibility of using the pre-growing disease index (PPDI), which has a gradation from 0 to 100 and covariance with the actual yield, sugar content and gross sugar yield per hectare, is tested. The pre-sowing PPDI value is compared with the actual yield from each specific field to really assess the possibility of using the PPDI index to characterise yield losses on production crops. It is determined that with an increase in the PPDI value, the gross yield of sugar beet, sugar content, and gross sugar yield decreased. The results of studies show that one unit of PPDI causes a loss of gross yield at the level of 0.24 t/ha and a decrease in the sugar harvest by 0.018 t/ha. That is why, to manage the risks of growing sugar beet, it is necessary to assess the phytopathogenic load of the soil. It is established that the most harmful and permanently identified phytopathogens are *Rhizoctonia solani* and *Fusarium* ssp, which indicates the need to select hybrids that are characterised by resistance or high tolerance to these pathogens. The information obtained can be used for timely identification of infection risks, development of effective management strategies, and improvement of agricultural techniques for growing sugar beet to reduce crop losses and increase the efficiency of agricultural products

Keywords: *Aphanomyces cochlioides*; *Rhizoctonia solani*; *Fusarium* spp.; phytopathogenic load; gross yield; sugar content

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INTRODUCTION

Sugar beet cultivation in Ukraine has several strategic tasks: providing the internal market with sugar, increasing export potential, and restoring soil fertility. Thus, beet farming is a socially and economically important branch of agriculture, which provides jobs, determines food security, and forms foreign exchange earnings in Ukraine. One of the promising management strategies for these cultivated plants is the use of pre-sowing soil microbiological analysis. This method can be an effective tool for predicting and preventing the spread of root rot, which is especially important for ensuring high quality and quantity of the crop. It is important to focus on quick detection and assessment of the risk of developing these diseases in soils to take timely and adequate measures to control them. Such an analysis can become a key element in the system of predicting and managing the risk of diseases, which will provide farmers with the opportunity to respond in time to potential threats to the sugar beet crop. The introduction of pre-sowing soil microbiological analysis in agricultural practices can help optimise agricultural techniques and provide stable conditions for growing this important agricultural crop.

According to data of I. Karas *et al.* (2019), in the conditions of Western Ukraine, root rot of various etiologies (*Rhizoctonia solani, Aphanomyces cochlioides, Fusarium spp*) cause substantial damage to sugar beet crops, and crop losses can be up to 80%, especially when growing sugar beet in a short-term crop rotation. The most common type of rot is fusarium rot, which substantially reduces the productivity of sugar beet roots. Thus, fungi of the *Fusarium* spp. genus affect the sugar beet throughout the growing season. They cause not only rotting of the root system of seedlings, fusarium rot, necrosis of vascular-fibrous bundles and leaves of sugar beet but also fusarium jaundice.

V. Rafiei *et al.* (2023) investigated various subgroups of *R. Solani,* enabling the identification of the AG2-2IIIB group, the representatives of which cause maximum harm in the cultivation of sugar beet. The interaction of pathological systems of *R. Solani* and *C. beticola* were also examined, which indicates early infection of sugar beet plants with cercosporum, if the plants were previously affected by rhizoctoniosis.

A study by Å. Olsson *et al.* (2019) demonstrated a negative correlation between the content of calcium ions and the development of root rot caused by *A. Cochlioides.* The importance of liming in terms of the availability of elements in the soil and the effect of calcium on the damage of sugar beet plants by root rot is demonstrated. In other paper, Å. Olsson *et al.* (2023) analysed the long-term effects of structured lime and ground limestone on the stability of soil aggregates, the risk of loss of mobile phosphorus, and the degree of soil disease damage in winter wheat, rapeseed, and sugar beet. The positive effect of lime use was demonstrated only on sugar beet due to a decrease in the level of root rot damage compared to the control; no effect was identified for winter wheat and rapeseed yield decreased.

Notably, *R. solani* and *A. cochlioides* have common features, which consist both in the possibility of infecting both sugar beet seedlings and plants at later stages of development. The role of microorganisms in the loss of agricultural products after harvesting is a key subject of the study by N.S. Bist *et al.* (2020). This review draws attention to the influence of microorganisms on the quality and shelf life of agricultural products. The study highlights the importance of understanding the interaction of microorganisms with collected products to effectively solve the problems of losses after harvesting in the agricultural sector. In addition, both pathogens remain in the soil for a long time, and mild warm winters lead to the preservation of the virulent pathogen and an increase in the level of pathogenicity. However, the pathogens themselves differ substantially. Taxonomically, they are not related, and the distribution of zoospores of *Aphanomyces* substantially depends on the high humidity of the soil. In addition, pathogens of *Rhizoctonia* spp have a much wider range of host plants, while *Aphanomyces* spp is a specific pathogen for sugar beet. Root rot of grain crops caused by phytopathogenic fungi is a serious problem for agricultural production. N. Grebenikova *et al.* (2018) investigated the causes and mechanisms of root rot development in cereals that cause phytopathogenic fungi. The types of fungi that most often cause this disease are analysed, and the factors that contribute to the spread of root rot in grain crops are also examined. The importance of this phenomenon for crop production is emphasised, and possible approaches to the control and prevention of root rot are being developed to ensure the stability and high yield of grain crops. Virulence factors in the interaction of a phytopathogen with a plant are an important topic that was considered by J. Pontes *et al.* (2020). In this context, the molecular and biological factors that determine the ability of phytopathogens to cause diseases and overcome the plant's defence mechanisms are considered. The study focuses on identifying and understanding these virulence factors, which may contribute to the development of new strategies for controlling phytopathogens and improving plant disease resistance.

Available means of limiting the spread of both pathogens are the following agrotechnological techniques: seed treatment with several fungicides, the use of tolerant hybrids, early sowing dates. However, none of these mechanisms of influence on the spread of pathogens guarantees 100% effectiveness, especially in the presence of both pathogens in the soil, and therefore, it is necessary to predict the risks of the development and spread of phytopathogens.

The purpose of the study was to introduce a predictive methodology for assessing the potential of soils from the point of view of suitability for growing sugar beet in short-term crop rotations, considering the problems of root rot, for making timely and correct management decisions on growing sugar beet in a particular field.

MATERIALS AND METHODS

These studies were initiated to support sustainable sugar beet production, which includes mandatory soil testing for nematodes. One of the issues of stable sugar beet cultivation is obtaining complete information about soil phytopathogens, namely the number and species composition of phytopathogens, which will allow making managerial decisions on sugar beet cultivation in the field. The resulting indicator of growing risk assessment is the pre-growing disease index (PPDI), which ranges from 0 to 100 and is based on the previously proposed development risk assessment *Aphanomyces* due to the level of moisture in the shoots (Schneider *et al.*, 1978; Lindgren *et al.*, 1995).

Microbiological analysis. The applied use of the study was tested on 45,000 hectares of short-term crop rotation over a 3-year period. A total of 1,890 soil analyses were performed. Soil samples were taken in the fields of the private enterprise "Western Bug" within the Lviv, Ternopil, and Chernivtsi regions during 2021-2023. More than 490 fields were analysed, from which 1,980 samples were taken one year before sugar beet sowing after the precursor was collected. The selection was conducted from a horizon of 10-15 cm from several points within the field. One average sample included samples from 10 sampling points each, which is averaged over 30 ha of the field.

Each soil sample was placed in 2 plastic containers with a diameter of 10 cm and kept at a temperature of 20°C for 4 days. Afterwards, 25 seeds of the Akazia KWS hybrid were added into these containers, which are not resistant to root rot. After the emergence of seedlings, daily monitoring was conducted for the presence of symptoms of infection. Any shoots with symptoms were transferred to potato-dextrose agar, where pathogens were identified by the nature of mycelium growth (Schneider *et al.*, 1978; Park & Grau, 1992). The duration of the test was 4 weeks. The index was calculated using the formula:

$$DI = \frac{[4*IS+3*IS2+2*IS3+IS4]}{[4*PE]*100}, \qquad (1)$$

where *DI* – infection rate, *ISj* – number of infected plants per week; *PE* – total number of plant emerged.

Index values indicate the level of risk of developing diseases, namely, a value of 30-45 indicates a moderate risk of the disease, a value greater than 45 indicates a high risk, and an indicator less than 30 – a low risk.

Statistical analysis – comparison of PPDI value with actual yield. The pre-sowing PPDI value was compared with the factual yield from each specific field to assess the possibility of using the PPDI index to characterise yield losses on production crops. For this task, all areas were divided into three risk categories (low, moderate, and high) based on PPDI and the following indicators were identified: gross yield, sugar content and sugar harvest per hectare, which were used to evaluate the performance of the field in each category (Windels *et al*., 2009). Covariance analysis (ANCOVA) was used to assess the relationship between variable yield parameters and PPDI among fields over different years. ANCOVA is a special type of regression analysis, it is a covariance analysis model in which both fictitious and quantitative explanatory variables can be applied. ANCOVA was performed for each yield parameter separately, where the line was suitable for each harvest year, and it was checked whether the slopes of the lines differed substantially. The study was conducted according to the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

RESULTS AND DISCUSSION

It was established that the most common soil phytopathogen that causes root rot are the representatives of the *Fusarium* ssp genus, which caused 24.07% of root rot manifestations. The least harmful among the identified pathogens were representatives of the *Phytium* ssp. genus – 2.05%. In turn, the presence of a high titer of phytopathogens in any case negatively affected the degree of root rot damage to sugar beet roots (Table 1).

Table 1. Frequency of occurrence of soil pathogens in soil samples

Pathogen	Infection index, %	Root rot, %
Aphanomyces cochlioides	9	2.18
Phytium ssp.	21	2.05
Rhizoctonia solani	53	21.93
Fusarium ssp	19	24.07

Source: compiled by the authors

As the PPDI value increased, the gross sugar beet yield, sugar content, and gross sugar yield decreased. Thus, fields characterised by a lower risk of root rot based on the PPDI value (14.17) on average had a 9.8 t higher root yield and a 1.93 t/ha higher gross sugar yield compared to high-risk fields (PPDI value 59.67) (Table 2).

Table 2. Average PPDI values and yield patterns

Risk category	PPDI	Gross yield, t/ha	Sugar content, %	Gross sugar harvest, t/ha
Low	14.17	74.5	17.24	12.84
Medium	38.96	69.8	16.94	11.82
High	59.67	64.7	16.87	10.91

Source: compiled by the authors

The correlation between the PPDI index value and gross yield is -0.9973, PPDI and sugar content -0.9574, between PPDI and gross sugar yield, it is -0.9998, which, in turn, indicates a close inverse linear relationship between these indicators. Based on the above, it can be argued that with an increase in the PPDI value, all indicators of the crop structure decrease (gross yield, gross sugar yield per ha, and sugar content). These results showed that the PPDI test can accurately predict the potential risks of root rot of various etiologies. Summarising the results obtained, it can be stated that with each unit of increase in the PPDI index, the yield in the fields under study decreased by 0.24 t/ha. A similar trend is typical for the gross sugar harvest per ha, which causes a change in the sugar content per unit of PPDI in the range of 0.018 t/ha. In addition, the identified high values of correlation coefficients between PPDI and gross yield, sugar content and gross sugar yield indicate a pronounced interdependence of these parameters. This highlights the importance of using PPDI to predict sugar beet yield and quality. The results indicate a systematic decrease in all aspects of sugar beet yield with increasing PPDI values. This close relationship allows identifying the potential risks of root rot exposure to sugar beet cultivation, allowing farmers to take effective measures to reduce crop losses and improve product quality. The PPDI test can serve as an effective tool for accurately predicting the potential risks of root rot in sugar beet, considering its impact on all aspects of yield. Thus, the ability to manage this risk can be improved by timely and accurate determination of PPDI values in the soil before cultivation.

These studies also identified some features of ecology and pathogenicity of the fungi. Firstly, a high presence frequency of *R. Solani* in soils was established, which confirms its widespread distribution among the examined samples for several years. It was detected in 53% of soil samples, but the percentage of root rot was 21.93%, compared to *Fusarium* ssp, which was 24.07%. Compared to other pathogens, such as *Fusarium* ssp, R. *Solani* was less frequent but resulted in a higher percentage of root rot. This factor, together with PPDI values, indicates a high risk of root rot, which can affect the gross yield and sugar content of sugar beet.

In turn, the development of root rot caused by *Aphanomyces* was not stable over the years and averaged 9% of the analysed samples. Given that the development of this phytopathogen mainly depends on the level of soil moisture, epiphytotics occur only under favourable conditions. Low stability in the development of root rot caused by *Aphanomyces* indicates the influence of climatic and soil conditions on the spread of this phytopathogen. In particular, its development was less stable in the context of years, and the impact on yield was less severe compared to *R. Solani*. This indicates that meteorological and agroclimatic conditions affect the activity of *Aphanomyces* and can determine the degree of its negative impact on the sugar beet culture.

Of particular importance for production is the ability to predict the types of root rot that can affect crops and substantially affect yields, which can be done using the PPDI test since it is able to predict the risks of epiphytotic development and potential yields. In addition, it is important to note the PPDI test's ability to identify different pathogens simultaneously and to determine their titer in soil samples. The test allowed demonstrating a higher level of pathogenicity of *R. solani*, a more harmful causative agent of the disease for commercial sugar beet crops, compared to *A. cochlioides*.

Notably, the PPDI test proved to be not only an effective tool for predicting the risks of root rot but also the ability to simultaneously determine the titer of various pathogens in the soil. This allows accurately determining the threat level from individual fungal pathogens and taking timely measures to control them. Finally, the low detection rate of *Pythium* spp points to their less substantial role in reducing yields in western Ukraine, as it is identified only in a limited number of samples and with a low percentage of root rot. Conditions for harmful effects of *Pythium spp*, in particular, *Pythium aphanidermatum*, can only be conducted under certain favourable soil temperature conditions during the growing season of plants, which limits their importance in this region.

The main task that all sugar beet producers are trying to solve is to increase the sugar harvest per unit area of sowing. A.K. Nurmukhammedov & O.M. Nevmerzhitska (2010) established that an important condition for increasing the profitability of beet cultivation is the search for disease-resistant and productive hybrids with increased sugar content and adaptability to local conditions. They focused on developing state-of-the-art disease and pest control systems, which is another area that helps maintain crop sustainability and health. It was determined that the use of biotechnologies in the breeding process also opens up new opportunities for creating hybrids with improved properties, such as resistance to stressful conditions and increased yields. Generalising, the development of modern sugar beet hybrids and the improvement of agricultural cultivation techniques are key factors for achieving the goal of increasing the sugar collection from each unit of the sown area and ensuring the stability of growing this crop in different climatic conditions.

The microbiological composition of the soil varies depending on the location of the soil. J. Yuan *et al*. (2020) examined the composition of healthy and affected soils, samples of which were taken from eight different countries. They identified that soil bacterial and fungal communities were clearly divided between sick and healthy soil samples that came from six crops in nine countries or regions. Alpha-diversity was consistently higher in the fungal community of healthy soils. Whereas the microbiomes of diseased soil contained more *Xanthomonadaceae, Bacillaceae, Gibberella,* and *Fusarium oxysporum*, the microbiome of healthy soil contained more *Streptomyces Mirabilis, Bradyrhizobiaceae, Comamonadaceae, Mortierella,* and non-pathogenic fungi *Fusarium*. In Turkey, in the province of Konya, M. Avan *et al*. (2021) differentiated 71 isolates of *Rhizoctonia* spp. with different levels of virulence. Based on virulence, isolates were divided into four categories: (I) 11 isolates: non-pathogenic, (II) 15 isolates: low-virulent, (III) 6 isolates: moderately virulent, and (IV) 39 isolates: high-virulent

Currently, due to the achievements of breeding, it has been possible to reduce the impact of rhizomania by using sugar beet hybrids that are resistant and tolerant to the pathogen but genetic resistance exists only for certain races of the pathogen, which, in turn, does not give full guarantees for the protection of crops from these diseases (Pavli *et al.*, 2011; Aleagha & Farzadfar, 2023). In a study by C.E. Windels *et al*. (2009), it was determined that the pathogen *R. solani* is widespread and reaches a high level of harmfulness. It is identified during the growing season and leads to a loss of yield of up to 50%.

Aphanomycete root rot, caused by the pathogen *A. cochlioides*, is also present in the region and especially progresses in wet years, in places where water stagnates, or with over-compacted soil. The presence of both pathogens in crops simultaneously is increasingly being identified, which is becoming a problem in short-term crop rotations. In turn, C.A. Strausbaugh (2020) confirmed that the interaction of two pathogens increases the likelihood of root rot damage to sugar beet. Thus, researchers used several variants of a combination of pathogens *Rhizoctonia solani* and *Leuconostoc* spp. and strains of one pathogen to inoculate root crops, which, as a result, led to an increase in root rot compared to treatments with only one type or strain of pathogen.

There are many methods for determining pathogens in the soil, which are constantly being improved. These are methods that can already be called classical and are based on the use of monoclonal antibodies or polymerase chain reaction (PCR) (Cahill, 1999). J.R. Botkin *et al.* (2022) indicate that for the diagnosis of the presence of *A. cochlioides* in the soil, a 4-week biological analysis of the soil and a 2-day culture analysis are used. However, molecular biological approaches allowed the development of an accelerated method for detecting this pathogen using qPCR, using specific primers for the mitochondrial DNA of the pathogen. This method allows assessing the harmfulness of aphanomycete rot using the disease severity index (DSI). However, this method allows assessing the presence or absence of risks of developing only one pathogen. M. Aragona *et al.* (2022) proposed a high-throughput sequencing (HTS) method for identifying pathogens in soil. This method allows applying a different approach to disease control strategies, considering pathogens in their environment and deciphering the complex interaction between microorganisms and cultivated crops. However, the authors believe that for the widespread implementation of this method, it is necessary to further examine and improve the economic and technical aspects.

R.M. Harveson *et al.* (2014) indicate a close relationship between the PPDI index and gross yield and sugar content of sugar beet for the US conditions. For comparison, index 1 in the current study causes a decrease in yield by 0.24 t/ha against 0.27 t/ha and a gross sugar yield of 0.018 t/ha against 0.049 t/ha for the United States. In general, the trend of dependence of the PPDI value and the main indicators of the crop structure remains.

The use of PPDI is a universal method for assessing the suitability of sugar beet cultivation and risk management since it is possible to simultaneously evaluate the entire complex of soil phytopathogens presented in soil samples.

These approaches are used in the assessment of fields in the state of emergency "Zakhidny Bug" and farmers who grow sugar beet for LLC "Radekhivsky tsukor".

CONCLUSIONS

The results of the study proved the effectiveness of the PPDI test in predicting the risk of root rot of various etiologies on sugar beet since the test allows for the simultaneous identification of the risk of developing several phytopathogens in one sample. A close inverse linear relationship between PPDI and gross yield, sugar content, and gross sugar yield per ha was also established. It is determined that the most harmful and permanently identified phytopathogens are *Rhizoctonia solani* and *Fusarium* ssp, which indicates the need to select hybrids that are characterised by resistance or high tolerance to these pathogens.

It was established that the most common soil phytopathogen that causes root rot were the representatives of the *Fusarium* ssp genus, which caused 24.07% of root rot manifestations. The least harmful among the identified pathogens were representatives of the *Phytium* ssp. genus – 2,05%. As the PPDI value increased, the gross sugar beet yield, sugar content, and gross sugar yield decreased. Thus, fields characterised by a lower risk of root rot based on the PPDI value (14.17) had an average 9.8 t higher root yield and a 1.93 t/ha higher gross sugar yield compared to high-risk fields (PPDI value 59.67).

Further scientific research may be aimed at improving the methodology of pre-sowing analysis, in particular, expanding the range of analysed microorganisms and clarifying their role in the development of root rot. It is also important to consider the interaction between different types of soil microorganisms and their impact on the pathogenicity of fungi, which can open up new opportunities for developing effective disease control strategies. Additional aspects of the research may include examining the impact of agricultural practices and various varieties of sugar beet on the structure of the soil microbiota and their interaction with pathogens. Expanding the geographical scope of research can also make an important contribution to understanding the variability of this phenomenon in different climatic and soil conditions.

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CONFLICT OF INTEREST

None.

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Використання передпосівного мікробіологічного аналізу ґрунту для прогнозування поширення кореневих гнилей цукрових буряків

Анотація. Однією з основних ґрунтових фітопатогенів цукрового буряка, що призводять до значних втрат врожайності та якості, є *Aphanomyces cochlioides* і *Rhizoctonia solani*. Оскільки можливості контролю захворювань є складними, а моніторинг патогенів є важливим для прогнозування ризиків, то створення доступних методів для попередньої оцінки полів набуває великого значення в сільському виробництві. Метою дослідження було впровадження прогностичної методики для оцінки потенціалу ґрунтів щодо їх придатності для вирощування цукрових буряків в системі короткоротаційних сівозмін. В якості рослини-індикатора використовувалося насіння цукрового буряка, яке не характеризується генетичною стійкістю проти зазначених захворювань. Протестовано можливість використання індексу передвирощувальних захворювань (PPDI), який має градацію від 0 до 100 і коваріацію з фактичною врожайністю, цукристістю та валовим збором цукру з гектара. Для реальної оцінки можливості використання індексу PPDI для характеристики втрат врожайності на виробничих посівах, нами було здійснено порівняння передпосівного значення PPDI з фактичною врожайністю з кожного конкретного поля. Встановлено, що зі збільшенням значення PPDI знижувались валова урожайність цукрового буряку, цукристість та валовий збір цукру. Результати досліджень показали, що одна одиниця PPDI обумовлює втрати валової врожайності на рівні 0,24 т/га та зменшення волового збору цукру на 0,018 т/га. Саме тому, для управління ризиками вирощування цукрових буряків, необхідно проводити оцінку фітопатогенного навантаження ґрунту. Встановлено, що найбільш шкодочинними та постійно ідентифікованими фітопатогенами є *Rhizoctonia solani* та *Fusarium* ssp, що вказує на необхідність підбору гібридів, які характеризуються стійкістю або високою толерантністю до вказаних збудників. Отримана інформація може використовуватися для своєчасного виявлення ризиків зараження, розробки ефективних стратегій управління та вдосконалення агротехнік вирощування цукрових буряків з метою зменшення втрат врожаю та підвищення ефективності агропродукції

Ключові слова: *Aphanomyces cochlioides*; *Rhizoctonia solani*; *Fusarium* spp.; фітопатогенне навантаження; валова врожайність; цукристість

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Phenological observations on the growth and development of saffron (*Crocus sativus* L.) in the conditions of the Right-Bank Forest-Steppe of Ukraine

Abstract. There is a need to summarise information using phenological models to develop a sustainable saffron production technology with further regulation of flowering at a certain phenological stage and determination of the appropriate flowering period to improve yield and

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quality under different environmental conditions. The purpose of the study is to establish the course of phenological phases of saffron growth and development in the conditions of the Right-Bank Forest-Steppe of Ukraine. Phenological observations and biometric measurements were performed in the study. According to field observations, there are a total of 6 phenological stages of saffron development. The rest period lasts from the third ten days of May to October and is divided into primary and secondary dormancy. During the primary dormant period, corms do not show external morphological changes and growth, but internal physiological and morphogenetic changes occur. In the secondary dormant period, the initial emergence of leaves and flowers and their differentiation take place. During the dormant period, saffron plants were left without aboveground organs. The flowering period falls in October. The passage of this phenological stage may be affected by changes in environmental conditions or agricultural technology. The growth of the root system began with the appearance of flowers and leaves. During the growing season, the growth of the leaf apparatus and the development of the root system continue. During this period, daughter corms are also formed from the buds of the mother corm. During the winter, the replacement corms continue to grow using the nutrient reserves of the mother corm. In early March, the development of the root system slows down and the daughter corms reach almost the final size. At the end of the growing season, the root system of the mother corm stops growing. The leaves begin to age from the top to the base. By the end of May, the daughter corms are fully developed and are preparing for the transition to a dormant state. The number of corms produced per unit area depends on the age of the plot, nutrient supply, and the level of agricultural technology. Older fields produce more corms. Due to the higher density, a larger yield of stamens is formed. Therefore, understanding the phenological reactions and influence of climatic factors on the stages of saffron growth and development in certain soil and climatic conditions is useful for future forecasting of harvest time

Keywords: phenological phase; BBCH; flowering; corms; cataphylls

INTRODUCTION

In the modern world, there is a need to investigate the phenological features of saffron, since this determines the key aspects of crop rotation optimisation and rational use of land resources. Analysis of saffron phenology is also important for the development of effective agrotechnical approaches that promote high-quality cultivation of this valuable plant species. Consideration of these features is a critical element in ecosystem management aimed at preserving the diversity and sustainability of natural environments. The study of saffron phenology is strategically important for scientific cooperation, contributing to the development of innovative agricultural methods and sustainable management of natural resources.

According to D. Kothari *et al.* (2021), saffron is one of the most valuable and expensive spices in the world. It is sold for EUR 30 thousand per kilogramme is due to its unique organoleptic properties and difficulties associated with its cultivation and harvesting. It is mainly grown in Iran, India, Afghanistan, Greece, Morocco, Spain, and Italy. Global saffron production is estimated at 418 t per year on 121 thousand ha.

E. Gupta *et al.* (2021) described how saffron is obtained from dried flower stigmas. About 150 thousand flowers are needed to produce 1 kg of saffron, as each stigma weighs about 2 mg. It has many uses in pharmaceuticals and folk medicine as a preservative, dye, and food ingredient. The main components responsible for the bitter taste and aroma of saffron are picrocrocin and safranal. Contrary to its many health benefits, a high dose of saffron can cause toxic effects on the human body, according to S. Sharma & D. Kumar (2022).

Results of chemical analysis of saffron stigmas along with the main components of saffron (crocins, picrocrocin, and safranal). L. Jarukas *et al.* (2020) found the presence of about 150 volatile and non-volatile compounds. These include carotenoids, individual polyphenols, flavonoids, and terpenes, whose particles vary depending on the place of origin, collection time, drying process, and storage conditions. Dried stigmas contain from 5 to 7% minerals, from 5 to 8% lipids, from 12 to 13% proteins, up to 20% reducing sugars, from 6 to 7% pentosans, from 9 to 10% gum and dextrins, and up to 0.3% essential oil.

Sparsely distributed vegetable crops and plants have become a new trend in the development of Ukrainian agribusiness. Understanding the economic advantages of high purchase prices and the availability of free niches in the market for the sale of their products, many farms became interested in their cultivation, as noted by S. Koliadenko *et al.* (2020) and N. Tretiak *et al.* (2021). Attracting educated and knowledgeable people to agribusiness can play a significant role in improving sales and export markets for this sector. The vast majority of companies that produce saffron use their own experience, without applying the scientific principles of marketing and trade. A. Karbasi *et al.* (2022) found that saffron's marketing margin is directly related to the retail price, and marketing costs such as wages and transportation costs increase the retail price.

N. Moratalla-López *et al.* (2019) proved that the petals of the saffron perianth account for 78.4% of the weight of the entire flower, stamens – 13.4%, stigmas – 7.4%, and the rods – 0.7%. Approximately 86 to 93% of the weight of saffron flowers is not used and is discarded after harvesting. Thus, given that saffron is delivered to the market by hundreds of kilogrammes annually, the production generates several hundred tonnes of waste. D. Cerdá-Bernad *et al.* (2023) note that saffron flower residues are high in fibre, and among the nutrients, carbohydrates are the most common, followed by proteins, and a small content of fat. They have high concentrations of glucose, fructose, lactic and malic acids, and minerals, in particular, K, Ca, and Mg. Polyunsaturated fatty acids also prevailed; of which linoleic acid was the most common. Agribusiness is constantly looking for innovative solutions to produce waste-free products. In particular, saffron flower waste can be considered as high-value-added ingredients that can be used in the food, nutraceutical, and cosmetics industries. Z. Khadfy *et al.* (2023) reviewed the use of bioactive compounds derived from saffron stigmata (*Crocus sativus* L.) and its by-products n nutraceutical and cosmetic applications. They investigated the use of bioactive compounds derived from saffron stigmas in skin care products. The antioxidant properties of these compounds can be used to protect the skin from oxidative stress, help to control the signs of ageing, and support skin health. Thus, a deep understanding of plant behaviour at different stages of growth is of paramount importance for improving quality, regulating production cycles, and reducing production costs.

The purpose of the study was to establish the course of phenological phases of saffron growth and development in the conditions of the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The research was conducted in a field experiment of the Department of Vegetable Crops in the "Fruit and Vegetable Garden" training laboratory of the National University of Life and Environmental Sciences of Ukraine during 2021-2023. The study was part of the state project "Development of innovative technologies for growing rare vegetable crops" (state registration number: 0122U001637) and the initiative project "Substantiation and development of innovative technologies for growing new vegetable crops" (state registration number: 0120U105682).

The experimental site was located in the Right-Bank Forest-Steppe of Ukraine. The soils of the experimental site were sod-medium podzolic coarse sandy-loam. Saffron was planted on September 1, 2021. Corms were planted in 20×10 cm spacing. The planting depth was 10 cm. A local species of saffron was used as planting material. The repetition of the experiment was threefold.

The phenological development of saffron plants was determined on the BBCH scale (Lopez-Corcoles *et al.*, 2015). According to the BBCH scale, the life cycle of saffron goes through 6 phases of development, each of which differs in its duration and recognition, where 0 – germination, 1 – leaf development, 4 – development of corms replacement, 5 – appearance of flower cataphylls, 6 – flowering, 9 – plant senescence. Stages of development 2, 3, 7, and 8 in saffron plants according to the extended BBCH scale are not observed. The presence of only the main phases is not an exhaustive criterion in the process of establishing specific phases of development. Therefore, for a more detailed description of the development stages, 10 subphases were used for each phase. They were indicated by two digits from 00 to 09.

The growth and development phases of saffron were determined visually simultaneously throughout the experiment. To determine the individual stages (the appearance of roots, the beginning of corm germination, the beginning of flower cataphil formation, etc.) that occur under the soil surface, the assessment was carried out on randomly excavated plants. The beginning of the phase was recorded when it was observed in 10% of plants on the site, in mass – in 75%.

This territory was characterised by a temperate continental climate with mild winters and warm summers. The sum of temperatures over 5°C for the warm period in 2021 was 2,334.4°C, in 2022 – 2,322.3°C, and in 2023 – 2,623.7°C, which is 1.0%, 0.5%, and 13.5% more than long-term norms, respectively (Fig. 1).

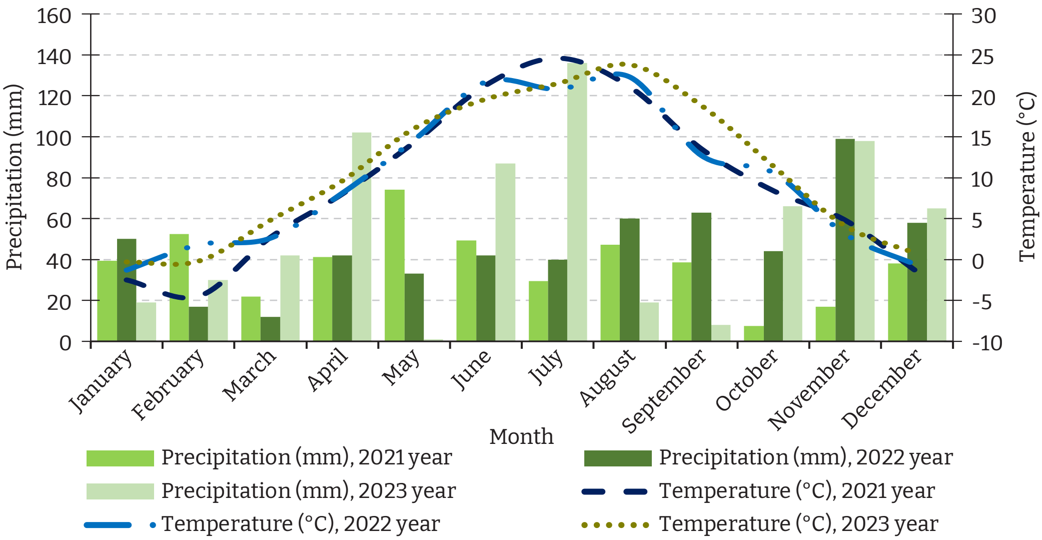

Figure 1. Average monthly air temperature and precipitation in the study area
Source: based on data from the weather station of the Borys Sreznevsky Central Geophysical Observatory

There was an uneven distribution of precipitation over the years from 456 mm in 2021 to 673 mm in 2023, which respectively amounted to -26.2% and 8.9% deviation from the norm of long-term data. In addition, the nature of precipitation is changing, namely, the number of inefficient heavy rains increases, which after long dry periods often cause more harm than good. In the winter months of 2021, 28.5% of annual precipitation fell, in 2022 – 22.3%, in 2023 – 16.9%; in the spring months – 30.1%, 15.5%, 21.5%; during the summer months – 27.6%, 25.4%, 36.0%; and in the autumn months – 13.8%, 36.8%, 25.6%, respectively. The study was conducted in compliance with the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

RESULTS AND DISCUSSION

Saffron has 6 main phenological phases: germination, leaf development, corm replacement development, appearance of flower cataphylls, flowering, and plant senescence (Table 1). The development period of saffron without aboveground organs lasted 182 days: from June 5 to October 2; while with aboveground organs it lasted 244 days: from October 3 to June 4. The corms became dormant after the leaves wilted. At the beginning of the dormant period, the mother corm showed no morphological changes or external growth. Saffron corm is marked by the ability to accumulate reserves of nutrients. Therefore, the nutrient reserves in the mother corms determine the growth and development of saffron, especially in the early stages.

Table 1. Phases of growth and development of saffron according to the extended BBCH scale

Phenological phase	International BBCH scale
Macro stage 0: germination	00-10
Mother corm is dormant. Apical and lateral sprouts are not yet developed	00
Beginning of bud swelling	01
Bud swelling is complete	03
Roots appear from the corm	05
Beginning of bud germination	07
Shoots are visible below the soil surface	08
Emergence: shoots (cataphylls) break through the soil surface	09
Macro stage 1: leaf development (assessed at the plant level)	1-19
Leaves begin to break through and develop from cataphylls	10
Leaf growth by 10% of the final length	11
Leaves reach 20% of the final length	12
Leaf growth by X...% of the final length, continues according to the same pattern until stage 18	1...
Leaves reach 90% of the final length	19
Macro stage 2: –	20-29
Macro stage 3: –	30-39
Macro stage 4: Corm replacement development	41-49
Corm replacement growth by 10% of the final size	41
Corm replacement growth by 20% of the final size	42
Growth of corms replacement up to X... % of the final size, continues according to the same pattern until stage 48	4...
Corm replacement growth up to 90% of the final size	49
Macro stage 5: Appearance of flower cataphylls	50-59
Beginning of the development of flower cataphylls. Stigmas are visible on the basal part of the stem	50
Appearance of flower cataphylls	55
Flower cataphylls are visible above the ground, wrapped in bracts	57
Flower cataphylls are still closed	59
Macro stage 6: Flowering	60-69
First perianth flowers are visible	60
10% of the maximum flower weight is reached	61
30% of the maximum flower weight is reached	63
50% of the maximum flower weight is reached	65
70% of the maximum flower weight is reached	67
End of flowering	69
Macro stage 7: –	70-79
Macro stage 8: –	80-89
Macro stage 9: Plant senescence	91-99
Leaf development is complete, the leaves are still green	91
Tops of the leaves begin to discolour	93
50% of the leaves turn yellow	95
Roots are dry and can easily fall off	96
Leaf senescence. Leaves are completely discoloured and the plant begins to go to a dormant state. Mother corm is completely dry	97
Leaves fall off the corm	98
Replacement corms are fully developed	99

Source: developed by the authors based on the conducted research

At the end of August, all parts of the flower were already differentiated. Despite the fact that important ontogenetic processes that determine the differentiation of vegetative (early August) and flower (late August) buds took place, no external signs of saffron development were observed. As soon as the buds swell, the corms begin to emerge from dormancy. Further, the appearance of roots at its base was observed, and subsequently, after the shoots (cataphylls) broke through the soil surface, seedlings appeared under the study conditions, plant shoots were observed from October 3 to October 8.

The flowers appeared simultaneously with the leaves or after the leaves appeared, usually depending on the weather conditions, in particular, on the temperature. Elevated air temperatures delayed flowering and caused leaves to appear earlier. Flower ontogenesis was observed from October 8 to October 28. The main stages of flower ontogenesis are shown in Figure 2. Studies have shown that the development of flowers is directly dependent on the size of the corm, and a quantitative relationship between these two parameters was found. In general, the heavier the mother corms, the more energy they transfer to the daughter corms, and before they became completely independent, the mother corm had a significant impact on their development. Accordingly, mother corms with optimal weight improved the growth process by increasing the leaf surface area and saffron yield due to the accumulation of more carbohydrates. It was noted that fewer flowers and daughter corms developed on the lateral buds relative to the apical buds.

Figure 2. Phenological stages of saffron growth and development according to the extended BBCH scale (0-67)

Note: macro stage: germination (0: 00, 05, 08, 09); leaf development (1: 10, 11, 12, 19); appearance of flower cataphylls (5: 57, 59); flowering (6: 60, 61, 63, 65, 67)

Source: developed by the authors based on the conducted research

The leaves and roots continued to grow during flowering. The growth of daughter corms decreased during the flowering period, as most of the energy was used for flowering and initial growth. After flowering, increased leaf growth was noted, and the first daughter corms began to appear on the mother corms. The development of daughter corms was observed throughout the entire vegetative growth of the plant.

The growth of the root system, leaves and corm development are interrelated. On the one hand, leaf development stimulated root growth, which, in turn, stimulated increased absorption of water and nutrients. On the other hand, due to the greater development of the roots, plants developed a larger number of daughter corms. The rate of vegetative growth of saffron in the first year was slower compared to subsequent years.

Each year, the plants repeated their phonological stages of growth and development. At the same time, the development of daughter corms on the mother corm was observed, which affected the annual increase in plant density.

In the third ten days of May, the leaves began to discolour, which indicated that the plant was beginning to pass into a dormant state of yellowing leaves (Fig. 3). The daughter corms were separated from the mother corms after the leaves dried, which was observed on June 4. Over the next year, each daughter corm continued to grow as a mother corm. From June to October, the absence of saffron vegetation cover was observed at the experimental site. The life cycle of saffron in the conditions of the Right-Bank Forest-Steppe of Ukraine is shown in Figure 4.

Figure 3. Phenological stages of saffron growth and development according to the extended BBCH scale (69-99)

Note: macro stage: flowering (6: 69); plant senescence (9: 91, 95, 96, 97, 99)

Source: developed by the authors based on the conducted research

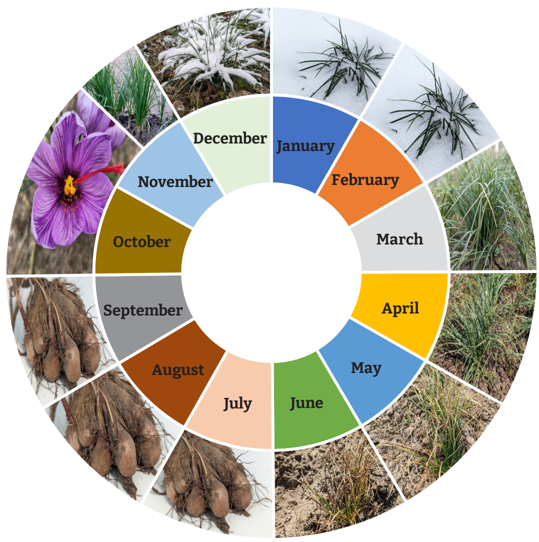

Figure 4. Biological cycle of saffron development

Source: developed by the authors based on the conducted research

The choice of flowering time is crucial for the plant, which directly affects the adaptability of plants to a particular environment. The physiological process of saffron flowering is very complex and depends on many external and internal factors. Flowering directly affects yield and productivity, so it is the most important stage in the development of saffron. J. Jose-Santhi *et al.* (2023)

found that flowering in saffron depends on environmental conditions, in particular, temperature and humidity levels. Since saffron has an annual growth and dormancy cycle, its flowering occurs in autumn, before that there is a summer period during which flowering induction occurs (Koocheki & Seyyedi, 2020). Indeed, over the years of research, it has been observed that higher water availability of plants affected the development of daughter corms in years with more precipitation, which allowed increasing the length, area and productivity of leaf photosynthesis, and obtaining daughter corms with a larger diameter and weight.

Saffron is a plant with a wide temperature range depending on the growing season, high ambient temperatures of 23 to 27°C are required to start flowering, and then the temperature drops to 10-17°C to develop flowers (Wang *et al.*, 2021). Autumn temperatures contribute to the development of the crop in the current year, and spring – in the next. It was found that the optimal temperature for the appearance of flowers is significantly lower compared to the temperature of flower development. This explains the difference in the time of flowering in places with excellent climates. H. Pirasteh-Anosheh *et al.* (2023) noted that excessively high autumn temperatures delay flowering, and in such regions, flowering occurs when the air temperature drops below 17°C. The current study also confirms that ambient temperature is crucial for saffron to come out of dormancy and stimulate the onset of flowering. Accordingly, during the period of flower development, the average air temperature was 8-11°C.

Light levels regulate plant growth, development, physiology, and metabolism (Klem *et al.*, 2019). The growth of flowers, roots, and corms improves when the proportion of blue and red light increases. The grown saffron in blue light had the highest photosynthetic activity with a high level of efficient electron transport and a lower level of energy dissipation. According to S. Moradi *et al.* (2021), blue light contributes to the development of corms and flower organs, while red light contributes to the development of leaves. Saffron needs partial shading at the level of 30% to achieve maximum growth and especially yield of stigmas. In addition, saffron can adjust its metabolism and adapt to stronger shading with an increase in shading up to 50% and especially 70% significantly improved morphological parameters, leaf surface area, aboveground biomass, weight and diameter of daughter corms (Mzabri *et al.*, 2021; 2022). Similar research results were also obtained, namely, the reaction of saffron plants to shading in the form of changes in growth and development Growing some saffron plants in the row spacing of asparagus, it was found that plants grown in the open ground without shading showed a lower intensity of green leaf colour compared to those grown in partial shading conditions. Probably, the degradation of chlorophyll was responsible for the change in green colour.

In addition, lower temperatures and higher soil moisture may have contributed to early flowering, which was observed in soils with a higher clay and silt content compared to sandy soils. Given that the corm is the main site of nutrient accumulation for stigma development, soil characteristics partially affected the number of flowers on the corm. Calcareous soils with phosphorus deficiency are considered the main difficulties on saffron-growing lands and can seriously affect plant growth and development, which will ultimately affect the stability of production (Daneshmandi & Seyyedi, 2019). Premature plant senescence on soils with a high clay content is explained by the increased synthesis of ethylene, which is caused by the possibility of limiting the development of the root system. In addition, the early plant senescence in the second year of cultivation is conditioned by climatic conditions, that is, less precipitation during the growing season than in the first year.

The results of morphological observations indicate that the process of transition to flowering in saffron is divided into 3 stages: 1) undifferentiated period (flower bud ≤1 mm long, and the apical growth point acquired a semi-conical shape); 2) period of early differentiation of flower buds (flower bud 1.5-2.0 mm, the growth point is raised, the rudiments of the perianth appear, reflecting the transition from vegetative to reproductive growth; 3) period of late differentiation of flower buds (flower buds >3 mm, the rudiments of the pistil began to differentiate, and the area of differentiation of the inner bud expanded and lengthened). The content of sugar, gibberellin, auxin, and zeatin continuously increased, while the content of starch and abscisic acid gradually decreased, which is consistent with the results of J. Hu *et al.* (2020).

Getting more flowers by extending the duration of flowering is the main task of saffron breeding. Accordingly, stimulating the expression of flowering-related genes by plant growth regulators is one of the possibilities for achieving this goal (Haghighi *et al.*, 2023). Along with other factors, the date of planting corms is an important factor determining the growth and yield of saffron. Under Yazd conditions, the early timing of saffron planting accelerated the plant development phases, so corms planted in early October sprang up earlier and observed a faster appearance of flowers and early full flowering (Pirasteh-Anosheh *et al.*, 2022).

There is a close relationship between the size of the mother corms and the productivity of saffron (Hassanzadeh Aval *et al.*, 2015). According to the study, with an increase in the size of mother corms, there is a decrease in the number of small corms weighing from 0.1 to 4 g, but the percentage of medium corms weighing from 4.1 to 8 g and large ones weighing more than 8 g increased (Koocheki & Seyyedi, 2016).

The use of iron nanochelate at a rate of 10 kg/ha increases the yield of dry stigmas by 133%, and the application of cow manure at a rate of 20 t/ha^{-1} – by 100%. It is also noted that the use of vermicompost (10 t/ha) and humic acids (10 kg/ha) in combination with biofertilisers provides an increase in the quantitative and qualitative yield of saffron (Hourani, 2023). It is obvious that the application of organic fertilisers plays an important role in improving the vegetative growth of saffron, the distribution of nutrients, which leads to an increase in the number of corms and their weight (Jami *et al.*, 2020).

L. Cardone *et al.* (2021) found that the saffron ecotype significantly affects all phenological and productive traits. The origin of corms had a significant association with early ripening and flowering interval. Before the beginning of flowering, 40.4 days usually passed from planting corms, and flowering lasted about 20 days. The ecotype from Italy (Sardinia) bloomed almost 6 days earlier than from Greece (Kozani), and had a longer flowering period. The flowering period of saffron in Italy is several weeks, usually between late October and early December. The results obtained in this study are consistent with findings of F. Gresta & G. Avola (2016), who reported that the daily flowering, and therefore, the yield of stigmas during this period is not constant, but shows from 1 to 4 peaks, during which there is a significant increase in the number of flowers.

Under Pampore conditions, the longest stage of ontogenesis in saffron is the vegetative phase, which lasted 142 days, followed by flower ontogenesis – 60 days, dormant period – 55 days, reproductive phase – 41 days, bud germination phase – 36 days, and plant senescence – 30 days (Yasmin & Nehvi, 2018). For the semi-arid territories of Iran, the leaf drying period falls at the end of spring. Recovery from dormant state is observed in mid-July – early August. Flowering is observed in the first half of August and lasts up to 1 month. Shoots appear at the end of flowering.

In April-May, when the dry period begins, the leaves age and wither, and the corms fall into a dormant state (Dewir *et al.*, 2022). F. Nehvi (2022) noted that during the dormant period, saffron corms show no morphological changes or external growth, and the tip looks like a dormant bud with protective cataphylls. The development of stamens, which precedes the laying of the perianth and the development of gynaecium, is observed in the period from the end of July to the beginning of August, regardless of whether the corms came from the field or were stored at a constant temperature. As of the beginning of September, all the organs of the flower are fully differentiated. The growing period of saffron varies in different countries and can be either annual or perennial: Italy (part of the South, Abruzzo and Tuscany) – 1 year; Spain and Italy (Sicily and Sardinia) – from 3 to 4 years; Morocco – from 5 to 6 years, Iran – from 6 to 8 years, Greece – from 10 to 12 years; India – from 10 to 15 years (Cardone *et al.*, 2021).

Phenological studies at various stages of plant growth and development are important for mitigating the negative effects of climate change, to which saffron is very susceptible, and for planning elements of the production system that include agrotechnical operations and flower harvesting processes. Harvesting flowers at optimal times is a very important step in saffron agribusiness, so the phenology of flowering in relation to climatic conditions is essential for a proper understanding of this process.

CONCLUSIONS

Saffron, compared to other widely cultivated crops, is a plant with numerous differences in ecological, physiological, and phenological terms. Among these differences, it is worth highlighting the following: the development of flowers precedes the development of other parts of the plant. The course of this process is conditioned by the reserves of nutrients accumulated in the corms. The onset of the flowering phase is accompanied by a decrease in air temperature in autumn, unlike the vast majority of agricultural crops, for which this period coincides with the period of warm and humid seasons. For saffron, only the stigma, which makes up 7.4% of the flower's weight, is considered a commercial product. Saffron development can generally be divided into three phases: generative, vegetative, and dormant. The physiological process of the generative phase occurs well in advance of visible flowering. The appearance of flowers was noted in the period from October 8 to October 28. The flowers may appear simultaneously with the leaves or sometimes after their emergence. The vegetative phase, which begins immediately after flowering, is the longest stage (244 days) in the annual saffron cycle. During this phase, leaves and corms develop. The leaves currently play the role of an assimilation resource for the development of corms and roots. During autumn and winter, corms develop slowly, and closer to spring, they begin to grow actively. The size of the mother corm significantly affects the development of daughter corms. The dormant phase occurred with the beginning of senescence (3rd 10 days of May) and leaf death (1st 10 days of June) and lasted until the beginning of autumn.

A detailed description and coding of the stages of saffron development is a useful and convenient tool for identifying the various stages of plant growth and development, which is necessary for implementing effective crop management methods that will ensure the high quality of the crop.

The main areas of further study should be aimed at creating and optimising new methods of growing saffron, such as hydroponics and vertical farming, due to which it would be possible to achieve an increase in the yield, quality, and efficiency of saffron production, and minimise dependence on climatic conditions and soil factors.

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CONFLICT OF INTEREST

None.

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Фенологічні спостереження за ростом та розвитком шафрану (*Crocus sativus* L.) в умовах Правобережного Лісостепу України

Анотація. Існує потреба в узагальненні інформації з використанням фенологічних моделей з метою розробки стійкої технології виробництва шафрану з подальшим регулюванням цвітіння на певній фенологічній стадії та визначенням відповідного періоду цвітіння для покращення врожайності та якості за різних умов навколишнього середовища. Метою досліджень було встановлення перебігу фенологічних фаз росту та розвитку шафрану в умовах Правобережного Лісостепу України. Проводили фенологічні спостереження та біометричні вимірювання у дослідженні. Згідно з польовими спостереженнями, існує загалом 6 фенологічних стадій розвитку шафрану. Період спокою триває з третьої декади травня до жовтня і розділяється на фазу первинного та вторинного спокою. Під час первинного періоду спокою бульбоцибулини не проявляють зовнішніх морфологічних змін та росту, але внутрішні фізіологічні та морфогенетичні зміни відбуваються. У фазі вторинного спокою відбувається початкове зародження листків та квіток і їх диференціація. У період спокою рослини шафрану залишились без надземних органів. Період цвітіння припадає на жовтень. На проходження цієї фенологічної стадії можуть впливати зміни умов навколишнього середовища або агротехніки. Ріст кореневої системи розпочинався разом з появою квіток і листків. Під час фази вегетації продовжується наростання листового апарату та розвиток кореневої системи. Також у цей період з бруньок материнської бульбоцибулини утворюються дочірні бульбоцибулини. Протягом зими бульбоцибулин заміщення продовжують рости використовуючи запаси поживних речовин материнської бульбоцибулини. На початку березня розвиток кореневої системи сповільнюється і дочірні бульбоцибулини досягають майже остаточного розміру. Під час закінчення вегетаційного періоду коренева система материнської бульбоцибулини припиняє ріст. Листки починають старіти від верхівки до основи. На кінець травня дочірні бульбоцибулини повноцінно розвинені та готуються до переходу в стан спокою. Кількість бульбоцибулин, що утворюється з одиниці площі, залежить від віку ділянки, забезпеченості поживними речовинами та рівня агротехніки. Старіші поля дають більшу кількість бульбоцибулин. Завдяки більшій густоті формується більший врожай тичинок. Тому, розуміння фенологічних реакцій та впливу кліматичних факторів на етапи росту та розвитку шафрану у певних ґрунтово-кліматичних умовах корисний для майбутнього прогнозування термінів збору врожаю

Ключові слова: фенологічна фаза; BBCH; цвітіння; бульбоцибулини; катафіли

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Influence of previous crops and soil tillage on the available moisture reserves in typical chernozem for spring barley cultivation

Abstract. The unstable yield of agricultural crops arises due to insufficient soil moisture supply at crucial moments of plant emergence and growth, complicating agriculture and exposing it to the risk of crop losses. The purpose of the study is to determine the impact of the soil tillage system and previous crops on the productivity of spring barley plants. This was a long-term stationary experiment (2021-2023) with the application of statistical data processing. The influence of four previous crops was investigated – grain maize (control), soybeans, winter rapeseed, and sunflower – and three main soil tillage methods. It is established that the highest significant moisture reserves in the 0-100 cm soil layer at the sowing period were formed when spring barley was placed after soybeans, exceeding the control variant (grain maize) by 3.2 mm in 2021, 3.6 mm in 2022, and 3.4 mm in 2023, and after winter rapeseed by 8.5 mm, 6 mm, and 5.7 mm, respectively, over the years. The use of shallow no-till cultivation provided an advantage over the control (ploughing) in all years of observation: by 2.2 mm in 2021, 1.8 mm in 2022, and 8.8 mm in 2023. During the sowing period of the studied crop, the control surpassed only surface no-till cultivation by 2.7 mm in 2022. The optimal option should be considered the combination of soybeans as a previous crop with shallow no-till soil cultivation at 14-16 cm, which ensured moisture reserves during the earing period of the crop in 2021 – 75.1 mm, in 2022 – 93.2 mm, and in 2023 – 92.2 mm, and at the time of harvest, these indicators were 60.7 mm, 67.3 mm, and 60.0 mm, respectively. The grain yield of spring barley under this option was the highest in the experiment, averaging 7.26 t/ha, which is 27.3% higher than the

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control. The results of the study can be used to realise the genetic potential of spring barley plants to form stable productivity

Keywords: agricultural crops; yield, no-till cultivation; conventional tillage; hydrothermal coefficient; available soil moisture reserves

INTRODUCTION

Moisture availability for agricultural crops depends on many factors that interact with each other. Firstly, the amount of precipitation in the form of rain or snow over the years of research, soil permeability, and air temperature. Moreover, previous crops and soil tillage methods are important elements in retaining soil moisture to achieve high and stable yields of spring barley, as their influence undoubtedly affects the final yield of this crop.

Soil moisture plays a very important role in the cultivation of spring barley. Particularly important is the availability of moisture during sowing and at the initial growth stages, when the seeds germinate and the root system develops. On the other hand, excessive moisture can also be harmful to plants. Excess moisture can lead to the development of fungal diseases and the suffocation of the root system, which can result in plant death, as noted in the studies by M.T. Abi Saab *et al.* (2019).

Proper placement of the crop in the crop rotation is key to high yield and success in agriculture. Crop rotation reduces weed infestation and damage to plants by pests and diseases and improves soil quality. V.V. Hamaiunova & T.O. Kasatkina (2018) established that primary tillage systems particularly affect the yield of agricultural crops, productivity, economic and energy efficiency of crop rotation.

M. Unkovich *et al.* (2023) in their studies indicate that improper soil tillage deteriorates the agrophysical indicators of its fertility, which leads to reduced tillering and root growth, and decreased water availability in the soil, nutrient uptake by the plant, which in turn reflects in the deterioration of grain quality and reduction of crop yield.

According to A. Panfilova *et al.* (2020), the main factors reducing spring barley yield in Ukraine are annual changes in climatic conditions, planting the crop after a previous crop such as sunflower, and the imperfection of the depth and method in the soil tillage system, which causes negative erosion processes and worsens the water regime and dehumification of chernozems. D. Cammarano *et al.* (2019) note that barley yield depends primarily on the amount of precipitation and soil water.

Soil tillage has a significant impact on the available soil moisture reserves, which affect soil structure, water permeability, and water distribution within it. Therefore, M.A. Porodko (2023) emphasises that the choice of soil tillage method can be crucial for preserving available moisture reserves and optimising the soil's water-physical properties for plants. However, moisture accumulation in the meter layer of chernozem during the winter period does not depend on the soil tillage method.

The study by V. Kyryliuk *et al.* (2019), conducted on medium loamy chernozems in the Right-Bank Forest-Steppe of Ukraine, has shown that disk tillage leads to a 31% decrease in profitability compared to chisel ploughing. The authors also highlight the importance of applying organo-mineral fertilisers and leaving straw in the field to increase yield. According to S.V. Usyk (2020), placing spring barley after grain corn provides the best results because the soil does not compact, and inter-row cultivation in corn growing technology helps clear the field of weeds.

The impact of previous crops on the available soil moisture reserves for spring barley can be significant. Some crops, after harvest, can leave a larger amount of plant residues in the soil, which leads to increased moisture in it. This can be beneficial for the subsequent sowing, as the increased soil moisture reserve can positively affect the growth of the next crop (Tsyliuryk *et al.*, 2020; Poliovyi *et al.*, 2023).

The purpose of the study is to establish the changes in accumulation and dynamics of soil moisture in spring barley yields depending on the primary soil tillage method and previous spring barley crops.

MATERIALS AND METHODS

The research was conducted during 2021-2023 in a stationary study of the Department of Agriculture and Herbology, established at the Separate Unit of the National University of Life and Environmental Sciences of Ukraine "Agronomic Research Station". Spring barley was grown after various previous crops (factor A): 1) grain corn (control); 2) soybeans; 3) winter rapeseed; 4) sunflower. The main tillage systems were also examined (factor B): 1) conventional tillage (control), which included ploughing to a depth of 23-25 cm; no-till shallow cultivation – disking to a depth of 14-16 cm; and no-till surface cultivation – disking to a depth of 6-8 cm. The sowing area was 250 m² (10 m × 25.0 m), with an accounting area of 180 m² (9 m × 20 m), the experiment was repeated four times, and the plot layout was systematic.

The soil of the research field is typical chernozem of the middle loamy type. The humus content in the plow layer of the soil is 4.05-4.38%, the pH of the salt extract is 6.9-7.3, and the cation exchange capacity is 32 mg-equiv. per 100 g of soil. The humus reserve in the meter layer is 387-405 t/ha. This soil type is typical for the Forest-Steppe zone, occupying 54.6% of its territory. Groundwater is located at a depth of 5-6 m.

To assess the moisture level, parameters such as precipitation, soil moisture, water regime, and hydrothermal indicators were analysed. The adequacy of the hydrothermal coefficient (HTC) to long-term data was assessed using the significance coefficient (SC). According to the scale, Ki values within 0 ÷ ± 0.3 are considered optimal; tendentiously elevated within + 0.4-1; tendentiously reduced within -0.4-1; significantly elevated within +1-2; significantly reduced within -1-2; extremely elevated > +2 and extremely reduced for K_i > -2.

The thermogravimetric method, following the standard DSTU ISO 16586:2005 (2008), was used to determine the total and plant-available soil moisture reserves at a depth of 0-100 cm. Soil samples were taken with an auger from the following layers: 0-10, 10-20, 20-30, 30-50, 50-70, 70-100 cm. For each variant, the total and plant-available moisture reserves were calculated. The water consumption coefficient for spring barley was determined by the calculated method based on the determination of soil moisture.

At the full maturity stage of spring barley, grain yield accounting was conducted by complete harvesting from the accounting areas in each variant of the experiment. This process included harvesting grains from different plots located in all repetitions of the experiment. During harvesting, grain purity and moisture were considered and standardised to 100%. This approach ensured an accurate determination of spring barley yield in each experimental variant and guaranteed the objectivity of the results.

Sowing of the Sebastian barley variety was performed at a temperature of the sowing layer of 2-3°C and upon reaching the physical maturity of the soil. The seeding rate was 4 million viable seeds/ha, the seeding depth was 3-4 cm, and the row spacing was 15 cm. The study was conducted in accordance with the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). Statistical analysis of the experimental data was performed using Excel from MS Office 365 and Statistica 10 software.

RESULTS AND DISCUSSION

The observations showed that the water regime of the soil in spring barley crops, along with previous crops and main tillage methods, has its own characteristics each year. The amount of moisture accumulated in the winter period is of great importance for the growth and development of spring barley as it provides favourable conditions for the plants at the early stages of vegetation. Analysing the data over the years of the study, it should be noted that the HTC indicators differed from each other by monthly values (Fig. 1).

In 2021, the beginning of the growing season was characterised by favourable moisture conditions. April and May of that year were excessively wet, with HTC indicators of 3.89 and 2.47, which are significant deviations from the long-term averages (K_i = 1.16 and 0.60). All subsequent months of 2021 had an HTC indicator not exceeding 1.0 and were dry, which is typical for this period (K_i = -0,27, 0,08, 0,02, -0,28) (Table 1).

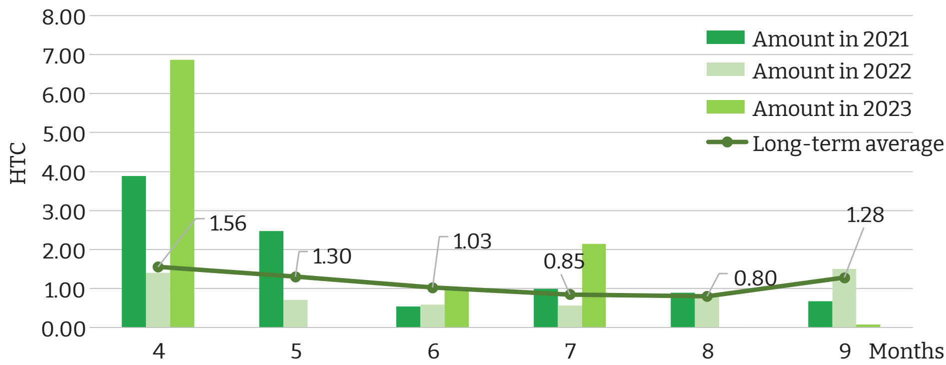

Figure 1. Monthly distribution of HTC (2021-2023)

Source: compiled by the authors

Table 1. Adequacy coefficient (K_i) of HTC indicator compared to the long-term norm

Years of the study	Vegetation period						For the growing season
	April	May	June	July	August	September	
2021	1.16	0.60	-0.27	0.08	0.02	-0.28	-0.09
2022	-0.17	-0.61	-0.49	-0.66	-0.01	0.13	-0.64
2023	5.37	-1.32	-0.02	2.95	-1.03	-0.70	-0.64

Source: compiled by the authors

The conditions of the 2022 growing season varied from dry in May and August (HTC 1.04, 1.50) to very dry in April, June, July, and August (HTC 0.7, 0.59, 0.56, 0.79, respectively), which is statistically confirmed by the significance coefficient of deviations (K_i = -0.61, -0.49, -0.66, and -0.05, respectively). The beginning of the 2023 growing season (April) was markedly different from other months in terms of HTC. According to HTC indicators, April was excessively wet at 6.87, which is statistically confirmed by a significant deviation from the long-term values, K_i = 5.37 – extremely high. In May, August, and September of the 2023 growing season, HTC was 0.0, 0.1, 0.8 respectively, characterising the area as arid, with significant deviations from long-term values (K_i = -1.3, -1.03, -1.70). June, with an HTC of 1.1, was slightly dry, but relative to long-term data, it was extremely high (K_i=2.95). July can be considered excessively wet with an HTC of 2.14, which is atypical for this period (K_i=2.95).

Thus, the 2023 growing season was characterised by variability in moisture levels across the months but overall was similar to the 2022 growing season for spring barley (Fig. 1, Table 1).

M. Daničić *et al.* (2019) noted that analysing the impact of climate change will allow for forecasting barley production and adjusting current cultivation practices to enhance efficiency.

Since spring barley requires optimal conditions for the growth and development of the root system, which significantly contributes to high yields, it is essential to consider soil conditions that can be regulated through the selection of previous crops and soil tillage systems (Netis & Onufran, 2012; Romaniuk, 2019).

An analysis of the study results on moisture reserves in the 0-100 cm soil layer, depending on the factors studied, showed that at the time of sowing, the impact of previous crops on the accumulation of available moisture in the soil was statistically significant compared to the control (corn for grain) after soybeans in 2021 – 3.2 mm, in 2022 – 3.6 mm, in 2023 – 3.4 mm, and after winter rapeseed – 8.5 mm, 6 mm, 5.7 mm respectively by year. When spring barley was planted after sunflowers, moisture reserves in the 0-100 cm soil layer decreased by 2.6 mm in 2021 and 0.2 mm in 2022 and 2023 compared to the control (Table 2).

Table 2. Change in available moisture reserves in the 0-100 cm soil layer, depending on previous crops and primary soil tillage systems

Cropping system (A)	Soil tillage system (B)	Moisture reserves								
		before sowing			earing			before harvesting		
		2021	2022	2023	2021	2022	2023	2021	2022	2023
Corn for grain (c)	Conventional tillage (c)	173.6	160.6	134.5	71.7	81.7	79.8	55.1	61.1	60.6
	Shallow no-till	173.9	164.2	140.1	74.7	95.1	90.4	56.5	62.8	63.8
	Surface no-till	174.4	155.0	149.0	73.4	93.0	91.0	53.7	59.6	62.0
Soybean	Conventional tillage (c)	175.9	160.6	136.6	72.6	82.2	79.2	57.2	63.4	59.8
	Shallow no-till	176.9	164.9	146.9	75.1	93.2	92.2	60.7	67.3	63.0
	Surface no-till	178.8	154.8	150.4	72.8	93.9	90.2	58.1	64.5	64.4
Winter rapeseed	Conventional tillage (c)	180.1	167.5	141.9	73.9	82.2	87.0	59.3	65.8	61.1
	Shallow no-till	182.8	167.5	149.2	74.8	93.2	90.4	62.4	69.2	63.8
	Surface no-till	184.6	162.6	149.6	74.8	94.6	91.8	63.0	69.9	63.2
Sunflower	Conventional tillage (c)	171.2	158.3	134.9	69.4	72.6	70.4	55.1	60.9	57.7
	Shallow no-till	171.3	157.4	146.9	69.5	75.2	73.0	56.5	62.0	61.3
	Surface no-till	171.8	163.5	150.4	69.6	74.1	71.9	53.8	59.6	58.7
HiP05 (AB)		**2.0**	**4.1**	**6.8**	**1.7**	**2.3**	**2.5**	**3.0**	**3.2**	**2.6**
Average for previous crops										
Corn for grain		174.0	159.9	141.2	73.3	89.9	87.0	55.1	61.2	62.1
Soybean		177.2	160.1	144.6	73.5	89.7	87.2	58.7	65.1	62.4
Winter rapeseed		182.5	165.9	146.9	74.5	90.0	89.7	61.5	68.3	62.7
Sunflower		171.4	159.7	144.0	69.5	74.0	71.8	55.2	60.8	59.2
HiP05 (A)		**1.0**	**2.0**	**3.4**	**0.9**	**1.1**	**1.2**	**1.5**	**1.6**	**1.3**
Average for basic tillage systems										
Conventional tillage (c)		175.2	161.7	137.0	71.9	79.7	79.1	56.6	62.8	59.8
Shallow no-till		176.2	163.5	145.8	73.5	89.2	86.5	59.0	65.3	63.0
Surface no-till		177.4	159.0	149.8	72.7	88.9	86.2	57.2	63.4	62.1
HiP05 (B)		**1.2**	**2.4**	**3.9**	**1.0**	**1.3**	**1.4**	**1.7**	**1.8**	**1.5**

Note: c – control
Source: compiled by the authors

The analysis of available soil moisture reserves in the one-meter soil layer, depending on the main tillage system, showed that shallow and surface no-till cultivation in 2021 and 2023 were at the same level and had an advantage over conventional tillage (control). In 2021, surface no-till cultivation surpassed the control variant (conventional tillage) by 2.2 mm, and in 2023 by 12.8 mm. In turn, shallow no-till cultivation had an advantage over conventional tillage by 1 mm in 2021 and by 8.8 mm in 2023, which is statistically significant. These results are confirmed by the studies of O.I. Tsilyuryk & V.P. Shapka (2014), where the advantage in moisture accumulation during the autumn-winter period by 18.1 mm (181 t/ha) was noted for chisel tillage compared to conventional ploughing. Furthermore, O.V. Pikovska (2012) proves that ploughing can lead to moisture loss due to decreased soil permeability, resulting from the destruction of soil structure and the formation of a hardpan after some previous crops. On the other hand, surface tillage (such as mulching) can help retain moisture in the soil by reducing evaporation and protecting it from wind and sunlight.

During the growing season, soil moisture was predominantly consumed for crop formation by barley plants and partly evaporated from the soil surface. During the heading phase and at the time of harvest, a decrease in moisture reserves in the one-meter soil layer was observed, and its trend depended on the studied factors.

Research by V.V. Gamayunova & A.V. Panfilova (2019) established that different soil moisture reserves and their usage intensity are determined by the amount of precipitation, temperature, and humidity. However, the general moisture dynamics in barley crops in all years of research followed the same pattern, with the main amount of moisture accumulating in the autumn-winter period and reaching its peak at the time of sowing, after which the crops gradually consumed it until the end of the growing period.

On average, over the years of research, the placement of spring barley after soybeans and winter rapeseed created the best conditions for the accumulation and preservation of soil moisture. The most effective tillage options were shallow no-till and surface no-till cultivation.

One of the indicators of effective water use by grain crops to achieve yield is the water consumption coefficient, which is determined by dividing the total water expenditure by the yield of the entire biomass or the main product. According to V.P. Kirilyuk & M.V. Shemyakin (2017), water supply during the growing season significantly affects soil moisture reserves and water consumption by spring barley. Specifically, during moderately dry growing periods, the total water consumption by barley plants ranged from 2030 to 2610 m^3/ha, during dry growing periods from 2015 to 2572 m^3/ha, and during very dry growing periods from 2099 to 2264 m^3/ha.

Research on the efficiency of water use by spring barley plants, depending on the tillage system and previous crop, showed that barley used water most efficiently when placed after soybeans and winter rapeseed, with water consumption coefficients of 26.9 m^3/t and 29.2 m^3/t, respectively. In absolute terms, this was 10.5 mm/t and 8.2 mm/t less compared to the control variant (corn for grain). The water consumption coefficient for barley plants placed after sunflower was 4.5 mm/t lower compared to their placement after corn for grain (Table 3).

Table 3. Water consumption of spring barley depending on the previous crop and tillage

Cropping system	Soil tillage system	Water consumption indicators					
		Wn	Wk	O	S	Y	K
Corn for grain	Conventional tillage (c)	156.2	58.9	218.9	316.2	9.7	344
	Shallow no-till	159.4	61.0	218.9	317.3	9.2	365
	Surface no-till	159.5	58.4	218.9	319.9	7.9	413
Soybean	Conventional tillage (c)	157.7	60.1	218.9	316.4	12.5	258
	Shallow no-till	162.9	63.7	218.9	318.1	12.3	266
	Surface no-till	161.3	62.3	218.9	317.8	11.4	284
Winter rapeseed	Conventional tillage (c)	163.2	62.1	218.9	320.0	11.7	284
	Shallow no-till	166.5	65.1	218.9	320.3	11.6	288
	Surface no-till	165.6	65.4	218.9	319.1	11.0	303
Sunflower	Conventional tillage (c)	154.8	57.9	218.9	315.8	10.3	322
	Shallow no-till	158.5	59.9	218.9	317.4	10.5	315
	Surface no-till	161.9	57.4	218.9	323.4	9.7	351
Average for previous crops							
Corn for grain		158.4	59.5	218.9	317.8	8.9	374
Soybean		160.6	62.0	218.9	317.5	12.1	269
Winter rapeseed		165.1	64.2	218.9	319.8	11.4	292
Sunflower		158.4	58.4	218.9	318.9	10.2	329
Average for basic tillage systems							
Conventional tillage (c)		158.0	59.8	218.9	317.1	11.0	302
Shallow no-till		161.8	62.4	218.9	318.3	10.9	308
Surface no-till		162.1	60.9	218.9	320.1	10.0	338

Note: c – control; W_p – soil moisture reserves at the beginning of the growing season, mm; W_k – productive moisture reserves in the soil at the end of the growing season, mm; O – amount of precipitation during the spring barley growing season, mm; S – total water consumption, mm; Y – yield, t/ha; K – water consumption coefficient, m^3/t
Source: compiled by the authors

According to the calculated water consumption coefficients, spring barley plants optimally utilized water per unit yield with the use of conventional ploughing at 302 m³/t. The water consumption coefficient increased by 6.0 and 36 m³/t respectively with the use of shallow and surface no-till cultivation. Thus, the application of shallow and surface no-till cultivation led to an increase in water consumption by barley plants per unit yield and inefficient use of water throughout the crop's growing season. These results are confirmed by the studies of O.I. Tsyliuryk *et al.* (2020), which found that the inclusion of disk tillage in the technology for growing spring barley significantly reduced grain yield and increased the water consumption coefficient by 1.1-1.2 times.

V. Bogužas *et al.* (2018) established that tillage methods of varying intensities did not significantly affect the moisture content in the upper soil layers, but in a dry year, the highest moisture content was recorded with no-till cultivation, while in a wet year, the differences were negligible.

The level of crop yield is the integral indicator of the effectiveness of the studied factors in cultivation technology. Statistical analysis of the obtained data indicates that the studied factors had a significant impact on the grain yield of spring barley. Over the years of research, it was found that the highest crop yield was formed after previous crops with the lowest water consumption coefficient, i.e., after soybeans – 7.12 t/ha, which is 35.4% higher than the control, where this indicator was 5.25 t/ha. The low yield after sunflower – 6.0 t/ha – is explained by insufficient reserves of productive moisture and the negative impact of volunteer plants from the previous crop. After winter rapeseed, the crop yield was 6.72 t/ha, which is significantly higher than after sunflower and corn for grain, but lower than after soybeans (Table 4).

Table 4. Spring barley yield depending on the studied factors, average for 2021-2023, t/ha

Previous crops (A)	Tillage systems (B)	Average yields, t / ha					
		AB	±, %, to control	A	±, %, to control	B	±, %, to control
Corn for grain	Conventional tillage (c)	5.70	-	5.26	-	-	-
	Shallow no-till	5.43	-4.82				
	Surface no-till	4.65	-18.42				
Soybean	Conventional tillage (c)	7.38	29.39	7.12	35.39		
	Shallow no-till	7.26	27.34				
	Surface no-till	6.73	17.98				
Winter rapeseed	Conventional tillage (c)	6.86	20.32	6.72	27.73		
	Shallow no-till	6.84	20.03				
	Surface no-till	6.45	13.16				
Sunflower	Conventional tillage (c)	6.05	6.14	5.99	14.00		
	Shallow no-till	6.20	8.77				
	Surface no-till	5.73	0.58				
HiP_{05}, t/ha, %		0.49	8.12	0.28	4.69	0.25	4.06
Average by tillage	Conventional tillage (c)	-				6.50	-
	Shallow no-till					6.43	-0.99
	Surface no-till					5.89	-9.33

Note: c – control
Source: compiled by the authors

The analysis of the averaged data for the primary soil tillage options indicates a 9.3% reduction in spring barley yield compared to the control when using surface no-till cultivation at 6-8 cm. However, increasing the depth of no-till cultivation to 14-16 cm in the second variant only slightly reduced the crop yield by 0.99% relative to the control The results of the study are confirmed by the data obtained by V. Kyryliuk *et al.* (2019), who established that the use of no-till cultivation reduced the yield of spring barley grain by 0.15-0.46 t/ha compared to conventional tillage (ploughing).

Analysing the impact of primary tillage for spring barley after each previous crop individually, the greatest yield reduction was observed after corn for grain with surface disking (-1.05 t/ha). In contrast, using shallow no-till cultivation after this crop resulted in a minor yield reduction of only -0.27 t/ha compared to the control. Conducting primary shallow no-till cultivation did not reduce the crop yield when placed after soybeans and winter rapeseed. When sunflower was used as the predecessor for this crop with shallow no-till cultivation, the spring barley yield was significantly higher (+8.8% t/ha).

Therefore, selecting the previous crop and optimising the depth and method of soil tillage for spring barley are crucial issues. The conducted study identified a previous crop for spring barley that, with an optimal primary soil tillage system, ensures consistently high crop productivity, especially in years with unfavourable climatic conditions.

CONCLUSIONS

Studies have confirmed the positive impact of the primary soil tillage system and previous crops on managing soil water properties and developing the productivity of spring barley plants on typical black soil of the Right-Bank Forest-Steppe. It was established that during the period of spring barley sowing, a high level of available moisture was ensured by combining shallow no-till cultivation at 14-16 cm depth and soy as the predecessor, with moisture levels of 176.9 mm in 2021, 164.9 mm in 2022, and 146.9 mm in 2023, which is significantly higher than the control.

The lowest levels of available moisture were ensured by conventional tillage, ranging from 137.0 mm to 175.2 mm, and sunflower, ranging from 144.0 mm to 171.4 mm. This explains the low yield of spring barley, which was 6.0 t/ha. Spring barley plants used water most efficiently during the growing season when conventional tillage was used (302 m^3/t) and when soy was the previous crop (269 m^3/t). The most inefficient water use was observed with the combination of corn as the previous crop and surface no-till cultivation (413 m^3/t), where the yield of the studied crop was the lowest at 4.65 t/ha. The highest crop yield was achieved after previous crops with the lowest water consumption coefficient, namely soy – 7.12 t/ha, which is 35.4% higher than the control, where this indicator was 5.25 t/ha.

Future research could focus on developing and testing environmentally sustainable agricultural systems that promote soil resource conservation and reduce the impact of agricultural activities on the environment. Additional studies could also explore the potential of agroecological methods that help restore and improve soil quality, particularly by stimulating microbiological activity and supporting healthy soil flora and fauna. Furthermore, innovative technologies that allow farmers to use resources more efficiently and reduce negative environmental impacts could be refined. It is also necessary to begin exploring the impact of different agricultural practices on the physical and chemical properties of the soil, such as structure, fluidity, acidity, and more. This can help determine optimal methods of soil tillage and care to preserve its fertility.

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CONFLICT OF INTEREST

None.

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Вплив попередників та обробітку ґрунту на запаси доступної вологи чорнозему типового за вирощування ячменю ярого

Анотація. Нестабільна врожайність сільськогосподарських культур виникає через недостатнє забезпечення вологою ґрунту у ключові моменти сходів та росту рослин, що ускладнює сільське господарство і піддає його ризику втрат врожаю. Метою досліджень було встановлення впливу системи обробітку ґрунту та попередників на формування продуктивності рослин ячменю ярого. Це був довготривалий стаціонарний дослід (2021-2023 рр.) із застосуванням статистичної обробки даних. Досліджувався вплив чотирьох попередників – кукурудза на зерно (контроль), соя, ріпак озимий, соняшник та трьох основних обробітків ґрунту. Встановлено, що достовірно найвищі запаси вологи в 0-100 см шарі ґрунту на період сівби формувалися за розміщення ячменю ярого після сої, у 2021 році на 3,2 мм, 2022 році на 3,6 мм, 2023 році на 3,4 мм більше порівняно з контрольним варіантом (кукурудза на зерно) та після ріпаку озимого, на 8,5 мм, 6 мм, 5,7 мм відповідно рокам. Використання безполицевого мілкого обробітку ґрунту забезпечує перевагу в усі роки спостережень над контролем (оранка) у 2021 – на 2,2 мм, у 2022 – на 1,8 мм, та у 2023 – на 8,8 мм. На період сівби досліджуваної культури контроль переважав лише над безполицевим поверхневим обробітком у 2022 року на 2,7 мм. Оптимальним варіантом слід вважати поєднання сої як попередника з мілким безполицевим обробітком ґрунту на 14-16 см, що забезпечує на період колосіння культури в 2021 році – 75,1 мм, 2022 – 93,2 мм, 2023 – 92,2 мм, а на час збирання культури ці показники становили, відповідно 60,7 мм, 67,3 мм., 60,0 мм. Урожайність зерна ячменю ярого за цього варіанту була суттєво найвищою в досліді й в середньому становила 7,26 т/га, що на 27,3 % вище контролю. Результати дослідження можуть бути використані для реалізації генетичного потенціалу рослин ячменю ярого з метою формування стабільної його продуктивності

Ключові слова: сільськогосподарські культури; урожайність; безполицевий обробіток; полицевий обробіток; гідротермічний коефіцієнт; запаси доступної вологи в ґрунті

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The impact of herbaceous plants on biodiversity and stability of pine plantations in Western Polissia

Abstract. In the field of ecology, more and more attention is paid to the analysis of the interaction of herbaceous plants with the structure of ecosystems, including forests. The aim of the study was to determine the impact of herbaceous plants on the biodiversity and stability of pine plantations in Western Polissia of Ukraine. To achieve this goal, in 2010-2023, the State Enterprise "Research Farm "Horodetske" assessed the diversity of herbaceous plant species, measured their number and cover, evaluated soil physical properties and biometric parameters of pine trees, and assessed how changes in the pine plantation ecosystem caused by herbaceous plants can affect carbon sequestration and oxygen productivity. The study found that herbaceous species among pine plantations in Western Polissia perform important ecological functions that contribute to the conservation and restoration of ecosystems. The presence of these plants enriches the soil with organic matter and helps maintain the structural and functional stability of ecosystems. The study showed that herbaceous plants contribute to the restoration of pine plantations by providing protection and support for young trees, and have a positive impact on their biometric parameters, increasing the total phytomass. Herbaceous plants also improve soil physical properties, such as pH, humus content, aggregate water resistance and water permeability, which can contribute to soil structural stability and the health of pine stands. In addition, the presence of herbaceous plants contributes to more efficient carbon sequestration and oxygen production, which is important for the balance of the air environment in the ecosystem. The results obtained are of great importance for environmental management and conservation of natural resources in the Western Polissia region, as they provide scientific basis for developing strategies for the conservation and restoration of forest ecosystems, taking into account the role of herbaceous plants in their functioning

Keywords: forest stand; phytomass; soil; carbon sequestration; oxygen production; forest communities

INTRODUCTION

Herbaceous plants play a significant role in shaping biodiversity and ensuring the stability of ecosystems, including pine plantations. They affect various aspects of forest communities, providing optimal conditions for the development and existence of not only the plants

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themselves, but also the living organisms that interact with them. The ability of herbaceous species to compete, adapt and interact with other ecosystem components makes them key players in maintaining biodiversity and preserving ecological stability.

The research of scientists aimed at studying the impact of herbaceous plants on the biodiversity and stability of pine plantations reflects a wide range of approaches and methods. For example, P. Gautam *et al.* (2021) examine the relationship between herbaceous species and pine trees at different stages of their life cycle, from sowing to the development of mature stands. The author has found that the presence of herbaceous species stimulates the formation of a favourable microenvironment for the growth and development of young pines, providing them with protection from competing plants. In addition, herbaceous species contribute to the formation of biological cover under the trees, which helps to preserve moisture and nutrients in the soil, and protects the roots of the pine from overheating and drying out. Other scientists, such as L. Gustafsson *et al.* (2020) and M. Mpanda *et al.* (2021), analyse the impact of herbaceous plants on the soil environment, water regime and forest community environment. The authors' research focuses on the role of herbaceous species in the formation of soil cover and its impact on the structure and functioning of ecosystems. Scientists have found that herbaceous plants affect carbon metabolism and nutrient availability for plants, and reduce soil erosion. In addition, there is an interaction between herbaceous plants and soil biota, such as microbes and fungi, which can affect the health and development of pine plantations.

A number of authors have focused on the impact of herbaceous plants on biodiversity due to their role in maintaining species and ecological functions in forest ecosystems. Therefore, it is strategically important, in conformity with Z. Hastings *et al.* (2022), it is therefore strategically important to study the impact of herbaceous plants on biodiversity by assessing their ability to create conditions for the life and development of various animal and plant species. The authors, in particular, Z. Zhao *et al.* (2021) and Y. Long *et al.* (2022), emphasize the need to consider the effectiveness of herbaceous cover restoration measures for the conservation of biodiversity and stability of forest ecosystems, in particular, after human intervention, such as logging or land use change. It is worth noting the ecosystem services provided by herbaceous plants, such as water filtration, climate regulation and maintenance of soil fertility. In this context, the study by M. Mamuye *et al.* (2022) notes the importance of grass cover for maintaining ecosystem functions and ensuring human well-being. After all, grass cover is an important source of food and shelter for many species of animals, from insects to large herbivores and carnivores. It can also be important for humans as a source of food, raw materials for the production of medicines and cosmetics, and for ecotourism and recreation.

A similar opinion is also expressed by V. Lavnyy *et al.* (2022), who argue that one of the possible impacts of herbaceous plants on biodiversity is their role in creating microclimate conditions that support a diversity of living organisms. Grass cover can create favourable conditions for various species of insects, small mammals, and birds, which in turn supports biodiversity. In addition, herbaceous cover can affect the stability of pine stands by competing for resources such as light, water, and nutrients. Some species of herbaceous plants can maintain soil stability by maintaining soil fertility, which contributes to the healthy development of pine plantations. Investigating the impact of herbaceous plants on the biodiversity and sustainability of pine plantations in Western Polissia is of great importance due to the uniqueness of this region in terms of natural diversity and forest ecosystems. Western Polissia, which is located within Ukraine, Belarus, and Poland, is known for its abundance of natural greenery, including pine forests and rich herbaceous vegetation. Here, the unique combination of biodiversity and forest ecosystems creates favourable conditions for research on the relationship between grassland and pine plantations (Valeriano *et al.*, 2021; Kimeichuk & Kaidyk, 2022).

In general, the lack of research on the impact of herbaceous plants on the biodiversity and stability of pine plantations indicates the complexity of this problem and the need for further research to understand and conserve forest ecosystems. The emphasis on this is important not only from the point of view of scientific knowledge, but also from a practical perspective, as it can play a critical role in solving problems of conservation and management of forest resources. The aim of the study is to investigate the impact of herbaceous plants on the biodiversity and sustainability of pine plantations in the Western Polissia region of Ukraine, in particular, to understand their role in the ecosystem and interaction with other environmental components. To achieve the stated goal, the following objectives were set: to assess the species composition of herbaceous cover in pine plantations, to study their impact on soil physical parameters and biometric parameters of pines.

MATERIALS AND METHODS

The research was conducted in 2010-2023 on the territory of Horodetske village council of Volodymyrets district, Rivne region, at the state enterprise "Research Farm "Horodetske", which belongs to the Institute of Agriculture of Western Polissia of the National Academy of Agrarian Sciences of Ukraine and is subordinated to the Ministry of Economic Development, Trade, and Agriculture of Ukraine. Its area is 106.3 ha. This area is located in the Ukrainian Polissia zone and the Western Polissia Forestry District. Most of the tree plantations at the enterprise grow in fresh subsoil conditions. Coniferous plantations occupy about 65% of the total area, and broadleaved plantations – about 35% (Fig. 1).

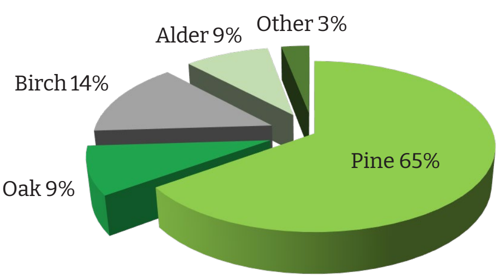

Figure 1. Share of tree species in Western Polissia
Source: compiled by the author

The study was based on the location of experimental plots in pine plantations with varying degrees of herbaceous plants: a control plot (30-45% herbaceous vegetation cover) and an experimental plot (50-75% herbaceous vegetation cover) of 0.25 ha each with a number of pine trees that should be at least 150 pcs.

The data on the diversity of plant species and their percentage was collected by recording all plant species found in the selected plots. The classical method of comparative forest ecology was used, with details on the forestry and taxation area. Soil pH was measured using a pH meter MT-300 – 2388-00005 (Chemtest, Ukraine). The humus content of the soil was assessed in the laboratory using the Turin method to a depth of 0-30 cm. The soil density was determined by the pycnometric method. The content of water-resistant aggregates in the soil was determined by the sieving method, in which the soil is sieved through a sieve with known mesh sizes, and then the content of large aggregates that did not pass through the sieve is measured. The water permeability of the soil was determined by the Nesterov method. The impact of herbaceous plants on the survival rate of pine plantations was determined by counting. The forestry-taxation method was used to determine the biometric parameters of the forest stand, in particular, equation (1) was used to determine the phytomass of the Scots pine crown:

$$P_{crown} = 8.379 + 0.087 * P_{boot}, \qquad (1)$$

where P_{crown} – crown phytomass, kg; P_{boot} – boot phytomass, kg.

Phytomass of a stand was defined as the phytomass of all trees in the stand per unit area. The volume of carbon sequestration was determined by measuring the amount of carbon absorbed from the external environment over a certain period. The oxygen productivity of the plantations was estimated using formula (2):

$$K = S * NPP * 1000, \qquad (2)$$

where K – oxygen productivity, NPP – net primary production (in grams of carbon per square metre per year, determined using a CO_2 analyser (PCE-CMM 5, Germany), S – area of reforestation (in ha).

Correlation and regression analysis was used to determine the relationship between the presence of herbaceous plants and the amount of carbon sequestration and oxygen production of pine plantations. The obtained research results were processed for their reliability using the multivariate method of analysis of variance MANOVA. Microsoft Excel software and the Statistica 10 software package were used for this purpose. To identify differences between the results, the Student's t-test was used with a significance level of $P \leq 0.05$.

RESULTS

The Ukrainian Polissia is a unique ecosystem region with rich vegetation adapted to humid conditions and diverse forest communities. In the western Polissia region of Ukraine, it is possible to find a variety of herbaceous plant species that reproduce in the region's conditions. As Polissia is characterized by high humidity and diverse forest communities, specific species of herbaceous plants can be found here. Some of them include: mosses and lichens that grow on trees, stones and soil, marsh plants such as *Sheuchzeria*, *Carex limosa*, *Menyanthes trifoliata*, *Calla palustris*, *Peucedanum palustre*, *Lysimachia vulgaris*, *Calamagrostis canescens*, as well as forest herbaceous plants such as *Fern*, *Veronica*, *Corydalis*, *Oxalis*, *Poa pratensis*, *Lolium pratense*, *Agrostis capillaris*.

When studying changes in topsoil vegetation, the main indicators are species composition and number of plants per unit area, projective cover, abundance, biomass, and average height. Particular attention is paid to the analysis of changes in the quantitative ratios of species, ecological groups, and plant life forms. The ratio of different ecological groups of herbaceous plants in the cover can be an indicator of the stage of degradation. Recreational impacts, regardless of the type of forest, contribute to the simplification of the structure and gradual destruction of the forest cover. In the later stages of degradation, when the undergrowth is thinned out, the soil becomes littered, its surface covered with layers of leaves, branches, rotten woody material, and other organic residues. This leads to the formation of a thick topsoil, which can prevent the penetration of water and air into the deeper soil layers, and impede seed germination and the development of the root system of plants. This process can contribute to the degradation of the forest environment, as it delays the regeneration of tree species and the development of vegetation, and therefore the conditions for tree species regeneration are deteriorating.

Grassy vegetation minimizes degradation and has a multifunctional impact on reforestation processes. Under certain conditions, it promotes the growth of young tree seedlings, protecting them from frost and overheating, and enriching the soil with nutrients. A diverse community of herbaceous plants can provide a number of benefits for forest restoration. For example, some herbaceous plants can improve soil structure and increase its water-holding capacity, creating a more favourable environment for tree seedlings. In addition, herbaceous plants can provide shade and protection from extreme temperatures, reducing the risk of frost damage and overheating to young tree seedlings. It is also important to note that herbaceous plants can contribute to the nutrient cycle in the soil, releasing essential nutrients through decomposition and improving soil fertility.

Prior to the study, we analysed the species composition of herbaceous plants in pine plantations at each site. Analysing the data obtained, about 20 species of herbaceous plants are found in the control and experimental plots, but the number of individuals of each species is different (Table 1).

Table 1. Diversity of herbaceous plants in pine plantations

No.	Type of herb plant	Number of specimens in the study area, pcs.	
		Control plot	Experimental plot
1	*Dactylis glomerata*	45	80
2	*Anthoxanthum*	30	56
3	*Poa pratensis*	20	39
4	*Lolium pratense*	35	76
5	*Agrostis capillaris*	50	60

Table 1, Continued

No.	Type of herb plant	Number of specimens in the study area, pcs.	
		Control plot	Experimental plot
6	*Thymus serpyllum* (Breckland thyme)	18	37
7	*Helichrysum arenarium*	12	29
8	*Sedum acre*	25	35
9	*Artemisia vulgaris*	22	28
10	*Calamagrostis epigejos*	15	20
11	*Veronica officinalis*	20	41
12	*Festuca ovina*	25	64
13	*Calluna vulgaris*	30	59
14	*Carex brizoides*	36	67
15	*Pteridium aquilinium*	28	74
16	*Viola odorata*	24	76
17	*Stellaria holostea*	37	58
18	*Galeopsis tetrahit*	43	73
19	*Lactuca sativa*	47	79
20	*Bidens frondosa*	29	68
21	*Calamagrostis arundinacea*	33	81

Source: compiled by the author

The herbaceous plants in pine plantations have a variety of effects on the soil. They ensure soil conservation by retaining topsoil and preventing erosion. They also contribute to the formation of organic fertilizer, improving fertility and carbon storage in the soil. The roots of herbaceous plants improve water absorption and drainage, which helps to improve soil structure and provide access to water for other plants, including pine trees. In addition, they help to increase biodiversity in the soil, creating a favourable environment for a variety of microorganisms and insects.

When analysing the impact of herbaceous plants on the physical properties of the soil, it should be noted that the experimental plot showed an increase in the pH level towards the neutral medium compared to the control plot, which may be due to an increase in the content of organic matter in the soil due to the growth of herbaceous plants. According to the results of the study, the humus content in the soil on the experimental plot was 21% higher than on the control plot, which indicates a positive impact of herbaceous plants on the processes of organic matter decomposition and humus formation. The experimental plot also showed a significant decrease in soil density compared to the control plot. This improvement in soil bulk may be due to an increase in the number of herbaceous plants that loosen the soil with their roots, which saves the soil environment from over-compaction. The study also found that the content of water-resistant aggregates in the soil on the experimental site was 16.8% higher than on the control site. This may indicate an increase in soil stability and its ability to withstand the damaging effects of water and erosion. In addition, the experimental plot showed a 21.5% increase in soil permeability compared to the control plot, which may be the result of a decrease in soil density and an increase in the amount of water-resistant aggregates (Table 2).

Table 2. Impact of herbaceous plants on soil physical properties

Indicator	Control plot	Experimental plot
Acidity, pH	5.5	6
Humus content, %.	3.3	4
Soil density, g/cm^3	1.2	1.44
Content of water-resistant aggregates in the soil, %.	26.8	31.3
Soil permeability, mm/h	65	79

Source: compiled by the author

In summary, the presence of more herbaceous plants in the experimental plot affected the physical properties of the soil, including an increase in pH, humus content, water-resistant aggregates, and water permeability. These changes suggest that the presence of herbaceous plants may improve soil structure and stability, which would consequently affect pine plantations.

As a result of the study, it was found that the presence of herbaceous plants has a significant positive impact on the processes of pine plantations restoration. Thus, on average, the growth of trees in the experimental plot increases by 20% compared to the control conditions. This allows us to conclude that herbaceous plants contribute to the creation of optimal conditions for the growth of pine trees. In addition, the percentage of survival of new seedlings reaches 60-82%, which indicates that herbaceous plants provide protection and support for young pine trees. Herbaceous plants in pine forests can have a positive impact by reducing competition between trees and contributing to their health by improving water absorption and soil fertility. This is achieved through a variety of biogeochemical processes, such as the influence of foliage and litter layers on the availability of nutrients in the soil. This positive impact of herbaceous plants in pine forests can improve forest stand biometrics, contribute to biodiversity and ecosystem maintenance. The expansion of herbaceous species can contribute to the formation of more resilient and diverse forest communities, while providing additional nutrition and protection for pine trees.

The study determined the impact of herbaceous plants on the biometric parameters of trees in the plots. Firstly, it was found that the average height of the pine boot in the experimental group is less than in the control group – 10 m vs. 11.5 m, respectively. The total phytomass in the experimental group is higher than in the control group – 93.7 thousand tonnes versus 88.6 thousand tonnes, respectively. The average phytomass of the boot and crown per 1 tree in the experimental group was also higher than in the control group – 168.8 kg vs. 252.7 kg, respectively (Fig. 2).

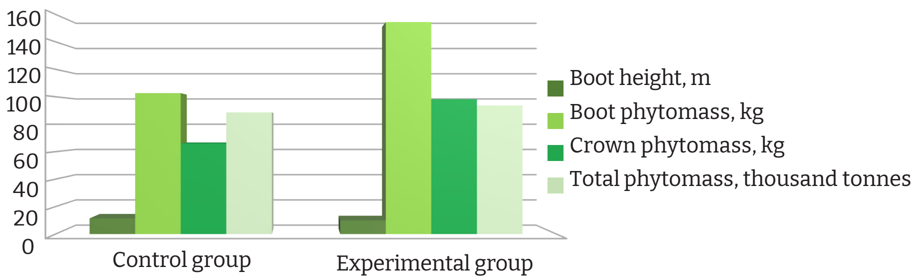

Figure 2. Average biometric parameters of the forest stand
Source: compiled by the author

Thus, from the data obtained, it can be argued that the growth of herbaceous plants affects the biometric parameters of pine trees, in particular, their height decreases, but the total phytomass of the plantation increases. Carbon sequestration and oxygen production are indicators of the biological activity of an ecosystem. They indicate the ability of plants and other organisms to carry out photosynthesis, the process by which green plants use sunlight, carbon dioxide and water to produce organic compounds, such as glucose, and release oxygen into the atmosphere.

It is worth noting that the amount of carbon sequestration and oxygen production differ significantly between the control and experimental plots. Thus, in the control plot, the volume of carbon sequestration is 64.6 thousand tonnes, while in the experimental plot, the volume of carbon sequestration is much higher and amounts to 214.3 thousand tonnes. This may be due to an increase in the number of herbaceous plants that are able to effectively absorb carbon during photosynthesis. On the control site, the volume of oxygen production is 139.2 thousand tonnes, while on the experimental site there is a significant increase in the volume of oxygen production, which is 361.5 thousand tonnes, which is an indicator of the positive impact of the presence of herbaceous plants on the photosynthesis process, which leads to an increase in oxygen production. In order to verify the reliability of the results obtained, a correlation and regression analysis was conducted. This highly effective statistical method is used to identify relationships between different variables. In this study, correlation and regression analysis was used to determine the correlation between the presence of herbaceous plants and the amount of carbon sequestration and oxygen production by pine forests. This analytical approach allows us to determine whether there is a relationship between the two, and if so, what it might be. The correlation component measures the strength and direction of the relationship between two variables. If a relationship is found, the regression component is used to model the relationship and predict one variable based on the other. In this case, the analysis will allow us to understand how the presence of herbaceous plants affects carbon sequestration and oxygen production in pine forests. According to the correlation and regression analysis, the reliability value for carbon sequestration and oxygen production was R = 1, which means that the model accurately describes the available data (Fig. 3).

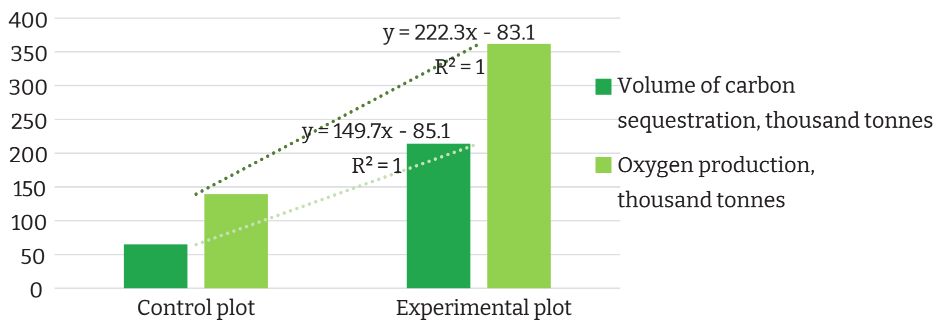

Figure 3. Correlation and regression dependence of the presence of herbaceous plants with the volume of carbon sequestration, thousand tonnes, and the volume of oxygen production, thousand tonnes of pine plantations

Source: compiled by the author

Thus, herbaceous plants, due to their sufficient leaf surface, are able to efficiently collect sunlight for photosynthesis, which contributes to more intensive carbon uptake and oxygen production. A greater number of such plants in the experimental plot can lead to an increase in photosynthesis, which in turn affects the carbon and oxygen balance in the ecosystem. This can be important for the ecosystem, as the balance between carbon and oxygen is critical for life on Earth. Oxygen produced during photosynthesis is essential for the respiration of most living organisms, while carbon sequestration helps to reduce the concentration of greenhouse gases in the atmosphere and contributes to the fight against global warming. Thus, increasing the number of herbaceous plants can have a positive impact on environmental sustainability and biodiversity conservation.

The study revealed a significant species diversity of herbaceous species in the studied pine plantations. It was found that herbaceous plants have a significant impact on the stability of pine plantations. They contribute to the preservation of soil cover, improve its physical properties, and reduce the risk of erosion. Studies have shown that herbaceous plants influence the natural regeneration of pine plantations. They help to increase the productivity and diversity of the new generation of trees. To summarize, the results of the study confirm the importance of herbaceous plants in the conservation of biodiversity and stability of pine plantations in the Western Polissia region.

DISCUSSION

Herbaceous plants have a positive impact on the health of pine trees by improving water absorption and soil fertility. This impact can improve forest stand biometrics and contribute to biodiversity. The study shows that herbaceous plants play an important role in maintaining soil cover, improving its physical properties, and reducing the risk of erosion. They also influence the natural regeneration of pine plantations, which increases the productivity and diversity of the new generation of trees.

The analysis of the study results confirmed the importance of herbaceous plants in shaping biodiversity and ensuring the sustainability of ecosystems, including pine forests. Herbaceous species are able to compete, adapt and interact with other ecosystem components, making them key players in maintaining biodiversity and preserving ecological stability. Y. Zhang *et al.* (2022) also investigated the impact of herbaceous plants on ecosystems. According to their study, herbaceous species play a significant role in maintaining biodiversity and ecological stability, which confirms the results of our study. Comparing our results with the authors' data, we can see similar trends in the impact of herbaceous plants on ecosystems, including pine forests. This highlights the importance of considering herbaceous species in ecosystem management and conservation.

Herbaceous plants can have a positive impact on understory and young plantations by reducing competition between understory trees for light, water, and nutrients. They can help to distribute these resources more evenly, which promotes healthy growth and development of the understory. C. Beierkuhnlein *et al.* (2023) and Q. Liu *et al.* (2020) studied the impact of herbaceous plants on understory and young plantations. Their research proved that the presence of herbaceous species helps to improve the conditions for the growth of young trees in the understory, providing them with access to the necessary resources. Comparing the results of the study with the authors' data, we can see similarities in the conclusions regarding the positive impact of herbaceous plants on the healthy development of the undergrowth and young pine trees.

The roots of herbaceous plants are able to hold soil, preventing it from being washed away during rain or snowmelt. This helps to preserve the soil layer, which is important for healthy plant growth. Herbaceous plants can create additional habitats for a wide variety of microorganisms, insects, and other living things to live and grow, which helps maintain the biodiversity of the forest ecosystem. R.M. Navarro-Cerrillo *et al.* (2023) and A.A. Shah *et al.* (2022), in a study on this aspect, found that herbaceous plants affect soil retention and promote biodiversity in forest ecosystems, which confirms similar findings on the importance of herbaceous plants for soil conservation and biodiversity.

The results of the study confirmed the importance of the interaction between herbaceous species and pine trees in the forest ecosystems of Western Polissia. The study has shown that the presence of herbaceous plants helps to improve the conditions for the growth and development of pine trees, which can be of great importance for the restoration and maintenance of sustainable forest stands. Comparison of the results with previous studies in this area confirms the consistency and complementarity of the findings. For example, studies by R.A. Slesak *et al.* (2020) and M.M. Qaderi *et al.* (2019) also point to the positive impact of herbaceous plants on the health and productivity of forest ecosystems. The authors' findings demonstrate the need to conserve and maintain the diversity of herbaceous species in forest ecosystems. Appropriate management of these elements of natural complexes can help to increase the resilience of forests to external stressors and maintain their productivity.

The diversity of herbaceous species contributes to the conservation and increase of biodiversity in the ecosystem, which in turn has a positive impact on the resilience and ability of the ecosystem to adapt to changes. The results of the study coincide with the data obtained by the authors in this area. For instance, the study by Q. Lyu *et al.* (2021) also confirms the positive impact of herbaceous species on the biodiversity and stability of forest ecosystems. After all, plants provide diversity among natural resources and ecosystem services, such as soil improvement, water conservation, erosion reduction. In addition, they contribute to greater resilience of ecosystems to environmental changes, thus helping to ensure the ecosystem's ability to adapt to environmental changes and rapid response to various stressors. The results of these studies emphasize the importance of sustainable management of herbaceous plants to ensure the sustainability and productivity of forests.

The study by C. Ramsey *et al.* (2023) indicates a significant impact of herbaceous species on the survival of pine trees in the early stages of their development. They found that the presence of certain herbaceous plant species promotes the survival and growth of pine trees in the early stages of their life. These results indicate an important interaction between herbaceous plants and trees in ecosystems, especially during the developmental stages when trees are still young and vulnerable. The presence of certain species of herbaceous plants can provide protection from weed competition, facilitate access to light and water, and provide other beneficial conditions for optimal growth of pine trees, as also noted in the present study.

The study confirms the opinion of Z. He *et al.* (2022), who emphasize the relationship between herbaceous plants and soil physicochemical properties. The study found that the presence of herbaceous plants can affect the physicochemical characteristics of the soil, such as pH, water holding capacity, structural properties, and others. These results indicate that the interaction between herbaceous plants and soil is an important factor in the formation and maintenance of soil quality. Herbaceous plants affect the soil not only through their root system, but also through the processes of biological decomposition of plant residues, which can change the chemical composition of the soil.

Another proof of this and confirmation of the results obtained is the opinion of M. Malashevskyi & O. Malashevska (2022), who believe that herbaceous plants play an important role in ensuring the stability of forest ecosystems. The presence of a diversity of herbaceous species can contribute to the conservation and maintenance of biodiversity, as well as have a positive impact on the physical and chemical properties of soil, which play an important role in ensuring the productivity and resilience of ecosystems. These findings highlight the importance of conserving and maintaining herbaceous plant diversity in forest ecosystems as a means to reduce soil erosion, conserve water resources and maintain the resilience of these ecosystems to external stressors.

The study found that grass cover significantly improved soil properties, including organic matter and soil structure. The results of the studies by K. Chao *et al.* (2023) and L.M. San-Emeterio *et al.* (2021) indicate that certain grass species may be more effective in improving soil organic matter and structure, which are important factors for the health and resilience of forest ecosystems. These findings highlight the need to consider herbaceous species diversity when planning and implementing forest conservation and restoration programmes, and indicate the importance of further research to understand the mechanisms of these effects and identify the most effective management strategies for forest ecosystems. Thus, the present study interacts with the results of other authors, confirming the importance of considering herbaceous plant diversity in the conservation and restoration of forest ecosystems.

The data obtained in this study emphasize the importance and interconnectedness of the various components of the ecosystem to ensure their stable functioning and conservation. The study adds to the knowledge of the impact of herbaceous species on the pine forest ecosystem, highlighting their role in conserving soil moisture and preventing soil from drying out. This demonstrates the importance of herbaceous plants in maintaining an optimal water regime for pine growth, which is reflected in their health and ecological sustainability. Such an impact not only helps to preserve forest ecosystems, but also improves conditions for their further development and increases their biodiversity (Chun *et al.*, 2020; Li *et al.*, 2021).

A study by M.T. Löbmann *et al.* (2020) also confirms that herbaceous plants can influence the health of forest ecosystems through their interactions with other environmental components. For example, they can create favourable conditions for the life and development of a variety of organisms, including soil microorganisms and insects, which in turn are important for the health of the forest environment. In addition, herbaceous plants can serve as a source of food and shelter for various animal species, which contributes to the conservation of biodiversity and ecosystem resilience. The results of the study by H. Xie *et al.* (2021), which found that the presence of herbaceous plants in pine forests significantly affects the biometric parameters of trees, also resonate with the present study. In particular, the authors proved that the average height of pine boots may be lower in the area with the presence of herbaceous plants. However, this is compensated by an increase in the total phytomass and the average phytomass of boots and crowns per tree. This influence indicates the importance of herbaceous plants in shaping the biometric characteristics of the forest stand in pine forests.

Importantly, herbaceous plants can contribute to the reduction of CO_2 through photosynthesis, which converts CO_2 into oxygen and organic matter. However, the extent of this contribution depends on various factors such as plant species, growth rate and environmental conditions. For example, fast-growing herbaceous plants with high levels of photosynthesis can potentially absorb more CO_2 than slow-growing plants. The study also confirmed the importance of photosynthesis and its impact on the balance of carbon and oxygen in the ecosystem. An increase in the number of herbaceous plants can lead to an increase in photosynthesis, which can have a positive effect on environmental sustainability and biodiversity conservation (Belmecheri & Lavergne, 2020; Ren *et al.*, 2024).

A study of the diversity of vegetation cover at different stages of forest development conducted by Z. Ni *et al.* (2021) showed changes in the composition of herbaceous cover at different stages of pine plantations development. Thus, in the early stages of forest formation, one composition of herbaceous plants may prevail, while in later stages this composition may change due to competition and other factors. Such changes in plant composition may occur over time and reflect natural processes of forest ecosystem development, such as succession and environmental changes, or may be the result of anthropogenic impacts, such as changes in forest management or human intervention. These studies can be important for understanding vegetation dynamics in forest ecosystems and developing management strategies to conserve and maintain the biodiversity and ecological resilience of these ecosystems.

CONCLUSIONS

Herbaceous species among pine plantations in Western Polissia perform several important ecological functions. They help to preserve soil and reduce erosion, as their roots hold the topsoil, preventing it from being washed away by rain and wind. In addition, herbaceous plants constantly regenerate and decompose, adding organic matter to the soil and enriching it. This creates favourable conditions for plant growth and promotes the development of various species of animals and microorganisms, which are important maintainers of forest ecosystem biodiversity. Thus, herbaceous plants play a key role in maintaining the health and stability of forest ecosystems in this region.

The study found that the presence of herbaceous plants has a significant positive impact on the regeneration of pine plantations. Herbaceous plants contribute to the creation of optimal conditions for the growth of pine plantations, providing protection and support for young trees. In addition, herbaceous plants affect the biometric parameters of pine trees on the plots, increasing the total phytomass of the plantation. In addition, herbaceous plants also have a significant impact on the physical properties of the soil, increasing pH, humus content, water-resistant aggregates, and water permeability. These changes suggest that the presence of herbaceous plants can improve soil structure and stability, which will consequently affect pine plantations.

The presence of more herbaceous plants in the experimental plot promotes photosynthesis and deepens the processes of the carbon cycle, which ensures more efficient carbon uptake and oxygen production, which can be important for the balance of carbon and oxygen in the ecosystem. Thus, these research results confirm the positive impact of herbaceous plants on pine plantations, which may be important for the sustainability and health of forest ecosystems in the Western Polissia region. The study may be limited geographically to a specific region of Western Polissia in Ukraine, and the results may be less universal for other forest ecosystems. Further research could be conducted to investigate the specific ecological functions performed by herbaceous species in forest ecosystems. This could include investigating their impact on nutrient cycling, water regime, and soil microbial diversity.

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CONFLICT OF INTEREST

None.

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Вплив трав'янистих рослин на біорізноманіття та стабільність соснових насаджень у Західному Поліссі

Анотація. У сфері екології все більше уваги звертається на аналіз взаємодії трав'янистих рослин зі структурою екосистем, в тому числі лісових масивів. Мета дослідження полягала у визначенні впливу трав'янистих рослин на біорізноманіття та стабільність соснових насаджень у Західному Поліссі України. Для досягнення поставленої мети впродовж 2010-2023 рр. на території державного підприємства «Дослідне господарство «Городецьке» проведено оцінку різноманітності видів трав'янистих рослин, вимірювання їх кількості та вкриття, оцінку фізичних властивостей ґрунту та біометричних показників соснових дерев, а також оцінку того, як зміни в екосистемі соснових насаджень, викликані трав'янистими рослинами, можуть впливати на обсяг поглинання вуглецю та киснепродуктивність. У результаті досліджень встановлено, що трав'янисті види серед соснових насаджень у Західному Поліссі виконують важливі екологічні функції, які сприяють збереженню та відновленню екосистем. Наявність цих рослин збагачує ґрунт органічними речовинами та сприяє підтримці структурної і функціональної стабільності екосистем. Дослідження показало, що трав'янисті рослини сприяють відновленню соснових насаджень, забезпечуючи захист та підтримку для молодих дерев, а також позитивно впливають на їх біометричні показники, збільшуючи загальну фітомасу. Також, трав'янисті рослини покращують фізичні властивості ґрунту, такі як рівень pH, вміст гумусу, водостійкість агрегатів і водопроникність, що може сприяти структурній стабільності ґрунту та здоров'ю соснових насаджень. Крім того, присутність трав'янистих рослин сприяє більш ефективному поглинанню вуглецю та виробленню кисню, що важливо для балансу повітряного середовища в екосистемі. Отримані результати мають вагоме значення для екологічного управління та збереження природних ресурсів у регіоні Західного Полісся, адже вони надають наукові підстави для розробки стратегій збереження та відновлення лісових екосистем з урахуванням ролі трав'янистих рослин у їхньому функціонуванні

Ключові слова: деревостан; фітомаса; ґрунт; поглинання вуглецю; продукування кисню; лісові угруповання

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Theoretical substantiation and development of ecologically friendly farming system in Ukraine

Abstract. Intensive farming has caused soil degradation, including the loss of humus, soil structure breakdown, compaction, and a decrease in both potential and effective fertility. Therefore, research into farming systems is highly relevant. In this regard, the purpose of this study is to scientifically substantiate, develop, and implement an ecologically friendly modern farming system under Ukrainian conditions. The primary methods used to determine the effectiveness of various farming systems and ensure the accuracy and reliability of experimental data were field, laboratory, and statistical methods. The study substantiated that an industrial farming system with the input of approximately 12.0 tonnes per hectare of crop rotation area of organic matter (8.0 tonnes per hectare of manure and 4.0 tonnes per hectare of plant residues) produces about 0.81 tonnes per hectare of humus, although 1.33 tonnes per hectare of it is mineralised, leading to a negative humus balance in the soil. The output of grain units in this system is 8.21 tonnes per hectare, feed units – 9.63, and digestible protein – 0.86 tonnes per hectare, with stability at 91.2% and profitability at 88.0%. The organic farming system, which includes the use of 24 tonnes per hectare of organic fertilisers and biological products to control weeds, diseases, and pests in agrocenoses, does not ensure a positive humus balance in the soil (-0.14 tonnes per hectare) and has significantly lower

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productivity. The no-till system, which involves the application of 12 tonnes per hectare of organic fertilisers in the form of root and stubble residues, by-products of crop production, and mineral fertilisers during sowing and foliar feeding, ensures a positive humus balance (+0.12 tonnes per hectare) but has productivity levels comparable to the organic system. The ecological system provides stable, economically viable, and resource-adequate productivity of arable land, enhances the quality indicators of products, and preserves and restores soil fertility. It increased the output of grain units by 8.9%, feed units by 7.2%, and digestible protein by 8.1%, ensuring high stability at 94.1% and an increase in production profitability by 8.5% compared to the control. The materials in this study are of practical value for agricultural enterprises of various ownership forms and will serve as technological guidelines for the implementation of modern, ecologically safe, economically and energetically justified agricultural production.

Keywords: industrial farming; ecological farming; organic farming; no-till; productivity

INTRODUCTION

Objective and subjective factors, such as the growing global population, climate change, resource shortages, and agricultural land reduction and deterioration, significantly impact the production of high-quality and safe agricultural products). Conventional farming methods often lead to soil degradation, reduced fertility, and erosion. Developing ecologically preserving systems helps maintain and enhance soil fertility, ensuring the sustainable development of the agricultural sector. The further increase in the use of chemical industry products results in dangerous environmental consequences and significant economic losses. According to Y. Skliar *et al.* (2021), modern intensive farming is often accompanied by extensive use of chemical fertilisers and pesticides, contaminating water resources and soils. Ecologically preserving farming systems help reduce the chemical load on the environment, maintaining its ecological balance.

Research by J. Liebert *et al.* (2022) and J. Wright (2022) conducted in the USA and EU countries, indicates that the greening and biologisation of agriculture is the only way to improve the situation. However, there is a lack of comprehensive research on the greening of agriculture in Ukraine. Research and testing of the joint application of organic, mineral, and next-generation fertilisers under the conditions of the greening of agriculture are highly relevant. A. Rudinskienė *et al.* (2022) established that the basis of soil fertility is the formation, presence, and accumulation of organic matter. The content, quality composition, and nature of the biochemical transformations of organic compounds in the soil determine its physical, physicochemical, and chemical characteristics, such as structure-forming capacity, water-air, thermal and technological properties, absorption capacity, composition and mobility of cations, buffering capacity, and reduction potential.

However, scientifically unsubstantiated farming has led to soil degradation and desertification, loss of fertility, natural biological properties, and buffer capacity. Over the last 100-120 years, the humus content in cultivated lands of Ukraine has decreased by twofold or more; in some fields, this decrease has been three to four times (Boyko *et al.*, 2019). A.M. Lishchuk *et al.* (2020) summarised that in the Odesa and Kherson regions, the areas of the organic agricultural land amount to 102.2 thousand hectares (3.93%) and 75.9 thousand hectares (2.95%), respectively, where grains, legumes, oilseeds, technical, vegetable, and melon crops are grown. Agroecological assessment of soils in the Kherson region revealed an imbalance of humus and nutrients, indicating a threat of fertility loss; therefore, measures are recommended to improve these indicators. According to O. Tarariko *et al.* (2021), 32% of arable land is affected by water erosion and 20% by wind erosion. In addition, acidic soils occupy 26%, saline soils 4.1%, and solonetzic soils 5.4% of arable land. This identifies Ukraine as one of the countries with the most intensive manifestation of the aforementioned degradation processes worldwide. R. Prăvălie (2021) found that aridity, wind and water erosion, salinisation, loss of organic carbon, and vegetation degradation are among the top five global soil degradation processes and are critical for human well-being, sustaining life, and the stability of Earth's ecosystems.

V. Pinchuk & Yu. Podoba (2023) investigated that an untapped reserve for increasing agricultural crop yields in farming is the optimisation of plants' absorption of light energy, as the current utilisation coefficient of photosynthetically active radiation (PAR) under production conditions is only 1-2%, with theoretically possible values of 10-15%. Humus, as a global accumulator of assimilated solar energy, is the second most important indicator of energy use in agro-landscapes. During 2000-2021, the energy capacity of soils in Ukraine annually decreased by 11.0-39.9 GJ/ha. During this period, soils lost between 0.6 to 2.0 t/ha of humus annually. Therefore, 26.3 to 95.0 t/ha of manure must be applied annually to compensate for the organic matter lost from the soil.

Analysing the eco-economic aspects of soil fertility restoration, O.V. Khodakivska *et al.* (2017) indicate that with the prolonged use of agricultural lands under conditions of deteriorating ecological situation and intensifying soil degradation processes, the leading strategy of modern agriculture should be the preservation, restoration, and enhancement of soil fertility, prevention of degradation processes, which are important factors in ensuring high-yielding, competitive agricultural production and guaranteeing environmental and food security for the population.

In addressing these tasks, the greatest impact comes from farming systems. Therefore, the *purpose* of the study is to theoretically substantiate and develop a farming system that should include the efficient use of land and agro-climatic resources, the biological potential of plants, the enhancement of soil fertility, and the development and implementation of advanced technologies for growing all field crops.

MATERIALS AND METHODS

The study on farming systems was conducted during 2001-2020 on the experimental fields of the production unit of the National University of Life and Environmental Sciences (NULES) of Ukraine "Agronomic Research Station", located in the Right Bank Forest-Steppe of Ukraine and part of the Bila Tserkva agro-soil region of Kyiv region. Geographic coordinates: latitude – 50° 06', longitude – 30° 11'. The groundwater level is at a depth of 5-6 metres. The soil of the experimental plots is represented by typical low-humus chernozem. The granulometric composition is coarse silty loam. In the 0-30 cm soil layer, the humus content at the beginning of these studies in 2001 was 4.00%. The mineral solid phase of the soil consists of 37% physical clay and 63% sand. The equilibrium bulk density of the soil is 1.16-1.30 g/cm^3, and the wilting point moisture (WPM) is 10.8%.

A high content of total and available forms of nutrients characterised the soils. The content of available phosphorus by the Machigin method is 45–55 mg/kg of soil, available potassium by the Machigin method is 180-210 mg/kg of soil (DSTU 4114-2002, 2003), and available nitrogen forms are 31-40 mg/kg of soil. These described soils occupy about 55% of the soil cover of the Forest-Steppe zone of Ukraine. Thus, the soil conditions of the field research site were typical for the zone. The practical testing of the developed measures was conducted in farms in the Kyiv, Vinnytsia, and Cherkasy regions, where soil conditions are similar to those of the Agronomic Research Station of NUBiP Ukraine.

The climate of the location of the experimental sites is moderately continental. The calculated average long-term hydrothermal coefficient (HTC) for the agronomic research station of NUBiP Ukraine from 2001-2020 was 1.10, indicating that the area is classified as dry. Thus, during the period from 2001 to 2020, moisture was the limiting factor that restricted the productivity of field crops.

The study was conducted in a stationary experiment involving two short-rotation crop rotations typical for the Forest-Steppe zone under market conditions with the following crop sequences: (first crop rotation) peas–winter wheat–sugar beets–spring barley–corn for grain; (second crop rotation) soybeans–winter wheat–sunflowers–spring barley–corn for grain. The structure of sown areas and the set of crops in the rotations were developed according to the market demand for products, farm specialisation, and natural-economic conditions. The experiment included reviewing the following farming systems: industrial (control), eco-friendly, organic, and no-till. Since 2000, the scientists of the Department of Agriculture and Herbology of NULES of Ukraine have been developing and analysing these systems.

The content of the farming systems was composed according to resource provision with the goal of expanded reproduction of soil fertility. The control variant of the farming system was the model of industrial farming, where the resource provision of programmed arable land productivity involved applying 12 tons of organic fertilisers and 300 kg of active mineral ingredients ($N_{92}P_{100}K_{108}$) per hectare, along with intensive use of pesticides. The fertiliser rates (organic and mineral) were calculated to ensure a positive humus balance, considering the development of animal husbandry. The ecological index of this farming system was 25 (300/12), indicating its industrial chemical nature.

The ecologically friendly farming system was characterised by the prioritised use of organic fertilisers – 24 tonnes/ha (12 tonnes of manure, manure compost, poultry litter, etc., 6 tonnes of plant residues, 6 tonnes of post-harvest green manure). Mineral fertilisers were applied at a rate of 150 kg/ha of crop rotation area ($N_{45}P_{55}K_{50}$). Plant protection from harmful organisms (weeds, pests, disease pathogens) involved using chemical and biological preparations according to the ecologically economic damage threshold criterion. The ecological index of this farming system was 6.2 (150/24).

The organic farming system was based solely on the use of natural resources. Organic fertilisers were applied at a rate of 24 tonnes/ha of crop rotation area. Only mechanical and biological methods were used to control harmful organisms. The ecological index of this farming system was 0 (0/24), indicating complete biological farming. The no-till farming system involved applying 12 tonnes of organic fertilisers in the form of root and post-harvest residues, crop production by-products (straw, corn stalks, soybeans, and sunflowers), and post-harvest green manure crops. No organic fertilisers were applied. Mineral fertilisers were applied at a rate of 200 kg ($N_{90}P_{50}K_{60}$) for the planned yield of the cultivated crops. Intensive use of recommended pesticides was employed. The ecological index for this farming system was 6.7 (200/14), indicating its chemical nature.

For all farming systems, organic fertilisers included manure, manure compost, poultry litter, non-commercial parts of the crop, and grown mass of post-harvest green manure. The rate of these fertilisers was calculated to ensure a positive balance of nutrients and humus, as well as the farm's ability to provide these types of organic fertilisers. Adherence to the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) was maintained during the study.

RESULTS AND DISCUSSION

The study results showed that at the beginning of the investigation of farming systems in 2001, the humus content in the 0-30 cm soil layer was 4.00%, while by 2020, it had decreased to 3.51%. Intensive farming over 20 years (intensive mechanical tillage; application of high rates of chemical substances – mineral fertilisers, pesticides, soil conditioners, growth stimulants, etc.) led to soil degradation – loss of humus, soil structure breakdown, compaction, and over time, reduced potential and effective fertility.

The industrial farming system is the most intensive and energy-consuming, and it involves using all suitable land for agricultural production. Fertilising the soil with only mineral fertilisers, applying growth stimulants, and chemical plant protection products is the simplest and most effective way to achieve high crop yields. However, this is the most dangerous and harmful method for consumers. It was established that the optimal ratio between applied organic and mineral fertilisers is disrupted in Ukrainian farming. From the period of peak agricultural intensity (1960s-1990s) to the present, the ratio of mineral to organic fertilisers ranged between 1:20 and 1:29. However, the ideal proportion is 15 kg of mineral fertiliser resources (f.r.) for every tonne of organic fertilisers. The industrial farming system is aimed at depleting the soil's potential fertility rather than its expanded reproduction, which is the main condition for the sustainable development of the industry. For example, the industrial farming system (Fig. 1) provides the addition of about

12.0 tons/ha of organic matter (8.0 tonnes/ha of manure and 4.0 tonnes/ha of plant residues). From this organic matter, about 0.81 tonnes/ha of humus were formed, but 1.33 tonnes/ha of humus were mineralised, resulting in a negative humus balance in the soil.

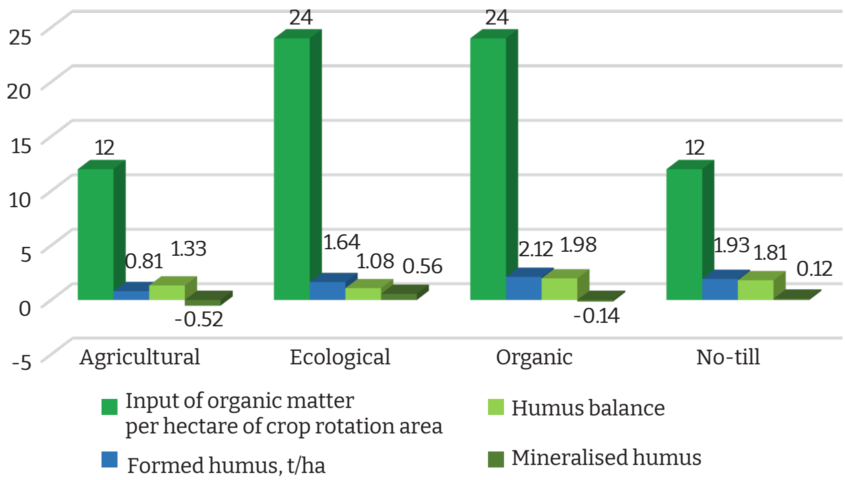

Figure 1. Influx of organic substances and humus balance in typical chernozem on 1 ha of crop rotation area, t (average for 2001-2020)

Source: developed by the authors

Such farming systems are feasible with high technical equipment of farms, sufficient quantities of organic and mineral fertilisers, means of protecting field crops from harmful organisms, high-quality seeds of high-yielding varieties and hybrids of agricultural crops, etc. Approximately 50% of all arable land in Ukraine should consist of such systems. Priority should be given to cereal, technical, and fodder crops within the structure of planting areas. Industrial farming systems should match the soil-climate potential of the specific zone and be soil-conserving and sustainable. However, the negative consequences of industrial farming may include increased energy and economic costs and the emergence of environmental problems (reduction of soil fertility, pollution of agricultural produce and the surrounding environment). Disruption of the NPK ratio in applied mineral fertilisers leads to agrophysical degradation of the soils, displacement of calcium ions and other divalent cations from the soil absorption complex, dispersion, and mineralisation of humus. The development of alternative farming systems, which are based on the ecological intensification of the industry, is one way to avoid these processes.

The proposed ecological farming system, which, along with the use of natural resources for soil fertility regeneration (organic fertilisers, green manures, by-products of plant production), does not exclude the normative application of mineral fertilisers and pesticides. It involves applying 24 tonnes/ha of organic fertilisers, which are 12 tonnes of manure, 6 tonnes of by-products, 6 tonnes of post-harvest green manure mass, and 150 kg of mineral fertilisers ($N_{45}P_{55}K_{50}$). Such a quantity of organic matter has enabled the formation of 1.64 tonnes/ha of humus. An organo-mineral fertilisation system promotes the least mineralisation of humus (at a level of 1.08 t/ha), leading to a positive balance of it in the soil (Fig. 1). To achieve bio-climatically justified yields (9.0-10.0 t/ha in feed units), the application of 150 kg/ha of active mineral fertiliser substances compensates for the deficiency of nutrients provided by organic fertilisers and from soil reserves. Hence, the ecological farming system ensures the enhanced reproduction of soil fertility.

The priority components of the system for protecting crops from harmful organisms in ecological farming are preventive, mechanical, and biological control measures and, when necessary, the ecologically and economically justified use of chemical agents (pesticides). Technologies for the production and application of protective bio-preparations, which replace artificial pesticides that, along with harmful microflora and fauna, destroy up to 90% of beneficial ones, are becoming widely used. The regenerative resources of protective bio-preparations have high selectivity and are ecologically safe for growing cereals, technical, vegetable, and fruit crops; they are also used in greenhouses against weeds, pests, and diseases of agricultural crops, achieving technical efficiency of 60-80% and above.

These studies established the high effectiveness of differentiated variable-depth tillage by method and depth, which naturally increases soil fertility and exhibits high phytosanitary properties. This is achieved by ploughing once every 4-5 years for row crops and no-till practices in the periods between ploughings for other crops. Under such a system, the subsequent ploughing moves the more fertile, albeit less structured, top layer of soil, along with the beginnings of weeds, pests, and disease agents from the topsoil layer to the depth of its cultivation, where they remain for 4-5 years and primarily (90-95%) lose their viability. The next ploughing, prepared for 4-5 years, restores the structure of the soil layer, naturally clears it from weeds, pests, and disease agents, and moves it to the surface.

The ecological farming system in the country should occupy 25-30% of arable land with a priority on cultivating crops whose products undergo primary shallow processing and are used for human consumption (potatoes, cereal grains, peas, soybeans, lentils, chickpeas, buckwheat, millet, squash, medicinal, vegetable, and other crops). The application of industrial-origin substances (mineral fertilisers, chemical plant protection products (PPP), chemical growth stimulators, industrial ameliorants, etc.) is performed while adhering to the ecological-economic threshold criterion for the presence of harmful organisms. The ecological farming system should be environmentally safe, highly productive, soil-protective, conserving, and adaptive to the respective soil and climatic conditions of Ukraine.

However, the highest level of making agriculture eco-friendly is organic production developed according to the laws of nature. Organic production models the natural process of soil formation. However, the removal of a significant portion of organic matter from the field through primary and secondary crop production necessitates increasing the rate of organic fertiliser application to maintain a positive humus balance and the possibility of developed livestock farming. The highest amount of organic matter added per hectare of arable land can reach up to 24 tonnes of organic fertilisers. This includes 12 tonnes of manure, 6 tonnes from non-commercial parts of cultivated crops, and 6 tonnes from the biomass of post-harvest cover crops, utilising various organic amendments such as manure composts and chicken manure. Furthermore, biological agents are applied to safeguard plants against harmful entities like weeds, pests, and pathogens. Under the influence of organic compounds released by the root system of plants, the intensified action of microorganisms and the absence of mineral fertilisers in the fertilisation system lead to enhanced mineralisation of humus, i.e., the conversion of the latter into minerals and mineral compounds. Mineralisation products are used by plants as nutrients, especially macronutrients – compounds of nitrogen, phosphorus, and potassium. According to the model of organic farming, the humus balance is negative and amounts to -0.14 t/ha per hectare of crop rotation area (Fig. 1).

In the no-till system, 12 tonnes of organic fertilisers come to 1 ha of crop rotation area in the form of root and post-harvest residues, secondary crop production (straw and stalks of cereal maise and sunflower) and post-harvest green manure crops. Organic fertilisers are not applied in the no-till technology. Such an amount of organic residues contributes to the formation of 1.93 t/ha of humus, while on average, about 1.81 t is mineralised per year, leading to a slightly positive balance of the latter (+0.12 t/ha).

The integral indicator of the effectiveness of farming systems is their productivity and, energy and economic efficiency. The productivity of individual crops and the crop rotation as a whole is an important indicator that enables a comparative assessment of crops from different biological groups and farming systems in general. Productivity is most often determined by the output of fodder, grain, and fodder protein units and by the amount of energy that accumulates in a production unit.

According to the data in Table 1, the productivity of the ecological farming system in terms of grain and fodder units is not inferior to the control variant – the industrial system. Moreover, it ensures a higher output of digestible protein by 10.4% in the first crop rotation and 8.1% in the second. The organic system and no-till have significantly lower productivity indicators compared to the control variant.

Table 1. Productivity of the studied agricultural systems and crop rotations (average for 2001-2020, yield from 1 hectare of crop rotation area, tonnes)

Agricultural systems	Performance indicators	Peas-winter wheat-sugar beet-spring barley-corn for grain	Soybean-winter wheat-sunflower-spring barley-corn for grain
Industrial (control)	Grain units	7.46	8.21
	Feed units	9.52	9.63
	Digestible protein	0.77	0.86
Ecological	Grain units	7.33	8.94
	Feed units	9.28	10.32
	Digestible protein	0.85	0.93
Organic	Grain units	4.98	5.37
	Feed units	5.46	7.05
	Digestible protein	0.53	0.59
No-till	Grain units	5.11	5.63
	Feed units	6.31	7.84
	Digestible protein	0.59	0.66

Source: developed by the authors

The results obtained convincingly demonstrate that ecological farming can achieve stable, bioclimatic, energetic, and economically justified productivity of arable land, improve the quality of crop production, and preserve and restore soil fertility (Table 2). On average, over two crop rotations, the proposed ecological farming system provided an 8.9% higher yield of grain units, 7.2 feed units, and 8.1% digestible protein over twenty years of research, ensuring high stability at 94.1% and an 8.5% increase in production profitability compared to the control.

Table 2. Comparative assessment of the effectiveness of agricultural system models (average for 2001-2020)

Indicators	Industrial (control)	Ecological		Organic		No-till	
		Absolute values	± % to control	Absolute values	± % to control	Absolute values	± % to control
Grain units, t / ha	8.21	8.94	+8.9	5.37	–34,6	5.63	–31,5
Feed units, t / ha	9.63	10.32	+7.2	7.05	–26,8	7.84	–18,6
Digestible protein, t / ha	0.86	0.93	+8.1	0.59	–31,4	0.66	–23,3
Stability, %	91.2	94.1	+3.2	81.3	–10,9	85.2	–6,6
Adequacy of resource provision	0.90	0.92	+2.2	0.81	–10,0	0.83	–7,8
Profitability, %	88.0	95.5	+8.5	90.7	+3.1	92.3	+4.9
Protein content in wheat grains, %	14.3	14.1	–1,4	12.5	–12,6	12.7	–11,2
Gluten content in wheat grains, %	28.7	28.3	–1,4	24.7	–13,9	25.2	–12,2

Source: developed by the authors

The findings of the studies have been implemented in the crop rotations of the Agrofirma Kolos LLC in the Kyiv region during 2005-2020, which contributed to an increase in soil organic matter content by 0.44% (from 3.94% to 4.38%).

Similar studies have also been conducted by other foreign and Ukrainian scientists. V. Pichura et *al.* (2021) found that over the past 30 years, there has been a 62% decrease in the productivity of agricultural crops due to soil degradation, climate change, and inadequate use of modern agro-technologies. Measures are needed to improve the agroecological situation and implement innovative approaches in agriculture. T.O. Chaika *et al.* (2019) and N. Trusova *et al.* (2021) indicate that the implementation of intensive crop cultivation technologies, which included the use of industrial substances such as mineral fertilisers and pesticides, has negatively affected the ecological state of the environment, soil fertility, and the quality and safety of agricultural products. Overall, the potential of agro-landscapes in Ukraine is only utilised at 30-50% due to the violation of ecological compliance of modern technologies and disregard for the requirements of agricultural and natural laws. According to V.P. Dmytrenko *et al.* (2017), anthropogenic organisational and technological contributions dominate the level and variability of crop yields. This indicates that the application of modern technologies and effective management of agricultural processes can significantly influence yield. Therefore, investment in the development of agro-technologies and the improvement of farmers' qualifications are key to stable and high yields.

Analysing the current state of Ukraine's soils and their fertility, S.A. Baliuk *et al.* (2021) note a 6.5% decrease in humus content across Ukraine from 3.36% to 3.14% over a twenty-year period. The decrease in humus content demonstrated in this study even exceeded these figures, reaching 12.3% from 4.00% to 3.51% over 20 years.

The obtained data on the possibility of reducing the amount of mineral fertilisers applied in ecological farming systems in the context of expanded use of organic fertilisers (manure, crop residues, and cover crops) are consistent with the studies by C. Li *et al.* (2022). Their research highlights the role of organic fertilisers in carbon sequestration in soil. Specifically, the use of organic fertilisers such as animal manure and crop residues allows for a reduction in the use of mineral fertilisers by an average of 20-30%.

The data on the negative humus balance in organic farming systems align with the findings of C. Maucieri *et al.* (2022), who indicate that organic farming does not have an advantage over conventional farming in terms of organic matter accumulation in soil. According to their multi-year results, 14 years after the introduction of organic farming, the humus content decreased relative to the initial data. This trend in organic farming is explained by a higher frequency of soil tillage for crop care and, on average, 32% lower crop yields with correspondingly fewer crop residues.

Similar results regarding the effectiveness of the no-till system were obtained by M.M. Al-Kaisi & R. Lal (2020), who point to carbon preservation in the soil. However, the data from Ya.P. Tsvei & M.S. Myroshnychenko (2020) indicate the absence of a significant increase in the amount of organic matter in the ploughed soil layer using no-till compared to conventional tillage. Moreover, the specifics of mineral fertiliser application in such farming systems (at sowing and foliar feeding) require additional inputs of nutrients for plants. Therefore, the no-till system requires both theoretical justification and practical research on increasing soil fertility through inputting organic matter into the soil, developing fertilisation systems, and plant protection systems against harmful organisms.

L. Tsentilo (2019) examined farming systems with different resource capacities over seven years. According to his results, the organo-mineral farming system with a balanced combination of organic and mineral fertilisers did not significantly differ in productivity from the mineral system. However, the organic system resulted in an average 36.5% decrease in crop productivity.

The results regarding lower productivity of organic farming compared to conventional farming align with the findings of D.J. Connor (2021). His analysis suggests that organic farming will require 2-3 times more land to achieve equivalent productivity than industrial farming. The efficiency of land use will decrease in inverse proportion. This is the main drawback of the impact of organic production on food security and nature conservation.

Research and practical experience of Ukrainian scientists indicate that in existing crop rotations in different soil-climatic zones of Ukraine, the most effective method is combined tillage and differentiated by depth. In particular, V. Adamchuk *et al.* (2016) indicate that ploughing is one of the most important tillage measures. However, it should not be done annually but periodically based on the deterioration of the structure of the upper 0-10 cm soil layer (structural coefficient less than 0.76). A mandatory condition for ploughing is the use of subsoilers or two-layer ploughs. Only in this case does it serve as a means of restoring soil structure, one of the most important factors in preserving its fertility. Similar research results are proposed by I. Prymak *et al.* (2016), which indicate the high effectiveness of a differentiated approach in choosing the method and depth of soil cultivation.

Thus, the basis of a modern, environmentally safe and energy-efficient farming system is compatibility with natural processes and strict adherence to agricultural laws. In the conditions of a market economy, the priority area of the study is the stabilisation of cropping area structures based on market relations; adaptive application of new generation organic fertilisers, crop residues, and wide use of cover crops; conservation tillage; implementation of crop protection systems from harmful organisms following the ecological-economic threshold of their population; use of microbiological preparations based on new isolated strains-producers, etc. The theoretical and practical results of the study have stimulated the development of certain branches of science and production and significantly changed the measures for managing soil fertility and crop productivity.

CONCLUSIONS

The recommended ecological farming system is a comprehensive approach to cultivating agricultural crops to achieve high soil productivity and preserve ecosystems. This system is based on scientifically grounded methods and practical research that optimise resource use, reduce negative environmental impact, and improve agricultural product quality and safety. The recommended system of ecological farming includes:

- Introduction of an organic-mineral fertilisation system, which includes the application of organic fertilisers at a rate of 22-24 tonnes per hectare of crop rotation area (10-12 tonnes/ha of manure or compost, 6 tonnes/ha of crop residues, 6 tonnes/ha of cover crops) and 150 kg ($N_{45}P_{55}K_{50}$) of mineral fertilisers. This resource content provides an ecological index of this system at 6.2, indicating the state of ecological farming and crop productivity within the range of 9.0-10.0 tonnes/ha of feed units.
- Implementation of a combined method involving varied-depth primary tillage in crop rotations is recommended. This method includes ploughing for row crops such as sugar beets, sunflowers, or maise for grain once every 4-5 years and non-ploughing techniques like different-depth chiselling and disking for other crops in the rotation.
- Combined crop protection system from weeds, pests, and diseases based on ecological-economic levels of harmful organism populations and the index of optimal selection of these measures.
- Use of biological preparations that improve nitrogen nutrition of crops, mobilise phosphorus and potassium in the soil, and enhance its biological activity.

Further research should focus on the theoretical justification and development of an environmentally conserving farming system in Ukraine, considering modern challenges and the needs of the agricultural sector. Research activity may include a deeper analysis of the relationships between agro-industrial production, ecological processes, and soil conditions, the development of new methods and technologies to preserve and restore soil fertility, reduce environmental impact, and increase the resilience of agricultural ecosystems to external factors.

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CONFLICT OF INTEREST

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Теоретичне обґрунтування та розроблення еколого-зберігаючої системи землеробства в Україні

Анотація. Інтенсивне землеробство стало причиною деградації ґрунтів – втрати гумусу, знеструктурення, переущільнення, зниження потенційної та ефективної родючості. Тому, актуальними є дослідження систем землеробства. У зв'язку з цим, метою досліджень стало наукове обґрунтування, розроблення та впровадження еколого-зберігаючої сучасної системи землеробства в умовах України. Для визначення ефективності варіантів систем землеробства, точності та достовірності експериментальної інформації провідними методами цього дослідження стали: польовий, лабораторний та статистичний. Дослідженням обґрунтовано, що промислова система землеробства з надходженням близько 12,0 т/га сівозмінної площі органічних речовин (8,0 т/га гною та 4,0 т/га рослинні рештки) забезпечує утворення близько 0,81 т/га гумусу, проте мінералізувалося його 1,33 т/га, що приводить до від'ємного балансу гумусу в ґрунті. Вихід зернових одиниць за цієї системи становить 8,21 т/га, кормових одиниць – 9,63, перетравного протеїну – 0,86 т/га за стабільності 91,2 % та рентабельності 88,0 %. Органічна система землеробства, що передбачає використання 24 т/га органічних добрив, застосування біологічних препаратів для контролювання бур'янів, хвороб та шкідників у агроценозах не забезпечує позитивного балансу гумусу в ґрунті (-0,14 т/га) та має суттєво нижчу продуктивність. Система No-till, що передбачає внесення 12 т/га органічних добрив у вигляді кореневих та пожнивних решток, побічної продукції рослинництва та мінеральних добрив при сівбі та позакореневому підживленні, забезпечує позитивний баланс гумусу (+0,12 т/га), проте має продуктивність на рівні органічної системи. Екологічна система забезпечує одержання стабільної, економічно вигідної та адекватної ресурсному наповненню ґрунтово-кліматичної зони продуктивність ріллі, підвищує якісні показники продукції, зберігає й відтворює ґрунтову родючість. Вона підвищила на 8,9 % вихід зернових одиниць, 7,2 кормових одиниць та 8,1 % перетравного протеїну, забезпечуючи при цьому високу стабільність на рівні 94,1 % та підвищення рентабельності виробництва на 8,5 % порівняно з контролем. Матеріали статті мають практичну цінність для сільськогосподарських підприємств різних форм власності та слугуватимуть технологічними регламентами впровадження сучасного екологічно безпечного, економічно і енергетично обґрунтованого виробництва сільськогосподарської продукції

Ключові слова: промислове землеробство; екологічне землеробство; органічне землеробство; No-till; продуктивність

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Chemical military-technogenic load on the soils of military training grounds

Abstract. Research on the military-technogenic burden on the natural environment as a result of international conflicts is relevant since military operations cause catastrophic consequences for the environment and natural resources, which can lead to irreversible disturbances in ecosystems. The study is devoted to the examination of the impact of military-technogenic loads on the soils of military training grounds. The paper considers methods of soil sampling and their analysis for the

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content of heavy metals and other chemical compounds and determines the impact of this load on the ecosystem and possible consequences for human health. The influence of military activity on the soil quality of military training grounds, in particular in the Cherkasy region, is analysed. The study includes the determination by X-ray fluorescence and atomic emission method of the content of various elements in the soil. The results showed a substantial iron content, which may be due to the use of explosives in military exercises. It is noted that despite the fact that exceeding the norms of maximum permissible content concentration, no heavy metals were recorded in the examined soils, and the maximum lead content approached the maximum permissible concentration, which requires further monitoring and control of this parameter. Ph determination showed a slightly acidic soil condition in combat exercise sites, which can affect plant fertility and growth. The content of nitrogen, phosphorus, potassium, and boron was assessed, and the results showed a lack of these nutrients for normal plant development. It is established that soil damage as a result of military operations can have a long-term negative impact and pose a threat to residents and territories. The results of the tests indicate a slight technogenic load at the sites of military exercises. The detected contamination of the examined samples is insubstantial, which indicates that the impact of military activities on the soil condition is limited. The results of the study will help to understand the possible health risks for people living near military training grounds and respond appropriately to protect their health

Keywords: chemical pollution; heavy metals; pollution monitoring; military exercises; environmental impacts

INTRODUCTION

An important task during the Russian-Ukrainian war is to localise the consequences of an environmental disaster as quickly as possible to minimise the damage caused by the Russian army to the environment and soil. The relevance of the study lies in the fact that the military-technogenic load on the soils of military training grounds has potentially severe consequences for the environment and human health. Armed conflicts and military operations can lead to substantial soil contamination with heavy metals, harmful chemicals and other dangerous compounds, which threatens environmental stability. The study on this issue will allow a better understanding of the scale of pollution and its possible consequences, which in the future can become the basis for developing effective measures to manage crisis situations and restore the environment after the end of a military conflict, quickly assess the amount of pollution, and develop ways to restore soils. Actions related to the storage, maintenance, testing, and even normal operation of military installations can lead to the spread of hazardous chemicals, fuels, lubricants, explosives, and other harmful compounds into the environment. This can cause soil and groundwater pollution, which in turn threatens human health, flora and fauna, and can also have negative environmental consequences for natural ecosystems in the long term. Therefore, examining the impact of military operations on soils is important for understanding and managing the environmental impact of military activities. Russia's full-scale invasion of Ukraine has destroyed and continues to destroy the country's infrastructure.

Firing and detonating all types of ammunition leads to chemical contamination of the soil. Shelling often causes fires in the fields. As a result, according to the data obtained by A.V. Skalny *et al.* (2021), fertile soil layers burn out, they are dehydrated and "sterilised", and both pathogenic microorganisms and useful biota die. Nutrients are also lost. Its upper fertile layer, which has been formed for centuries, is being destroyed. In addition, many toxic compounds enter the soil. Rocket explosions produce carbon monoxide and carbon dioxide, water vapour, nitrogen oxides, formaldehyde, cyanide vapours, and a large amount of toxic organic substances. Many toxic compounds are also produced, such as sulfur and nitrogen oxides, which, when oxidised, cause acid rain. They can alter the pH of the soil and cause chemical burns to plants and the respiratory mucosa of humans, birds, and mammals. Large amounts of mercury, zinc, cadmium, copper, nickel, lead, phosphorus, and barium accumulate in the places of shelling, the levels of which exceed the norm by dozens of times. According to the state environmental Inspectorate, as of October 1, 2022, losses caused by Russian troops to Ukraine's environment amounted to UAH 1.256 billion. Of this amount, losses to land resources amounted to UAH 407 billion, of which more than UAH 2 billion – due to soil pollution (McNutt & Hildebrand, 2022). It is hard to underestimate the importance of soil in an ecosystem. Military operations have a substantial impact on the natural state of the soil, as note by T. Stadler *et al.* (2022). The war in Ukraine and its extensive media coverage substantially increased professional and public attention to the burden on the environment in general and on soil pollution in particular, caused by military operations (Shukla *et al*., 2023). Military exercises at training grounds are accompanied by an increase in the negative impact on the environment. Y.M. Krylova-Grek (2022) noted that the destruction of the ground also occurs during explosions of ammunition, the construction of trenches, dugouts, and other combat positions. This is usually observed at objects such as training grounds, in particular, tank training grounds and shooting ranges. Heavy technogenic loads caused by the movement of vehicles, mainly tracked vehicles, lead to soil erosion, siltation, or waterlogging, which exceeds the permissible limits and poses a threat to the environment. The soil of landfills is additionally contaminated with various metal waste, such as shell casings, sheathed parts of explosive devices, and even ammunition left unexploded. S. Yang *et al*. (2021) noted that these substances pose a substantial danger to human and nature life and health, as they can be potential sources of poisoning and pollution of water sources, soil, and air. Such materials can be stable for a long period of time and remain active even after the end of hostilities, so they must be removed and processed by specialised methods for destruction or safe storage to prevent possible negative consequences for ecosystems and human health.

Yu. Shaforost *et al*. (2022) established that the negative impact on the environment is not limited to the formation of huge amounts of garbage and waste. It also includes emissions of hazardous materials such as asbestos, various industrial chemicals, and fuels that enter the soil, water sources and air, causing serious pollution and toxicity problems. As a result, a person is at risk of poisoning and other negative health effects, which can lead to serious diseases and even death. Such soil is degraded, the waterproof layer of bedrock is destroyed, soil fauna dies, and soil erosion occurs, which leads to global climate change. As a result, not only the air and soil can be polluted, but also groundwater. Since agricultural products are grown on this soil, and groundwater is used as drinking water, all these elements enter the food chain of living organisms, in particular, humans. A.J. Barker *et al*. (2021) argue that the problem is that military-technogenic loads on the soils of military landfills can lead to serious environmental pollution with toxic substances and heavy metals. Military actions cause destruction of natural resources, soil pollution, increased erosion and reduced soil fertility, which can affect agricultural production and threaten human health due to the migration of toxic substances to plants and water sources. Such contamination may have long-term impacts on the region's ecosystems and biodiversity. Understanding this problem is important for developing crisis management strategies and restoring environmental balance after the end of military conflicts.

The purpose of the study was to conduct a chemical assessment of the level of soil contamination at a military training ground in the Cherkasy region.

MATERIALS AND METHODS

For soil analysis, samples were taken on the territory of a military facility in one of the villages of the Cherkasy region. Sampling was conducted in the spring period (March 2023), after the snow melted. Soil samples were taken in various places: in the crater (the centre of the explosion), on the periphery of the explosion, places affected by mortar and artillery attacks, the use of small arms, and the neutralisation of ammunition. Test sites were selected to examine the most dangerous and technogenic-burdened areas. Preliminary soil samples were taken directly from the combat training sites. Sampling was conducted in the morning on a clear day before the temperature rose. In the morning, when exposed to sunlight, the soil may be slightly drier, which makes sampling easier and prevents the humidity of the samples from increasing. In addition, the morning hours are usually a time of minimal activity and air movement, which avoids contamination of samples with dust or aerosol particles in the air. Soil samples were taken from different depths – 5, 20, and 30 cm. In total, about 20 soil samples were collected. The study provides an analysis of only 5 soil samples, as the examination of other samples is ongoing, and their results are not yet ready for inclusion in the analysis.

Soil samples were taken at various sections of the military training ground. Some samples were taken in the centre of the crater formed during the explosion of a 120 mm MP-120 mortar (manufactured by the Ukrainian Armor company) and on the periphery of this crater. In addition, other soil samples were collected in the centre of the crater formed by the explosion of an 82 mm mortar and on its periphery. Another soil sample was taken on the territory of the training ground outside the war zone. The soil samples were the same for all variants. Each sample was placed in a package that was clearly marked with a label indicating the place of sampling. The sampling sites of the objects under study are shown in Table 1.

Table 1. Soil samples selected for research

Sample number	Place of selection
Sample No. 1	Soil from the crater, centre (*120-mm* calibre mortar)
Sample No. 2	Soil from the crater, centre (*82-mm* calibre mortar)
Sample No. 3	Soil from the crater, periphery (*120-mm* calibre mortar)
Sample No. 4	Soil from the crater, centre (*82-mm*calibre mortar)
Sample No. 5	Soil on the territory of the training ground outside of combat operations

Source: developed by the authors

The elemental composition examination of the soil (boron (B), copper (Cu), manganese (Mn), zinc (Zn), iron (Fe)) was conducted in the laboratory of the LLC "Ukravit Company" in the city of Cherkasy, using an inductively coupled plasma atomic emission spectrometer ICP 9800 Shimadzu (Japan), which has international accreditation DSTU EN ISO/IEC 17025:2019 (2019). All studies were conducted in accordance with the current regulatory documents, the responsibility for the accuracy of which is borne by the laboratory.

Soil and geochemical surveys were performed using the following methods: easily hydrolysed nitrogen (DSTU 7863:2015, 2015), pH of salt extract, mobile phosphorus compounds (P_2O_5) (DSTU 4115-2002, 2002), potassium exchange (DSTU 7861:2015, 2015), moving boron compounds (ISO 22036:2024, 2024), moving iron compounds (DSTU 4770.4:2007, 2007), moving manganese compounds (DSTU 4770.1:2007, 2007), moving copper compounds (DSTU 4770.6:2007, 2007), mobile zinc compounds (DSTU 4770.4:2007, 2007).

The atomic emission analysis method is important for determining the heavy metal content in soil with quantitative accuracy and high sensitivity. Therefore, the analysis of the content of heavy metals in the soil was conducted by this method. Atomic emission spectrophotometry was performed from an acetate-ammonium buffer solution (ph = 4.8).

The elemental composition of soils was also analysed using X-ray fluorescence. X-ray fluorescence spectra were obtained on the Rigaku EDXRF spectrometer (Japan) with an energy dispersion detector in the energy range from 2 to 10 keV. The spectra were recorded and processed using the ElvaX software. The dried soil was placed in special moulds and examined in the educational and scientific laboratory for physical and chemical research of materials at the Bohdan Khmelnytskyi Cherkasy National University. Such an integrated approach to the collection and analysis of soil samples allows obtaining objective data on the state of soils at military training grounds, which is important for assessing the environmental situation and developing measures to improve it. Monitoring and analysis of such data is necessary to ensure environmental safety on the territory of military training grounds and ensure sustainable development.

RESULTS AND DISCUSSION

An important tool for assessing soil quality, detecting its contamination, examining agricultural opportunities, and checking the content of minerals necessary for plant growth and yield is soil analysis for the content of harmful substances and heavy metals. The X-ray fluorescence method of elemental analysis has shown high efficiency and reliability in conducting such inspections and is widely used in industry, agriculture, and scientific research. This method allows obtaining complete and reliable information about the composition of substances, regardless of their origin and aggregate state, for a minimum period of time.

The results of elemental analysis obtained using the X-ray fluorescence method were performed for all soil samples. However, the results of only one sample are presented as an illustration since the results of the analysis of other samples showed similarities with each other. As can be seen, elemental analysis showed substantial iron (Fe) content and the presence of elements such as silicon, potassium, calcium, titanium, vanadium, manganese, and tungsten. In particular, titanium-based alloys with vanadium additives are used in aviation and rocket technology. Figure 1 shows the results of X-ray fluorescence of the soil of sample No. 2.

This method allows accurately determining the concentration of various chemical elements, including heavy metals, which can be potentially dangerous to the environment and human health. The atomic emission method is a fast and reliable way to determine the content of heavy metals in the soil, which allows detecting any contamination in time and taking the necessary measures for their further control and management. The obtained research results are shown in Table 2.

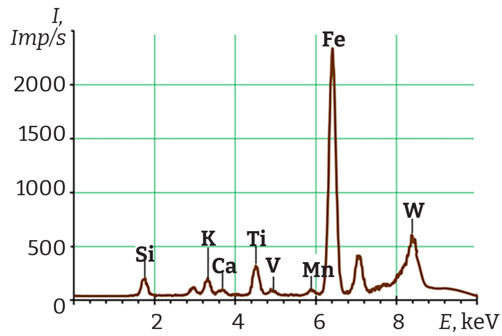

Figure 1. Soil X-ray fluorescence spectrum (sample No. 2)

Note: *I*, Imp/s – signal intensity, pulses per second; *E*, keV – the energy of characteristic radiation, kiloelectronvolts.

Source: compiled by the authors

Table 2. Heavy metal content in the soils of a military training ground

Metal content (mobile form)	Cu, mg/kg	PB, mg/kg	Zn, mg/kg	Mn, mg/kg	Fe, mg/kg
MPC, mg/kg	3.0	6.0	23.0	1500.0	Not normal
Sample No. 1	1.1	5.9	9.1	18.6	32
Sample No. 2	1.1	2.8	8.2	18.2	31
Sample No. 3	2.8	4.2	15	20.1	36
Sample No. 4	1.5	2.4	8.0	18.01	30
Sample No. 5	0.9	1.0	6.0	16.0	18

Note: MPC – maximum permissible concentration

Source: developed by the authors

Excess of the maximum permissible concentration in the examined soils was not recorded, which indicates a satisfactory condition of the soils according to certain parameters. However, it is worth paying attention to the fact that the lead content in sample No. 1 was maximum and close to the maximum permissible concentration, which is the reason for caution and the need for further monitoring of this parameter.

The highest content of manganese in soils reached 20.1 mg/kg, respectively, 5 metres from the crater. The smallest amount – 16.0 mg/kg was identified on the territory of the training ground outside of combat operations. Manganese is a heavy metal belonging to hazard class 3. The presence of manganese above the threshold level has a detrimental effect on the human body, which is manifested in the destruction of the central nervous system (Fig. 2)

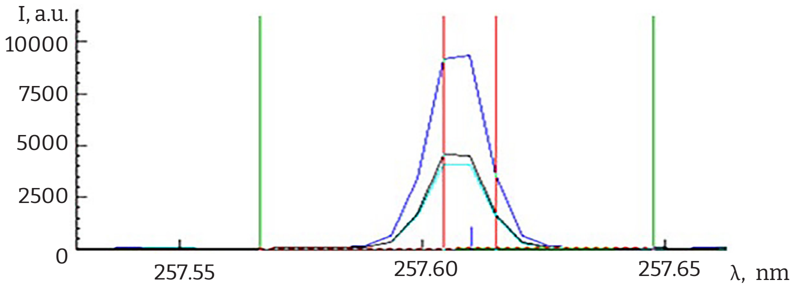

Figure 2. Emission spectrum of a sample in the determination of manganese (sample No. 2)
Note: I, a.u. – intensity of radiation, arbitrary units; λ, nm – wavelength, nanometers.
Source: compiled by the authors

This indicates that the manganese content in the soils varied depending on the sample collection location. The highest manganese content, which amounted to 20.1 mg/kg, was found in samples taken 5 metres away from the crater, which may indicate the influence of combat activities on the concentration of this metal in the soil. Conversely, the lowest manganese content, which amounted to 16.0 mg/kg, was found in the area of the training ground outside the combat zone, which may indicate a lesser impact of military-technogenic pressure on these areas. Exceeding the content of the determined metals poses a threat not only to the soil but also to humans. Dangerous substances can migrate from the soil into plants and from there into the bodies of people who consume these plants as food. Since the area on the training ground is rugged, with little vegetation and minimal migration of heavy metals into plants, the restoration of the soil cover is complicated because the transfer of heavy metals into vegetation is practically absent.

When analysing soils, it is important to remember one of the key indicators – pH. Analysing the soil pH is crucial because it allows determining the level of acidity or alkalinity of the environment. This indicator is of great significance for assessing soil fertility, as most plants can optimally develop within a certain pH range. For example, acidic soils can affect the availability of certain macro- and micronutrients to plants, which can lead to nutrient deficiencies and, consequently, reduced yields. Conversely, overly alkaline soils can be unfavourable for most plants due to nutrient dissolution and may cause salt stress. Therefore, determining the soil pH helps identify potential problems and establish necessary measures to improve fertility and optimise conditions for plant growth and development. Conclusions about soil acidity or alkalinity can be made by determining the pH of the soil's water and salt extracts. This is also one of the indicators of soil fertility. Table 3 presents the results of soil sample studies based on the pH parameter and the mobile forms of some elements.

The soils in the areas of military training (samples No. 1-4) are slightly acidic (pH = 3.8-4.2), while the soil sample No. 5 is practically close to neutral (pH = 6.2). This can be explained by the fact that a large number of explosions and the dispersion of heavy metals occur during military training, which can lead to changes in the chemical composition of the soil and a decrease in its pH. The results showed that the soils in the military training areas have a significantly lower pH, which may be the result of the decomposition of explosive substances and other chemical reactions that occur during such events. On the other hand, soil sample No. 5, taken outside the areas of military activities, has an almost neutral pH value, which may indicate a lesser impact of military loads and pollutants on this area. If the soil is too acidic, it hinders the achievement of high yields. Moreover, acidic soils enhance the migration of heavy metals, while alkaline soils limit the mobility of potentially toxic elements. In addition, plants cannot fully obtain nutrients from the soil because excessive acidity inhibits the activity of beneficial microorganisms that decompose various forms of organic residues, which in turn release available nutrients for plants. The best and most favourable indicator is considered to be pH close to neutral.

Important nutrients for plants that determine their health and development are nitrogen, phosphorus, potassium, boron, and sulfur. The presence of these elements in the soil is critical to providing plants with necessary nutrients. Therefore, this study carefully analysed the content of these nutrients in the soil. Nitrogen plays a key role in the formation of proteins and other vital organic compounds in plants. It is a component of amino acids, enzymes, and nucleic acids. Phosphorus is necessary for photosynthesis, energy transfer, and metabolism regulation. Potassium promotes plant growth and development, regulates water balance, and resistance to stress. Boron is necessary for the development of flowers and seeds, cell wall formation, and metabolism regulation. Sulfur is a component of amino acids, vitamins, and enzymes; it is important for protein synthesis and metabolism regulation. The analysis of these elements in the soil allowed determining how well the soil is supplied with essential nutrients for plant growth and development. Such analysis helps identify the nutritional needs of plants and develop strategies to support their optimal health (Table 3). The availability of mobile forms of alkaline hydrolysable nitrogen and sulfur is very low, the mobile forms of phosphorus are at a medium level, and the exchangeable potassium is low (according to the classification of F.A. Yudin).

Boron does not occur in a free state in nature. It is present in soils in two forms: inorganic and organic. For normal development, microorganisms and plants use boron in its inorganic form and then convert it into an organic form. After they complete their life cycle and die, the organic form of boron oxidises and turns back into an inorganic form. In the soil, boron is found as the acid H_3BO_3 (at pH 5-9) or the anion $[B(OH)_4]^-$ (at pH >9.2). It enters the plant in the form of the boric acid anion $BO3_3^-$. Based on the degree of supply of water-soluble boron (in mg per 1 kg of soil), soils are divided into the following groups: I – very low <0.15 mg, II – low 0.15-0.33 mg, III – medium 0.33-0.50 mg, IV – high 0.50-0.70 mg, V – very high >0.70 mg (Esringü *et al.*, 2011). The content of mobile boron in the studied soil samples varies from 0.057 to 0.060 mg/kg (Table 3). The overall assessment of the condition of the studied samples in terms of mobile boron content is characterised as very low (>0.15 mg/kg), indicating a low potential for growing agricultural crops (Fig. 3).

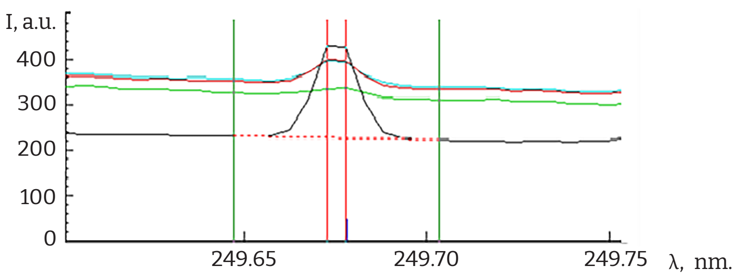

Figure 3. Emission spectrum of the sample in determining boron (sample No. 2).
Note: I, a.u. – intensity of radiation, arbitrary units; λ, nm – wavelength, nanometers.
Source: developed by the authors

Overall, according to estimates by experts from the Food and Agriculture Organization of the United Nations, boron deficiency is one of the major constraints on global crop production Boron deficiency is considered the second most important micronutrient for agricultural crops after zinc (Goldbach *et al.*, 2002). Military conflicts have a significant impact on soil characteristics, mainly due to the occurrence of certain physico-chemical disturbances and contaminations. These consequences are especially dangerous for soils used in agriculture. They can have a serious impact on soil fertility and its ability to maintain high yields. Analysis of global experience shows that military actions can cause significant changes in the quality and structure of soils. Based on the analysis conducted by A. Berhe (2006) and D. Vidosavljević *et al*. (2013), the concentration of heavy metals in the soil significantly increased during the Croatian War. The levels of arsenic, mercury, and lead in areas where intense fighting occurred exceeded the national legislative standards. After the end of the Croatian War in 1995, about 23% of the country's territory, approximately 13,000 km^2, was contaminated with about 2 million mines. However, now only 3% of these contaminated areas remain mined, and they are planned to be cleared by 2026, which will be 30 years after the war ended. The area of mined territories in Ukraine exceeds that of three Croatias. The intensity of hostilities during the Russian invasion is much higher than in the Croatian War, especially in terms of the density of mined areas.

According to M. Sadiq *et al*. (1992), after the Persian Gulf War, there was an increase in the content of heavy metals in the soil. The highest concentrations were recorded for cadmium, cobalt, chromium, lead, nickel, titanium, vanadium, and tungsten. Exceeding the maximum allowable concentrations of heavy metals in soils occurred as a result of military conflicts in Bosnia and Herzegovina, Iran, Kuwait, the Northern Mariana Islands, and others (Broomandi *et al*., 2017; Tomić *et al*., 2018a; 2018b). L.V. Mishchenko (2010) investigated the impact of military activities on the ecological state of the environment. L.I. Odosiy *et al*. (2015) noted that even if there are less contaminated areas on military training grounds where direct hostilities do not occur, military-technogenic pressure still leaves a mark on the soil. Y. Kopytsia & T. Semenchenko (2022) claim that daily hostilities and unexploded ordnance negatively affect all ecosystems, but the soil suffers the most. Each explosion destroys the soil layer, damaging the ecological and agricultural potential of the country. It is evident that the occupiers are trying to create unfavourable living conditions for future generations. The war waged by Russia is a challenge not only for Ukraine but for the entire world. Hostilities have destroyed forests, soils, and nature reserves, and more than 200,000 hectares of land are contaminated with shells, mines, and ammunition fragments.

Previous attempts to assess the condition of military training grounds and adjacent areas have already been conducted by N. Lisova (2017), P. Broomandi *et al*. (2020), Yu. Zaitsev *et al*. (2022) did not consider the load that occurs due to the explosion of artillery shells of different types with varying gunpowder charge masses. A clear analysis of the chemical composition of soils and their changes under the influence of military-technogenic loads underscores the importance of examining chemistry in agricultural higher education institutions (Pozharytskyi & Shaforost, 2022). Understanding the chemical processes occurring in the soil is crucial for ensuring the sustainability and fertility of soils, which are key to the agricultural sector. M.J. Lawrence *et al.* (2015) noted that military activities predominantly have a negative impact on the structure and functioning of ecosystems, manifesting in habitat destruction, environmental pollution, and decreased biodiversity. However, in some cases, military activity can have a positive effect, such as creating exclusion zones that promote population recovery or introducing new technologies that aid in conservation research.

All of this indicates a significant interest in the problem of chemical military-technogenic load on the soils of military training grounds. However, many aspects of this problem still require further exploration. For instance, it is important to conduct more detailed studies on the specific impact of different types of military activities on the composition and quality of soils and to develop effective strategies for rehabilitation and restoration of ecological sustainability in such areas. Thus, further studies in this area are of great importance for the preservation of the environment.

CONCLUSIONS

Soil analysis for the content of harmful substances and heavy metals is an integral part of assessing soil quality and its agricultural potential. The X-ray fluorescence method of elemental nalysis has proven to be an effective and reliable tool for such assessments, providing complete and accurate information about the composition of substances in the soil. The results showed a high iron content, which may be related to military activities occurring at the training ground, such as the use of explosions, artillery shelling, and other military measures, where iron may be used in various forms or materials, affecting its concentration in the soil. The atomic emission method of analysing heavy metals also allowed for precise determination of their concentration with high sensitivity and accuracy. It should be noted that although there were no recorded exceedances of maximum allowable concentrations (MAC) in the studied soils, the maximum lead content approached the MAC, requiring further monitoring and control of this parameter. Manganese, as a heavy metal, significantly impacts the human body, so its concentration in the soil is important to consider.

The analysis showed a difference in manganese content depending on the sampling location, indicating variability in its concentration in the combat zone compared to areas outside of it. Chemical studies of the soils at the military training ground in the Cherkasy region to assess the environmental situation have led to several important conclusions. The results of the tests indicate a slight technogenic load at the sites of military exercises. The detected contamination of the examined samples is insubstantial, which indicates that the impact of military activities on the soil condition is limited. The mobile content of heavy metals, which is an ecological-geochemical criterion for determining zones of ecological risk, also confirms this conclusion. All soil samples showed a significant decrease in indicators responsible for soil fertility, such as nitrogen, phosphorus, potassium, sulfur, and trace elements. This may be a consequence of the use of explosives at the training ground, affecting soil biological activity and fertility.

In this context, it is important to pay special attention to baseline soil quality indicators and consider the amount of pollutants from various sources, including the volumes of explosives used. The study concluded that the technogenic load on the soils after military training is minimal. However, despite the detected minor contamination, continuous monitoring of soil quality remains critically important to ensure environmental safety and sustainable use of natural resources. Research on the chemical military-technogenic load on military training ground soils opens up broad possibilities for further studies in this area. In the future, it is necessary to investigate more deeply the impact of such loads on human health and the environment. It is also important to examine the effect of chemical pollution on vegetation and biodiversity, as this will help to understand the consequences for ecosystems better and identify possible ways to restore natural habitats.

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CONFLICT OF INTEREST

None.

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Хімічне воєнно-техногенне навантаження на ґрунти військових полігонів

Анотація. Дослідження про воєнно-техногенне навантаження на природне середовище внаслідок міжнародних конфліктів є актуальним, оскільки воєнні дії спричиняють катастрофічні наслідки для екології та природних ресурсів, що може призвести до незворотних порушень у екосистемах. Стаття присвячена дослідженню впливу військово-техногенного навантаження на ґрунти військових полігонів. У роботі розглянуто методи відбору проб ґрунту, їх аналіз на вміст важких металів та інших хімічних сполук, а також визначено вплив цього навантаження на екосистему та можливі наслідки для здоров'я людини. Проаналізовано вплив військової діяльності на якість ґрунтів військових полігонів, зокрема в Черкаській області. Дослідження включає визначення методом рентгенівської флуоресценції та атомно-емісійним методом вмісту різних елементів у ґрунті. Результати показали значний вміст заліза, що може бути пов'язано з використанням вибухових речовин у військових навчаннях. Зазначено, що попри те, що перевищення норм гранично допустимої концентрації вмісту важких металів у досліджуваних ґрунтах не було зафіксовано, максимальний вміст свинцю наближався до гранично допустимої концентрації, що вимагає подальшого спостереження та контролю за цим параметром. Визначення pH показала слабо-кислий стан ґрунтів в місцях проведення бойових навчань, що може впливати на родючість та ріст рослин. Досліджено вміст азоту, фосфору, калію та бору, результати показали недостатність цих поживних речовин для нормального розвитку рослин. Встановлено, що пошкодження ґрунтів внаслідок воєнних дій може мати тривалий негативний вплив та становити загрозу для жителів та територій. Результати аналізів свідчать про незначне техногенне навантаження на місцях проведення військових навчань. Виявлене забруднення досліджуваних зразків є незначним, що свідчить про те, що вплив військової діяльності на стан ґрунтів є обмеженим. Результати дослідження допоможуть зрозуміти можливі ризики для здоров'я людей, які проживають поблизу військових полігонів, та вжити відповідних заходів для захисту їх здоров'я

Ключові слова: хімічне забруднення; важкі метали; моніторинг забруднення; військові навчання; екологічні наслідки

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