Sustainable Soil and Water Management Practices for Agricultural Security

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Agriculture is an industry of great importance that plays a vital role in addressing global food security. However, it faces significant risks due to climate change, such as extreme weather events, water scarcity, soil degradation, which can lead to reduced crop yields. By 2050, it is projected that the need for food security will double, which will require increased reliance on mechanization, chemicals, freshwater, and energy. These changes may have an impact on ecosystem health. To address these challenges, it is important to consider shifting from traditional farming systems to ecological farming systems that employ holistic approaches for sustainable food production. This transition suggests the need for climate-smart agriculture, which involves integrating economic, environmental, and social principles. It includes employing practices such as no-till farming, crop diversity, and precision irrigation to enhance soil health and ecosystem services. Embracing this proactive approach is crucial for adapting agriculture to climate change and meeting future food demands sustainably.

The chapter provides information on crop evaporation and water consumption during different growth stages, influenced by prevailing weather and climate conditions. This data serves as the basis for designing and implementing effective water regulation strategies. The authors conducted an assessment of the weather and climate in Western Polissia of Ukraine, and performed computer simulations of diverse climate scenarios. These simulations were based on comprehensive forecasts and models, considering key parameters of hydro-melioration systems, local climatic conditions, water management techniques, and the productivity of drained lands under various natural, agronomic, and reclamation conditions. Long-term forecasts were utilized to determine the vegetative values of total evaporation and the water demand of drained lands under changing weather and climatic conditions. Additionally, the authors evaluated the technological efficiency of different methods for moistening drained lands.

In the realm of agricultural research, this study delves into the ecological state of agricultural land use, shedding light on significant trends in the transformation of land relations. The article meticulously evaluates the ecological state of land by considering the degree of anthropogenic load. Through rigorous analysis, it establishes the coefficient of ecological stability of the territory, providing valuable insights into the intensity of land use. The research also formulates diverse scenarios depicting the functioning of contemporary agroecosystems within agricultural land use. Furthermore, the study identifies pivotal pathways for a successful transition toward an adaptive farming system, crucial for the establishment of efficient agricultural land use. This research area specifically focuses on investigating the impact of ecological sustainability of the territory on rational land use within agricultural enterprises, emphasizing its paramount importance in the broader context of ensuring food security.

The chapter considers soil carbon sequestration potential as a characteristic associated with the genesis of soils and the degree of their degradation. Various options for estimating the soil carbon sequestration potential based on comparing potentially achievable and actual levels of organic carbon content in soils are considered. Possible scenarios of carbon losses and carbon sequestration by the soils of Ukraine for the period up to 2050 are discussed. A method of spatial quantitative assessment of soil sequestration potential is proposed, considering the heterogeneity of relief and the degree of erosion degradation of soils. The implementation of the method is presented in the case of an experimental site located in the forest-steppe of Ukraine (Kharkiv region). It was shown that underestimation of the features of soil spatial heterogeneity can lead to errors in the estimation of the soil organic carbon sequestration potential up to 50% of the average value.

The mathematical problem addressed in this study concerns the formation of subsurface and surface runoff during storm precipitation in a low-slope area featuring both undeformed and surface-deformed soils. Approximate relationships governing the water accumulation on the surface of these soils and the movement of the saturation front were derived. Additionally, the timeframe for infiltration and groundwater closure, as well as the dissipation of the surface layer following the cessation of precipitation, was determined. Utilizing generalized initial data for fine soils along with a two-layer soil configuration at the experimental site, the accuracy of the derived relationships was evaluated. This study delves into the process of soil wetting during the formation of a low-permeability interlayer on the surface, resulting from compaction and swelling. A detailed analysis was provided for the comparison of subsurface runoff under conditions of varying degrees of deformation, both with and without surface deformation.

This chapter presents opportunities to use vegetative plants or their residues on the soil surface as a primary main indicator that restrains the development of erosion processes. Technological measures of soil cultivation that create different levels of erosion control efficiency presented, directly affecting the presence of post-harvest residues on the surface and indirectly the conditions of growth and development of crops in the conditions of unstable and insufficient moistening of Left Bank Forest Steppe, which is especially pronounced in the spring period. The methods and types of soil cultivation to strengthen this indicator by preserving the post-harvest residues of the previous crop for a certain period of time are considered. The compensating ways for an inevitable weakening of plant development and a decrease in their yield against the background of minimal tillage are presented to solve a problem of the same values of erosion resistance in agrocenosis with different tillage options during the growing season of crops in the rotation.

The crucial topic of soil acidity and its effects on global food security are the main focus of this chapter. Owing to its immediate effects on plant growth, development, and productivity as well as its capacity to fend off biotic stresses, such as diseases and insect pests, soil acidity, an abiotic stress, has gained significant attention in the agricultural community. Although the effects of aluminum (Al) toxicity on plants have received considerable attention, few studies have examined the harmful effects of low pH on plants. Low pH in agricultural soil can cause oxidative stress and electrolyte leakage through increased generation of reactive oxygen species (ROS), hinder CO2 assimilation, and impact plant water intake. This study delves into the mechanisms underlying plant growth under acidic conditions and highlights the strategies employed by plants to withstand and adapt to acidic stress. This chapter offers valuable insights into strategies for enhancing plant resistance to acidic soils and ensuring food security in the face of increasing water scarcity.

Rice systems in Ukraine are built on territories with saline soils, and with a complex hydrogeological situation. A method of calculating ecologically safe periods for growing dryland crops on saline soils is proposed, which will help to optimize the structure of rice rotations and prevent soil degradation. The considered technologies for leaching of saline soils, which make it possible to ensure qualitative soil desalination, to shorten the duration of leaching, to lower the level of groundwater, to improve the oxygen regime of the soil. The methods for calculating the technological parameters of capital and preventive soil leaching of saline soils have been developed. These methods allow improving the water permeability of the soil, attracting a natural thermal effect, reducing the volume of freshwater, and preventing the restoration of salts. It can be an important step in restoring fertility and increasing the productivity of rice systems in the face of water scarcity and climate change.

Developing a predictive system for water deficit analysis in the Black Sea Lowland, especially in climate change, involves integrating various data sources, modeling techniques, and technological tools to forecast water availability and demand. The analysis of the change in moisture deficit in the Kherson region is provided for the period from 1955 to 2022. A description of temperature gradients across the Kherson region is provided. The distribution of precipitation throughout the years in terms of quantity and intensity is provided. As part of the Black Sea Lowland, the Kherson region is critically important for southern Ukraine's agriculture and water security. Given the region's reliance on irrigation and the challenges posed by climate change, developing a predictive system for water deficit analysis is essential. Such a system can help stakeholders make informed decisions to ensure sustainable water management and mitigate the adverse effects of water scarcity.

The methodology for developing the technical and economic justification for the construction of irrigation systems is presented, based on a multidisciplinary approach. The goal of this approach is to provide a thorough and persuasive rationale for the implementation and construction of irrigation systems to reduce risks in agricultural practices and enhance agricultural productivity, considering a complex array of influencing factors. This approach involves quantitative modeling of various scenarios with different sets of parameters that characterize the state of irrigation management taking into account the increased level of agricultural production considering climate changes, natural moisture conditions, soil characteristics, crop structures, irrigation methods, types of irrigation equipment, efficiency coefficients of irrigation systems, etc. The development of the technical and economic justification is considered using the example of land use by the State Enterprise “State Farm “Pioneer” in the Kherson region.

The chapter presents a scientific and methodological approach to justify investment projects for restoring irrigation systems in southern Ukraine that were not damaged by hostilities. It focuses on irrigation systems in the Odessa region covering up to 10000 hectares with water supply from local sources. The economic efficiency of investment projects for system restoration is analyzed under different agricultural scenarios. Proposals for modernizing a small irrigation system in Odessa are developed, considering legislative reforms for water user organizations. The chapter evaluates the technical condition of infrastructure, land use, legislative reforms, climate change, and water resources availability. Legal aspects of irrigation restoration are examined, and modernization plans are proposed with results mapping. Profitability indicators are calculated for various investment return scenarios, comparing them with the basic business scenario. Sensitivity analysis is conducted to assess project resilience to changes in key parameters.

Irrigation plays an important role in solving the food security problem. Hence, subsurface drip irrigation (SDI) becomes more and more widely used. Its expansion requires studies to determine the parameters of wetted zones for various conditions. We propose to study the process of wetted zones formation in soil using mathematical modeling by solving the initial-boundary value problem for moisture transport equation in vadose zone of soil. Using the proposed approach, the determination of wetted zones under SDI was performed for Ukrainian soils of different texture. Based on the results of mathematical modeling, the main parameters of wetted zones were determined. Empirical dependencies of wetted zone parameters on the structural parameters of SDI systems and pre-irrigation threshold were also established. With a decrease in the pre-irrigation threshold, all wetted zone parameters increased and the process of zone's formation for sands, sandy loams, and light loams can be described by linear dependencies, while for medium loams, heavy loams, and clays they have a polynomial form.

The chapter outlines strategic approaches to the post-war restoration of irrigated agriculture in the Southern Steppe of Ukraine, with a focus on the Kherson region, which has been severely impacted by military operations. The region has faced significant anthropogenic damage, including military degradation of soil cover, destruction of the Kakhovka Dam and Reservoir, looting of reclamation systems, and loss of fertile soil layers. The chapter proposes a comprehensive set of ecological and remedial measures, including agronomic, remedial, and technical interventions, to restore the irrigated agriculture system. One of the keys is the restoration of hydro-technical structures such as the Kakhovka Hydro Power Plant in a revised framework. This entails an evaluation of the infrastructure and the implementation of necessary upgrades or modifications to ensure reliable functioning in the post-war context. The chapter emphasizes the importance of integrating ecological considerations into restoration efforts, such as soil conservation practices and the protection of natural habitats.

The chapter demonstrated the ecologically friendly way to obtain safe and high quality of medicinal herbal supplements under environmental changes. Global warming has a significant impact on medicinal plant productivity, including changes in the strategies of disease agents that compromise health and food security. Plant pathogens increase their ability to survive and reproduce intensively, resulting in strengthened plant disease severity, contamination of raw materials with toxic fungal metabolites, and yield losses. The repeated application of biologicals has proven to be effective in addressing this issue. The positive impact of microbial preparations on Calendula officinalis L. was observed in various aspects such as field seed germination, plant vegetative mass, and root system development. Treated calendula plants showed reduced stress during drought periods compared to the control group. Additionally, there was a significant decrease in leaf disease incidence and severity. This led to an improvement in the quality of calendula inflorescence weight and seed mass.

Plants are known as a source of secondary metabolites and have been used as antimicrobials in human health, animal health and crop protection. With the development of organic agriculture, new methods have been developed to innovate with plant extracts as herbicides, insecticides and fungicides in agriculture. The aim of this chapter is to review the literature on potential plants that could be used to develop new natural fungicides to combat foodborne fungal contamination. It will describe of the most cited plants as antifungal in agriculture, methods extraction and antifungal tests. Then, it will present newly discovered compounds from plants as effective antimicrobial agents in food manufacturing.

In this study the expression of drought-resistance marker genes ZmNHL1, ZmVPP1, ZmNAC111: the antiradical activity, relative water content and biochemical chromatographic profiling of the phenolic compound complex in the leaves of maize plants treated by biopreparations under drought stress, was investigated. Drought stress significantly affected the expression of stress-responsive genes in plants under the action of biopreparations (in 4-7 folds). The maize leaves in the variant with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha were characterized by the high content of total content of phenolic compounds, highest antiradical activity (88.2%), the most active glycosylation processes of flavonoids (up to 13%), the highest relative water content (97.3%) compared to the control. PCA and PLS-DA showed that the alterations of secondary metabolites, induced by biopreparations, serve as an initial mechanism for activation of the plant's antioxidant system, leading to a more robust defence system post-stress signals.

Preface

The sustainable management of soil and water resources has never been more critical than it is today. With the mounting pressures of population growth, urbanization, and climate change, the need to secure food, water, and energy for future generations is both an urgent and complex challenge. These challenges are not confined to any single region; they are global in scope, impacting every nation and community that relies on agriculture for food security and economic stability.

In a world where the challenges of climate change, population growth, and dwindling natural resources increasingly threaten global food security, the importance of sustainable agricultural practices cannot be overstated. As we face an uncertain future marked by unpredictable weather patterns, water scarcity, and soil degradation, it becomes imperative to rethink how we manage the natural resources that are foundational to our food systems.

In recent years, the interconnectedness of water, soil, and agricultural productivity has become increasingly evident. The degradation of these vital resources has profound implications not only for food production but also for the environment and human well-being. As climate patterns shift and water availability becomes more unpredictable, the need for innovative and sustainable approaches to soil and water management is paramount.

This book, "Sustainable Soil and Water Management Practices for Agricultural Security," aims to provide a comprehensive overview of the current state of these essential resources and to present strategies and practices that can help safeguard them for the future. Through the combined expertise of leading scientists, researchers, and practitioners, we have compiled insights and findings that underscore the importance of integrating sustainable practices into agricultural systems worldwide.

As the editor of this comprehensive reference book, I, Lyudmyla Kuzmych—Chief Researcher at the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine, Professor at Kherson State Agrarian and Economic University, Visiting Scholar at Pennsylvania State University—and my esteemed contributors, have endeavored to illuminate the intricate and essential relationships among these vital sectors. Our goal is to provide readers with the knowledge and tools needed to address the challenges of today and to prepare for the uncertainties of tomorrow.

This book is intended for a broad audience, including researchers, students, policymakers, and practitioners in the field of agriculture. It is structured to provide a comprehensive overview of the challenges we face, as well as the practical solutions that can be implemented to overcome them. Through a detailed examination of sustainable soil and water management practices, the book aims to equip readers with the knowledge and tools necessary to enhance agricultural productivity while preserving the environment.

The chapters that follow are grounded in the latest research and case studies from around the world, offering a global perspective on the implementation of sustainable practices. From soil conservation techniques to advanced drainage and irrigation systems, the topics covered in this book reflect the diverse approaches required to meet the complex needs of modern agriculture.

Organization of the Book

Chapter 1: Climate-Smart Agricultural Practices

Agriculture's significance in global food security is undeniable, yet it faces daunting challenges from climate change, including extreme weather events, water scarcity, and soil degradation, which threaten crop yields. By 2050, food security needs will likely double, necessitating increased mechanization, chemical use, and resource consumption, potentially harming ecosystems. This chapter advocates for a shift from traditional farming to climate-smart agriculture, emphasizing holistic, sustainable food production. Practices such as no-till farming, crop diversity, and precision irrigation are highlighted as essential for enhancing soil health and ecosystem services. Adopting these strategies is vital for adapting agriculture to climate change and sustainably meeting future food demands.

Chapter 2: Formation of Water Demand for Drained Lands in Variable Climatic and Agricultural Land Reclamation Conditions

The chapter provides information on crop evaporation and water consumption during different growth stages, influenced by prevailing weather and climate conditions. This data serves as the basis for designing and implementing effective water regulation strategies. The authors conducted an assessment of the weather and climate in Western Polissia of Ukraine, and performed computer simulations of diverse climate scenarios. These simulations were based on comprehensive forecasts and models, considering key parameters of hydro-melioration systems, local climatic conditions, water management techniques, and the productivity of drained lands under various natural, agronomic, and reclamation conditions. Long-term forecasts were utilized to determine the vegetative values of total evaporation and the water demand of drained lands under changing weather and climatic conditions. Additionally, the authors evaluated the technological efficiency of different methods for moistening drained lands.

Chapter 3: Research the Influence of Ecological Sustainability of the Territory on Rational Land Use in Agricultural Enterprises in the Context of Food Security

This chapter explores the ecological state of agricultural land use, examining the trends in land transformation and the impact of anthropogenic activities. It introduces a coefficient of ecological stability to assess land use intensity and proposes scenarios for modern agroecosystems. By focusing on ecological sustainability, this research identifies pathways for transitioning to adaptive farming systems, crucial for efficient agricultural land use and food security. The study emphasizes the importance of rational land use in agricultural enterprises to ensure sustainable food production in the face of environmental challenges.

Chapter 4: Spatial Heterogeneity of Soil Carbon Sequestration Potential and its Estimation Using GIS Technologies and Remote Sensing Data

This chapter investigates soil carbon sequestration potential, considering soil genesis and degradation levels. It presents methods for estimating this potential by comparing achievable and actual soil organic carbon levels. The study discusses scenarios of carbon loss and sequestration in Ukrainian soils until 2050 and proposes a spatial quantitative assessment method using GIS and remote sensing data. The findings from an experimental site in Ukraine's forest-steppe highlight the importance of considering soil spatial heterogeneity in carbon sequestration estimates, which can significantly impact the accuracy of these assessments.

Chapter 5: Modeling of Subsurface Runoff and Surface Runoff During Storm Precipitation in Low-Slope Undeformed and Surface-Deformed Soils on Agricultural Lands

This chapter addresses the mathematical modeling of subsurface and surface runoff during storm events in low-slope areas with varying soil conditions. It derives relationships for water accumulation and movement, infiltration timeframes, and groundwater closure. Using data from an experimental site, the study evaluates the accuracy of these relationships and examines soil wetting processes under different conditions. The research provides a detailed analysis of subsurface runoff in undeformed and surface-deformed soils, offering insights into water management on agricultural lands during storm events.

Chapter 6: Influence of Soil Tillage Methods on the Protective Role of Vegetation Cover

This chapter explores the role of vegetation cover and post-harvest residues in preventing soil erosion. It evaluates various soil tillage methods that enhance erosion control by maintaining surface residues and supporting crop growth in unstable moisture conditions, particularly during spring. The study presents soil cultivation techniques that strengthen erosion resistance and discusses compensatory strategies for maintaining crop yields under minimal tillage conditions. The findings highlight the importance of soil management practices in enhancing vegetation cover's protective role and ensuring sustainable agricultural productivity.

Chapter 7: Plant Tolerance to Soil Acidity in the Era of Climate Change: Biotech & Breeding for Sustainable Agriculture

This chapter examines soil acidity's impact on plant growth and global food security, particularly its effects on plant stress resistance and productivity. It delves into the mechanisms of plant adaptation to acidic conditions and strategies to enhance tolerance. The study highlights the detrimental effects of low pH on plants, such as oxidative stress and impaired water uptake, and explores breeding and biotechnological approaches to improve resistance. These insights are crucial for developing sustainable agricultural practices that ensure food security amidst increasing soil acidity and water scarcity.

Chapter 8: Environmentally Safe Technologies for Leaching Saline Soils in Rice Systems to Enhance their Productivity

This chapter presents technologies for leaching saline soils in Ukrainian rice systems to enhance productivity and prevent degradation. It proposes methods for calculating ecologically safe periods for dryland crop cultivation and optimizing rice rotations. The study discusses techniques for effective soil desalination, reducing groundwater levels, and improving soil oxygen regimes. By developing parameters for capital and preventive soil leaching, the research aims to restore soil fertility and increase rice system productivity, addressing the challenges of water scarcity and climate change.

Chapter 9: Predictive Assessment of Changes in Water Needs of Accompanying Crops of Rice Crop Rotation in Changing Modern Conditions

This chapter focuses on forecasting the water needs of crops accompanying rice in changing climatic conditions. It presents an approach for developing adaptive measures to climate change, optimizing water and energy resource use in rice systems. The study includes a machine experiment on water needs assessment for various crops under different agro-melioration conditions. By comparing these results with real production data, the chapter offers valuable insights into resource-saving regimes and technological solutions for rice system modernization, ensuring sustainable water management.

Chapter 10: Analysis of Moisture Deficit in the Kherson Region within the Context of Climate Change

This chapter analyzes moisture deficit trends in the Kherson region from 1955 to 2022, providing insights into temperature gradients and precipitation patterns. It emphasizes the importance of developing a predictive system for water deficit analysis, integrating various data sources and modeling techniques. Given the region's reliance on irrigation and the challenges posed by climate change, such a system is essential for sustainable water management and mitigating water scarcity's adverse effects on agriculture and food security.

Chapter 11: The Methodology of Technical and Economic Justification for the Construction of Irrigation Systems to Prevent and Reduce Risks in Agriculture

This chapter presents a multidisciplinary methodology for the technical and economic justification of irrigation system construction. The approach aims to provide a comprehensive rationale for implementing irrigation systems to reduce agricultural risks and enhance productivity. It involves quantitative modeling of various scenarios considering climate changes, soil characteristics, crop structures, and irrigation methods. Using a case study from the Kherson region, the chapter highlights the importance of integrating multiple factors to develop effective irrigation management strategies and support agricultural resilience.

Chapter 12: Increasing the Economic Efficiency of Irrigation Restoration Investment Projects in the Face of Climate Change

This chapter discusses a scientific approach to justify investment projects for restoring irrigation systems in southern Ukraine. Focusing on the Odessa region, it evaluates the economic efficiency of restoration projects under different agricultural scenarios. The chapter proposes modernization plans for small irrigation systems, considering legislative reforms and climate change impacts. It includes an assessment of infrastructure, legal aspects, and water resource availability, offering profitability indicators and sensitivity analysis to ensure project resilience and support agricultural productivity.

Chapter 13: Simulation of Wetted Zones Under Subsurface Drip Irrigation

This chapter explores the parameters of wetted zones under subsurface drip irrigation (SDI) using mathematical modeling. It addresses the initial-boundary value problem for moisture transport in soil, providing a framework for determining wetted zones for various soil textures. The study establishes empirical dependencies of wetted zone parameters on SDI system structures and pre-irrigation thresholds. The findings offer valuable insights for optimizing SDI systems to enhance irrigation efficiency and support sustainable agricultural practices.

Chapter 14: Strategic Ways of Post-War Restoration of Irrigated Agriculture in the Southern Steppe of Ukraine

The chapter outlines strategic approaches to the post-war restoration of irrigated agriculture in the Southern Steppe of Ukraine, with a focus on the Kherson region, which has been severely impacted by military operations. The region has faced significant anthropogenic damage, including military degradation of soil cover, destruction of the Kakhovka Dam and Reservoir, looting of reclamation systems, and loss of fertile soil layers. The chapter proposes a comprehensive set of ecological and remedial measures, including agronomic, remedial, and technical interventions, to restore the irrigated agriculture system. One of the keys is the restoration of hydro-technical structures such as the Kakhovka Hydro Power Plant in a revised framework. This entails an evaluation of the infrastructure and the implementation of necessary upgrades or modifications to ensure reliable functioning in the post-war context. The chapter emphasizes the importance of integrating ecological considerations into restoration efforts, such as soil conservation practices and the protection of natural habitats.

Chapter 15: Restoration of Drainage Systems as the Foundation for Agricultural Production Stability and Ecological Balance of Ukrainian Polissia

The changing conditions of crop cultivation and the shift in the use of drained lands necessitate the restoration of drainage systems, expanding their functional tasks, and ensuring water regulation on drained lands. The research focuses on agricultural lands in the farms of LLC "Vasiuty and LLC Bilinsket" in the Kovel district of the Volyn region of Ukraine. Studies conducted on reclaimed lands of the drainage systems "Melnitska" and "Bobrovka" have shown that the implementation of a complex of works to restore open and collector-drainage canals to design specifications, the operation of hydraulic structures, allowed for timely drainage of excess water in the spring period and regulation of soil water regime in the early vegetation period. Maintaining moisture in the active soil layer within close to optimal limits at the end of the vegetation period is possible through the accumulation of additional water reserves in the open channel network. Yield indicators of the studied crops (winter wheat, maize, sunflower) on drained lands have been determined

Chapter 16: Ensuring Food Security Through Biocontrol in Medicinal Plant Cultivation

The chapter demonstrated the ecologically friendly way to obtain safe and high quality of medicinal herbal supplements under environmental changes. Global warming has a significant impact on medicinal plant productivity, including changes in the strategies of disease agents that compromise health and food security. Plant pathogens increase their ability to survive and reproduce intensively, resulting in strengthened plant disease severity, contamination of raw materials with toxic fungal metabolites, and yield losses. The repeated application of biologicals has proven to be effective in addressing this issue. The positive impact of microbial preparations on Calendula officinalis L. was observed in various aspects such as field seed germination, plant vegetative mass, and root system development. Treated calendula plants showed reduced stress during drought periods compared to the control group. Additionally, there was a significant decrease in leaf disease incidence and severity. This led to an improvement in the quality of calendula inflorescence weight and seed mass.

Chapter 17: Plant Extracts as Antimicrobial Agents Against Fungal Food Contamination: Plant Methods Extraction, Antifungal Testing Phytochemicals

Plants are known as a source of secondary metabolites and have been used as antimicrobials in human health, animal health and crop protection. With the development of organic agriculture, new methods have been developed to innovate with plant extracts as herbicides, insecticides and fungicides in agriculture. The aim of this chapter is to review the literature on potential plants that could be used to develop new natural fungicides to combat foodborne fungal contamination. It will describe of the most cited plants as antifungal in agriculture, methods extraction and antifungal tests. Then, it will present newly discovered compounds from plants as effective antimicrobial agents in food manufacturing.

Chapter 18: The Role of Biologicals Azotohelp®, Liposam®, and Organic-Balance® as Mitigators of Abiotic Stress in Maize Plants

In this study the expression of drought-resistance marker genes ZmNHL1, ZmVPP1, ZmNAC111: the antiradical activity, relative water content and biochemical chromatographic profiling of the phenolic compound complex in the leaves of maize plants treated by biopreparations under drought stress, was investigated. Drought stress significantly affected the expression of stress-responsive genes in plants under the action of biopreparations (in 4-7 folds). The maize leaves in the variant with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha were characterized by the high content of total content of phenolic compounds, highest antiradical activity (88.2%), the most active glycosylation processes of flavonoids (up to 13%), the highest relative water content (97.3%) compared to the control. PCA and PLS-DA showed that the alterations of secondary metabolites, induced by biopreparations, serve as an initial mechanism for activation of the plant's antioxidant system, leading to a more robust defence system post-stress signals.

In Conclusion

The contributions in this edited volume present a robust synthesis of the current strategies, innovative methodologies, and critical reflections on the post-war restoration of irrigated agriculture, with a specific focus on the Southern Steppe of Ukraine. Chapter 14, by Lavrenko, Ladychuk, and their colleagues, underscores the necessity of a holistic approach to rehabilitating the region's devastated agricultural infrastructure. Their work highlights the integration of ecological considerations, agronomic measures, and technical interventions, providing a comprehensive blueprint for the restoration efforts in the Kherson region.

The destruction of key hydro-technical structures, such as the Kakhovka Dam and Reservoir, along with the degradation of soil and reclamation systems, presents unprecedented challenges. However, the proposed strategies offer a pathway toward not only recovery but also the advancement of sustainable agricultural practices. The emphasis on evaluating and upgrading infrastructure, combined with soil conservation and habitat protection, aligns with global best practices and ensures that restoration efforts are both effective and enduring.

As the editor, I recognize the significance of this chapter within the broader context of post-war recovery and agricultural resilience. The insights provided by the authors serve as a critical resource for policymakers, practitioners, and researchers engaged in the reconstruction of war-torn regions. The integration of multidisciplinary approaches and the commitment to ecological sustainability reflected in this chapter exemplifies the forward-thinking solutions required to address the complex challenges of post-war agricultural restoration.

In conclusion, the strategies outlined for the Southern Steppe of Ukraine represent a beacon of hope and a model for other regions facing similar adversities. By fostering collaboration among local communities, government agencies, and international partners, we can rebuild resilient agricultural systems that support food security and sustainable development for future generations.

I would like to express my deep gratitude to all those who have contributed to this work, from the authors who shared their expertise to the institutions that supported our research. The task of ensuring agricultural security in the face of global challenges is formidable, but with collaboration, innovation, and a commitment to sustainability, it is one that we can meet together.

Editor:

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Chapter 1
Climate-Smart Agricultural Practices

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ABSTRACT

Agriculture is an industry of great importance that plays a vital role in addressing global food security. However, it faces significant risks due to climate change, such as extreme weather events, water scarcity, soil degradation, which can lead to reduced crop yields. By 2050, it is projected that the need for food security will double, which will require increased reliance on mechanization, chemicals, freshwater, and energy. These changes may have an impact on ecosystem health. To address these challenges, it is important to consider shifting from traditional farming systems to ecological farming systems that employ holistic approaches for sustainable food production. This transition suggests the need for climate-smart agriculture, which involves integrating economic, environmental, and social principles. It includes employing practices such as no-till farming, crop diversity, and precision irrigation to enhance soil health and ecosystem services. Embracing this proactive approach is crucial for adapting agriculture to climate change and meeting future food demands sustainably.

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BACKGROUND

Agriculture is a high-risk industry, but it is also a crucial one. With the global population continuing to grow, urbanization persisting, disposable income rising, consumption habits changing, and the amount of fertile soil remaining limited, it is imperative to move beyond traditional farming (Mehrabi et al, 2022).

A number of socio-economic factors exert an influence on agricultural practices in Ukraine. These include land ownership reforms, government policies such as subsidies and regulations, the challenges of technological adoption, market access, and infrastructure limitations, the availability of labour and the skills of the workforce, the impacts of climate change, global market dynamics, financial constraints, and the role of education and extension services (Skydan et al, 2023; Pyvovar et al, 2024). These factors collectively influence the productivity, sustainability, and economic viability of Ukraine's export-oriented agricultural sector.

The term "food security" is defined by the FAO (2003) as the "physical and economic access to sufficient food to meet dietary needs for a productive and healthy life". The most urgent challenge facing society is the necessity to enhance the production of food and raw materials through the intensification of agricultural practices. Providentially, digital technologies offer powerful tools to improve operations and promote social and environmental sustainability.

Ukraine's productive lands can play a crucial role in doubling global food security by 2050. With sustainable management practices, these lands can produce food crops for export and support the world's growing population. It is imperative to transition towards more sustainable and responsible farming practices to ensure long-term food security and environmental health. However, current industrial farming practices, despite their high yields and profits, are causing increased ecosystem disservice. The intensification of farming practices will have long-term detrimental effects on ecosystem services.

Traditional agricultural practices in Ukraine heavily rely on deep plowing, inefficient irrigation, mono-cropping, and burning of crop residues. These practices are associated with increased agroecosystem disservices. Both irrigated and rainfed lands are impacted by the loss of soil organic matter (SOM), accelerated erosion, drought, secondary salinization, compaction, intermittent flooding, and increased pest and disease pressures. These factors inevitably result in poor soil health and reduced crop productivity.

Conventional agricultural practices in Ukraine routinely neglect environmental sustainability (Zhovtonog O.I., 2015 a). In the regions, where irrigation is crucial, these practices have led to a widespread deterioration in soil-water-plant-air relationships. It is important to adopt sustainable agricultural practices to ensure the long-term health of the environment and the success of the agricultural industry.

Industrial farming and land privatization prioritize high-profit margins over sustainability, neglecting soil and water management (Didenko N.O. et al, 2016).

To meet the demands of global food security for a growing population, agriculture must implement sustainable farming practices based on novel and holistic strategies. These practices can remediate degraded soils, improve overall crop production, and increase agricultural resiliency. The researchers (Aziz I. et al, 2013; Islam R. et al, 2013; Islam R. 2015; Zhovtonog O.I., 2015 b; Irkitbay A. et al, 2023) provide strong evidence for the effectiveness of these strategies.

The unprovoked invasion of Ukraine has caused challenges in energy and food supply, exacerbating vulnerabilities in food systems already weakened by the effects of climate change and the COVID-19 pandemic. Experts warn of a potential global food crisis, with ripple effects on security, migration, and political stability, similar to or worse than the 2007-2008 crisis (Cordaid, 2022). The war in Ukraine has significantly impacted all economic activities, including agriculture, a key driver of the economy.

The combination of these practices, climate change, and the consequences of war have greatly affected soil and water quality, as well as agricultural productivity. There is a clear need for further study and improvement to adapt time-tested agricultural practices to the new reality in Ukraine, as the dissemination of science-based knowledge on this topic is currently limited.

The research promotes the concept of climate-smart agriculture as an integrated farming system based on proven, novel, and holistic approaches, including conservation tillage, crop diversity with multifunctional cover crops, and precision fertigation. The system increases crop productivity and food quality sustainably, improves soil resilience and water and nutrient use efficiency, reduces greenhouse gas emissions, and supports food security for a growing global population.

CONSERVATIONAL TILLAGE

Mechanical tillage is the foundation of crop cultivation technology. To achieve optimal results, the soil in layer 0-30 cm, should have bulk density of 1.1-1.3 g/cm^3, a total soil porosity of 50-55%, and a content of water-soluble aggregates (0.25-10 mm) of more than 70%. Additionally, the soil should have a density of up to 30 kg/cm^2, a soil porosity of at least 15% by volume, a water permeability of more than 30 mm/h, and prevent erosion processes. Plowing is a necessary step for growing crops. Incorporating plant residues into topsoil or burning them is also essential and needs more research justification. It can be normal for the soil surface to remain uncovered for a short period of time.

A differentiated tillage system in crop rotation reduces energy costs by 25-30%, reduces weed infestation by 2.5-3.0 times, and increases grain yield by 1.5 t/ha of crop rotation area. In general, a differentiated tillage system has both positive and negative characteristics as reported by researchers at Iowa State University (2020) and CRP. Environmental Conservation (2020). The positive effects include the formation of an optimal structure of the topsoil, which provides plants with the optimal development of the root system and efficient use of nutrients; clearing the soil of weed seeds; deep incorporation of organic fertilizers and crop by-products, which increases their humification. Negative effects include deterioration of soil structure, increased water and wind erosion, increased mineralization of soil organic matter, agrophysical degradation of the latter, and high energy and resource consumption.

Conservation tillage is a highly effective agricultural management approach that minimizes the frequency and intensity of tillage operations, resulting in significant economic and environmental benefits. This approach is widely recognized as a best practice in modern agriculture. By leaving at least 30% of plant residues on the soil surface for erosion control and moisture conservation, the soil structure is improved, leading to increased yields and reduced costs.

The analysis clearly demonstrates that fertilizers have the greatest impact on crop yields, accounting for approximately 40%. Crop protection follows with a contribution of 15-25%, while varieties and hybrids account for 20%. Only 15-20% of the impact is due to tillage, which is the most resource-intensive element of the technology.

Conservation tillage offers several benefits. It reduces carbon dioxide and greenhouse gas emissions, decreases reliance on farm machinery and equipment, and lowers fuel and labor costs. Additionally, conservation tillage practices enhance soil health, minimize runoff, and limit erosion. By leaving the soil undisturbed and covered with residues, these practices provide potential environmental and economic benefits.

Conservation tillage practices, such as strip tillage or zonal tillage, have been proven to contribute significantly to the sustainability of agricultural systems. The use of narrow strips for seed preparation, ranging from 5 to 20 cm in width, is an effective way to achieve this. Tined tillage or vertical tillage is a superior method of preparing arable land compared to zero tillage (no-till), as it results in little compaction and a good cover of residues on the surface. Tined tillage or vertical tillage is a superior method of preparing arable land compared to zero tillage (no-till), as it results in little compaction and a good cover of residues on the surface. It is important to note that each method has its own advantages and disadvantages depending on the specific context in which they are used (Ferro N.D. et al., 2014; Skrylnyk Ye. et al, 2021).

Ridge tillage, which involves creating ridges and furrows, is also a viable option. The ridges can vary in width, and the furrows can be parallel to the contour lines or sloped, depending on the moisture conservation or drainage objectives. It is worth noting that the ridges can be semi-permanent or constructed annually, which affects the amount of residue material left on the surface.

Reduced tillage and retention of residues from the previous crop significantly enhance both soil fertility and crop productivity, making them important soil management practices for promoting sustainable agriculture (Kravchenko Y. et al, 2012; Skrylnyk Ye. et al, 2021).

Conservation tillage will undoubtedly play a crucial role in sustainable agricultural development in the future. It is less studies have paid little attention to the long-term effects of conservation tillage on soil microbial composition and metabolic activity, given its importance. Wang Ch. et al (2018) conducted a 15-year study comparing three tillage practices (no-tillage, ridge tillage, and conventional tillage) on black soil to determine the most effective method for improving soil health. Their findings demonstrate that no-tillage is the most effective method for improving soil health. Florine D. et al (2016) conducted a study and established that tillage depth was identified as the main factor influencing the variation in microbial diversity after 6 years of research on conversion from conventional to reduced tillage, tillage regime ranking after the depth of tillage, and the fate of crop residues was found not to influence microbial diversity.

Converting from conventional tillage (CT) to continuous no-till reduces farming costs and improves soil functional capacity, enhancing agroecosystem services. No-till allows crop residues to accumulate on the surface, reducing air, water, and energy exchange between the soil surface and the atmosphere. These reductions decrease soil temperature and evaporation, retain soil moisture for longer periods, and support efficient decomposition of crop residues. They act as residue mulch on the soil surface, as demonstrated by studies conducted by Lobell D.B. et al (2006), Franzluebbers A.J. et al (2002), Hendrix P.E. et al (1986), and Halpern M.T. et al (2010). This approach offers a range of potential benefits, including increased fungal dominance in soil food webs, greater accumulation of SOM and associated nutrients, reduced greenhouse gas (GHG) emissions, increased aggregate formation and stability, improved soil hydrology, and enhanced soil quality to support economic crop production. These benefits have been demonstrated in numerous studies, including those by Islam R.K. and Weil R.R. (2000), Crovetto C.C. (2006), and Van Groenigen et al (2010).

The conversion from plow-tillage to minimum till and no-till farming enhances the SOM pool. Enrichment of this parameter is essential for maintaining the fertility of Chernozems, advancing food security, and improving the environment. This conclusion is supported by a 10-year study conducted by Kravchenko Y. et al (2012) on a long-term experimental site in Ukraine. The study shows that switching from conventional to reduced soil tillage systems increases SOM concentrations in the 0 to 10 cm soil layer and leads to the accumulation of carbon (C) in fulvic acids and humins. Although there were no significant differences in SOM storage in the 0 to 100 cm layer among tillage systems, reduced tillage systems had a higher proportion of labile soil organic carbon (SOCL), a lower ratio of C in humic acids to C in fulvic acids, and more humic acids with molecular masses ranging from 110 to 2000 kDa.

Despite the importance of transitional no-till in soil ecosystem functioning, the impact of this practice on crop yields is still debated. However, the major barriers to transitional of no-till, such as greater immobilization of N and P, transient soil compaction, weed pressure, and stratification of SOM and nutrients, can be effectively managed with the use of cover crops in rotation with agronomic crops. Research has unequivocally shown that continuous no-till for 7-9 years produces higher yields than conventional tillage fields. This approach can jump-start no-till, often eliminating any yield decrease.

CROPPING DIVERSITY

Appropriate crop rotation practices are crucial for determining crop productivity and ensuring sustainable agriculture. Noncompliance with these practices can lead to the deterioration of soil biochemical characteristics and land degradation. It is essential to adhere to these practices to maintain healthy soil and maximize crop yields. Crop diversification is a proven approach for achieving sustainable cropping systems and food production while addressing the agro-environmental effects of conventional monoculture systems (Di Bene et al, 2022).

Intercropping is a highly effective strategy for mitigating the effects of climate change in arid regions. Vlahova V. (2022) in her review, presented the main types of intercropping and their numerous advantages. This sustainable farming system creates balance with the environment, optimizes resource utilization, and minimizes damage from diseases and pests. Intercropping is a highly beneficial farming practice that leads to higher crop yields and improved soil erosion control. By utilizing plant growth resources such as water, nutrients, and sunlight more efficiently, intercropping enables plants to thrive and produce more abundant crops. While intercropping patterns are more effective than monocropping in suppressing weeds, their effectiveness can vary greatly. Overall, intercropping is a proven method to increase diversity in an agricultural ecosystem.

At the same time, intensive tillage and monocropping have adversely affected the quality of soils through accelerated loss of soil organic matter (Njaimwe A. et al, 2016). Generally, the results indicated that, in the short term, cover crops, especially oats, have a greater influence on SOC accumulation and aggregate stability than tillage, irrespective of soil type.

Monocrop cultivation of winter wheat for 80 years gradually increased yields, provided more productive varieties were sown. These findings were demonstrated by Demidov et al (2019), showcasing the importance of implementing these measures for successful wheat cultivation. A range of agrotechnical measures, including proper soil cultivation, rational use of fertilizers, timely sowing with optimal seeding rates, and crop care, influenced the amount and stability of wheat yields.

To preserve the economic potential of land and minimize land degradation factors, it is crucial to establish precise rules regarding sunflower monocropping, a common practice in Ukraine and many other countries. The findings provide valuable insights into the effects of this practice and can inform future decision-making with confidence. In this case, Kussul et al (2022) conducted a thorough evaluation of the impact of sunflower monocropping on vegetation indices obtained from MODIS datasets in Ukraine, one of the largest sunflower exporters in Europe.

Farmers can successfully implement crop diversification through various methods, such as cover crops, crop rotation, intercropping, and agroforestry (Altieri M.A., 1995; Wezel A. et al, 2014). Incorporating sufficient crop diversity in rainfed crop rotation systems can be challenging, but it is a key management principle in conservation agriculture systems. Therefore, it is important to prioritize crop diversification despite limited cash crop options resulting from soil and climatic conditions or markets (Alcon F. et al, 2020).

Soltys O. and Cherechon O. (2019) analysis of long-standing research conducted by scientists at the Institute of Grain Crops of the National Academy of Agrarian Sciences of Ukraine revealed that yield capacity is significantly higher when scientifically-based crop rotations are used without the application of fertilizers, compared to the variant of no crop rotation. Furthermore, they successfully optimized the number of fields in a crop rotation. Many-field crop rotation is an efficient method for securing high levels of agrarian production. Short crop rotation is the most reasonable option for enterprises with a small land area.

Farmers worldwide confidently use multiple cropping for food production across all levels of agricultural technology (Andrews D.J. and Kassam A.H., 2015). The profitability of crop diversification adoption at the farm level can significantly enhance the resilience of agricultural systems. The main objective is to identify high specialty crops, new crops, or adopt varieties, off-season varieties, and production systems to open up new opportunities for farmers.

Agricultural diversification refers to changes in the mix of crops, enterprises, and activities at the household level. The concept of agricultural intensification has increased crop productivity. Hufnagel J. et al (2020) argue that agricultural intensification has increased crop productivity but simplified production with less diversity in cropping systems, greater genetic uniformity, and more homogeneity in agricultural landscapes.

Neglecting important factors such as crop rotation can lead to the overuse of land and a decrease in soil quality. It is crucial to consider the long-term effects of farming practices and prioritize sustainable methods. This approach can lead to significant environmental and socio-economic problems in the future. Farmers are often unable to implement crop rotations to their full extent due to the short-term nature of land leases. Dorosh et al (2020) assert that their methodological approaches for organizing crop rotations in a changing market and climatic environment are based on short-term crop rotations, the dynamics of crop placement depending on ecological and economic factors, the formation of homogeneous fields based on quality indicators, the selection of crops based on land evaluation before cultivation, and the mandatory environmental assessment of projected crop rotations using balance calculations.

According to Moore et al (2023), increasing diversity in cropping systems has great potential to address environmental problems associated with modern agriculture, such as erosion, soil carbon loss, nutrient runoff, water pollution, and loss of biodiversity. To support a transition to multi-cropping systems, plant breeders must adjust their breeding programs and objectives to better represent diverse systems, including diverse rotations, alternate-season crops, ecosystem service crops, and intercropping systems.

Cropping systems experiments are vital in devising sustainable weed management strategies. According to Benaragama et al (2024), most research on cropping systems lacks a framework for understanding weed dynamics and providing sustainable weed management solutions.

Romashchenko M.I. et al, (2023) present a robust mathematical model for the formation of optimal crop rotations in the forest-steppe of Ukraine. The model is based on expert estimates of the efficiency of "predecessor-crop" pairs and overcomes the limitations of classical experimental research methodology.

In general, crop rotation significantly enhances agricultural output without additional inputs, even though its design may need to take into account different climates, soils, crops, and farming practices to achieve its full potential in terms of agronomic and ecological benefits.

COVER CROPS

Cover crops have been studied for over a century. However, it is now widely recognized that their complex interaction with the Earth's biosphere, lithosphere, hydrosphere, and atmosphere is of utmost importance. Previous cover crop research has mainly focused on evaluating their impact on subsequent crop yield. Cover crops provide multiple ecosystem services, including soil organic carbon sequestration, nitrous oxide emissions reduction, wind and water erosion prevention, weed control, and soil microbial community improvement. Understanding these benefits is crucial for developing sustainable agricultural production systems. Continuous research is published to gain a comprehensive understanding of the ecosystem services provided by cover crops. Cover crops have been successfully integrated into conservation agriculture systems in various regions worldwide, as demonstrated researchers by Flower K.C. et al, (2012), Andriarimalala J.H. et al, (2013), Shelton R.E. et al, (2018), Rugare J.T. et al, (2019).

Van E.E. et al, (2023) conclusively demonstrate that cover crops provide numerous benefits, including increased subsequent crop yield, SOC storage, weed suppression, soil microbial activity, and wildlife biodiversity. Furthermore, cover crops effectively mitigate N_2O emissions, reduce wind and water erosion, and suppress plant pathogens. It is important to note that the magnitude of these benefits may vary depending on the cover crop type, location, and duration of cover cropping. Barriers limiting the adoption of cover crops into production systems include cover crop termination methods, designing crop rotations to fit cover crops, additional costs associated with cover crop integration, and uncertainty related to economic returns with cover crops.

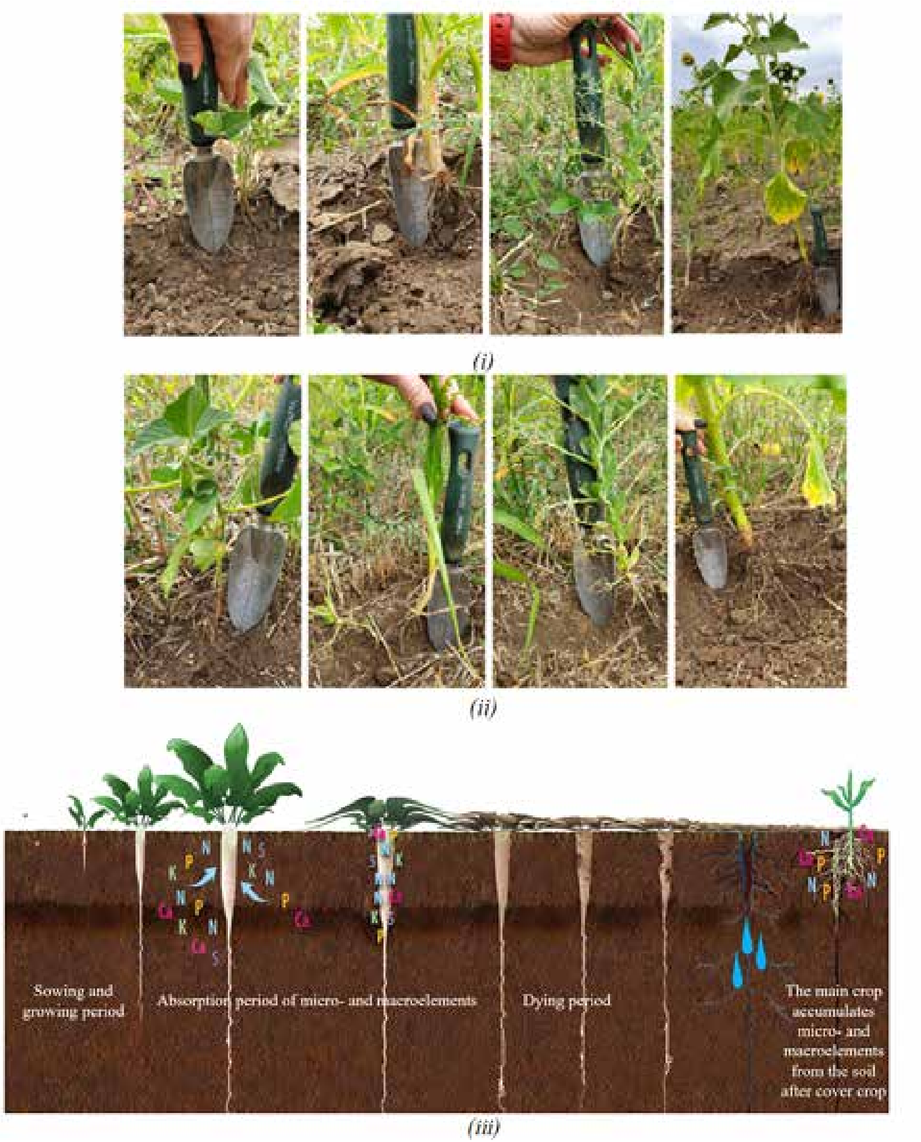
Wang J. et al, (2021) analyzed the studies around the world and found that cover crops decreased precipitation storage efficiency (PSE) by 33.4% and soil water storage for the whole profile (SWSPT) at soil depth by 13.2%, but increased water storage to 30 cm depth (SWSP30) by 6.0% ($P < 0.05$) compared to no cover crop. The cover crops did not affect subsequent crop yield, but decreased evapotranspiration (ET) by 6.2% and increased water use efficiency (WUE) by 5.0% ($P < 0.05$) compared to no cover crop. The effect of cover crops on these parameters varied by soil and climate conditions in different regions. Leaving cover crop residue on the soil surface or incorporating it into the soil reduced PSE, SWSPT, and ET, but increased SWSP30 and WUE compared to residue removal. Maintaining cover crop biomass at 5 Mg per ha and leaving a 20-d interval between cover crop termination and subsequent crop planting also increased PSE and SWSP30. They also summarized that cover crops had minimal effect on succeeding crop yield, WUE of succeeding crops can be increased with cover crops by decreasing evapotranspiration.

Cover crops have a significant impact on soil and subsequent crops. They improve soil organic carbon and nitrogen sequestration, inhibit weeds and pests, and enhance soil physical and chemical properties. Cover crops have a positive impact on soil microbial activity. Implementing a crop rotation structure with appropriate intervals between the main with mix of cover crops will accelerate the system's adaptation to soil improvement by supporting the vitality and diversity of soil organism communities. This will, in turn, strengthen biological control of diseases, pests, and weeds. Crop residues accumulate on the surface as mulching material under no-till technologies. This allows for to reduction of the exchange of air, water, and energy between the soil surface and the atmosphere (Lobell D.B. at el, 2006).

Sui X. et al (2021) provided a systematic review to clarify the effects of cover crops on various soil indicators, such as soil nutrients, moisture, pH, physical indicators (including soil bulk density and total porosity), biological indicators (including soil enzyme activity and soil microbial diversity), and environmental factors (including greenhouse gas emissions, heavy metals, and water quality). Zhang J. et al, (2023) demonstrated that cover crops are a proven strategy for achieving sustainable agricultural production and high crop yields, while also providing valuable ecological services such as reducing soil erosion and nutrient loss. Farmers should consider using cover crops to improve their crop yields and protect the environment.

To ensure optimal soil health, it is essential to sow a cover crop mixture enriched with at least three groups of crops, including cereals, oilseeds, and legumes, after harvesting the main crop. It is recommended to use a minimum of 7-9 different species of crops to achieve the best results. Figure 1 presents the different soil structures resulting from plowing and no-till practices after 2 years of research in Southern Ukraine, as well as the roots of cover crops and also presents the scheme and the life cycle of the cover crop during its vegetation.

Figure 1. Cover crop root systems and soil structure under different tillage practices: (i) no-till; (ii) plowing, and scheme of the life cycle of the cover crop during vegetation (iii)



Cover cropping is a highly effective climate-smart strategy for regenerating low-fertility soils. To combat soil erosion, soil fertility, water quality, weeds, and climate change, many acres of cover crops are being planted around the world. The results of this strategy are promising in arid and semi-arid regions. Despite this, there is still much to learn about the mechanisms of soil organic carbon (SOC) storage and soil health improvement in semi-arid irrigated cropping systems (Acharya P. et al, 2024).

According to Haramoto E.R., (2019), seeding rates lower than current recommendations can provide adequate weed suppression and ground cover while small grain cover crops grow, due to their tillering ability.

Cover crops can provide multiple agroecosystem services to crops produced in conservation agriculture systems. Cover crop mixtures can be used to mitigate disservices and increase the multifunctionality of ecosystem services. In a three-year study, Finney D.M. et al, (2017) investigated the effects of cover crop selection on the provisioning of multiple ecosystem services. They examined 10 cover crop treatments and eight ecosystem services to determine how the identity and number of species affected multifunctionality. The study found that certain services, such as cover crop biomass production, weed suppression, and nitrogen retention, consistently co-occurred. The study confidently identifies a set of bundled services that include cash crop production, nitrogen supply, and profitability. It asserts that as some services increase, other services decrease, limiting multifunctionality. However, the study found that functionally diverse mixtures ameliorate disservices associated with certain monocultures, thereby increasing cover crop multifunctionality.

Dubrovin V. et al, (2022) determined that the total greenhouse gas emissions amount to 4015 kg/ha of CO_2-eq after 4 years of experience in the model 4-field crop rotation under the conditions of the combining tillage system for sunflower and maize without intermediate crops and reduced processing for wheat and barley. Switching to a reduced tillage system can reduce emissions by 30.1%. The data shows that including two cover crops in two crop rotation fields before spring crops results in a negative balance of greenhouse gas emissions of -377 kg/ha of CO_2-eq during this period. Furthermore, switching to no-till for all crops after a 4-year rotation period resulted in a significant reduction of 1221 kg/ha of CO_2-eq. These findings demonstrate the effectiveness of these sustainable practices in reducing greenhouse gas emissions.

Thapa V.R. et al, (2023) demonstrated that cover crops and diverse crop rotations can lead to significant SOC sequestration rates of 271 kg C per ha per year and 235 kg C per ha per year, respectively, in the top 30 cm of soil. It is important to note that the potential for SOC sequestration may vary depending on soil type and tillage practices. In medium-textured soils, the response of SOC to cover cropping or diverse crop rotation is significantly more pronounced than in other soils. Diverse cropping systems with conservation tillage sequester 10% more SOC than conventional tilled crop-fallow systems, which is greater than the SOC sequestration achieved with diverse cropping or conservation tillage alone. The rate of SOC sequestration was high in the first five years after the adoption of conservation practices and decreased over time to reach a new equilibrium. This observation is significant.

Cover crops are a crucial component of a continuous no-till, environmentally friendly system, that can maintain short-term yields and ultimately increase crop yields in the long run. Cover crops, especially legumes, fix atmospheric nitrogen and recycle nitrogen in the soil, accumulate soil organic matter, and improve soil structure and water infiltration to increase crop yields. Radish, for instance, reduces soil compaction, increases water infiltration, and fumigates soil to suppress disease and pests. Cereal rye, on the other hand, provides a living mulch to effectively control weed growth. Long-term cover crops can enhance crop yields, improve soil quality, and provide environmental and economic benefits (Hoorman et al, 2009). Studying the long-term effects of continuous no-till and cover crops is needed, however, to improve our understanding of soil-water management for enhanced agroecosystem services in climate change.

According to Blanco-Canqui H. et al, (2015), cover crops have been shown to alleviate soil compaction, improve soil structure and hydraulic properties, mitigate soil temperature, improve microbial properties, recycle nutrients, and suppress weeds. While cover crops may increase or have no effect on crop yields, they may reduce yields in water-limited regions by reducing available water for subsequent crops.

The limited studies available indicate that grazing and haying of cover crops do not adversely affect soil and crop production, suggesting that the removal of cover crop biomass for livestock or biofuel production may be another benefit of cover crops.

Yang L. et al, (2023) summarize that cover crops can provide the biofuels industry with a new source of biomass for bioenergy production. Oilseed crops such as canola, sunflower, and soybean are commodities and have been used to produce biodiesel and sustainable aviation fuel (SAF). Other cover crops such as rye, clover, and alfalfa have been tested on a small or pilot scale to produce cellulosic ethanol, biogas, syngas, bio-oil, and SAF.

Cover crops offer numerous ecosystem services, such as improving soil quality, crop-livestock systems, and the environment. However, it is important to note that the benefits of cover crops vary depending on the site. Further research is needed to fully understand the multi-functionality of cover crops in different climates and management scenarios, as well as the short- and long-term economic returns from cover crops.

THE DIRECTION OF FUTURE RESEARCH

Nowadays, the study of resource efficiency issues, such as no-till technology, and indicators of soil quality assessment, requires a more detailed examination together with the role of nutrients, cover crops, and their mixtures, which have not been fully investigated. It is important to acknowledge that there is still no unanimous opinion on the dependence of crop productivity on methods of soil management, and therefore, it is necessary to continue exploring and evaluating different approaches to this issue.

Future research could potentially benefit from focusing on types of cover crops, breeding cover crop cultivars, and exploring the interactive effects of cover crops with other sustainable land management practices, in addition to their potential long-term effects.

One possible approach to conducting research is by exploring the potential benefits of digitalizing climate-smart agriculture practices. This could involve utilizing digital agriculture tools and services (DATs) in climate-smart agriculture practices to promote enhanced adaptation, reduce GHG emissions, and increase productivity for small-scale agriculture.

CONCLUSIONS

Climate-smart agriculture is a proven way to adapt farming and mitigate climate change. Climate-smart agriculture is crucial to addressing the major challenge of sustainable food production in the 21st century, given the global environmental problems such as war, climate change, population growth, and natural resource degradation, including soil and biodiversity loss.

This approach combines both traditional and modern knowledge and skills to create environmentally friendly agricultural practices. It involves the use of conversational tillage methods, crop diversification, and the implementation of cover crops that are resilient to the effects of climate change. By adopting climate-smart farming methods, incomes can be increased while helping to address climate change and strengthen global food security around the world.

Sustainable food production must adopt a climate-smart approach. This is the need of the hour and is receiving increasing attention worldwide in the context of sustainable food production in a changing world.

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Chapter 2
Formation of Water Demand for Drained Lands in Variable Climatic and Agricultural Land Reclamation Conditions

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ABSTRACT

The chapter provides information on crop evaporation and water consumption during different growth stages, influenced by prevailing weather and climate conditions.

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This data serves as the basis for designing and implementing effective water regulation strategies. The authors conducted an assessment of the weather and climate in Western Polissia of Ukraine, and performed computer simulations of diverse climate scenarios. These simulations were based on comprehensive forecasts and models, considering key parameters of hydro-melioration systems, local climatic conditions, water management techniques, and the productivity of drained lands under various natural, agronomic, and reclamation conditions. Long-term forecasts were utilized to determine the vegetative values of total evaporation and the water demand of drained lands under changing weather and climatic conditions. Additionally, the authors evaluated the technological efficiency of different methods for moistening drained lands.

BACKGROUND

The research holds significant relevance due to the pressing issue of global climate change affecting regions worldwide, including Ukraine. These changes directly impact the functioning of hydro-melioration systems and crop cultivation conditions. Agricultural production, particularly on lands with regulated water regimes, is intricately tied to meteorological conditions. Therefore, timely information on anticipated climate changes is crucial for decision-making (Abrantes et al, 2018; Malézieux et al, 2009; Prasuhn et al, 2013; Wallander et al, 2021).

The current stage of agricultural development, especially on lands with regulated water regimes, presents several unresolved challenges. There is a lack of sufficient methods to assess the ecological and economic feasibility of implementing remedial measures considering climate change. Hence, there's an urgent need to understand the projected consequences of global climate changes and make adaptive decisions to mitigate their impacts (Dickeyet al, 1981; Eekhout et al, 2018; Kuzmych et al, 2022a,2023a, 2023b,2023c; Rokochinskiy et al, 2019, 2020; Turmel et al, 2015; Yakymchuk et al, 2022; Yan Xin et al, 2023).

For drained territories with shallow groundwater tables, weather and climate conditions play a vital role in shaping soil and groundwater conditions, influencing soil processes during crop growth stages. Projected temperature increases and heightened aridity due to climate change will likely reduce natural moisture levels and increase water demands for crop cultivation on drained lands. Consequently, additional irrigation technologies will be required to supplement moisture levels. Thus, understanding the total water demand for cultivated crops and its variations is essential for designing effective water regulation strategies in response to climate change. This involves selecting and justifying appropriate water regulation methods, structures, and operational modes for drainage systems, along with calculating their parameters (Castrignano et al, 2020; Gholami et al, 2013; Huffman et al, 2013; Hunter et al, 2019; Korobiichuk et al, 2017, 2020; Mirzaei et al, 2021; Rokochinskiy et al, 2023b).

Therefore, this study aims to evaluate changes in water consumption during crop cultivation on drained lands in Western Polissia of Ukraine, under evolving climatic conditions. The goal is to provide a basis for justifying adaptive solutions to address these changes.

Since the first step in assessing changes in water consumption of crops is the study of changes in the weather and climate conditions of the territory, to solve this task, we conducted a statistical analysis of long-term retrospective and modern data of climate observations in the village. Western Polissia of Ukraine according to the following research options (Al-Kaisi.and Lowery, 2017; Auerswald et al, 2021; Jetten et al, 2003; Kopittke et al, 2019; Pimentel, 2006; Kuzmych et al, 2022b, 2023d, 2023e,2023f; Prykhodko et al, 2023; Rokochinskiy et al, 2019, 2020, 2023a, 2023b; Ulko, 2021):

- option 1 – "Base": characteristics of the main weather factors and their normalized values for the growing season (IV-X months), obtained from long-term retrospective data (1891-1964);
- option 2 - "Transitional": in transitional conditions (1965-1990), normalized long-term average values of the main weather factors and their distribution during the growing season were obtained;
- option 3 – "Last": received in modern conditions for 1991-2022 dynamics and normalized multi-year average values of the main meteorological factors and their distribution during the growing season.

According to (Basic et al, 2004; Kutsenko and Timchenko, 2016), the calculation was carried out for five typical groups of calculation years according to the conditions of heat and moisture supply during the growing seasons of the population: very wet (p=10%); wet (p=30%); medium (p=50%); arid (p=70%) and very arid (p=90%) according to such basic meteorological characteristics as: amount of precipitation (P, mm); average air temperature (T, oC); the amount of air humidity deficit (D, mm); average relative air humidity (N,%) and their derivatives: evaporation rate (E0, mm), which is determined by the well-known formula of M.M. Ivanova (Rokochinskiy et al, 2023a); moisture availability coefficient (kW, mm) as the ratio of precipitation to evaporation.

The generalized results of the calculation of the vegetation values of the main meteorological characteristics and their derivatives by calculation years and by research options for the conditions of the Western Polissia of Ukraine are given in the Table 1.

The given data convincingly testify to the presence of changes in the weather and climate conditions of the Western Polissia of Ukraine (Rokochinskiy et al, 2019), indicate a steady trend towards increasing aridity of the climate in the region. In particular, recent years have been characterized by record temperature maxima (for example, in 2018, the average air temperature during the growing season was 16.6 °C with a multi-year average norm of 13.5 °C) and increased seasonal unevenness of precipitation, which negatively affects the reserves of natural soil moisture available for cultivated crops.

In general, the current vegetation values of the main meteorological characteristics are already within the limits of their predicted changes (Bechmann et al, 2021; Prykhodko et al, 2023; Rokochinskiy et al, 2023a), therefore, further studies on the assessment of changes in water demand during the cultivation of agricultural crops on the drained lands of the Western Polissia of Ukraine were carried out by us for modern weather and climate conditions according to the "Recent" research option.

Evaporation, the value of which is determined by the weather and climatic conditions of the area, is the basis for the formation of the water demand of agricultural crops. Today, three main groups of methods for determining evaporation are considered: methods for determining water vapor flows from the evaporating surface to the atmosphere; methods of heat balance determination; water balance methods.

Table 1. Vegetation values of the main meteorological characteristics and their derivatives by calculation years and by research options for the conditions of the Western Polissia of Ukraine

Indicators, models		**Years of estimated supply,** ***p*****,%**				
		10%	**30%**	**50%**	**70%**	**90%**
Amount of precipitation *(P, mm)*	*«Base»*	575.1	509.1	443.0	377.0	310.9
	«Transitional»	544.4	471.9	434.9	375.2	307.9
	«Recent»	559.0	510.8	443.3	418.0	347.8
Average air temperature *(T. °C)*	*«Base»*	12.7	13.1	13.5	13.7	14.2
	«Transitional»	12.9	13.3	13.8	13.8	14.4
	«Recent»	13.3	14.0	14.2	14.5	14.3
The amount of air humidity deficit *(D. mm)*	*«Base»*	698	785	849	943	1036
	«Transitional»	722	805	884	923	1044
	«Recent»	729	854	914	946	1098
Average relative humidity *(H. %)*	*«Base»*	80.6	77.7	75.3	72.1	69.4
	«Transitional»	81.8	78.7	73.9	73.0	70.7
	«Recent»	76.7	75.8	73.5	72.5	68.5

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Table 1. Continued

Indicators, models		**Years of estimated supply, *p*,%**				
		10%	**30%**	**50%**	**70%**	**90%**
Evaporation *(E^o. mm)*	*«Base»*	425.8	478.9	517.9	575.2	632.0
	«Transitional»	440.4	491.1	539.2	563.0	636.8
	«Recent»	444.7	520.9	557.5	577.1	669.8
Coefficient of moisture certainty supply *(k_W. mm)*	*«Base»*	1.35	1.06	0.86	0.66	0.49
	«Transitional»	1.24	0.85	0.81	0.67	0.48
	«Recent»	1.26	0.98	0.80	0.72	0.52

In connection with the complex dependence of evaporation on numerous factors that determine it. at this time there are many models of the connection of the intensity of evaporation with the indicators affecting it which differ in the degree of complexity. Such models were developed by I.A. Sharovim. G.K. Lgovim. S.I. Kharchenko. A.R. Konstantinov. M.I. Budyko. M.V. Danylchenko. D.A. Shtoyko. H.L. Penman. L. Turk and others. - for the irrigation zone. in the practice of drainage reclamation. the formulas of A.M. Kostyakova. A.I. Ivytskyi. A.I. Sharova. V.F. Shebeko. A.M. Yangol, and others (Rokochinskiy et al, 2023a, 2023b).

Among the foreign developments such as Blaney and Kridle, Thorntwein, and Penman-Monteith methods are the most popular (Alexandridis et al, 2013; CTIC–Conservation Tillage Information Center, 1998; Janeček et al, 2012; Khan et al, 1988; Smart Farming Technologies for Sustainable Agricultural Development, 2019).

In Ukraine the method of water balance calculations during the moistening of drained has gained wide application and official status (Rokochinskiy et al, 2019). by Yangol (Prykhodko et al, 2023). It is based on the use of the same frequency of precipitation and air humidity deficit. which determines the amount of total evaporation.

Since water demand depends on the climatic conditions of the area the water regime of drained soils which in turn is determined by the change in weather and climate conditions and water regulation technologies as well as the growth and development of cultivated crops. Solving the problem of assessing the change in water demand of crops under conditions of climate change requires the application of an appropriate set of forecasting and simulation models which should include a local climate model of the water regime and water regulation technologies of drained lands. The model of the development and formation of the crop of cultivated crops which are implemented according to a long-term forecast (Choden and Ghaley, 2021; Rokochinskiy et al, 2023a).

For the effective implementation of tasks of this kind the Department of Water Engineering and Water Technologies of the National University of Water and Environmental Engineering has developed a complex of hierarchically connected forecasting and simulation models. the practical application of which is regulated by the relevant industry standards of the State Water Agency of Ukraine (Rokochinskiy et al, 2023b) and the corresponding software complex developed by us with substantiation of design decisions in the creation and functioning of water management and reclamation facilities (Rokochinskiy et al, 2023a):

- regarding climatic conditions of the area or meteorological regimes;
- regarding the water regime and water regulation technologies of drained lands;
- regarding the productivity of drained lands.

The model of the water regime and technologies of water regulation connects the parameters of regimes and technologies and therefore has a universal character and is basic in the created complex of forecasting and simulation models for the justification of project decisions on ecological and economic grounds.

The use of such complex of forecasting and simulation models enables the selection and justification of the best version of the technology of water regulation of drained lands taking into account the need for additional moistening according to the determined water demand of cultivated crops in variable climatic conditions.

RESEARCH METHODS AND MATERIALS

The formation of water demand for drained lands in variable climatic and agricultural land reclamation conditions is a complex process that requires careful consideration of various factors. Here is an outline of the key components involved (Rokochinskiy et al, 2023a, 2023b):

- Climatic Factors: The climatic conditions of the region including precipitation patterns temperature variations and evapotranspiration rates play a crucial role in determining water needs for drained lands. Understanding the climatic variability is essential for assessing water availability and demand throughout the year.
- Soil Characteristics: Soil properties such as texture structure, porosity, and moisture-holding capacity influence water retention and drainage capabilities. Different soil types have varying water demands, and management practices must be tailored accordingly.
- Crop Requirements: The type of crops grown on drained lands and their respective growth stages significantly impact water requirements. Different

crops have varying water demands at different growth stages, and agricultural practices must align with these requirements to optimize water usage.

- Topography and Drainage Systems: The topographical features of the land and the efficiency of drainage systems affect water distribution and management. Proper land leveling installation of drainage infrastructure, and maintenance of water conveyance systems are essential for effective water management on drained lands.
- Water Availability: The availability of water from natural sources such as rivers, reservoirs, groundwater, and rainfall, determines the irrigation water supply for drained lands. Water availability may vary seasonally and annually, necessitating adaptive water management strategies.
- Technological Advances: Advancements in irrigation technologies such as drip irrigation, sprinkler systems, and soil moisture sensors, enable more efficient water use on drained lands. Implementing innovative irrigation techniques can help optimize water usage and improve crop yields.
- Environmental Considerations: Environmental factors including ecological sustainability, habitat conservation, and water quality preservation must be integrated into water management plans for drained lands. Balancing agricultural productivity with environmental protection is essential for long-term land reclamation success.
- Policy and Regulations: Government policies, regulations, and incentives related to water management, land reclamation, and agricultural practices influence decision-making processes and resource allocation. Compliance with regulatory requirements and adherence to best management practices are essential for sustainable water use on drained lands.

Research methods are based on the application of systems theory with the basics of a system approach, system analysis, and modeling oriented to the widespread use of computers and appropriate software and information support in the development of modern approaches to justifying technical, and technological solutions for water regulation of drained lands under climate change conditions (Valenzuela, 2020; Rokochinskiy et al, 2019).

To realize this goal we planned and carried out simulation modeling of various climate scenarios in an accelerated time scale for the average conditions of the Western Polissia zone of Ukraine.

Predictive calculations during simulation modeling are performed under the following multiple variable conditions:

– by soils $\{g\}$ $g = \overline{1, n_g}$ (n_g=3) which are characterized by different levels of potential fertility according to the quality in the corresponding points and the share f_g of distribution within the object: 1-turf-podzolic clay bound-sandy (B=28 points) f_g =0.4; 2-peat medium-strength low-ash (B=38 points) f_g =0.6;

- according to the typical zoned crops grown for this zone $\{k\}$ $k = \overline{1, n_k}$ (n_k=3) and the corresponding share of their own areas f_k: 1-winter wheat - (project yield 4.7 t/ha), f_k =0.3; 2-potatoes – 25 t/ha, f_k =0.2; 3-perennial grasses – 3,5 t/ha, f_k =0.5;

– according to the typical (estimated) conditions of heat and moisture supply during the growing season of the population $\{p\}.p = \overline{1, n_p}$ (n_p=5);
– by various methods of water regulation of the aggregate $\{s\}$, $s = \overline{1, n_s}$ (n_s=4): D – drying (s=1); PS - preventive sluicing (s=2); HS – humidifying sluicing (s=3); SI - sprinkler irrigation (s=4).

RESULTS AND DISCUSSION

The results of predictive calculations based on the simulated simulation were processed by us according to the following scheme and presented in the appropriate sequence:

1. Determination and analysis of the conditions for the formation of total evaporation in variable weather-climatic and agro-melioration conditions in relation to variable meteorological regimes calculated according to the conditions of heat and moisture supply of vegetation periods, types of cultivated crops, soils and water regulation technologies of drained lands are presented in Tables 2, 3 and for the visualization - in Figures 1, 2.

Table 2. The formation of average annual vegetation values of total evaporation in relation to the types of cultivated crops and water regulation technologies on drained lands

Crop	Part	Total evaporation during vegetation, m^3/ha			
		D	PS	HS	SI
Mineral soils					
Winter cereals	0.2	1840	1892	1952	2007
Potatoes	0.2	3365	3482	3792	3965
Perennial grasses	0.3	4117	4253	4620	4868

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Table 2. Continued

Crop	Part	Total evaporation during vegetation, m³/ha			
		D	PS	HS	SI
Vegetables	0.3	3699	3799	4116	4328
Weighted average	1.0	**3386**	**3490**	**3770**	**3953**
Peat soils					
Winter cereals	0.2	1839	1898	1953	2018
Potatoes	0.2	3382	3516	3793	4106
Perennial grasses	0.3	4169	4295	4594	4876
Vegetables	0.3	3708	3822	4112	4383
Weighted average	1.0	**3407**	**3518**	**3761**	**4002**

Note: D – drying; PS - preventive sluicing; HS - humidifying sluicing; SP - sprinkler irrigation

Figure 1. Formation of average annual vegetation values of total evaporation concerning the types of cultivated crops and water regulation technologies on drained lands

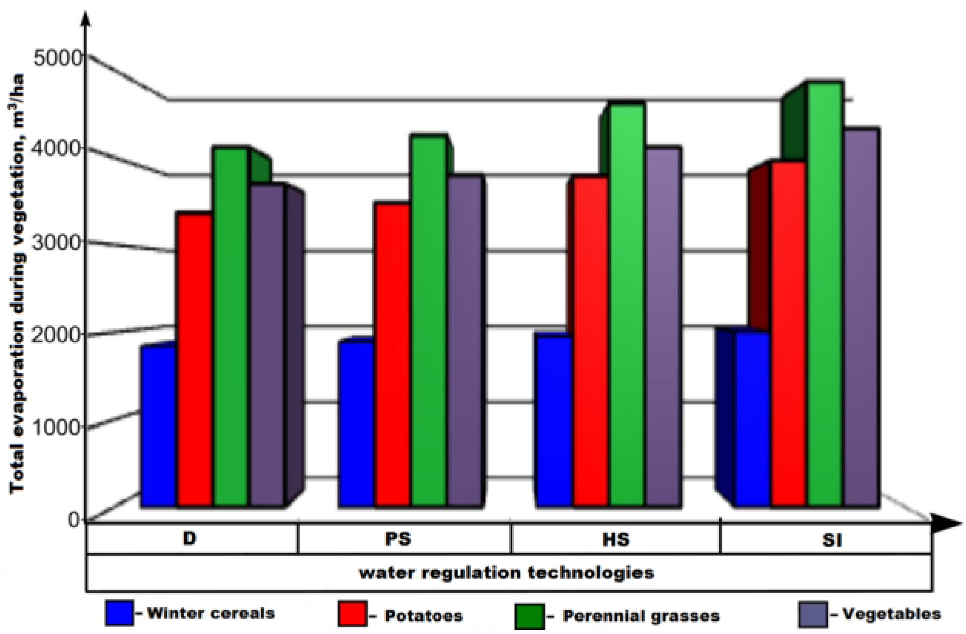
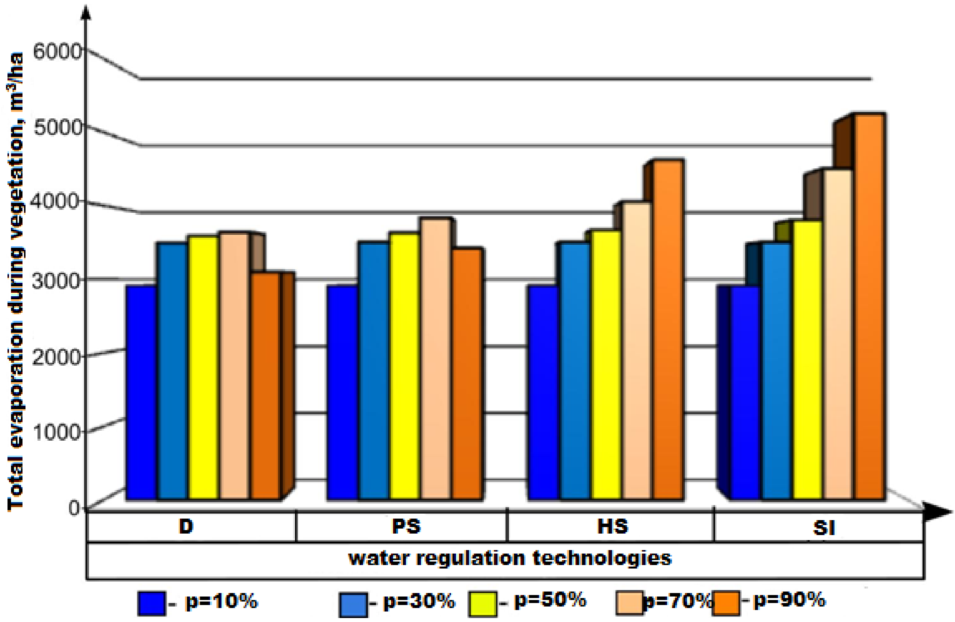


Table 3. The formation of vegetation values of total evaporation concerning the climatic conditions of the calculation years under different technologies of water regulation on drained lands

Years of estimated supply, *p*,%	**Total evaporation during vegetation, m³/ha**			
	D	**PS**	**HS**	**SI**
Mineral soils				
10	2911	2911	2911	2911
30	3492	3500	3500	3500
50	3594	3627	3655	3822
70	3614	3819	4089	4362
90	2991	3281	4646	5137
Weighted average	**3386**	**3490**	**3770**	**3953**
Peat soils				
10	2911	2911	2911	2911
30	3494	3505	3505	3505
50	3588	3631	3668	3804
70	3640	3835	4052	4505
90	3096	3426	4621	5252
Weighted average	**3407**	**3518**	**3761**	**4002**

Figure 2. The formation of vegetation values of total evaporation concerning the climatic conditions of the calculation years under different technologies of water regulation on drained lands



The obtained results are the basis for the further determination of the amount of water consumption during the cultivation of crops in the drainage reclamation zone of Ukraine under variable climatic conditions.

2. Determination and analysis of water demand according to the main indicators of the mode and technique of moistening (irrigation and moistening standards, the number of irrigations, water supply modules, etc.) for the comparative characteristics of moistened sluicing and sprinkler irrigation as the most common moistening technologies on drained lands.

The results of the calculations for determining the water demand are presented in the form of diagrams, which in a comparative form reflect the values of the maximum water supply modules for a very dry (p=90%) year in a decade section when growing the designed crops on mineral soils (a) and peat soils (b) at different technologies of water regulation are presented in (Figures 3, 4).

Figure 3. Dynamics of the maximum average decadal values of water demand according to the water supply module in dry periods of vegetation (p=90%) with humidifying sluicing of drained lands: a) mineral soils b) peat soils

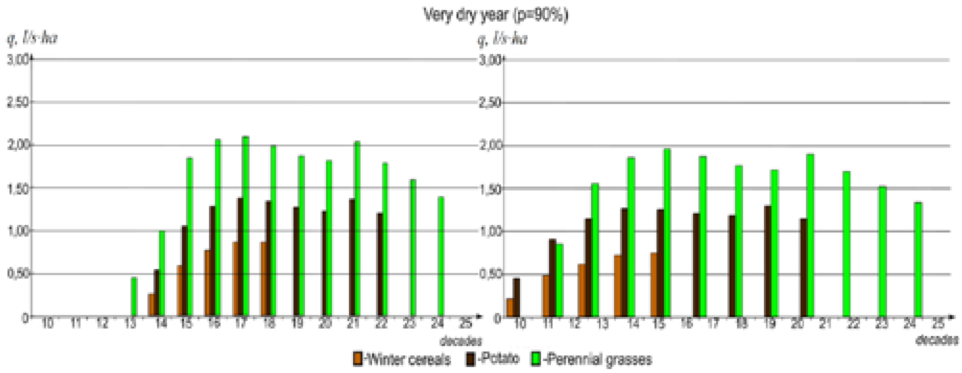
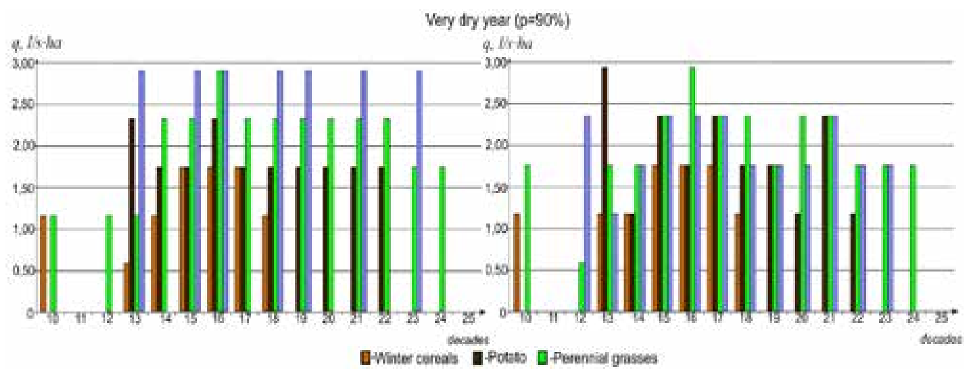


Figure 4. Dynamics of the maximum average decadal values of water demand according to the water supply module in dry periods of vegetation (p=90%) during sprinkler irrigation of drained lands: a) mineral soils b) peat soils



It was established that the current maximum average decadal values of the module of water supply during subsoil moistening of drained lands, as the most common technology of their moistening, similar to the module of drainage flow, also have a pronounced variable character. There is a significant change in their values concerning modern climatic conditions according to their variation (from 0.55 l/s•ha in a dry year to 2.0 l/s•ha in a very dry year), the type of cultivated crops (from 0.17 l/ s•ha for cereals up to 0.9 l/s•ha for perennial grasses), type of soil (from 0.5

l/s•ha to 2.2 l/s•ha). For the forecast conditions, these changes consist of variations in climatic conditions (from 0.55 l/s•ha in a dry year to 3.8 l/s•ha in a very dry year), the type of cultivated crops (from 0.5 l/s• ha for cereals up to 3.9 l/s•ha for grasses), type of soil (from 0.5 l/s•ha to 3.9 l/s•ha). At the same time, the water demand of cultivated crops increases almost two to three times and determines the need for their regular moistening in the specified zone.

Generalized results regarding the variation and formation of the average decadal values of water supply modules during subsoil moistening under variable current and forecast weather-climatic, agro-melioration conditions and the system as a whole in the Western Polissia zone of Ukraine are presented in the Table. 4

Table 4. Variations and averaged values of water supply modules during subsoil moistening under variable current and forecast weather-climatic, soil, and agro-melioration conditions of the Western Polissia of Ukraine

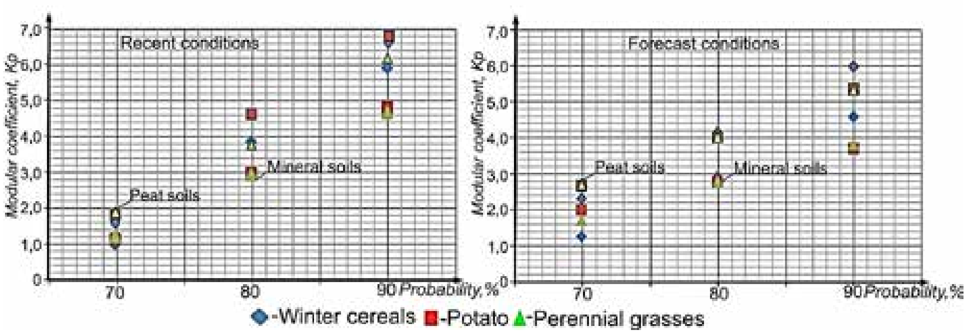
Crop	**Share of culture in crop rotation**	**Calculation modules of water supply, l/s•ha**					
		Current climatic conditions			**Forecasted climatic conditions**		
		p=70%	**p=90%**	**Weighted average values**	**p=70%**	**p=90%**	**Weighted average values**
Mineral soils							
Winter cereals	0.2	0.00-0.00 0.00	0.86-0.25 0.17	**0.12-0.04 0.02**	0.49-0.00 0.12	1.79-0.27 0.69	**0.39-0.04 0.13**
Potatoes	0.3	0.32-0.02 0.06	1.35-0.53 1.06	**0.28-0.08 0.17**	1.16-0.72 0.70	2.66-0.52 1.67	**0.68-0.26 0.42**
Perennial grasses	0.5	0.54-0.02 0.06	2.08-0.44 1.32	**0.44-0.07 0.21**	1.66-0.51 0.86	3.67-0.91 2.13	**0.96-0.26 0.53**
According to the system as a whole	**1.0**	**0.33-0.01 0.04**	**1.48-0.37 0.90**	**0.30-0.05 0.14**	**1.16-0.49 0.59**	**2.72-0.36 1.53**	**0.69-0.17 0.37**
Peat soils							
Winter cereals	0.2	0.00-0.00 0.00	0.86-0.25 0.30	**0.13-0.03 0.05**	0.41-0.6 0.06	1.75-0.32 0.60	**0.37-0.13 0.10**
Potatoes	0.3	0.00-0.00 0.00	1.35-0.53 0.97	**0.20-0.07 0.14**	0.97-0.41 0.55	2.73-0.61 1.62	**0.65-0.19 0.38**
Perennial grasses	0.5	0.46-0.02 0.05	2.08-0.44 1.04	**0.43-0.06 0.17**	1.44-0.69 0.76	3.95-0.36 2.51	**0.95-0.22 0.57**
According to the system as a whole	**1.0**	**0.23-0.01 0.03**	**1.62-0.37 0.87**	**0.30-0.05 0.14**	**1.09-0.54 0.56**	**3.14-0.48 1.86**	**0.74-0.38 0.42**

Note: 0.23-0.26 – maximum and minimum values of water supply modules;
0.03 – weighted average values of water supply modules.

The presented results show that the values of water supply modules during subsoil moistening, both for the selected main factors and for the system as a whole, differ significantly (more than several times), first of all, from their maximum current ones (modern conditions from 0.12 l/s•ha to 0.44 l/s•ha, forecasted from 0.37 l/s•ha to 0.96 l/s•ha), and average vegetation values (modern conditions from 0.04 l/s •ha to 0.44 l/s•ha, forecasted from 0.39 l/s•ha to 0.96 l/s•ha), which significantly differ from the recommended calculation of their values.

Based on the statistically processed results of the simulation modeling discussed above, supply curves were constructed for the averaged maximum values of water supply modules during subsoil moisture during the growing season of the main crops grown on drained mineral and peat soils (Fig. 5).

Figure 5. Supply curves of the averaged maximum average decadal modules of water supply with subsoil moisture for the main crops grown on drained mineral soils and peat soils in the conditions of the Western Polissia of Ukraine



For the studied conditions, the distribution curves of the values of the water supply modules are most accurately described, in contrast to the drainage flow module (Rokochinskiy et al, 2019), by the binomial Pearson curve of type I:

$$y = y_0\left(1 + \frac{x}{a}\right)^{m_1} \cdot \left(1 + \frac{x}{a_2}\right)^{m_2}, \quad (1)$$

where a, a_2 - coefficients of variation, and m_1, m_2 - coefficients of asymmetry of the Pearson curve of type I, determined by the method of least squares, are presented in the Table. 5.

Table 5. Characteristics of variation a, a_2 and asymmetry m_1, m_2 for maximum values of water supply modules

Coefficients of variation and asymmetry							
Current climatic conditions				**Predicted climatic conditions**			
a	a_2	m_1	m_2	a	a_2	m_1	m_2
2,13 3.48	2.25 3.61	2.99 3.82	1.20 1.38	1.33 2.21	1.45 2.47	2.37 2.74	1.28 1,41

Note: 2,13 – coefficients of variation and asymmetry for mineral soils;
3,48 – coefficients of variation and asymmetry for peat soils.

The obtained results show that the law of distribution of water supply modules during subsoil moistening is generally similar in nature, but opposite in direction to the change of the law of distribution of the drainage flow module during the operation of the DS in the drying mode and corresponds to the nature of the change in the laws of the distribution of the main climatic characteristics (precipitation, temperature, deficit of relative air humidity) in the studied conditions and confirms the determining dependence of their formation on them.

Therefore, the conducted studies and the results obtained from them determine the need to take into account the significant variability of the real values of the water supply module according to the variable natural-agro-ameliorative conditions of the real object during subsoil moistening of drained lands by improving existing methods and approaches to justifying their estimated optimal values when developing reconstruction projects, modernization, construction and operation of a hydroelectric power plant with two-way regulation of the water regime regularly.

The obtained results regarding the determination of total evaporation, water consumption, and technological efficiency of moistening of drained lands in the variable natural-climatic and agro-melioration conditions of the Western Polissia of Ukraine convincingly indicate the need to reassess the capabilities and technical condition of existing drainage systems by changing their functional capabilities for conducting moistening activities on drained lands permanently.

The final choice of water regulation technologies when justifying the type, design, and parameters of the system can be determined based on predictive and optimization calculations taking into account modern economic and environmental requirements (Rokochinskiy et al, 2023a, 2023b).

FUTURE RESEARCH DIRECTIONS

Prospects for further research consist, first of all, of the need to study this issue based on a long-term forecast of possible changes in the weather and climate conditions of the Western Polissia Ecoregion of Ukraine in the nearest future.

CONCLUSIONS

The formation of water needs for drained lands in variable climatic and agricultural land reclamation conditions requires a holistic approach that considers climatic, soil, crop, topographical, technological, environmental, and regulatory factors. By integrating these components into water management plans, stakeholders can optimize water usage, enhance agricultural productivity, and ensure the sustainable utilization of drained lands.

Thus, the current level of climate change, the impact of which is already felt in agricultural production, primarily on lands with a regulated water regime, presents us with the need to solve many tasks, the main of which is the need to make decisions on adaptation to climate change in general and the increase in water demand when growing crops on drained lands in particular. This requires a review of the existing requirements for the justification of regime-technological and constructive solutions in the design and construction of drainage systems, taking into account these changes. The results of the study can be effectively used in justifying adaptive measures to predict climate changes and developing projects for the reconstruction and modernization of drainage systems in the region following the program “Irrigation and drainage strategies in Ukraine for the period until 2030”.

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Chapter 3
Research on the Influence of Ecological Sustainability of the Territory on Rational Land Use in Agricultural Enterprises in the Context of Food Security

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ABSTRACT

In the realm of agricultural research, this study delves into the ecological state of agricultural land use, shedding light on significant trends in the transformation of land relations. The article meticulously evaluates the ecological state of land by considering the degree of anthropogenic load. Through rigorous analysis, it establishes the coefficient of ecological stability of the territory, providing valuable insights into the intensity of land use. The research also formulates diverse scenarios depicting the functioning of contemporary agroecosystems within agricultural land use. Furthermore, the study identifies pivotal pathways for a successful transition toward an adaptive farming system, crucial for the establishment of efficient agricultural land use. This research area specifically focuses on investigating the impact of ecological sustainability of the territory on rational land use within agricultural enterprises, emphasizing its paramount importance in the broader context of ensuring food security.

BACKGROUND

In view of the changes in the mechanism of development of the country's agrarian policy brought about by the land reform in Ukraine, the conditions and forms of agricultural land use are fundamentally changing. These changes are further strengthened within the framework of administrative and territorial reform. They especially concern the use of agricultural lands of territorial communities. As a result of the implementation of the land reform in Ukraine, there have already been significant changes in the development of rural areas, not for the better. In many cases, these changes hinder the development of the village and territorial community. At any stage of the development of society, the state must constantly ensure the rational use of land, and primarily agricultural land (Bohira, 2021; Dorosh, 2015; Kovalenko et al., 2022).

Despite all the variety of methods for assessing the sustainability of agrolandscapes, examples of practical application and recommendations for applying their results, the lack of a single concept for arranging agrolandscapes does not allow to eliminate the shortcomings of these methods and to reasonably apply their results. The use of simplified approaches to the assessment of the component structure of agrolandscapes can lead to false conclusions regarding the optimal directions of prospective territorial development of the region, the scope of relevant measures and the places of their implementation. Assessment methods provide initial information for the development and implementation of the necessary measures to ensure the sustainability of agricultural landscapes. Disadvantages limit the use of existing methodical approaches for justifying directions for optimizing the structure of agricultural landscapes. In modern conditions, in the context of countering global challenges, it is necessary to specify methodical approaches to the formation of ecologically sustainable highly productive agricultural landscapes at the regional and local levels, taking into account the spatial location of lands (Artamonov at al., 2019; Kuzmych et al., 2023a, 2023b; Frolenkova et al., 2023; Rokochinskiy et al., 2021, 2023a, 2023b).

Voytkiv P. notes that a general geoecological analysis of the studied territory will make it possible to improve land use both in the territories of individual administrative units and within territorial communities (Voytkiv at al., 2022).

Each type of anthropogenic impact on agricultural landscapes can be described by a number of factors that directly characterize the degree of manifestation of anthropogenic load. Such factors can be:

– the number of applied fertilizers and plant protection products per unit of area per year;
– the number of passes of heavy agricultural machinery across the field per year, which affect soil compaction;
– depth of tillage;
– mass of soil, which is annually lost with harvesting, etc.

The index of general species recognition is built on the basis of the principle of cause-and-effect relationships between the main forces of changes in the state of the environment and is closely related to the state of biodiversity. The index can be interpreted as an indicator of the degree of opportunity. Also, basic qualitative indicators that indicate the ecological balance of agricultural landscapes, their stability and the degree of transformation under the influence of economic activity are the coefficients of anthropogenic load and ecological sustainability (Cherlinka at al., 2012).

The presence of untouched natural areas of vegetation, which contribute to the improvement of the general condition, has the most positive effect on the state of agricultural landscapes. The natural subsystem in agricultural landscapes is the main carrier of resource-regenerating and environment-forming functions. Taking into account the dominant influence of agricultural nature management, the diverse structure of land use and the specialization of agriculture, in the opinion of N.V. Stratichuk, it is advisable to determine the quantitative characteristics inherent in this type of nature management in terms of administrative districts. In order to rationally assess anthropogenic transformation of agricultural ecosystems, it is necessary to assign the rank of anthropogenic transformation to each type of land use. To take into account the volume of transformation of the territory of the administrative district (or the region as a whole), each type of agricultural land is also assigned an index of the depth of transformation (Stratichuk, 2018).

Yanbo Q. and other researchers also point out the importance of optimizing the spatial model, which focuses on the quantitative scale and spatial planning for territorial-spatial planning. The territorial spatial model should become the basis for the sustainable development of the global social ecological system (Yanbo at al., 2023). Spatial network analysis is useful for monitoring the efficiency of ecological networks and supporting decision-making, management and planning (De Montis at al., 2016).

The rational use of agricultural lands in economic activities at the local level in the agricultural sector must be ensured by using modern resource- and energy-saving technologies, innovative technological systems of agricultural production, and a scientific approach to soil fertilization. To ensure the improvement of the level of efficiency of land use and optimization of its structure in agricultural enterprises, it is necessary to create and regulate the land protection program. The purpose of such programs is to reproduce, preserve useful properties, and increase the level of soil fertility. For this, it is necessary to strengthen measures to increase the responsibility of owners and users of land plots for illegal use of land plots. On the other hand, it is advisable to develop a real organizational and economic mechanism for their stimulation and motivation in order to preserve the useful properties of the land and improve the ecological state of the environment (Avramenko, 2006; Ivaniuk, 2021).

Budziak V. suggests that effective agricultural land use should be understood as the process of forming economically profitable and at the same time ecologically balanced directions of agricultural land use with the help of effective economic, ecological, legal, organizational and social mechanisms. Management of the land fund is carried out according to the principle of administrative-territorial management within the limits of authority. Land legislation provides for the provision of rational use of land and its protection by landowners and land users themselves in the process of land management, which is closely related to nature management. Rational land use is ensured by a number of factors, namely:

– conscious application of economic laws in force in society;
– land survey (cadastral survey, topographic survey, mapping, classification, zoning, etc.);
– maintenance of the state land cadastre (registration of land plots, accounting of the quantity and quality of land, soil grading);

– forecasting and planning the use and protection of land resources;
– land management planning;
– resolution of land disputes; control over land use and protection (Budziak, 2011).

The use of land is accompanied by the transformation and change of its main natural original properties, the appearance of new ones. The agricultural economy of Ukraine has been undergoing intensification processes for a long time with an increase in cultivated areas. These are plowing of areas previously covered with grassy vegetation, irrigation in arid areas and draining of swamps in wet areas. Such transformations affected the natural environment. Often these transformations become undesirable, going beyond the scope of the initial consequences. In Ukraine, the area of arable land is 33.3 million hectares, or 80% of the area of agricultural land; 2.2 million ha - hayfields (5% of agricultural land); 5.2 million hectares are pastures (11% of agricultural land).

Ecological and economic justification of the use of agricultural land must be preceded by a complex of organizational and technical measures regarding land management. For this, it is necessary to systematize: information on economic indicators and specialization of the agricultural producer; the number of available lands, their structure, area; placement of land plots; soil cover, the availability of human and material and technical resources, transport junctions, the market for the sale of agricultural products and a number of other factors.

In contemporary circumstances, transitioning agricultural production to a new ecologically adaptive system, incorporating environmental considerations, legal frameworks, and established standards, stands as a pivotal and impactful step towards addressing Ukraine's pervasive environmental crisis. The primary aim of such an approach is to establish ecologically balanced farming systems that ensure the prudent utilization and regeneration of natural resources, notably land. This entails harmonizing social, environmental, and economic criteria within specific agricultural land use settings (Tykhenko at al., 2021). A key tool in creating such environmentally secure agroecosystems is land management, serving as a gauge of society's approach to maximizing the efficiency of agricultural areas, or agrolandscapes. However, societal demands don't always align with ecological considerations, necessitating land management that comprehensively accounts for potential negative social, economic, and environmental consequences leading to ecological crises within specific agricultural territories (Kryvov at al., 2011).

The formation of environmentally secure agroecosystems within modern agricultural practices has been extensively investigated by numerous scholars (Espolov at al., 2018; Koptyuk at al., 2023; Kulchytska, 2010; Slavhorodska, 2018; Stepenko, 2013; Tretiak at al., 2001). This concept represents a novel approach to effective land management by establishing innovative models of adaptive farming systems. Yet, comprehensive exploration of the development and functioning scenarios of contemporary agricultural production remains incomplete.

The purpose of research aims to evaluate how the ecological stability of a territory and its anthropogenic load influence the organization of rational land use amid the evolving landscape of land relations in Ukraine.

ASSESSING ECOLOGICAL STABILITY: A STUDY OF UKRAINE'S TERRITORIAL ECOSYSTEMS

In modern conditions, the transfer of agricultural production to a fundamentally new ecologically adaptive system of farming, its structural change with mandatory consideration of environmental factors, legislation, requirements, and approved standards is definitely an important and effective prerequisite for successfully overcoming the existing ecological crisis, which has actually struck Ukraine all components of its natural environment.

The main goal of such a policy should be:

- – ensuring rational use and reproduction of natural (including land) resources with ecologically balanced farming systems;
- – optimal coordination of social, ecological and economic criteria of certain agricultural land use (territory).

Land management is the main state mechanism for the formation of such ecologically safe agroecosystems. Land management is a certain indicator of society's attitude to ways and methods of the most efficient and rational use of agricultural territories (agrolandscapes). However, social needs are not always determined by the ecological feasibility of using land resources. That is why land management should be based on a deep awareness of all the negative phenomena (social, economic, ecological) that can lead to an ecological crisis of some agricultural land use (territory) (Kryvov at al., 2011).

The concept of the formation of ecologically safe agroecosystems can be considered as a new approach to the effective management of land potential as a result of the creation of new models of adaptive farming systems. Development and functioning scenarios of modern agricultural production are also understudied.

The formation of sustainable agricultural production mainly begins with the existing specialization of specific agricultural enterprises and the level of agricultural intensity.

Sustainable functioning is based on scientifically based specialization of agricultural enterprises, where the fields of animal husbandry and crop production are harmoniously correlated, as well as agricultural crops that improve the soil and have a positive effect on its fertility (Barvinskyi at al., 2018). On this basis, the optimal structure of sown areas is formed, a flexible system of crop rotation with the best predecessors is developed, and resource- and energy-saving agricultural technologies are implemented.

As a result of the alienation of matter and energy, recirculation is significantly strengthened and, accordingly, the costs of anthropogenic resources to restore lost soil fertility and maintain the energy potential of the entire existing agroecosystem increase. Therefore, the narrow crop specialization of production systems causes a decrease in the structure of sown areas of the share of agricultural crops with a high ability to improve the surrounding natural environment, in particular, perennial leguminous grasses. The reduction in the number of animals, on the one hand, reduces the need to grow such crops as perennial grasses, post-harvest and post-harvest feed mixtures, and on the other hand, it leads to a significant reduction in the volume of livestock waste accumulation - manure. As a result, in crop rotations, the balance of organic matter (humus) and plant nutrients becomes negative, the number of unacceptable precursors increases, and the phytosanitary condition deteriorates significantly (Barvinskyi at al., 2015).

The detrimental evolution of the agroecosystem results from extensive farming practices that disregard essential elements like crop rotations, proper territorial organization, and structured sown areas. Such practices lead to a specific degradation within the agroecosystem and a reduction in overall humus reserves. This destructive pattern characterizes contemporary agriculture in recently established agricultural formations operating on leased grounds (Tykhenko at al., 2021).

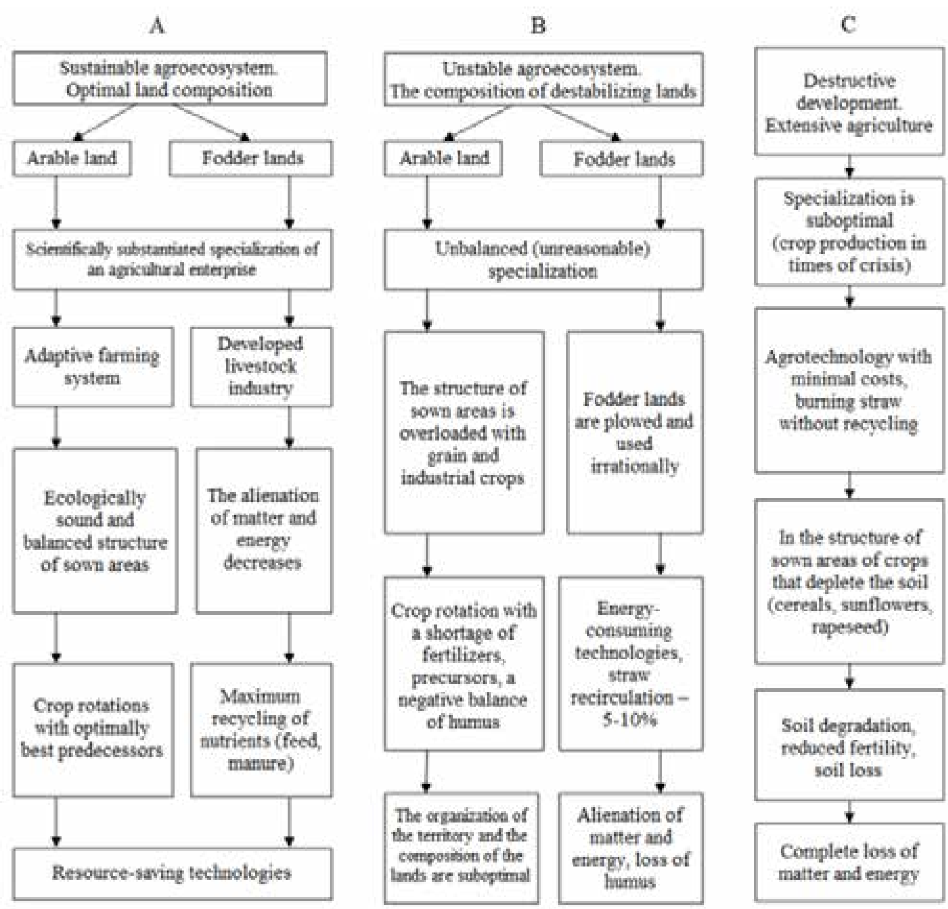
Figure 1 showcases the varied operational scenarios of modern agroecosystems. These scenarios underscore the necessity for targeted land management within specific areas, notably agricultural enterprises facing catastrophic or near-catastrophic environmental conditions. In these instances, developing corresponding land management projects that reorganize the territory and agricultural systems to normalize the ecological balance becomes imperative (Kryvov at al., 2005). It's crucial to remember the fundamental principle that environmentally acceptable land use ensures environmental sustainability, while adverse environmental conditions result in substantial economic losses.

Ukraine has garnered substantial experience in formulating and executing diverse land management projects geared toward organizing land use, particularly focused on agricultural soil protection systems. The implementation of capital-intensive measures seeks to counteract erosion processes, especially on excessively plowed slopes, caused by intensive land use.

However, for Ukraine, where the extent of plowed land surpasses ecological norms nearly twofold, such approaches are deemed unjustifiable. The nation possesses ample space suitable for cultivating major crops, even on slopes up to 3°, rendering these practices unnecessary (Barvinskyi at al., 2018). Consequently, when conducting land management in these agricultural enterprises, the emphasis lies on implementing predominantly organizational and economic measures. This involves utilizing only lands (soils) suitable for specific purposes.

Modern adaptive agricultural systems need to consider not only natural conditions like climate, relief, and soil but also individual landscape elements. The selection of the most appropriate land for cultivating major crops remains pivotal within these adaptive systems.

Figure 1. Operational scenarios of contemporary agroecosystems (Conducted research)

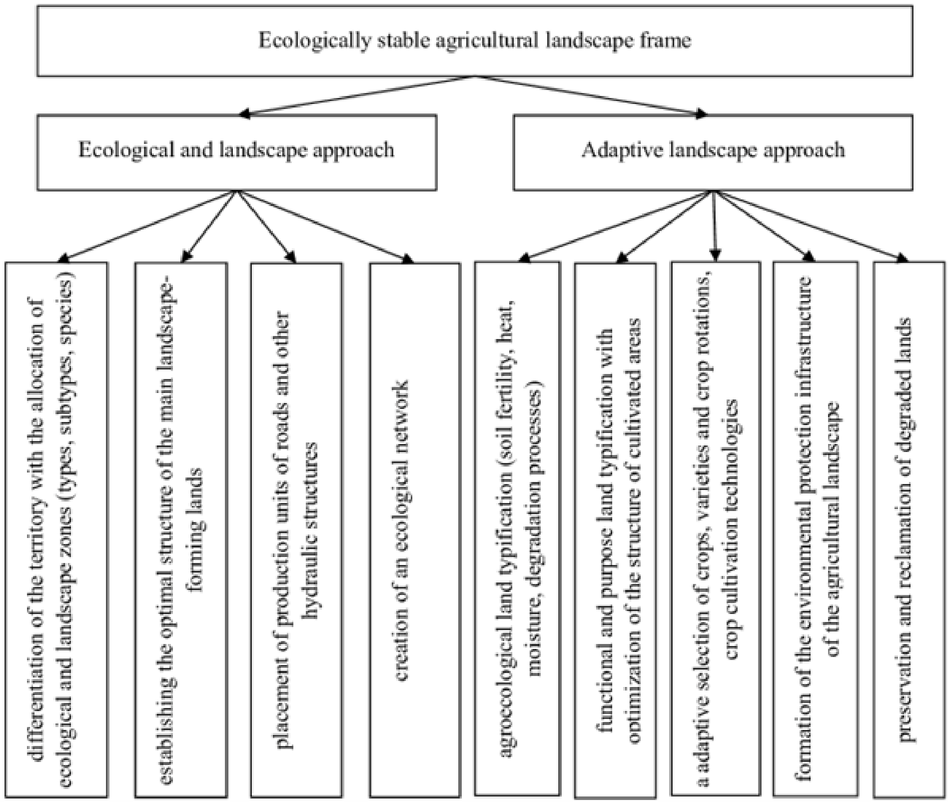


In Ukraine, the issue of determining the limit of arable territory remains relevant. An agrolandscape can be formed if the ratio of destabilizing lands (arable land) and stabilizing ones (pastures, hayfields, forests, etc.) was 40-42% and 58-60%, but at the same time, the agrolandscape can provide different stability (Chumachenko, 2008; Barvinskyi at al., 2018). However, if even an organized territory with an optimal ratio of lands, but without taking into account the relief, soil and other natural and anthropogenic conditions, then land degradation will develop in such a territory.

Therefore, only the quantitative characteristics of what is on the territory of the agricultural landscape do not provide an opportunity to ecologically balance it. An agrolandscape, in the middle or outside of which the same lands are located in different ways, can have a radically different level of ecological sustainability. This occurs in cases where, for example, arable land is located only in those places where the land is most suitable for agricultural use; forest lands are placed in the form of strips, so-called “corridors”, which preserves and creates habitats for birds and animals.

It is obvious that the post-Soviet design principles do not meet modern requirements for preventing degradation processes and are imperfect in modern realities. Therefore, it is necessary to switch to modern landscape approaches to the organization of the territory, which will ensure the ability of the agricultural landscape to recover naturally (Figure 2).

Figure 2. Approaches to the formation of an ecologically stable agrolandscape framework (Conducted research)



The organization of the territory based on the ecological and landscape approach makes it possible to find the right ways to optimize the structure of land in Ukraine through the determination of optimal indicators for specific regions. With this approach to the organization of the territory, the ratio of land in each specific case is individual and depends on the natural and climatic zone, topography of the area, hydrographic, soil and other natural and anthropogenic conditions [Shevchenko at al.,2017; Shevchenko at al., 2023].

The main principles of the ecological landscape approach in agriculture are:

– transformation of agricultural land into sustainable agrolandscapes;
– formation of a landscape-stable spatial structure of the agricultural landscape;
– implementation of land protection measures of permanent effect, taking into account the peculiarities of the agricultural landscape;

– soil protection organization and amelioration of the agrolandscape, etc. (Bryndzya, 2014; Forman, 2010).

Taking into account the above principles, the essence of the ecological-landscape approach is to create a stable agrolandscape framework from long-term territory organization elements that make it possible to increase the stability and productivity of problematic agrolandscapes (Kryvov at al., 2011).

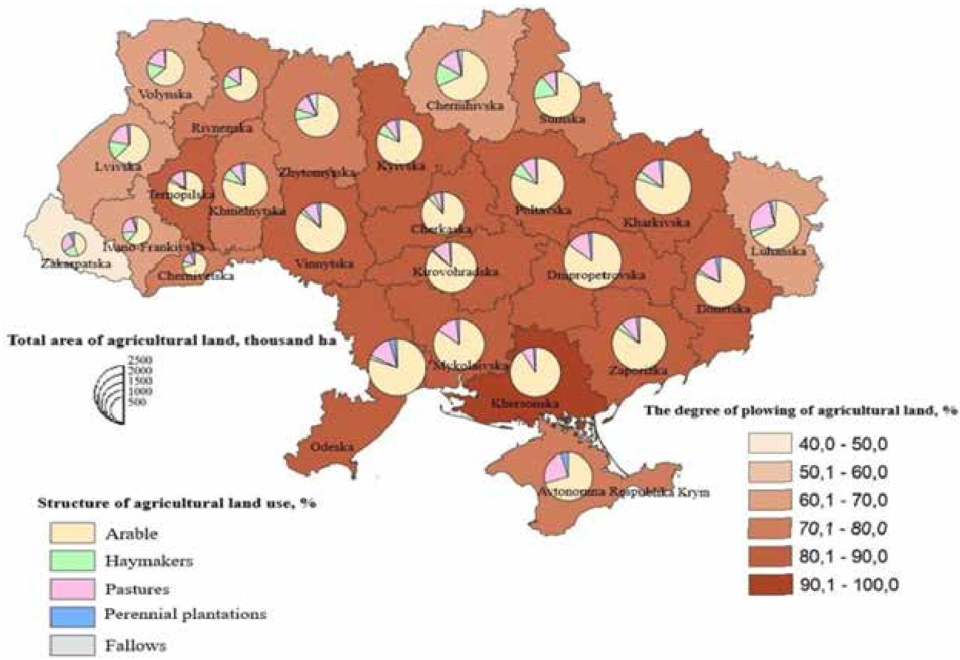
The ecological-landscape approach to the spatial development of the territory involves the formation of a system of measures to protect the agricultural landscape as a result of reducing the negative factors affecting it. At the same time, optimal conditions for the sustainable development of rural areas are formed. The protection of the agricultural landscape involves the preservation and maintenance of the natural structure and connections within it, both during economic activity and after its termination.

Recently, the adaptive landscape approach (Figure 2) has received significant development, which is carried out taking into account the category of agrolandscape and its main morphological units: localities, tracts, sub-tracts, facies (Barvinskyi at al., 2018; Tykhenko at al., 2024).

The implementation of the landscape approach is implemented with the help of the soil protection system of agriculture in combination with the contour and reclamation organization of the territory, which ensures the most rational use of land resources, and also creates conditions for soil protection from degradation (Martyn at al., 2020a; Martyn at al., 2020b).

The study of the structure of the most valuable land in Ukraine – agricultural land - is of great importance in the process of analyzing the state of agricultural land use. Thus, the largest specific weight in Ukraine is arable land, which occupies an area of 32541.3 thousand hectares (78.4%) of the total area of agricultural land, which indicates a high level of plowing. At the same time, the level of plowed agricultural land ranges from 90.3% (Kherson Oblast) to 44.4% (Zakarpattia Oblast) (Fig. 3).

Figure 3. The structure of agricultural land use in Ukraine and the degree of plowed agricultural lands (Conducted research)



Analyzing other types of agricultural land, hayfields occupy 2406.4 thousand hectares, pastures – 5434.1 thousand hectares, perennial plantations – 892.4 thousand hectares, fallow lands – 233.7 thousand hectares of the country's territory.

GIS is an important tool for collecting, storing, displaying, and analyzing spatial information about the city's territory in relation to spatial objects. The studies of some scholars (D. Liashenko et al., 2021) and others present the peculiarities of geographic information support for Kyiv city administration. Other authors have proposed specific approaches to the functioning of the geographic information system of the State Land Cadastre to improve information on the regulatory assessment of land plots for participants in land relations. The approaches to geoinformation support for the evaluative zoning of community territories proposed by the authors were implemented during the development of the Methodology for Normative Monetary Valuation of Land Plots, as well as the definition of a set of basic rules for creating an electronic document containing geospatial and other data on the results of work on normative monetary valuation of land for their inclusion in the State Land Cadastre (Martyn et al., 2022).

Characteristic signs of the transformation of the water regime, especially for irrigated areas, are signs of a sharp change in productivity indicators, which can be obtained with high accuracy based on the analysis of satellite images. Studies (Zgurovsky et al., 2023) have established the territorial and temporal distribution of the analysis of the impact of the occupation on the condition of agricultural fields in the temporarily occupied and non-occupied territories.

Geoinformation mapping of land resources based on remote sensing data involves the selection of certain categories of land cover and land use in the GIS environment based on satellite and aerial photographs. The functionality of the ArcGIS software package covers all the tasks that may arise in the process of geographic information mapping, and therefore it is advisable to use it as an environment for decoding remote sensing data and presenting mapping results. This statement can be substantiated both by the technical characteristics of the ArcGIS software package and by the considerable popularity of this product among land resources researchers (Bondarenko et al., 2014; Openko at al., 2023b).

Evaluating the modern structure of land resources depending on their economic use, it is worth noting that Ukraine has developed a fairly high level of development of living space. After all, about 65% of its territory is involved in economic use (Table 1), of which only 35.3% (21.3 million hectares) are ecologically stabilizing lands. In addition, according to the type of economic use of land, the largest specific weight falls on agriculture – 69.8%.

Table 1. The structure of land resources of Ukraine according to their economic use

Type of economic use of land	Total, thousand ha	Share of the total territory, %	Including, thousand ha		
			arable	under construction	under ecologically stabilizing lands
Agriculture	42131.0	69.8	32173.4	1162.0	8795.6
Residential and other buildings	987.1	1.6	59.8	576.0	351.3
Including for waste removal	16.5	0.0	–	–	–
Forestry	8868.4	14.7	1079.1	791.7	6997.6
Water management	243.9	0.4	1.6	28.8	213.5
Industry and others	1653.7	2.7	223.2	968.0	462.5
Including for the development of minerals, quarries	157.1	0.3	–	–	–
Protection of the natural environment	2909.8	4.8	1.0	1.5	2907.3
Protection of people's health	160.9	0.3	3.2	47.4	110.3
Culture, spirituality, etc	170.8	0.3	42.2	69.4	59.2

continued on following page

Table 1. Continued

Type of economic use of land	Total, thousand ha	Share of the total territory, %	Including, thousand ha		
			arable	under construction	under ecologically stabilizing lands
Other unused land	3229.3	5.4	1044.1	777.2	1408.0
Total lands	60354.9	100.0	34627.6	4422.0	21305.3
Share of the total area, %			57.4	7.3	35.3

Source: calculated and compiled by the author based on data (National report, 2021).

However, the assessment of the distribution of land resources according to their economic use does not sufficiently reflect its economic and ecological validity. For this purpose, it is necessary to carry out an analysis of the evaluation of the ecological stability of the territory and the anthropogenic load on land resources (Openko et al., 2023a).

In the realm of land conservation and the preservation of soil fertility, specific benchmarks have been established, encompassing maximum admissible soil pollution levels, soil quality criteria, optimal land ratios, and indices for assessing land and soil degradation. These quality standards for agricultural land are implemented to forestall degradation and serve as monitoring parameters for the soil's overall quality (Barvinskyi at al., 2015; Openko at al., 2023c).

The ecological landscape significantly impacts the agro-ecological state of soil cover and other elements within agricultural landscapes. Soil's ecological state serves as a comprehensive measure reflecting its ecological stability, fertility levels, and pollution extents.

Research conducted by I. Rytorska and E. Hoike (Tretiak at al., 2001) has yielded ecological stability coefficients for various types of land: built-up areas and roads – 0.00; arable land – 0.14; forested areas – 0.38; perennial plantations and shrubs – 0.43; residential areas – 0.50; grasslands – 0.62; pastures – 0.68; natural ponds and swamps – 0.79; natural forests – 1.00. The ecological stability coefficient for a land utilization area with varying land compositions (Ke.s) is computed using formula 1.

$$K_{e.s} = \frac{\sum(K_i * P_i)}{\sum P_i} * K_r \qquad (1)$$

where:

$K_{e.s}$ – coefficient of ecological stability of the land of the i-th type;
P_i – land area of the i-th type;
K_r – coefficient of morphological stability of the relief (1.0 – for stable areas and 0.7 – unstable).

The anthropogenic load coefficient ($K_{a.l.}$) quantifies the extent of human activities' influence on the environment, encompassing its impact on land resources. This particular measure is calculated using formula 2.

$$K_{a.l} = \frac{\sum (P_i * B_i)}{\sum P_i} \quad (2)$$

P_i – represents the land area with a specific level of anthropogenic pressure, measured in hectares.
B_i – signifies the rating of the particular area with its corresponding level of anthropogenic pressure.

The scale for the coefficient of anthropogenic pressure varies: reserves carry a coefficient of 1; areas under forest belts, shrubs, forests, swamps, and submerged lands hold a coefficient of 2; natural grazing lands and meadows along streams carry a coefficient of 3; arable lands and perennial plantations have a coefficient of 4; while lands used for industrial purposes, transport, or settlements are assigned a coefficient of 5.

ILLUSTRATIVE EXAMPLE

Land management stands as a complex, multifaceted process integral to society's economic system, shaped by production relations, land ownership structures, and other production means. These characteristics imply several key considerations:

– evaluating the economic efficiency of land utilization necessitates a system of economic relationship-based indicators, considering both collective and personal interests alongside public welfare.
– as land is part of the natural environment, preserving soil fertility conditions and ecological aspects is imperative.
– efficiency indicators must highlight the impact of land management, comparing it with corresponding costs and ensuring qualitative consistency and quantitative comparability across diverse elements of land management projects.
– the time gaps between capital investment and their outcomes mandate a comparison of temporally disparate effects and costs (Tykhenko, 2010).

Land use encompasses environmental, economic, and social facets, with overall efficiency divided accordingly. However, in Ukraine, due to the absence of a fully functional agricultural land market, leasing dominates land relations. Short lease durations lead to neglectful land resource management by tenants, often uninterested in preserving non-owned land. Moreover, aging landowners focused on maximizing rental income further exacerbate this issue. Consequently, past centralized planning approaches for soil protection, relying on budgetary funding, are inadequate in modern times.

Intensified agricultural production without ecological safety measures has imperiled lands, perpetuating their degradation and posing a substantial challenge to achieving ecological and economic efficiency in land use. The decline in agricultural enterprise profitability further limits reinvestment opportunities for soil protection measures.

The study of a set of soil regime indicators under different cultivation technologies is very important for analyzing land use methods. The protection of agricultural land should be one of the main measures to regulate land relations in Ukraine, and for the rational use of land it is important to study a set of soil indicators in specific natural and climatic conditions (Pikovska, 2021). The factors of rational land use should be integrated indicators of ecosystems, taking into account their zonal and regional characteristics. Studies have shown that with minimal tillage, moderate, strong, and very strong correlations between indicators of phosphate status and other indicators of soil fertility have been found (Koshel at al., 2024; Tykhenko at al., 2024). The main task of landowners and land users should be to restore soil fertility, which can only be achieved through its rational use.

Assessing environmental efficiency becomes pivotal in comprehensive land use, primarily involving land management's impact on the environment and land use patterns. Evaluating ecological stability and anthropogenic load becomes crucial in gauging agricultural land quality. Coefficients representing these factors help assess the rationality of land fund structures.

State policies concerning agricultural land use should integrate two concepts: the efficient and intensive utilization of land for food supply and the implementation of measures for land resource protection. Rational land use hinges on defined purposes, guiding specific methods, resource placement, land composition, and control measures (Espolov at al., 2018).

Soil degradation poses a significant threat to food security and imposes environmental constraints on agricultural expansion. Key agroecological parameters include soil, climate, and relief. The coefficient of ecological stability of a territory signifies efficient land resource utilization, reflecting intensive land use levels. Table 2 displays the results of the study area's ecological stability calculation.

Table 2. Determining the ecological stability of the Kiev region's territory through calculations

Lands	Coefficient ecological stability of the land, K_i	Land area (thousand ha), P_i	$K_i * P_i$	$K_{e.s.}$
Arable	0.14	1,367.7	191.48	-
Fallows	0.60	13.7	8.22	-
Perennial plantings	0.36	40.7	14.65	-
Hayfields	0.62	116.4	72.17	-
Pastures	0.68	136.4	92.75	-
Total agricultural land	-	1,674.9	379.27	0.23
Forests of natural origin	1.00	632.5	632.50	-
Shrubs	0.43	17.2	7.40	-
Built-up land	0.00	116.0	0.00	-
Other lands	0.00	196.0	0.00	-
Ponds and swamps of natural origin	0.79	175.5	138.65	-
Total land	-	2,812.1	1,157.81	0.41

Source: own calculation by the authors

The assessment of territory stability relies on the value of $K_{e.s}$:

– below 0.33 indicates environmentally unstable land use.
– between 0.34 and 0.50 suggests relatively unstable land use.
– within the range of 0.51 to 0.66 indicates medium stability in land use.
– above 0.67 signifies ecologically stable land use.

In the Kyiv region, the ecological stability coefficient for agricultural lands stands at 0.23, while the overall land use territory of the region reaches 0.41. These figures indicate that the Kyiv region's territory is relatively unstable, and specifically, the land dedicated to agriculture is environmentally unstable. The anthropogenic load factor, detailed in Table 3, illustrates the significant impact of human activities on the environment.

Table 3. Assessment of lands based on their level of human-induced stress

Lands	The score impact of land on the territory, B_i	Land area (thousand ha), P_i	$B_i * P_i$	$K_{a.l.}$
Arable	4	1,367.7	5,470.8	-
Fallows	3	13.7	41.1	-
Perennial plantings	4	40.7	162.8	-
Hayfields	3	116.4	349.2	-
Pastures	3	136.4	409.2	-

continued on following page

Table 3. Continued

Lands	The score impact of land on the territory, B_i	Land area (thousand ha), P_i	$B_i * P_i$	$K_{a.l.}$
Total agricultural land	-	1,674.9	6,433.10	3.84
Forests of natural origin	2	632.5	1,265.0	-
Shrubs	2	17.2	34.4	-
Built-up land	5	116.0	580	-
Other lands	0	196.0	0.0	-
Ponds and swamps of natural origin	2	175.5	351.0	-
Total land	-	2,812.1	8,663.50	3.08

Source: own calculation by the authors

The coefficient measuring the anthropogenic load on agricultural lands within the Kyiv region equated to 3.84, surpassing the national average by 11.5%. Extensive plowing, particularly on agricultural lands, diminishes soil fertility and exacerbates the region's ecological challenges. However, solely focusing on plowed land fails to entirely represent the ecological and economic efficacy of land use. Examining the plowing coefficient – calculated as the ratio of arable land to the total agricultural land area – stands as a more prudent approach (Polianskyi, 2019). In this region, the plowing coefficient stands at 64%, indicating a negative aspect of agricultural land utilization.

The forest cover ratio, depicting the proportion of forests, shrubs, and forest belts in the land structure, accounts for 14%, below the national average of 18%. Forest resources, when combined with other natural assets, constitute vital elements contributing to the country's productive capacities, serving as tools for economic development, meeting societal needs, and functioning as both objects and products of labor.

The Kyiv region manifests a satisfactory ecological condition, yet the structure of its agricultural landscapes approaches suboptimal values. Minor structural adjustments and preservation of the existing ecological balance within the agricultural land ratio are recommended (Slavhorodska Y., 2018). However, substantial areas in the land fund exhibit unsatisfactory soil properties – erosion, deflation, waterlogging – stemming from both human-induced factors and adverse natural characteristics. These lands are categorized as degraded and unproductive due to their low fertility.

Distorted proportions among arable land, natural forage, and forest lands have adversely impacted the resilience and condition of agro-landscapes. Contemporary agricultural challenges emerge from unresolved economic and environmental issues, notably the disruption in the balance among arable land, natural lands, forests, and water resources, leading to soil degradation.

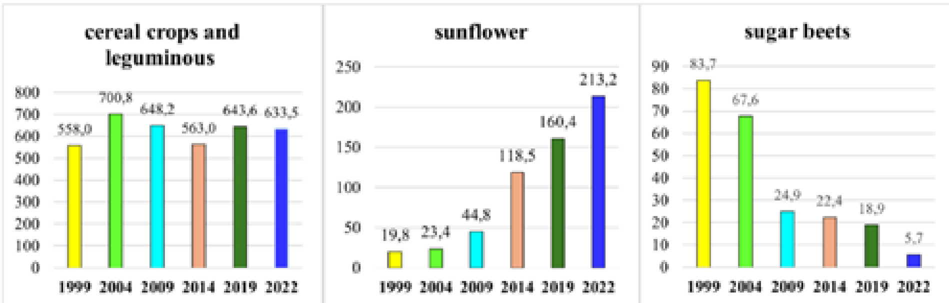
Establishing sustainable agricultural production starts with specialized agricultural enterprises and their level of agricultural intensity. Sustainable agroecosystem functioning relies on scientifically informed enterprise specialization, harmoniously aligning livestock and crop production, integrating soil-enhancing crops, and adopting energy-efficient technologies. This involves crafting optimal sown area structures, flexible crop rotation systems with superior predecessors, and implementing energy-saving methodologies ((Barvinskyi at al., 2015)).

Agricultural lands within the Kyiv region encompass highly valuable productive areas (54.8%) boasting an average humus content of 3.1%, conducive to cultivating a wide range of forest-steppe and Polissya typical crops. The region's agricultural sector holds significant investment appeal due to favorable natural and climatic conditions, advantageous economic and geographic positioning, and a well-developed production and market infrastructure (Kozlovska, 2015).

Producers in the region predominantly specialize in highly profitable but soil-depleting crops like sunflower, rapeseed, and soybeans. Notably, from 1999 to 2022, there was a slight overall increase (5.66%) in sown areas for agricultural crops within the Kyiv region. However, this period saw significant shifts in crop distribution, particularly increased cultivation of highly profitable export-oriented crops. The structural changes in sown areas within the Kyiv region from 1999 to 2022 illustrate this trend (Figure 4).

Over the same period, the sunflower sown area surged by 90.72%, disrupting the crop rotation system and contributing to soil depletion. Cereal and legume sown areas saw a 20.38% increase from 1999 to 2004 but decreased by 9,61% from 2004 to 2022. Concurrently, the sown area dedicated to sugar beet witnessed a significant decline (93,19% decrease from 1999 to 2022) due to displacement by more profitable yet less costly crops. The disregard for crop rotations, pursuit of high profits, neglect of land protection measures, and continual “soil fatigue” collectively lead to soil degradation.

Figure 4. Cultivated land area for crops in the Kiev region, measured in thousands of hectares (Primary statistical office in the Kyiv region - agricultural harvest records (1999-2022))



Assessment of the ecological stability of land use within the regions of Ukraine by calculating the coefficient of ecological stability shows that it is stably unstable ($K_{e.s}$. = 0.40). In such regions as Dnipropetrovsk region, Donetsk region, Zaporizhzhya region, Kirovohrad region, Odesa region, Mykolaiv region, Poltava regionit is even ecologically unstable and only in Zakarpattia region it is ecologically stable. As for the coefficient of anthropogenic load ($K_{a.l.}$), which characterizes the degree of influence of human activity on the state of the environment, including land resources, it is 3 points in the country as a whole and is characterized by an average level (National report, 2021). Characteristics of the ecological state of land use by region of Ukraine are given in Table 4.

Table 4. Characteristics of the ecological state of land use in the region of Ukraine

Administrative and territorial formation (region)	$K_{e.s.}$*	**Ecological stability of land use**	$K_{a.l.}$**	**The level of anthropogenic load of land use**
ARK	0.41	Stably unstable	3	Average
Vinnytska	0.33	Ecologically unstable	4	Considerable
Volynska	0.57	Medium stable	3	Average
Dnipropetrovska	0.28	Ecologically unstable	4	Considerable
Donetska	0.29	Ecologically unstable	4	Considerable
Zhytomyrska	0.55	Medium stable	3	Average
Zakarpatska	0.71	Ecologically stable	3	Average
Zaporizka	0.27	Ecologically unstable	4	Considerable
Ivano-Frankivska	0.62	Medium stable	3	Average

continued on following page

Table 4. Continued

Administrative and territorial formation (region)	$K_{e.s.}$*	Ecological stability of land use	$K_{a.l.}$**	The level of anthropogenic load of land use
Kyivska	0.41	Stably unstable	3	Average
Kirovohradska	0.27	Ecologically unstable	4	Considerable
Luhanska	0.41	Stably unstable	3	Average
Lvivska	0.53	Medium stable	3	Average
Mykolaivska	0.28	Ecologically unstable	4	Considerable
Odeska	0.31	Ecologically unstable	4	Considerable
Poltavska	0.33	Ecologically unstable	4	Considerable
Rivnenska	0.60	Medium stable	3	Average
Sumska	0.42	Stably unstable	3	Average
Ternopilska	0.34	Stably unstable	4	Considerable
Kharkivska	0.34	Stably unstable	4	Considerable
Khersonska	0.34	Stably unstable	3	Average
Khmelnytska	0.35	Stably unstable	4	Considerable
Cherkaska	0.36	Stably unstable	3	Average
Chernivetska	0.51	Medium stable	3	Average
Chernihivska	0.47	Stably unstable	3	Average
Ukraine	**0.40**	**Stably unstable**	**3**	**Average**

Source: own calculation by the authors according to the methodology of scientists of the Institute of Land Management of the National Academy of Sciences of Ukraine

*less than 0.33 – the territory is ecologically unstable; from 0.34 to 0.50 – stable unstable; from 0.51 to 0.66 – passes into the limits of average stability; exceeds 0.67 – ecologically stable.

** 5 points – a high degree of anthropogenic load (land of industry, transport, settlements); 4 points – significant (arable land, perennial plantations); 3 points – average (natural fodder grounds, limed streams); 2 points – insignificant (forest strips, bushes, forests, swamps, under water); 1 point – low (micro-reserves).

Therefore, ecological and economic requirements regarding the general state of land use, which has approached the dangerous limit beyond which irreparable ecological processes may occur, are not met in Ukraine.

CONCLUSIONS

In the context of escalating soil degradation caused by increased anthropogenic pressure and disruption of agrolandscape ecological stability, it becomes crucial to optimize the balance of natural ecosystems and implement anti-erosion strategies at both local and regional levels.

To effectively transition into an adaptive system that integrates ecological and economic elements in modern agriculture, several key measures are imperative:

– Develop or enhance landscape farming systems.
– Implement strong economic incentives affecting land use entities, making ecologically detrimental practices economically unsustainable.
– Withdraw from intensive cultivation of unproductive lands based on established criteria while implementing a comprehensive set of reclamation measures on arable lands. This approach aims to bolster agroecosystem productivity and conserve soil fertility.
– Optimize the land composition of agricultural enterprises by integrating environmental standards into the spatial organization of territories.
– Ensure a consistent balance of humus in crop rotations by applying fertilizers and maximizing nutrient recirculation.
– Enhance the structure of cultivated areas by introducing adaptable crop rotations, reducing reliance on row crops, and expanding the cultivation of perennial grasses.

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Chapter 4
Spatial Heterogeneity of Soil Carbon Sequestration Potential and Its Estimation Using GIS Technologies and Remote Sensing Data

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ABSTRACT

The chapter considers soil carbon sequestration potential as a characteristic associated with the genesis of soils and the degree of their degradation. Various options for estimating the soil carbon sequestration potential based on comparing potentially achievable and actual levels of organic carbon content in soils are considered. Possible scenarios of carbon losses and carbon sequestration by the soils of Ukraine for the period up to 2050 are discussed. A method of spatial quantitative assessment of soil sequestration potential is proposed, considering the heterogeneity

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of relief and the degree of erosion degradation of soils. The implementation of the method is presented in the case of an experimental site located in the forest-steppe of Ukraine (Kharkiv region). It was shown that underestimation of the features of soil spatial heterogeneity can lead to errors in the estimation of the soil organic carbon sequestration potential up to 50% of the average value.

BACKGROUND

Despite all the efforts of the world's community, the Greenhouse Gases (GHG) emissions still haven't decreased enough, and global temperature rise continues. It makes issues of atmospheric carbon capture and removal critically important, along with emission reduction and decarbonization of economics, which focused on COP28 in December 2023 (COP 28, 2023).

One of the ways of reducing the amount of carbon dioxide in the atmosphere is a carbon sequestration (CS). Carbon sequestration it is the capturing and long-term storage of atmospheric carbon in plants, soils, geologic formations, and the ocean. Carbon sequestration occurs both naturally and as a result of anthropogenic activities (Selin N. E., 2023). The U.S. Geological Survey USGS divides two major types of CS: geologic and biologic. Geologic CS is the process of storing carbon dioxide (CO_2) in underground geologic formations. The CO_2 is usually pressurized until it becomes a liquid, and then it is injected into porous rock formations in geologic basins (USGS, 2017). Essentially, geologic CS is the final stage of the most anthropogenic carbon capture and storage processes. Biologic carbon sequestration is the storage of atmospheric carbon in vegetation, soils, woody products, and aquatic environments (USGS, 2017).

Climate experts claim that approximately 9 – 11 Gt of CO_2 must be removed from the atmosphere annually to maintain a long-term average global temperature rise of no more than 1.5°C (Baugh L. S., 2023). According to the Global Carbon Project report (GCP, 23) total global CO_2 emissions (fossil + land use change) was 40.9 Gt in 2023. About half of all CO_2 emitted continues to be absorbed by land and ocean “sinks” globally, with the rest remaining in the atmosphere, where it causes climate change. As shown by Zhu et al., (2010), in the 2000s, annual carbon sequestration by terrestrial ecosystems in the United States accounted for an even smaller part of the carbon budget —approximately only 25% of all carbon emissions.

Meanwhile, according to Global CCS Institute report (2023), there are only 41 large-scale carbon capture projects in operation around the world, capturing roughly 49 Mt of CO_2 annually. That’s a tiny amount (less than 0.25%) compared to the biological sequestration of carbon. Although biological carbon sequestration is insufficient to offset anthropogenic GHG emissions, it is still the most effective way to capture and remove atmospheric carbon. Thus, the potential ability of terrestrial ecosystems to carbon sequestration shouldn't be underestimated.

It is a wonder that when biological sequestration is mentioned in official documents it means firstly reforestation and wetlands restore. However, the main role in the carbon sequestration is played by soils. Soil is one of the most powerful sinks of carbon in the world and soil recovery is a real mechanism for reducing GHG in the atmosphere (Abdullah et al., 2018; Kuzmych et al, 2022; Lal, 2004; Lal, Smith and Jungkunst 2018; Han et al., 2016; Yakymchuk et al., 2022; FAO, 2022;).

Global carbon cycle estimates (Scharlemann, 2014) indicate that land cover is not only a regulator of the global carbon cycle, but also the largest concentrator of terrestrial biogenic carbon, storing at least three times more carbon than the atmosphere or terrestrial biomass. According to Hiederer and Köchy, (2011); Ruesch and Gibbs, (2008); Schanderman et al., (2009) the share of carbon in terrestrial ecosystems fixed in soils, depending on climatic conditions, is 47.7-96.2% and absolutely predominates in most ecosystems. The leading role of soils in carbon sequestration in our time is beyond doubt Abdullah et al., (2018); Lal, (2004); Han et al, (2016).

Soil's significance in reducing the carbon content in the atmosphere is manifested in two ways: indirectly through providing the necessary conditions for the vital activity of plants and animals and, accordingly, synthesis and accumulation of terrestrial ecosystems' biomass, and directly through the carbon storage of organic residues in the form of complex organic compounds what's known as "humus". Andrés et al. (2022) referred to humus as highly decomposed soil organic matter (SOM), in which original plant and animal debris cannot be identified. Humus is the most resistant and complex form of organic matter, produced not only by partial decomposition of organic residues, as Andrés et al. (2022) write, but also by soil-specific processes of chemical synthesis, so-called "humification". Since organic humus compounds are resistant to decomposition, its average age in soils is usually more than 1000 years (from about 500 years for protein attachments to more than 2500 years for the polyphenolic bulk of humus compounds). This is why the recovery of humus content in soils is a more preferable option for long-term carbon sequestration than temporary storage in biomass.

According to the estimates of Scharlemann, Tanner, Hiederer and Kapos (2014) for landscapes of cool temperature moist, cool temperature dry and warm temperature dry zones, typical for Ukraine, the share of organic carbon contained in the soil is from 76% (Dry Steppe) to 92% (Forest-Steppe and Steppe) of the total carbon of terrestrial ecosystems.

Thus, assessment of soil carbon sequestration ability or carbon sequestration potential of soil (SOCseq) is critically important for reliable estimation of potential carbon sequestration capacity of the ecosystems and correct calculations of global carbon budget. In our opinion, determining the upper limit of possible accumulation of carbon in the soil is fundamentally important in predicting its sequestration because it allows researchers to develop specific measures for specific areas.

Quite a few researchers emphasize that the rate of carbon sequestration by soils is not constant, and it gradually decreases until the soil reaches a certain equilibrium level of humus content (Lal et al., 2018). However, there is no consensus on exactly how this slowdown in sequestration occurs and how to quantify its pace. This happens due to the complex processes of organic matter transformation in soils and a great variety of soils, keeping in mind possible combinations of soil formation factors that affect the course of carbon accumulation. Thus, when estimating the sequestration potential, most studies assess carbon sequestration rate of soil, as "constant during the first 30-50 years". The source of this approach can be the work of a recognized authority in assessing the carbon sequestration potential of R. Lal and his colleagues. They approximate time to achieve equilibrium of the soil carbon system by stimulating carbon sequestration, which, according to their estimates, is 25-50 years for most soils (Lal et al., 2018).

However, it is obvious that the change in the rate of carbon sequestration over time will depend not only on natural and climatic conditions and the amount and quality of organic matter entering the soil, but also on soil condition, and in particular the degree of degradation (here by degradation we mean the processes that lead to the loss of organic matter). However, it is obvious that the change in the rate of carbon sequestration over time will depend not only on natural and climatic conditions and the amount and quality of organic matter entering the soil, but also on soil condition, the degree of degradation. The relative share of lost organic carbon compared to equilibrium non-degraded soils characterizes the degradation degree. It determines the undersaturation of the soil with carbon, and, consequently, the temporal dynamics of carbon sequestration.

The issue of the soil carbon sequestration potential assessment on a global scale has been preliminarily solved in the form of a global map of carbon sequestration potential (GSOCseq maps) at 1 km resolution for agricultural lands. The map shows the predicted SOC reserves of mineral soils in the 0–30 cm layer that could be achieved over 20 years after the adoption of sustainable soil management (SSM) practices aimed at increasing carbon input into cropland and pasture soils. SOC stocks in the top 30 cm layer of mineral soils were projected for over 20-years term after the adoption of Sustainable Soil Management (SSM) practices oriented to increase carbon inputs to cropland and grassland soils) (Peralta et al., 2022; FAO, 2022). Work on the creation was carried out by FAO in 2019-2021 with the participation of 110 countries. To date, the first version of such a map has been created, presenting the results of modeling carbon sequestration under four land use scenarios (business as usual (BAU) and three different SSM scenarios). However, given the enormous complexity of the task, this map has a number of limitations, namely, the potential for sequestration of organogenic, saline, hydromorphic soils is not taken into account, as discussed in (FAO, 2022). Moreover, global generalized assessments do not take into account erosion processes, as well as features of humus accumulation in slope and eroded soils. Moreover, there wasn't information about Ukraine for GSOCseq map and authors used a so-called "Gap-filling Layer" for Ukraine's soils (FAO, 2022). That is the reason the doubted results were obtained for Ukraine (GLOSIS).

In the current USGS soil carbon sequestration models (Zhu et al., 2010; Lui et al., 2003), soil erosion is considered only as one of the pathways for soil carbon loss and a mechanism of the organic carbon (Corg) redistribution in the landscape. However, the influence of erosion on the rate of sequestration and the amount of accumulated carbon has remained unnoticed.

As the results of studying the self-overgrowth of technogenic dumps as a model of primary soil formation show (Makhonina, 2004; Seredina et al., 2012), the rate of carbon sequestration gradually decreases with time and the total amount of carbon absorbed by the soil is inversely proportional to the initial content of organic carbon in the substrate. Similar data on a decrease in the rate of sequestration over time were obtained by Sanderman et al. (2010), Ergina (2013), Lam et al. (2013). The same point of view is shared by Sommer and Bossio (2014). Zomer et al., 2017, assessing the global potential for carbon sequestration, suggest that the linear trend of carbon sequestration by soils in case it's targeting stimulation can be continued for 15-20 years with a further decrease in rates. According to Sommer and Bossio (2014), carbon sequestration is described by a nonlinear model. After 30 years, the amount of carbon absorbed annually by the soil is reduced to at least half the original amount, since the more humus-saturated the soil is, the less it binds carbon.

Consequently, dehumified soils, especially moderately and heavily eroded ones, will have a greater carbon sequestration potential compared to well-fertilized or non-eroded flatland soils. This is confirmed by Liu et al. (2003), who showed that the carbon accumulation capacity of eroded soils is inversely proportional to the erosion manifestation degree. Moreover, van Oost, et al. (2009) even suggest that erosion increases total landscape carbon sequestration because eroded soils continually capture additional atmospheric carbon relative to equilibrium soils that are not affected by erosion.

Thus, for modelling carbon sequestration processes and carbon budget calculation, an important issue is to determine the upper limit of carbon accumulation in the soil-plant system. The soil carbon sequestration capacity is limited by such factors as soil genesis (type of soil formation), particle size distribution, and hydrothermal conditions of the territory, which are characterized by the amount and ratio of heat and moisture input.

Polupan et al. (2004) found the maximum sustainable level of organic carbon content in the automorphic soils (SOC) of Ukraine based on the content of physical clay (soil particles less than 0,01 mm) in the parent rock and depending on the hydrothermal conditions of soil formation. For instance, for typical chernozems at present, the natural ratio of SOC content to physical clay content (PhC) is 0.05-0.09. Physical clay is the sum of soil particles <0.01 mm size.

Attempting to soil recarbonization above this limit, including the application of high doses of all types of organic fertilizers, will result in an unsustainable increase in organic carbon content, which will tend to return to its natural lower level as soon as artificial soil carbon saturation stops. An exception is an applying the chemically inactive carbon compounds (biochar) which in fact is a foreign component in a soil. Biochar's carbon is usually not involved in the soil biogeochemical cycle and may probably be used for anthropogenic carbon sequestration, without considering of soil features.

The soil formation conditions on slopes and flatlands differ due to differences in the water, heat, and light (insolation) supply. Consequently, the potential ability for humus accumulation in the flatland and slope soils is also different. The peculiarities of the SOCseq of slope soils are determined by a combination of two differently directed factors: 1) erosion degradation degree, which generally contributes to an increase in the sequestration potential and 2) slope's xeromorphism or comparative slope aridity, which lead to reducing of the soil carbon sequestration capacity because a slope aridisation contributes to the natural formation of shallow profile soils poorer in humus.

The part of sloping lands among the total cultivated area in different countries is very significant. In Ukraine, according to (Martin et al., 2015), 48% of arable soils ($1.6 * 10^5$ km^2) are located on lands with a surface steepness of more than 1 degree, potentially susceptible to water erosion. In Asian countries for instance, which are characterized by mountainous terrain, this problem is much more acute. Thus, according to (Hilger et al., 2013), 65% of arable land in Thailand and 40% of all land in Vietnam is located on erodible slopes. 69.8% of Cultivated Land Area in Yunnan Province, China has an Average Slope of 15.62° (Chen and Shi, 2020) It is obvious that with such a scale of distribution of slope lands, ignoring the characteristics of humus accumulation on the slopes will lead to colossal errors in assessing the SOCseq.

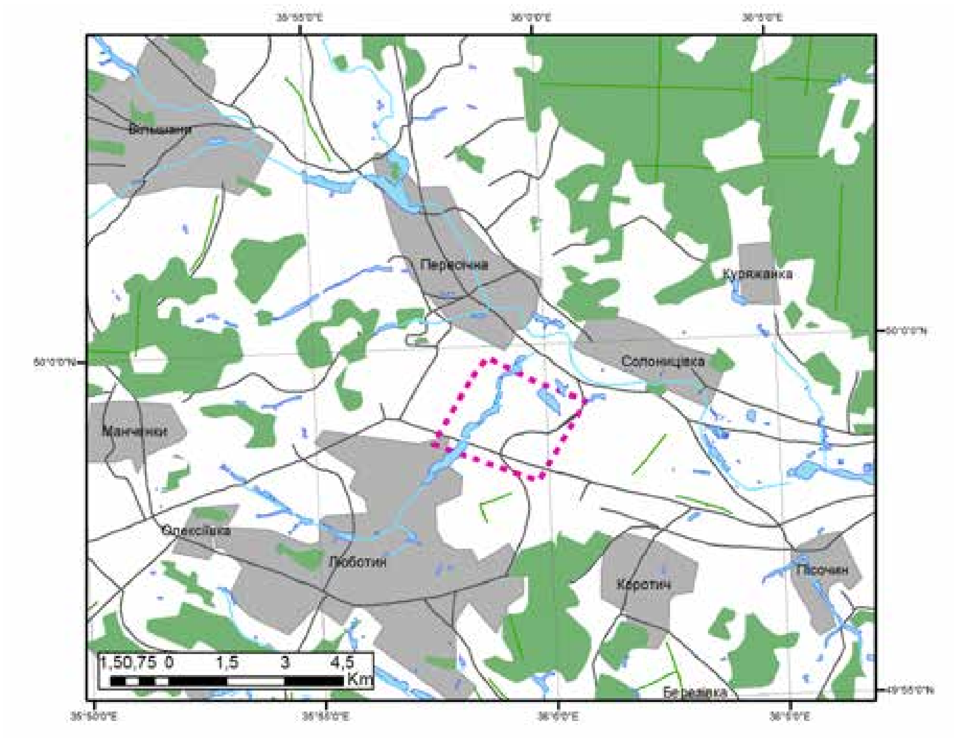
The main purpose of the chapter is demonstrating the method assessment of the soil carbon sequestration potential, considering slope soil formation features and soil erosion degree based on remote sensing data, geostatistics, and geoinformation relief analysis.

METHOD OF SPATIAL QUANTITATIVE ASSESSMENT OF SOIL CARBON SEQUESTRATION POTENTIAL

Research area and methods

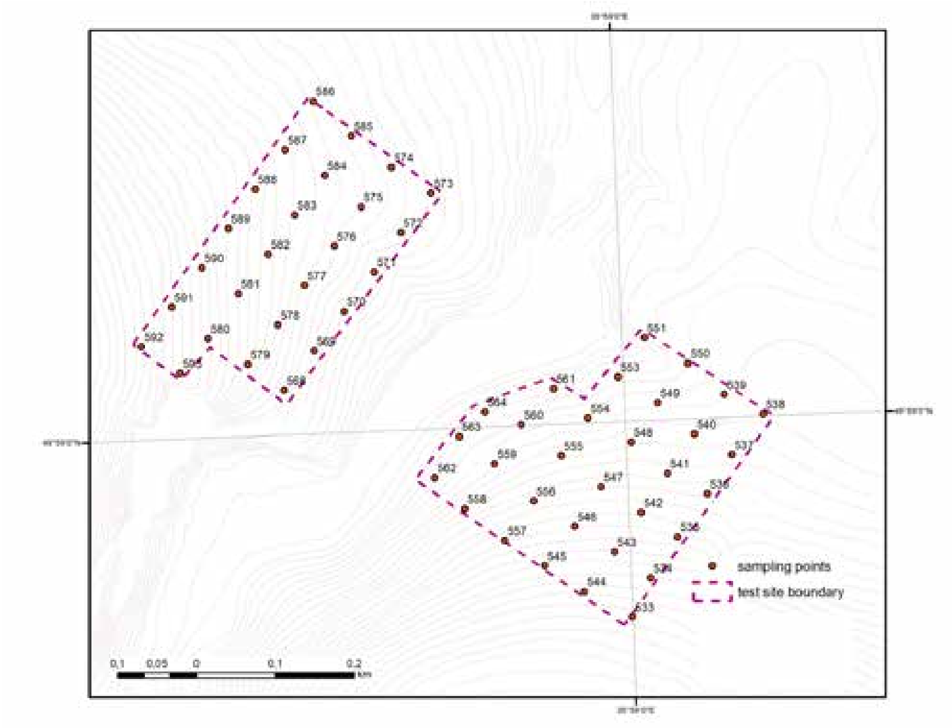
The research was carried out at an experimental site located in the Kharkov region (Ukraine). Geomorphologically, the experimental site consists of two slopes – south-eastern and north-western exposures, between which the floodplain of the Lyubotynka River runs. The surface elevations vary from 181 m to 118 m. The south-eastern slope is high (maximum absolute height is 181 m) and in the lower third, it is steep with a surface slope of up to 7-9°, dissected by ravines. The north-western slope is gentler, with a steepness of the surface up to 3-5°, the absolute height of its surface does not exceed 150 m. The floodplain of the Lyubotynka River is from 250 to 400 m wide, and has a weakly expressed microrelief, as usual of the small river floodplains of plain areas. The absolute elevation of the floodplain surface is 117-118 m above the sea. The total researched area was 60 hectares as shown in Figure 1.

Figure 1. Topographic map of the study area



A detailed soil survey of the territory showed that prevail soil types on the researched sites are Luvic Chernozem and Phaeozem on a loess-like loam parent rock. Significant fluctuations in the thickness of the soil profiles of the studied soils (from 43 to 87 cm) is explained, on the one hand, by the influence of various factors of soil formation, and, on the other hand, by the action of erosion processes. For detailed study of the soil carbon content two sites with an area of 18.7 hectares and 22.5 hectares, respectively, were allocated, located on the slopes of the opposite exposure (Figure 2). At these sites, 57 soil samples were taken on a regular grid with a step of 100 m. Soil samples were taken from a 0-20 cm soil layer. As numerous studies show, in chernozem soils, the most active processes of synthesis and destruction of organic matter occur in a layer of 0-20 cm. Although the humus profile of chernozems in Ukraine can have a thickness of more than 100 cm, active processes of organic carbon circulation primarily affect the top layer of soil. Thus, according to Larionova et al., 2008, the renewal rate of humus compounds in chernozem in the 0-20 cm layer is about four times higher than in the 40-60 cm layer and lifetime of them are 697 and 2742 years respectively. According to Chaban et al., 2010, at a depth of more than 40 cm, differences between arable soils and 55-years fallow become statistically insignificant. In conditions of complex terrain with erosion manifestation, it is the arable layer that is most relevant for assessing the possible potential for carbon accumulation, since it is a comparatively homogeneous product of the annual mixing of topsoil as a result of its tillage. While the underlying soil layers can vary dramatically depending on the position in the relief. The location of soil sampling points is shown in Figure 2.

Figure 2. Soil sampling points location



In all soil samples SOC was measured by the wet oxidation method using potassium dichromate in a sulfur medium and soil particle size distribution by the pipette method.

Used data and data analysis

The Sentinel 2A satellite images were used. The images were uploaded using the Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home) service. The date of the shooting is 25.08.2019, the cloud cover is 0%, and the image processing level is 2A. The DEM was constructed from a topographic map at a scale of 1:10000 (1984). The pixel size is 10*10m.

All geodatasets were converted to the WGS-1984 coordinate system in the UTM zone 36 N projection. World Geodetic System (WGS-1984) datum and Universal Transverse Mercator (UTM) projection system with Zone 38 N were used for all datasets.

Analysis of satellite imagery and DEMs was done using ArcGIS 10.4 software. Geostatistical data analysis and mapping were also performed in ArcGIS 10.4. to match them geometrically.

RESULTS AND DISCUSSION

Obtaining a detailed map of soil carbon content is the initial step in any soil carbon sequestration potential assessment. Modern technologies offer various effective methods for this purpose. Remote sensing data, such as satellite imagery, aerial imagery, and drone imagery, can be used to construct maps of soil carbon content (Angelopoulou et al., 2019; Wang et al., 2018; Gholizadeh et al., 2018; Diek et al., 2016; Hu, 2020; Vaudour et al., 2013; Žížala et al., 2019; Steinberg et al., 2016). Geostatistical methods can also be employed to create of SOC content maps (Kumar, 2013; Chen et al., 2015). In recent years, a combination of remote sensing and geostatistical methods has been a popular approach (Mallik et al., 2020; Hounkpatin, 2021; Mondalet al., 2017; Wang et al., 2018).

In this study, two methods were used to map SOC in the soil: 1) interpolation of discrete SOC values obtained from laboratory analysis of soil samples taken on a regular grid; 2) transformation of a satellite image using a geoformula. This method has been widely tested and accepted, including for soils in Ukraine (Shatokhin and Achasov, 2008; Chorniy and Abramov, 2016; Byndych, 2017; Truskaveczkyj et al., 2017).

The soil samples analysis showed that the study area's topsoil layer (0-20 cm) is characterized by an average degree of variability in the main soil parameters. So, for example, the range of soil organic carbon content (Corg) values is 1.25-2.55%, with an average value of 1.9% as was shown in Table 1.

Table 1. Some statistical parameters of the studied soils

Soil parameter	Mean	Median	Min	Max	Variance	SD	Cv	SEM
SOC	1.90	1.87	1.25	2.55	0.07	0.26	13.89	0.03
PhC	51.09	50.53	39.45	63.08	17.66	4.20	8.22	0.56
Sand	12.27	11.45	3.23	29.24	38.57	6.21	50.61	0.82
Silt	52.96	54.01	35.37	65.62	48.05	6.93	13.08	0.92

continued on following page

Table 1. Continued

Soil parameter	Mean	Median	Min	Max	Variance	SD	Cv	SEM
Clay	34.76	35.01	25.81	42.75	18.23	4.26	12.28	0.57

Notes: SOC— soil organic carbon content in the soil layer 0–20 cm, %;
PhC - particles of size less than 0.01 mm;
Sand - particles of size from 0.05 to 2 mm;
Silt - particles of size from 0.002 to 0.05 mm;
Clay - particles of size less than 0.002 mm;
SD - standard deviation;
Cv - coefficient of variation;
SEM - Standard error of the mean.

Let's focus on the PhC. Physical clay is a significant characteristic of particle size distribution in scientific institutions in the former USSR countries. A similar parameter that holds physical significance is the sum of Silt and Clay granulometric fraction. It is also important to note the weak correlation between SOC and particle size distribution parameters (Table 2).

Table 2. Correlation between soil parameters

Parameters	SOC	PhC	SOC/PhC	Sand	Silk	Clay
SOC	1					
PhC	**0.26**	1				
SOC/PhC	**0.79**	**-0.37**	1			
Sand	-0.19	**-0.66**	0.27	1		
Silk	0.14	**0.34**	-0.09	**-0.79**	1	
Clay	0.08	**0.48**	-0.20	**-0.31**	**-0.34**	1

Note: abbreviation the same as table 1; statistically significant correlation coefficients are given in bold.

This is not typical for chernozem soils, which usually have an accumulation of humus in the top part of their profile, clay content proportionally. In modal non-eroded chernozems, a direct positive linear correlation between SOC and the PhC in the topsoil is typically observed. Thus, the lack of correlation in the research area is explained by soil erosion, which leads to the reduction of the soil profile, with mixing of topsoil to lower soil humus poor horizons. Therefore, the spatial variation in SOC content in the topsoil of the research area is primarily influenced by erosion rather than the variability in granulometric composition.

Preliminary correlation analysis of the links between the spectral brightness of soils and their properties showed (Table 3) that the closest link (r = 0.72) was observed between SOC and the Red band data, (B4, 665 nm), which is close to the other authors results for the Ukraine chernozems (Shatokhin and Achasov, 2008; Chorniy and Abramov, 2016; Byndych, 2017; Truskaveczky, 2006).

Table 3. Correlation between soil parameters and Sentinel 2 image spectral band data

Soil parameters	Sentinel 2 spectral bands												
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B8a**
SOC	**-0.36**	**-0.54**	**-0.57**	**-0.72**	**-0.37**	0.12	0.15	0.12	-0.05	**-0.38**	**-0.41**	**-0.30**	0.18
PhC	**-0.30**	-0.25	-0.24	-0.25	-0.18	-0.04	-0.04	-0.03	0.01	-0.05	-0.24	-0.14	-0.03
SOC/ PhC	-0.15	**-0.34**	**-0.39**	**-0.52**	-0.25	0.13	0.15	0.11	-0.06	**-0.31**	-0.25	-0.19	0.17
Sand	0.23	0.21	**0.27**	**0.27**	0.23	0.09	0.09	0.09	0.09	0.16	**0.27**	0.10	0.08
Silt	-0.17	-0.18	-0.16	-0.12	-0.09	0.00	0.00	0.02	0.02	-0.25	-0.19	-0.13	0.02
Clay	-0.09	-0.05	-0.17	-0.14	-0.22	-0.14	-0.14	-0.17	-0.17	0.13	-0.12	0.05	-0.15

Note: abbreviation the same as table 1; statistically significant correlation coefficients are given in bold

The link of SOC with the B4 data is described by the regression equation:

$$B4 = 1348{,}15 - 227{,}49 * SOC \qquad (1)$$

Using the ArcGIS Raster Calculator tool, a cartogram of the SOC content in the topsoil was obtained using the equation 1 (Figure 3).

Given that only 51% of the variability (R^2=0.51) of the soil spectral brightness can be explained by the content of organic carbon, this map, obviously, only gives an approximate assessment of the SOC and its spatial variability. However, mapping SOC from remote sensing has a lot of undeniable advantages, primarily in increasing spatial coverage while reducing costs, so this method is virtually no alternative for large-scale spatial assessments.

Maps based on laboratory analyses of soil samples are a priori more accurate than those based on satellite data, but they are also much more expensive.

The Kriging ArcGIS tool was used to map the SOC in the study area using the spatial interpolation of soil sample analysis data. The interpolation result is shown in Figure 4. Since the range of carbon content using the Kriging method is given by the range of analytical data, as opposed to regression calculation based on the spectral brightness of the soil, we see that, depending on the mapping method used, both the range of values obtained, and the spatial distribution of SOC differ significantly.

Figure 3. Test ground's SOC map made by the remote sensing data

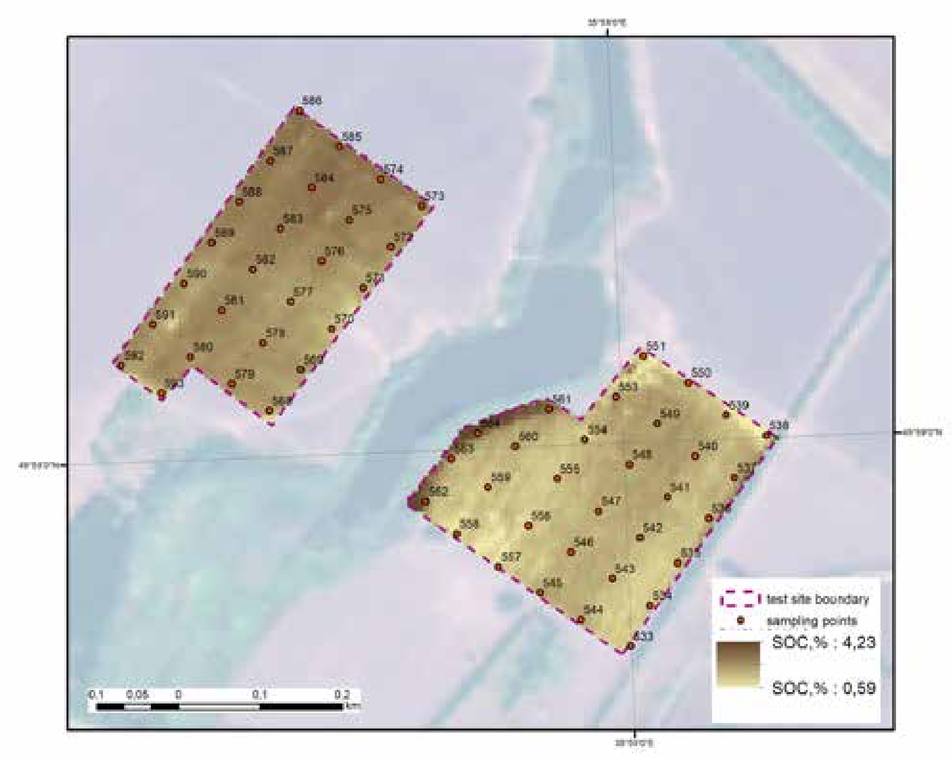
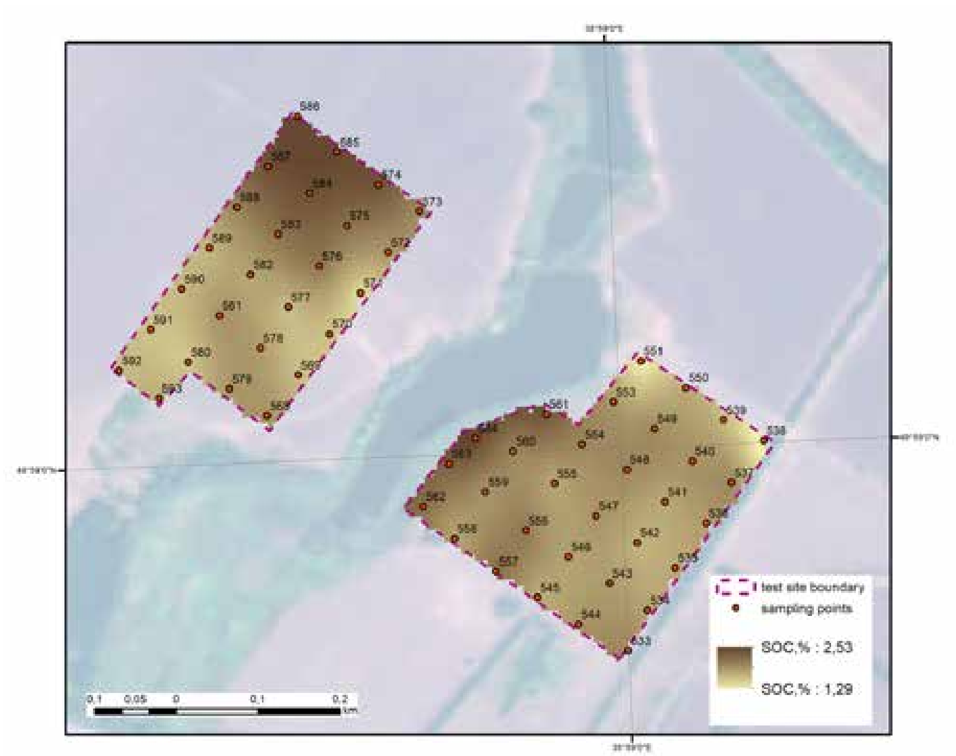


Figure 4. Kriging-based SOC map



However, obtaining spatial information on actual SOC content solves only half of the problem. We consider the soil carbon sequestration potential (SOCseq) as the maximum possible humus capacity of a soil (the potential amount of organic carbon that can be captured and stored by the soil for a long time as sustainable humus compounds). SOCseq can be calculated using the equation:

$$SOC_{seq} = SOC_{0} - SOC_{1} \tag{2}$$

where: SOC_0 – potentially possible sustainable content of organic carbon in the soil;
SOC_1 – actual SOC content at the time of sequestration potential assessment.

Thus, the next step to assess the potential of sequestration is to compile a forecast map of maximum equilibrium humus content in soils, considering the features of soil formation for a specific area. The solution to this problem is possible by formalizing the soil formation like some kind of equation, which idea was first proposed by V.V. Dokuchaev (1883) and that was represented lately as the equation by Jenny (Jenny, 1941). In both cases, relationships between soil parameters and soil formation factors were not expressed numerically, but it is these theoretical approaches that are the basis of modern modelling in soil science (Willgoose, 2018). Quantitative assessment of soil formation conditions will make it possible to obtain a model of soil cover for a specific territory, and, accordingly, to quantify the parameters of humus accumulation and soil thickness.

The main part of the arable land of Ukraine (67.7%) is represented by chernozem soils, the total area of black soils in Ukraine is 27.8 million hectares, which is about 9% of all black soils in the world (Pozdniak, 2016). Chernozems are automorphic soils with an accumulative type of soil formation, formed on loess and loess-like loams under the conditions of a subboreal weakly arid climate, characteristic of the Steppe and Forest-Steppe of Ukraine. A typical feature of the chernozems' soil formation process is no influence of the groundwater and the critical importance of relief as a transformer and regulator of hydrothermal conditions. On homogeneous parent rocks, the biotic factor effect also depends primarily on the relief-caused microclimatic conditions.

Because most of all chernozems are formed on loess deposits, which are characterized by a quite similar mineralogical and granulometric composition, the influence of the mezorelief on the natural, pre-anthropogenic, formation of the chernozems of Ukraine can be considered decisive.

Thus, if the influence of terrain on soil formation would be quantitatively formalized, a "potential" soil cover model can be derived. This model would represent the soil parameters that can be formed in specific landscape conditions without human-induced changes. The primary characteristic of this "potential" model is the soil organic carbon content. For the SOCseq assessment the methodology of the relief geoinformation analysis described in the (Achasov et al., 2019[a,b]) was used.

To quantify the impact of mezorelief on soil formation, it is proposed to use the xeromorphism coefficient (Kk), which characterizes the change in hydrothermal conditions of soil formation for a particular relief area in comparison with a horizontal surface. The xeromophism coefficient is defined as the ratio of insolation coefficient (Ki) to relative wetting coefficient (Kw).

$$Kk = Ki / Kw \tag{3}$$

Ki characterizes the ratio of the amount of direct solar radiation entering the real slope, compared with the amount of solar radiation falling on a horizontal surface, and is calculated according to (Achasov et al, 2019[a,b]).

Kw characterizes the ratio of the amount of water entering the soil on a given slope, compared with the amount of water entering the soil located on a horizontal surface, and is calculated according to (Achasov et al, 2019[a,b]).

The coefficient, which characterizes the potential soil organic carbon (SOC) content in soils, is derived from an empirical model based on the results of numerous field studies conducted on uneroded chernozem soils of the forest-steppe and steppe regions of Ukraine (Achasov, 2010; Achasov et al., 2019a, b). The regression model obtained from these studies was subsequently used to calculate the "potential" SOC content in soils. It is essential to note that the model developed is not for virgin soils but for arable soils. Consequently, the calculated sequestration potential represents the humus accumulation system for arable soils. In virgin soils, the sequestration potential will be higher. However, in the foreseeable future, a significant reduction in arable soils is not expected, and assessments of the potential characteristic of arable soils will be more adequate to real conditions.

The influence of relief on soil formation cannot be fully reflected by the xeromorphism factor Kk. However, Kk can be used as an initial approximation to quantify the hydrothermal conditions at each point of the relief. The effectiveness of Kk in studying soil cover has been confirmed for the conditions of the Steppe and Forest-Steppe of Ukraine. Research has shown that Kk for non-eroded chernozems is closely related to the humus content in chernozems and the depth of their profile, and it can act as a predictor in soil mapping. As result of analyzing the Digital Elevation Model (DEM) obtained from a topographic map, several maps characterizing the slope, exposure, coefficients of insolation, and xeromorphism factor of the studied area were constructed. Subsequently, a map of the potential of SOC content in non-degraded soils was created based on the regression dependence between Kk and SOC (Figure 5)

This method offers the advantage of obtaining a spatial representation of soil formation potential and SOC accumulation using a digital elevation model. DEM allows the formalizing of hydrothermal conditions of soil formation. That is why we called it the "method of relief geoinformation analysis".

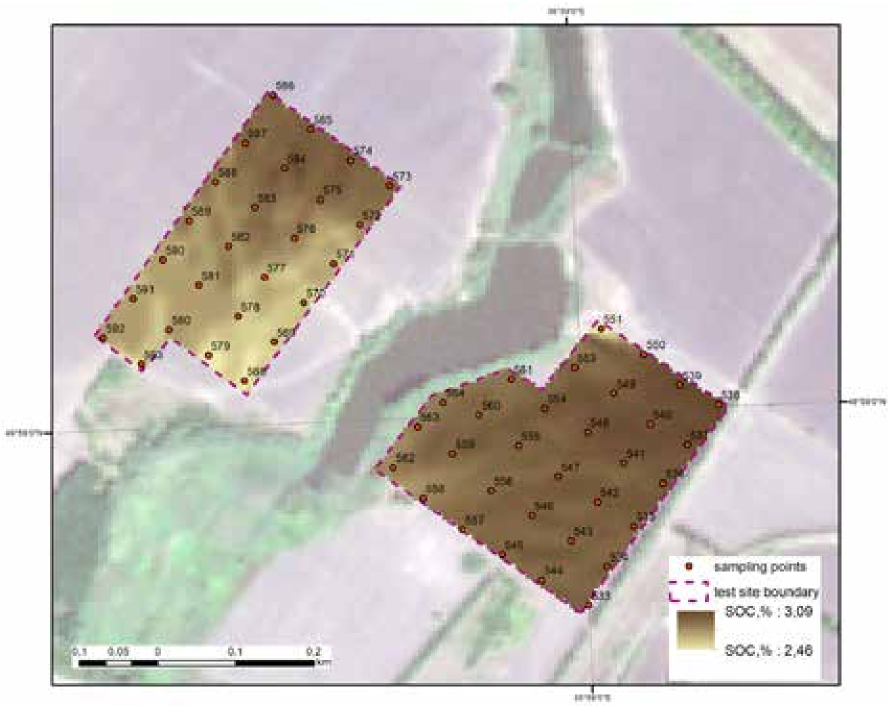
The advantage of this method is the possibility of obtaining a spatial representation of the potential for soil formation and SOC accumulation based on a single digital elevation model, the analysis of which makes it possible to formalize the hydrothermal conditions of soil formation. In this case, it is assumed that the rest of the factors of soil formation are constant.

The limitations of the method using are:

1. Homogeneity of the territory in terms of parent rock and granulometric composition. It should be noted that for the territory of the Forest-Steppe and the Steppe of Ukraine, this condition is observed for fairly large territories.
2. Particle size distribution of soils. The model was designed for soils with physical clay content in the range of 40 to 70%.

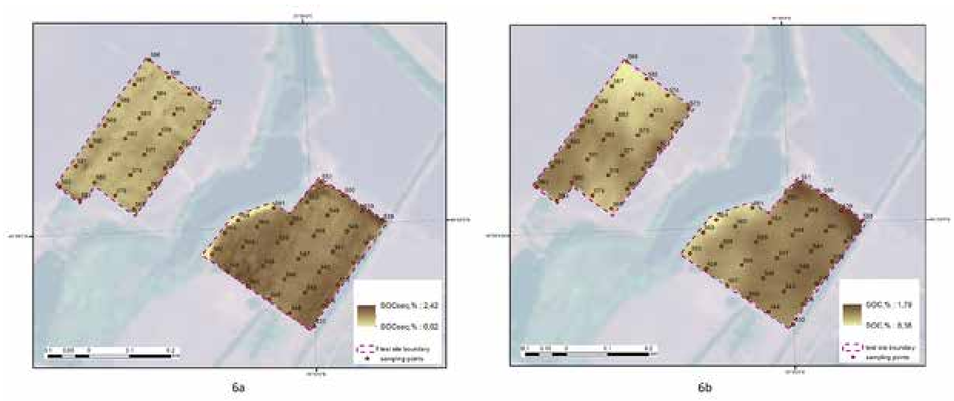
3. Soil type. The method is designed for automorphic chernozems. For soils of different genesis, it is necessary to obtain reliable empirical dependences of SOC on relief parameters beforehand, for further use in computational spatial models.

Figure 5. Potential SOC content in the topsoil (SOC_0) designed by the method of relief geoinformation analysis



The territory of the study sites fully complies with the above restrictions. Therefore Figure 5 can be considered to represent the situation of the maximum possible accumulation of SOC for the actual landscape hydrothermal conditions. Thus, we obtained the maps of the actual SOC content (Figures 3 and 4) and a map of SOC potential content (possible accumulation) (Figure 5). To quantify the carbon sequestration potential of soils in the study area, maps 3 and 4 were subtracted from map 5 using the Map Algebra tool of ArcGIS.

Figure 6. Maps of topsoil SOCseq (%) designed by remote sensing data (a) and the soil sampling data (b)

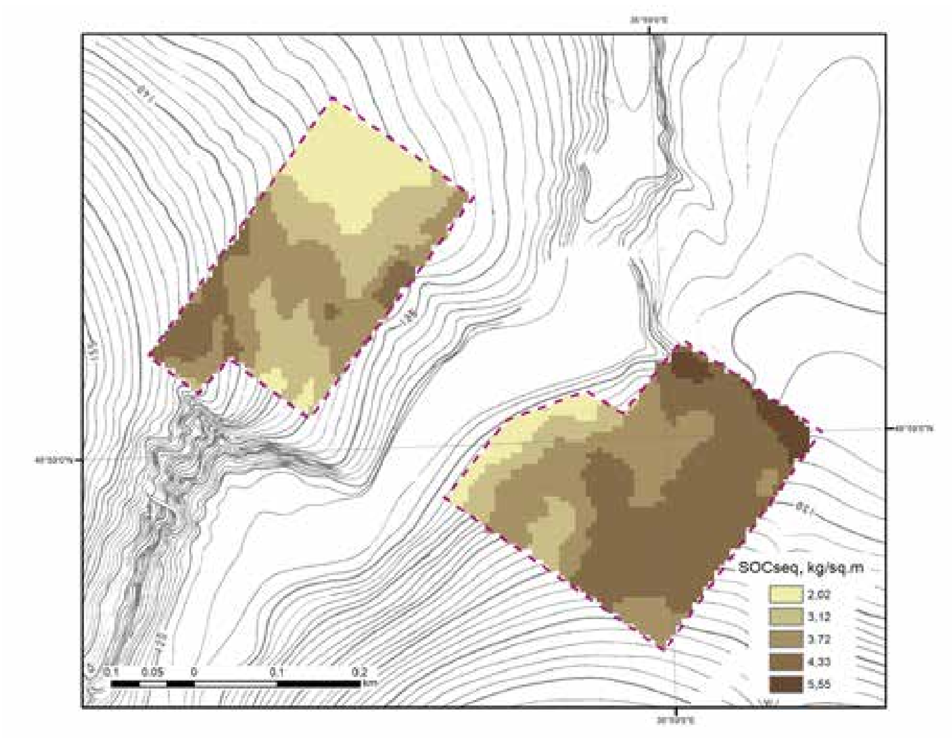


The resulting maps (Figure 6) reflect the amount of SOC (%) that could be additionally accumulated (sequestrated) in soils in case of implementation of sustainable soil management (SSM) practices to prevent their further degradation and increase the SOC content in soils (application of organic fertilizers, soil protection crop rotations, etc.). A comparison of Figures 6a and 6b shows that the general spatial structure of SOCseq is quite similar. For example, in both cases, the potential for POC accumulation is higher at test site Nº2 (southeast) compared to test site Nº1 (northwest). The similarity of the internal pattern of the plots is also traced. However, there are differences due to the relatively low accuracy of map 6a, which is based on remote sensing data. As already mentioned, in this case, map on the Figure 6b is a priori more accurate, so we used it further to quantify SOCseq.

Table 4. Results of SOCseq assessment in the test areas

SOCseq zone	Zone area, m^2	SOCseq, kg/m^2				Difference with weighted average	
		min	max	average	total, kg/area	kg/m^2	% from average
1	5426.34	1.28	2.77	2.02	10980.20	-1.59	-43.95
2	8196.47	2.77	3.46	3.12	25554.53	-0.49	-13.64
3	12530.36	3.46	3.98	3.72	46636.43	0.11	+3.10
4	12979.97	3.98	4.67	4.33	56156.22	0.72	+19.84
5	1082.90	4.67	6.44	5.55	6014.96	1.94	+53.86
Summa	40216.04				145342.35		

Figure 7. Result topsoil SOCseq map of the test site



A quantitative assessment of the carbon sequestration potential in the arable layer (0-30 cm) of the test sites was carried out and a final map of the SOCseq in kg/m^2 was designed (Figure 7). The 5 zones with different sequestration potential were allocated. Analysis of the Figure 7 shows that on a limited area of about 40 hectares, the SOC sequestration potential varies from 1.28 to 6.44 kg/m^2 i.e. more than 5 times. With a weighted average sequestration potential of 3.61 kg/m^2, the total amount of organic carbon that can be sequestered in the soil of this site is $145.34*10^4$ kg (Table 4). While the deviation of the SOCseq from the weighted average value for individual clusters ranges from -44% for the least eroded areas to +54% for the most eroded ones. This shows that ignoring the features of humus accumulation in the slope soils can lead to errors in sequestration estimates at the level of ±50%.

THE OTHER OPTIONS OF THE SOCseq QUANTIFY

Our proposed simplified approach to quantifying the sequestration potential based on the difference between the actual initial natural level of organic carbon content (equation 2) was previously tested by us for Ukraine soils using four different approaches to obtain initial natural SOC content data. In (Achasova et al., 2022) we suggested four possible ways to assess the potential of soil carbon sequestration:

1. By assessing the difference between arable soils and virgin soil analogues. For Ukraine's chernozems, the average SOCseq estimated this way was 41 t/ha (from 12 to 60 t/ha). These data are consistent with estimates from (Lal, 2021) who indicate that restoration of degraded chernozems could sequester 0.7-1.5 t/ha/y. Comparison of current SOC content with data for virgin soils gives the highest values compared to other approaches. The average relative reduction of organic carbon content in the ploughed chernozems in comparison with the virgin land was estimated as 28.8-30.5%. Unfortunately, this method has significant limitations, as there are almost no fertile virgin soils left in Ukraine. Fallow lands cannot be a full-fledged analogue of virgin soil because they are usually partially restored soil that has not reached equilibrium.
2. By estimating the difference between historically known data and the results of modern soil and agrochemical surveys. As our research has shown, such estimates give results close to those of real surveys of virgin soils (Table 5). Therefore, they are quite adequate for estimating the contribution of carbon sequestration to total emission reductions at the state level.

Table 5. Potential of carbon sequestration of arable soil in Ukraine (for 0-30 cm layer)

Zone	Arable soils area, ha*10^6	The potential of carbon sequestration in soils (0-30 cm layer)			
		t/ha	Total, t*10^6	%*	CO_2e-t*10^6
Polissia	5.14	4.2	23.3	3.1	85.3
Forest-Steppe	11.73	27.6	350.3	46.2	1284.3
Steppe	15.58	22.8	384.2	50.7	1408.9
Total	32.45	21.5	757.7	100	2778.4

*Share from total potential sequestration

As this estimation showed, major carbon losses occurred in the soils of the Forest-Steppe and Steppe of Ukraine with higher natural fertility and those used more intensively in agricultural production. Therefore, the soils of the Forest-Steppe and Steppe account for almost 97% of Ukraine's soils carbon sequestration capacity. The total sequestration potential of Ukraine's soil estimated in this way is 757.7 Mt C, or 2.78 Gt CO_2e.

3. The third possible way to determine the theoretically possible level of carbon accumulation in the Ukraine soils at the level of the soil genetic subtype is using the empirical coefficients. Studies of Ukrainian soil scientists have established a quantitative dependence of humus accumulation in soils depending on their genesis, hydrothermal conditions of soil formation and particle size distribution of soil-forming rocks. To characterize the ability of different types of soils to accumulate humus (Polupan et al., 2008), they propose a number of calculation coefficients. The authors propose to use the Coefficient of relative accumulation of humus (CRAH) to estimate the potential carbon content in the topsoil. CRAH is the ratio of humus content in the soil layer 0-30 cm to 10% of the content of physical clay (PhC). PhC is the sum of soil particles less than 0.01 mm. PhC is the main characteristic of the particle size distribution in the scientific schools of the countries of the former USSR. We calculate CRAH for a soil layer of 0-30 cm by the equation:

$$CRAH = 10H/PhC \tag{4}$$

where H – humus content is soil, %; PhC – physical clay content in soil, %

Polupan et al. (2008) proposed regression equations of CRAH dependence on HTC (Selyaninov hydrothermal coefficient) for the period April-September for the main soil types and subtypes. Traditionally in Soviet times, when determining the humus content in soils, they analytically determined the content of organic carbon (Corg), calculated the humus content by multiplying the Corg content by a factor of 1.724. Accordingly, it is possible to transform CRAH into Coefficient relative accumulation of organic carbon (RAC coefficient) by the equation:

$$RAC = CRAH/1.724 \tag{6}$$

The sequestration potential was calculated using the RAC coefficient for Luvic chernozem (PhC = 48%, RAC = 0.64) and Phaeozem (PhC = 49%, RAC = 0.42). SOC_0 was calculated by the equation:

$$SOC_0 = PhC * RAC/10 \tag{7}$$

For the Lubotin test area SOCseq estimated using RAC coefficient was 36.8 t/ha. In fact, it is similar to average result obtained by the method of relief geoinformation analysis (36.1 t/ha).

4. Finally, the fourth approach was estimating a theoretically possible level of carbon accumulation based on empirical models. It was considered in detail in this chapter. In contrast to the first two methods, this method will give slightly reduced values of the sequestration potential, as empirical models use the parameters of arable soils, already dehumified relative to virgin analogues. This approach will lead to more realistic values of sequestration, if used in intensive agricultural production in compliance with technological requirements for the preservation of organic matter.

Simulation of carbon sequestration process is also possible by using mathematical models of humus accumulation, for example RothC (Coleman and Jenkinson, 2014; Shirato, 2020). However, this model needs verification and adaptation to the conditions of Ukraine. We do not know what the upper limit of carbon accumulation is. Moreover, the course of simulated sequestration rigidly relates to climatic parameters and the quantity of coming organic residues in conditions of real farms is not always possible to predict.

POSSIBLE SCENARIOS OF CARBON LOSSES AND CARBON SEQUESTRATION BY THE SOILS OF UKRAINE FOR THE PERIOD UP TO 2050

The assessment of the potential impact of climate change on the dynamics of carbon in Ukrainian soils is based on existing climate change forecasts for Ukraine. It is a complex and multifaceted issue, influenced by various factors such as temperature, precipitation, and land use practices. These projections are significant due to Ukraine's high vulnerability to climate change, which is expected to bring about rising temperatures, shifting precipitation patterns, more frequent floods, and changes in natural disasters, ultimately impacting agriculture and food supply.

This impact is expected to result in the following changes, depending on climate trends (Balabukh, 2023; Vozhegova et al, 2021; Krakoska et al., 2021; Wilson, et al., 2021; World Bank, 2021):

1. The growing season is projected to start earlier and last longer, potentially leading to increased bioproductivity and the ability to grow heat-loving crops for a longer period. However, the increase in bioproductivity may be limited by a lack of moisture.
2. Significant warming during winter months may lead to the spread of diseases, pests, and heat-loving invasive species, potentially reducing crop productivity and necessitating increased use of pesticides. This could negatively affect the balance of soil organic matter and pose challenges for organic farming, which avoids chemical plant protection products.

3. Rising temperatures and slight changes in rainfall, amid a backdrop of increasing aridity, will have several detrimental effects on soil organic matter balance, particularly under conditions of insufficient moisture. These effects include:
   a) Decrease in the bioproductivity of natural and agricultural landscapes due to lack of moisture, as the climate has already become drier throughout Ukraine.
   b) Deterioration of the assimilation of mineral fertilizers by agricultural plants and an increase in unproductive losses of nitrogen from mineral fertilizers, due to the aforementioned lack of moisture [1][2].
   c) The increase in aridity will exacerbate forest growing conditions, contribute to the loss of trees, and lead to the accumulation of deadwood in forest belts. This will complicate reforestation efforts, necessitating increased attention to agroforestry measures. Otherwise, the destruction of forest belts will result in increased erosion processes, exacerbated effects of droughts and frosts, yield losses, and a decrease in the content of organic carbon in the soil.
4. The changing distribution of precipitation throughout the year is expected to increase the unevenness of precipitation, with an increase in the number, duration, and intensity of downpours against the backdrop of longer dry periods. This will lead to intensified water erosion processes, deflation, and a further decrease in soil organic matter content. Additionally, an increase in aridity and a decrease in groundwater levels will lead to local improvements in soil and vegetation conditions in some hydromorphic landscapes mainly in the Polissya zone. Increasing bio productivity and a positive organic matter balance could be expected as a result of the change of anaerobic conditions to aerobic ones and the formation of more suitable conditions for vegetation growth and humification. However, these improvements will be limited, because currently the area of overwatered soils in Ukraine is just about 14% of arable soils (AgroPolit,com, 2019), and we haven't enough data for estimation of which part of them will be improved. So, most likely it will not significantly affect overall trends.
5. The existing trends of climate change predict a progressive decrease in soil organic carbon content in Ukraine due to increased soil degradation, decreased fresh organic residue supply, and the corresponding predominance of organic matter mineralization over humus formation. To achieve zero and positive humus balance (carbon sequestration by soils), it is necessary to take measures to stop soil degradation and stimulate humus accumulation. Several studies have highlighted the impact of climate change on soil moisture limitation and aridity, emphasizing the critical role of soil moisture in land-atmosphere interactions and its influence on ecosystems and society.

6. The search results provide a comprehensive understanding of the relationship between climate change and soil moisture-based terrestrial aridity, emphasizing the multifaceted characteristics of dryland aridity changes and the critical role of soil moisture in land-atmosphere feedbacks. These findings support the scientific basis for the projected increase in aridity and its implications for soil and ecosystems.

The measures for Ukraine to address the impact of climate change on soil and vegetation conditions include:

1. Removing degraded and ecologically vulnerable lands from arable land and converting them to tinning and afforestation.
2. Conducting an inventory of degraded lands and establishing field-protective forest plantations.
3. Implementing agrolandscape arrangement of erosion-hazardous lands with anti-erosion measures to halt erosion processes.
4. Renewing the system of agroforestry plantations.
5. Minimizing tillage in a reasonable, technologically, and economically justified manner.
6. Adhering to soil-protective crop rotations on erosion-prone lands, including the recommended share of continuous sowing crops and perennial grasses.
7. Using chemical and physical soil reclamation.
8. Remediating disturbed soils.
9. Selecting varieties and hybrids adapted to new climatic conditions.
10. Optimizing mineral nutrition and irrigation to prevent unproductive losses of mineral fertilizers and moisture.
11. Using organic fertilizers, including composts based on various organic materials.
12. Growing energy crops on marginal lands and utilizing them as biofuels.
13. Employing agrotechnical and hydraulic methods for snow and moisture retention in the fields.
14. Implementing ecologically sound afforestation and alkalinization to mitigate the additional soil drying effect of forest ecosystems in arid conditions and promote the accumulation of organic carbon in steppe ecosystems.

These measures are essential to counter the projected decrease in soil organic carbon content and to promote soil health and sustainability in the face of climate change. The cited sources provide insights into the climate change impacts on soil moisture, aridity, and soil organic carbon content in Ukraine, emphasizing the need for adaptive measures to mitigate these effects.

CONCLUSIONS

1. The soil carbon sequestration capacity in mineral soils is limited. The upper limit of possible carbon accumulation in natural soils is determined by a complex of soil-forming factors. Such as landscape hydrothermal conditions, the plant cover, or more widely biocenosis features, the properties of parent rocks, and the influence of groundwater (hydromorphysme).
2. The soil carbon sequestration is a nonlinear process, with a gradual attenuation of the rate of carbon accumulation as the soil approaches an equilibrium state. Therefore, estimates of the rate of carbon sequestration per year can be valid only for a limited time interval, and without considering it will lead to erroneously inflated estimates of the sequestration potential.
3. That is why we consider that it is more correct to assess the sequestration potential as the total mass of carbon that soils are capable of accumulating starting from a given moment. The soil carbon sequestration potential is proposed to be assessed by the difference between the potentially possible content of organic carbon in the soil for specific landscape conditions and its content at the assessment moment.
4. Potential ability of black soils to accumulate organic carbon strongly depends on physical clay content (DSTU 4362:2004). And it's crucial significant on a regional level of estimation of carbon sequestration potential. However, at a local level the most important factors that determined SOCseq value are erosion processes and slope xeromorphism while a soil texture is not so influent.
5. To calculate the potential content of organic carbon in soils, we used an empirical model of the dependence of SOC content in chernozems on soil formation conditions, which were characterized using our proposed xeromorphism coefficient Kk.
6. Soil erosion changes the potential soil carbon capacity, increasing the soil sequestration potential, but its realization requires the implementation of SSM practices to prevent soil erosion and soil recarbonization. According to our estimates (Achasova et al., 2022), the carbon sequestration potential of Ukrainian chernozems varies from 12 to 60 t/ha. These data are consistent with assessment by (Lal, 2021), who indicates that SOC sequestration with improved management of degraded chernozems could be 0.7-1.5 MgC/ha/year.
7. Non-eroded soils on slopes, due to increased xeromorphism, usually have a reduced sequestration potential compared to flatland soils. Ignoring soil erosion and slope xeromorphism factors in SOCseq assessment can lead to errors in estimates of sequestration potential at the level about of $\pm$ 50%. For instance, in this research is shown that for area 40 ha deviation of the SOCseq from the

weighted average value ranges from -44% for the least eroded areas to +54% for the most eroded ones.

8. To achieve carbon neutrality of the economy, it is necessary to focus efforts on the reproduction of humus content in the soils of agricultural lands. Dehumified over the long history of agricultural use, Ukraine's soil can now be a huge reservoir for sequestration of organic carbon. According to rough estimates, Ukraine's arable land alone is potentially capable of absorbing 757.7 Mt of carbon or 2.78 Gt CO_2e.

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Chapter 5
Modeling of Subsurface Runoff and Surface Runoff During Storm Precipitation in Low-Slope Undeformed and Surface-Deformed Soils on Agricultural Lands

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ABSTRACT

The mathematical problem addressed in this study concerns the formation of subsurface and surface runoff during storm precipitation in a low-slope area featuring both undeformed and surface-deformed soils. Approximate relationships governing the water accumulation on the surface of these soils and the movement of the saturation front were derived. Additionally, the timeframe for infiltration and groundwater closure, as well as the dissipation of the surface layer following the cessation of

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precipitation, was determined. Utilizing generalized initial data for fine soils along with a two-layer soil configuration at the experimental site, the accuracy of the derived relationships was evaluated. This study delves into the process of soil wetting during the formation of a low-permeability interlayer on the surface, resulting from compaction and swelling. A detailed analysis was provided for the comparison of subsurface runoff under conditions of varying degrees of deformation, both with and without surface deformation.

BACKGROUND

Modern climate change has had a significant impact on agricultural production. This leads to a deficit in water supply, which is the main limiting factor for the sustainable functioning of agriculture. New conditions for growing crops are being formed, which manifest as an increase in soil moisture deficit and a decrease in groundwater reserves. Changes in the technological maps of crop cultivation by modern agricultural enterprises are occurring, and the fraction of hydrophilic crops in the structure of crop rotations is significantly increasing (Parry M.L. et al, 1990; Romashchenko M.I. et al, 2020).

Precipitation is the main source of natural water in agricultural lands in the humid zone of Ukraine. Modern fluctuations in annual precipitation occur, on average, almost within the climatic norm, but the general trend is a significant redistribution of seasonal and monthly precipitation (Kyrychenko O. S., 2020; Buksha V. F., 2009; Kuzmych L. et al, 2023). Simultaneously, with an insignificant change in the amount of precipitation in general, the character and intensity of precipitation in Ukraine changed significantly. The number of cases in which half or the entire monthly norm of precipitation falls with a few hours has increased (Kyrychenko O. S., 2020; Buksha V. F., 2009).

An increase in the likelihood of excessive precipitation is noted in the reports of the Intergovernmental Panel on Climate Change (IPCC) and a special report on adaptation to natural hazards, including excessive precipitation (Field C. B., 2012).

Despite a wide range of possible future changes in average precipitation, it is predicted that extreme precipitation events in all seasons may become more intense, leading to a 10-25% increase in the number of wettest days of the year, surface runoff, and rain floods by the end of the century (Wilson L. et al, 2021; Coppola E. et al, 2021; Gutiérrez J. M. et al, 2021).

In the context of increasing soil water deficits and decreasing groundwater reserves due to climate change and the cultivation of moisture-loving crops, the role of precipitation in agricultural production is growing significantly. In general, the trends in the meteorological conditions during the vegetation season observed in recent decades include an increase in air temperature and uneven distribution, changes in the character, intensity, and structure of precipitation, and an increase in the number of cases of heavy rainfall, which are local in nature (O. G. Tatarchuk O. G., 2019; Balabukh V.O., 2008; UkrGMI, 2013; Kuzmych L. et al, 2021, 2022a,b, 2023a,b). As a result, unproductive losses of rainwater have been increasing, hindering sustainable agricultural production in the zone of sufficient atmospheric moisture, which covers Polissya and the northern territories of the Forest-Steppe of Ukraine. Therefore, their conservation and economic use are of great practical significance.

The purpose of the study is to model the formation and dynamics of subsurface and surface runoff during storm precipitation in a low-slope area with undeformed or surface-deformed soils.

Therefore, the accumulation, conservation, and further economic use of water resources supplied by precipitation are of great practical importance. Mathematical modeling methods can significantly contribute to the rational regulation of the water conditions of agricultural land, taking into account heavy precipitation. Their application in rainy periods makes it possible to identify the component of precipitation that enters the soil, determine the time of closure of the infiltration water with the groundwater, and the resulting rise in the water table (WT), that is, an increase in moisture reserves within the aeration zone.

Research results

Extensive theoretical and experimental studies on the wetting of natural porous structures have been conducted for several decades (Verigin N.N., 1977; Poliakov V.L., 2008; Oleinik A.Ya., 1987; Polubarinova-Kochina P.Ya., 1977). Their main results are discussed and developed in a monograph (Poliakov V.L., 2014). At the same time, these studies are usually based on a simplified idea of the accumulation capacity of unsaturated soils. This study focused on the role of groundwater and moisture reserves in the aeration zone in soil saturation.

The dynamics of rainwater are considered separately and in detail when a low-permeability interlayer (seal) with abnormal seepage properties forms on the soil surface because of its local compaction and swelling. Depending on the intensity of rain and the physical and mechanical properties of the soil cover, two characteristic situations are possible. In the first case, light rain, incoherent structure, and dense packing of soil particles guarantee the stability of the seepage characteristics. In the second situation, heavy rain, cohesion of the structure, and loose packing precisely contribute to the formation of a thin, more compact, and less permeable layer on the day surface (Assouline S., 1989, 1997). The newly formed interlayer can not only slow down the infiltration process but also change the characteristics of soil wetting in general.

Thus, the infiltration that previously occurred with lower precipitation may have been replaced by wetting with incomplete saturation (percolation) in the case of higher precipitation. Indeed, it is quite realistic that the permeability decreases so sharply that the rate of water filtered through the porous seal may be less than the saturated hydraulic conductivity of arable layer k_1.

The observed local transformation of soil in areas with a slope can lead to redistribution of storm precipitation in favor of surface runoff. Considering the specificity of the impact of storm precipitation on the soil water conditions in the humid zone of Ukraine, theoretical studies of their inflow to the layered porous structure and the downward movement of water under the influence of gravity on WT, as well as its concomitant accumulation, were performed separately for the two situations mentioned above.

The first situation was considered in accordance with a typical two-layer soil. WT was steady in the subsoil layer at depth Z_0 before the rain. Simultaneously, the moisture profiles in the arable layer ($0 \geq z \geq -m_2$)) and the unsaturated part of the subsoil layer $(-m_2 > z > -Z_0)$ are described by known functions $\theta_1(z)$ and $\theta_2(z)$, respectively. Here, the vertical coordinate axis was directed upward, and its origin was located on the soil surface. The storm rain fell during the period $[0, T_r]$ with an average intensity ε, and $\varepsilon > k_1$. Consequently, a layer of water with a variable height $H(t)$ is formed on the surface of the sloping area, which flows along it with an average velocity q_s.

WETTING OF UNDEFORMED SOIL. THEORETICAL ASPECTS

The infiltration process was divided into several stages. In the first stage, a saturation front is formed at $t = 0$ and moves from the day surface ($z = 0$) to the boundary between the layers ($0 \geq Z_w(t) > -m_2$). For this stage, the mathematical problem with respect to the unknowns H and Z_w includes the equation of the rainwater balance in the surface interlayer

$$\frac{dH}{dt} = \varepsilon - q_s - k_1 \frac{H + Z_w}{Z_w} \tag{1}$$

and arable layer

$$\mu_1(Z_w) \frac{dZ_w}{dt} = k_1 \frac{H + Z_w}{Z_w}, \tag{2}$$

and the initial conditions

$$t = 0, Z_w = H = 0. \tag{3}$$

Here, $\mu_1(Z_w)$ is the saturation deficit function that characterizes the capacity available for rainwater in the unsaturated arable layer. In general, μ is determined based on the moisture distribution in the aeration zone before rain, that is, $\theta_i(z)$, $i = 1{,}2$. It is obvious that at WT $(z = -Z_0)$, θ is equal to the total moisture capacity θ_m and with an increase in z to the maximum value $(Z_w - Z_0)$, it monotonically decreases to the minimum $\theta(Z_0 - Z_w)$. Thus, under conditions of intensive soil wetting

$$\mu(Z_w) = \theta_m - \theta(Z_0 - Z_w). \tag{4}$$

In general, the value of surface runoff (q_s) depends on many factors, and its contribution to precipitation can vary widely. When analyzing in detail the water-physical state of agricultural lands in the humid zone under modern conditions, it is advisable to pay special attention to extreme situations when precipitation is mainly spent on subsurface runoff or surface runoff. Significant difficulties occur in modeling the surface water flow. Because of the extremely limited information on the volume and characteristics of surface runoff formation, we have to limit ourselves to rough estimates of q_s. As a first approximation, it is permissible to consider the relationship between q_s and the precipitation intensity ε, that is, formally set by the function $q_s(\varepsilon)$. Considering its obvious limit value $q_s(k_1) = 0$ and assuming the linear nature of this dependence, etc.

$$q_s(\varepsilon) = \alpha_\varepsilon(\varepsilon - k_1),$$

it is sufficient for the approximate calculation of q_s to specify the value of coefficient α_ε that corresponds to the territory under consideration. The methodology outlined above can then be applied to calculate both runoffs using a value of ε that is easily measured. More reliable results could be obtained if the dependence of q_s on H was established. A special (representative) section was distinguished in the surface flow in both cases. The flow characteristics of this flow allow a description of the balance and dynamics of rainwater in the considered area with a slope as a whole. For in-depth theoretical studies, it is necessary to consider the two-dimensional character of changes in hydrological characteristics (in the longitudinal and vertical directions). Here, considering the practical orientation of such studies and the difficulties in obtaining reliable initial information, it is sufficient to limit ourselves to a simplified approach based on hydraulic theory and the equations of motion of a fluid with variable mass.

To summarize the results of the theoretical studies, the basic dimensional model (1)-(3) is reduced to a dimensionless model using the coefficient k_1 and the thickness of the arable layer m_1 as scales. Then

$$\overline{H} = H/m_1,\ \overline{Z}_w = Z_w/m_1,\ \overline{\varepsilon} = \varepsilon/k_1,\ \overline{q}_s = q_s/k_1,\ \overline{t} = k_1 t/m_1$$

and the specified model is simplified to the form

$$\frac{d\overline{H}}{d\overline{t}} = \overline{\varepsilon} - \overline{q}_s - \frac{\overline{H} + \overline{Z}_w}{\overline{Z}_w}\ ; \tag{5}$$

$$\mu_1\left(\overline{Z}_w\right)\frac{d\overline{Z}_w}{d\overline{t}} = \frac{\overline{H} + \overline{Z}_w}{\overline{Z}_w}\ ; \tag{6}$$

$$\overline{t} = 0, \overline{Z}_w = \overline{H} = 0. \tag{7}$$

The result of combining (5) and (6) is

$$\mu_1\left(\overline{Z}_w\right)\frac{d\overline{Z}_w}{d\overline{t}} = \overline{\varepsilon} - \overline{q}_s - \frac{d\overline{H}}{dt}. \tag{8}$$

Integrating (8) with respect to (7), we find the expression for $\overline{H}$

$$\overline{H}\left(\overline{t},\overline{Z}_w\right) = (\overline{\varepsilon} - \overline{q}_s)\overline{t} - F_1\left(\overline{Z}_w\right), \tag{9}$$

where $F_1\left(\overline{Z}_w\right) = \int^{\overline{Z}_w} \mu_1(\xi)d\xi$. Thus, the original problem is reduced to a simpler one with respect to $\overline{Z}_w^0$, namely, it includes the equations

$$\mu_1\left(\overline{Z}_w\right)\frac{d\overline{Z}_w}{d\overline{t}} = 1 + \frac{(\overline{\varepsilon} - \overline{q}_s)\overline{t} - F_1\left(\overline{Z}_w\right)}{\overline{Z}_w} \tag{10}$$

and the first condition (7). It is not possible to determine an exact solution to this problem. However, using modern powerful computing tools, namely packages of mathematical analysis programs for applied computing (Mathcad, MATLAB, etc.), it is easy to obtain a numerical solution using various methods. Approximate analytical solutions can be alternatives to numerical solutions. They allow for simple and highly accurate engineering calculations of the infiltration process and its consequences.

To solve a problem (7) and (10) approximately, we consider $\bar{t}\left(\bar{Z}_w\right)$ as the desired function. After averaging $\bar{t}$ in the range of zero to $\bar{Z}_w$, the following equation is derived for the average current value of $\bar{t}_a$

$$\bar{t}_a\left(\bar{Z}_w\right) = \frac{1}{\bar{Z}_w}\int_0^{\bar{Z}_w}\int_0^{\zeta}\frac{\xi\mu_1(\xi)}{(\bar{\varepsilon}-\bar{q}_s)\bar{t}_a\left(\bar{Z}_w\right)-F_1(\xi)+\xi}d\xi d\zeta. \tag{11}$$

Hence, the corresponding $\bar{t}_a$ can be easily determined by fitting to a given $\bar{Z}_w$. The corresponding relative time was then calculated for the given $\bar{Z}_w$ and $\bar{t}_a$

$$\bar{t} = \int_0^{\bar{Z}_w}\frac{\xi\mu_1(\xi)}{(\bar{\varepsilon}-\bar{q}_s)\bar{t}_a-F_1(\xi)+\xi}d\xi. \tag{12}$$

Similarly, the relative time required for the saturation front to reach a given relative depth $\bar{Z}_w$ was calculated using a different approach. The first calculation step was determined by fitting $\bar{t}_a$ from the equation

$$2\bar{t}_a = \int_0^{\bar{Z}_w}\frac{\xi\mu_1(\xi)}{2(\bar{\varepsilon}-\bar{q}_s)\bar{t}_a-F_1(\xi)+\xi}d\xi. \tag{13}$$

In the second step, the corresponding time is determined using equation (12). In fact, two approximate analytical solutions were obtained, which differ only in the determination of the relative average time; according to the first solution, it is calculated by equation (11), and according to the second solution, by equation (13).

Complete saturation of the arable layer was possible in the case of prolonged precipitation. The corresponding relative time $\bar{t}_1$ is determined either numerically based on (7) and (10) or analytically using (11)–(13), assuming $\bar{Z}_w = 1$.

Having analyzed the wetting of the arable layer, it is advisable to consider two realistic scenarios of the infiltration process. The first scenario is realized if rain does not stop at $t > t_1$. The new mathematical problem is also formulated with respect to $\bar{H}$ and $\bar{Z}_w$, but taking into account the second initial water-physical state of the pore medium $\left(\bar{H}^0 > 0, \bar{Z}_w^0 > 0\right)$, its lower permeability ($k_2 < k_1$), and capacity ($\mu_2 < \mu_1$). Thus, this problem has the following dimensionless form

$$\frac{d\bar{H}}{d\bar{t}} = \bar{\varepsilon} - \bar{q}_s - \bar{k}_2\frac{\bar{H}+\bar{Z}_w}{\bar{Z}_w+\bar{k}_2-1}, \tag{14}$$

$$\mu_2\left(\bar{Z}_w\right)\frac{d\bar{Z}_w}{d\bar{t}} = \bar{k}_2\frac{\bar{H}+\bar{Z}_w}{\bar{Z}_w+\bar{k}_2-1} \tag{15}$$

$$\bar{t} = \bar{t}_1, \bar{H} = \bar{H}^0 = (\bar{\varepsilon} - \bar{q}_s)\bar{t}_1 - F_1(1) \ ; \bar{Z}_w = 1 \ ; \tag{16}$$

where $\bar{k}_2 = k/k_1$, $\mu_2(\bar{Z}_w) = \theta_{m2} - \theta_2(\bar{Z}_0 - \bar{Z}_w)$. By analogy with the problem (7), (10), we obtain after some transformations of the system (14), (15) the problem with respect to

$$\bar{H}(\bar{t},\bar{Z}_w) = \bar{H}^0 + (\bar{\varepsilon} - \bar{q}_s)(\bar{t} - \bar{t}_1) - F_2(\bar{Z}_w), \tag{17}$$

where $F_2(\bar{Z}_w) = \int_1^{\bar{Z}_w} \mu_2(\xi)d\xi$. Then the simplified problem will include the equations

$$\mu_2(\bar{Z}_w)\frac{d\bar{Z}_w}{d\bar{t}} = \bar{k}_2\frac{\bar{Z}_w + \bar{H}^0 + (\bar{\varepsilon} - \bar{q}_s)(\bar{t} - \bar{t}_1) - F_2(\bar{Z}_w)}{\bar{Z}_w + \bar{k}_2 - 1} \tag{18}$$

and the second condition (16). The procedures for the numerical solution of the problems, the first of which includes the first condition (7) and equation (10), and the second procedure includes the second condition (16) and equation (18), are identical. The approximate analytical solution has a parametric form, similar to (11) and (12). Here, the parameter is also the average value of $\bar{t}_a$, which is calculated by fitting from the equation

$$\bar{t}_a(\bar{Z}_w) = \bar{t}_1 + \frac{1}{\bar{Z}_w - 1}\int_1^{\bar{Z}_w}\int_1^{\zeta}\frac{\mu_2(\xi)(\xi + \bar{k}_2 - 1)}{\xi + \bar{H}^0 + (\bar{\varepsilon} - \bar{q}_s)\left[\bar{t}_a(\bar{Z}_w) - \bar{t}_1\right] - F_2(\xi)}d\xi. \tag{19}$$

Subsequently, the relative time for the saturation front to reach a depth of $\bar{Z}_w > 1$ is proposed to be determined by the equation

$$\bar{t} = \bar{t}_1 + \int_1^{\bar{Z}_w}\frac{\mu_2(\xi)(\xi + \bar{k}_2 - 1)}{\xi + \bar{H}^0 + (\bar{\varepsilon} - \bar{q}_s)(\bar{t}_a - \bar{t}_1) - F_2(\xi)}d\xi. \tag{20}$$

If $T_r < t_1$, then the soil is saturated according to the second scenario, and the only source of water for it is the newly formed surface layer. The gradual decrease in the H level and with it, the saturation front is described by the adjusted model (5)–(7). The changes concern ε (assumed to be 0) and the initial conditions, which are now

$$T_r = t_r, \bar{H} = \bar{H}_r = (\bar{\varepsilon} - \bar{q}_s)\bar{t}_r - F_1(\bar{Z}_{wr}) \ ; \bar{Z}_w = \bar{Z}_{wr} \ ; \tag{21}$$

where $\bar{Z}_{wr}$ is set according to (7), (10), or (11)-(13) when $\varepsilon > 0$. In this case, the simplified problem with respect to $\bar{Z}_w$ includes the equation

$$\mu_1\left(\overline{Z}_w\right)\frac{d\overline{Z}_w}{d\bar{t}} = 1 + \frac{\overline{H}_r - q_s(\bar{t} - \bar{t}_r) - F_1\left(\overline{Z}_w, \overline{Z}_{wr}\right)}{\overline{Z}_w}, \tag{22}$$

where $F_1\left(\overline{Z}_w, \overline{Z}_{wr}\right) = \int_{\overline{Z}_{wr}}^{\overline{Z}_w} \mu_1(\xi)d\xi$, and the second condition (21). The numerical solution of problems (21) and (22) are found in the standard manner. An approximate analytical and numerical solution involves the determination of parameter $\bar{t}_a$ from the equation

(23)

and secondly the time of the saturation front lowering in the absence of precipitation

(24)

Calculations of the dynamics of the infiltration water runoff at the moment of contact with the groundwater . In both considered scenarios of the infiltration process, this moment is formally established numerically or analytically based on the equation

(25)

Thus, to determine in equations (20) and (24), the upper limit of the integrals should be considered equal to .

To reliably assess the effects of the infiltration process in non-flooded soil, it is necessary to study the transient processes in the new aeration zone in detail. Such an approach to calculating the water characteristics of agricultural land under heavy precipitation is difficult for engineers because it requires the involvement and solution of a nonlinear nonstationary moisture transfer model and its specific information support. However, in practice, it is sufficient to limit integrated assessments of water resources. Such an assessment can be carried out using data on the total amount of precipitation that has entered the soil as well as on the equilibrium moisture distribution under conditions favorable for evapotranspiration. If these conditions are met, the moisture profiles covering the entire aeration zone are used: in the arable layer (0), in the lower part of the root zone and, accordingly, in the upper part of the subsurface layer (), in the lower part of the unsaturated subsoil layer below the arable, that is, the aeration zone (), then the balance equation for rainwater in the soil is

(26)

allows to establish by fitting a new (after closure of infiltration water and groundwater) position of WT. Note that equation (26) does not consider the differences between the water retention curves formed after prolonged drainage and soil wetting. At the same time, such a consideration is not labor-intensive if relevant information is available. Because the profiles adapted to the mark, it is possible to form a general view of the moisture reserves in the aeration and root zones, as well as their availability to crops.

CALCULATION OF EXAMPLES AND DISCUSSION OF RESULTS (UNDEFORMED SOIL)

Quantitative analysis was performed on numerous examples to illustrate the results of the mathematical modeling of soil wetting and the formation of an unfiltered water layer on its surface. The subject of the calculations was, first, the infiltration process in the first stage, when it was initiated by rainwater from the surface layer (the second stage with the formation of a drainage front, as well as the final stage of infiltration before soil flooding, were not analyzed owing to the limited volume of the chapter); second, the process of rainwater accumulation on the soil surface. In both cases, their main relative water-physical characteristics were calculated, namely the depths and as functions of time and . The sources of initial information were, first of all, data from experimental studies at the research sites of the Institute of Water Problems and Land Reclamation NAAS of Ukraine (Voropai H. et al, 2023), as well as data on soil properties and water balance items generalized on a global and regional scale. For greater generalization, only dimensionless characteristics were determined while changing the relative arguments within a wide range. Attention was paid to the saturation of the arable layer, which did not reduce the value of the results. Indeed, and were determined when the soil was saturated below the arable layer at a given depth. In addition, different (in the adopted classification for horizon A, extreme, and one intermediate) variants of the particle size distribution of the arable layer were considered (FAO-UNESCO, 1974; FAO, 2006).

In the preparatory stage, significant difficulties arose when choosing expressions for the function of the saturation lack of the arable layer . In practice, its considerable variability is due to various factors involved in the formation of the water conditions of agricultural land, such as the depth of groundwater, evaporation, and the water demand of soil biota. Considering the alternately variable direction of water-physical processes, especially on reclaimed lands, the stochasticity of changes in the characteristics being calculated, and their large amplitude, the equilibrium state was chosen for the soils under consideration as a representative state. Indeed, this water-physical state of the soil is central to the virtually unlimited set of states realized in practice. Therefore, to estimate soil water resources in such a situation, it is justified to use water retention curves or, in other words, basic hydrophysical characteristics (BHC) (Globus A.M., 1987, 2001). If the BHC is represented in the general form , then the desired saturation deficiency is initially defined as , where is selected depending on the wetting conditions. In this case, is the relative current difference . The relationship between and was established based on the equilibrium suction pressure profile . A similar procedure, which was used in relation to the data on the BHC of the arable layer for the experimental site «Yarynche» (drained lands of the «Melnytska» and «Bobrovka» reclamation systems, Volyn region), allowed us to represent as the following linear function (corresponds to =1.2 m)

(27)

For the second series of examples, expressions for were used, which were derived from generalized data on the BHC for the upper horizon (A) of layered soil structures (FAO-UNESCO, 1974; FAO, 2006). Specifically, these data correspond to the generally accepted approximation expression (Van Genuchten, 1980)

(28)

where is the residual moisture, the values of which, together with the values of the hydraulic conductivity , are summarized in Table 1.

Table 1. Values of water-physical constants for horizon A (HYPRES database)

Particle size distribution of soil					cm/day
Coarse dispersed	0.403	0.025	0.0383	1.377	60.0
Medium dispersed	0.439	0.01	0.0314	1.18	12.0
Finely dispersed	0.502	0.01	0.0367	1.101	24.8

Thus, the equation for corresponding to (28) is (29)

First, we analyzed the suitability of the two approximate analytical solutions presented in this chapter for engineering calculations. In this case, possible errors were evaluated for the example of the arable layer of the «Yarynche» experimental site, where is according to (33), and at , which corresponds to =3.47 mm/min taking into account 0.6 m/day. The corresponding graphs of the saturation front lowering within the specified layer (=0.12) and the entire homogeneous aeration zone (), calculated numerically and using equations (11)–(13), are shown in Figure 1. The deviation of the approximate values of (II solution) from the reference values (numerical calculation) was on average 0.4% at time and increased to 7.0% at time for the groundwater and infiltration water closure. When using the first analytical solution, the similar error was 17.3%.

The series of calculations for the above-mentioned «Yarynche» site was continued to determine the response of the main water-physical characteristics to a hypothetical increase in effective precipitation = 1 (0.417 mm/min) to = 5. (Figure 2) and (Figure 3) were determined at three fixed points in time corresponding to the initial, intermediate, and final stages of saturation of the arable layer. In parallel with the numerical calculations, the equations (12) and (13) were also used to further assess the accuracy of the second analytical solution. The error increases with a decrease in to a maximum of 5.9% at =1. The depths of the soil saturation zone and surface water naturally increased over time, reaching situational maxima at = 5 and = 0.2 and amounted to 1.873 and 0.713 or 56.2 and 21.4 cm, respectively. If the moistened soil is two-layered, the calculation period in the first stage should be limited to time . Curve 1 in Figure 2 has practical meaning in the case of homogeneous soil with the hydraulic conductivity = 0.6 m/day or, in extreme cases, when > 0.526 m. Otherwise, in the range 1 to has to be calculated using the same methodology, but involving . The unphysical values of at lower values of are explained by the imperfection of the mathematical model, which does not reflect the influence of the capillary forces in the unsaturated zone on the saturation front. However, the errors in the calculations caused by this simplification approach zero with the development of the infiltration process and an increase in . The methods of model correction are discussed in a monograph (Poliakov V.L., 2014).

Figure 1. Dependence (arable layer): 1 - approximate solution I; 2 - numerical (reference); 3 - approximate II

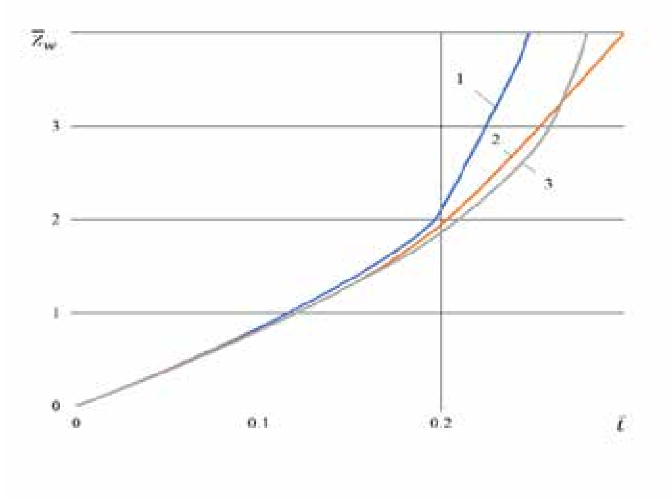


Figure 2. Dependence : 1 - = 0.2; 2, 3 - = 0.1; 4 - = 0.05; 1, 2, 4 - numerical (reference);3 - analytical (12), (13)

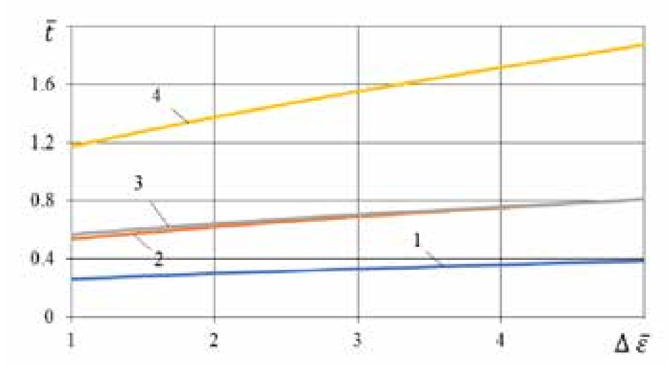
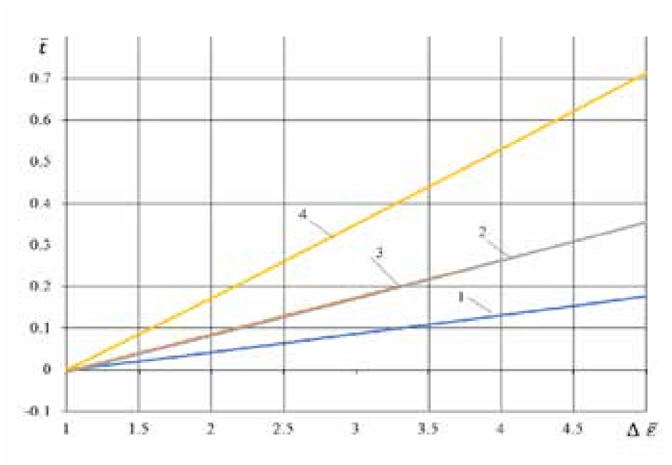


Figure 3. Dependence : 1 - = 0.2; 2, 3 - = 0.1; 4 - = 0.05; 1, 3, 4 - numerical; 2 - analytical



In the second series of examples, similar calculations were performed for the three types of soils of horizon A, as described above. Significant differences in the grain-size distribution of the selected soils (arable layer) naturally led to significant differences in their hydrophysics and hydraulic conductivities. Initially, we calculated the movement of the saturation front in the arable layer and the rise of the water level on its surface at a single value of (5) and according to (29). The data on and obtained using the numerical methods are presented in Figures 4 and 5. In addition, the dependences of and were determined for Soil 3 in parallel using the second analytical solution. A comparison of the reference and approximate graphs indicated the high accuracy of this analytical solution, regardless of the water-physical properties of the soil. The faster movement of the relative mark of the saturation front in the case of low-permeability Soil 3 is due to the procedure of de-dimensioning the initial model. For the same reason, the graphs in Figure 5 for different soils were placed close to each other. They will differ significantly if we present an increase in the dimensional depth in real-time.

Figure 4. Decrease in the saturation front in the arable layer over time: 1 - analytical; 2-4 - numerical; 1, 2 - soil 3; 3 - soil 2; 4 - soil 1

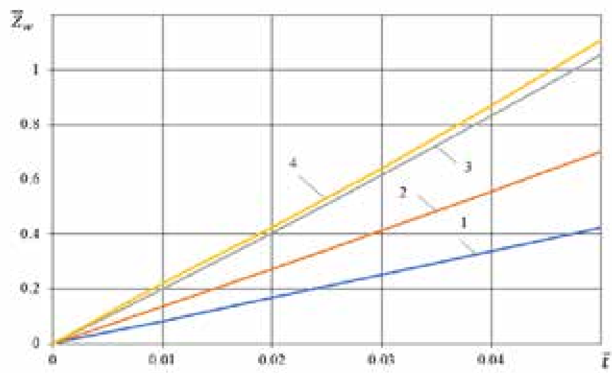
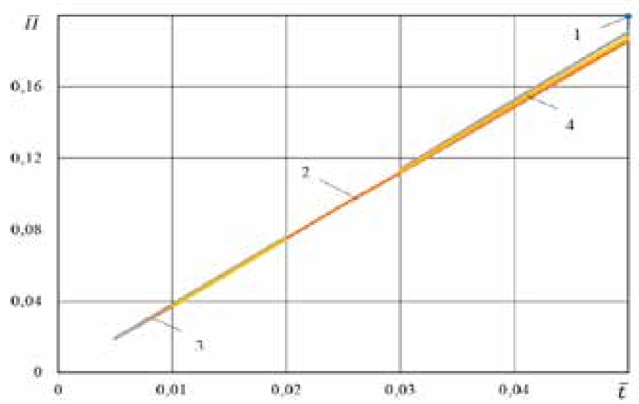
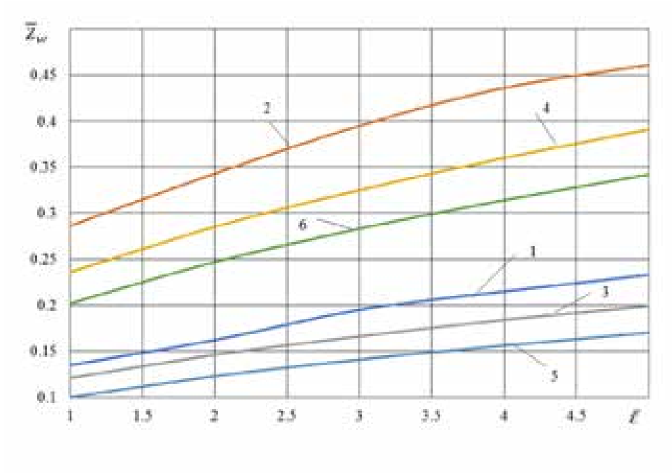


Figure 5. Water level rise on the soil surface: 1, 3, 4 - numerical; 2 - analytical; 1 - soil 1; 2, 3 - soil 3; 4 - soil 2



However, to compare the infiltration processes in soils with significantly different water-physical properties, it is necessary to partially return to dimensional variables and parameters. To establish the specific dependencies of on , two representative time points (15 and 30 min) and a base value of = 1 mm⁄day = 0.417 mm/min were chosen. Because the mathematical model and calculation equations use only dimensionless quantities and and serve as scales, and had to be recalculated at each calculation step. For example, the reference values of were 2.085 and 4.17×10^{-2} for Soil 1, and continuously varied 2.398 to 11.99. Similar conversion calculations were performed for Soil 2 and 3. The final results for (is invariant) are shown in Figure 6. It is logical that because of the accelerated movement of the saturation front, the more permeable arable layer is saturated faster, and as a result, the accumulation of water on the soil surface slows down accordingly.

Figure 6. Dependence : 1-3 - = 30 min; 4-6 - = 15 min; 1, 4 - soil 1; 2, 5 - soil 2; 3, 6 - soil 3



WETTING OF DEFORMED SOIL. THEORETICAL ASPECTS

While soils are easily deformed by mechanical impact and are capable of firmly fixing water, heavy rain often causes the formation of a weakly permeable surface interlayer with a thickness of and a hydraulic conductivity . This often turns out in situations where the velocity of water filtered through it is less than and is often significantly lower. Consequently, the arable layer must be wetted for some time owing to its incomplete saturation. This affects the modeling of soil wetting by precipitation in two ways. First, if we neglect the usually insignificant influence of capillary forces on the infiltration in the interlayer from the undeformed arable layer, the initial mathematical model will be formed by the equations of groundwater flow in the interlayer and the water balance on the soil surface.

(30)

(31)

and the nonuniform initial condition generalizing (7)

(32)

and the boundary conditions

(33)

Here, is the piezometric head in the interlayer, is the seepage velocity, and is the correction owing to the suction of water by the capillary forces from the interlayer into the undeformed unsaturated soil.

It should be noted that the water level was due to the accumulation of part of the precipitation on the day surface during the saturation of the interlayer. Considering the small value of , this level should be significantly lower than the current values during the calculation period. Nevertheless, is formally considered but is not further specified.

The solution to the problem in (30) and (33) is as follows:

(34)

The degree of soil deformation under the influence of intense rain should decrease rapidly with depth, and hydraulic conductivity should increase accordingly. However, obtaining information on the distribution of over the interlayer height is extremely problematic. Therefore, we must use the effective (constant) coefficient in our theoretical studies. In this case, (34) is simplified as

(35)

The rate of infiltration increased over time according to the following equation:

(36)

Because of the relatively low permeability of the interlayer (), the soil is only soaked for a long time, so that the moisture content near its surface increases but does not reach the total moisture capacity. At the first and often only stage of wetting, the influence of soil hydrophysical properties on its rate is insignificant and is reflected in the original problem through the relatively small parameter . As the surface water level rises, the rate increases according to (36) (), and with prolonged intense precipitation, time may occur when it equals . From this point onward, the infiltration process begins with the formation of a saturation front that limits the expanding saturation zone (Poliakov V.L., 2008, 2014). The level reaches the mark at specified moment and

(37)

To determine the time , you need to know .

The solution to the problem (28), (29) is given in two convenient forms for calculations, namely

(38)

(39)

As water accumulated on the soil surface, the seepage velocity at the outlet of the interlayer and, accordingly, the moisture at the upper boundary of the undeformed arable layer increased. With prolonged precipitation, the level of can rise to a point at which the seepage velocity is equal to and the moisture reaches a maximum value of . The corresponding relative time is calculated using the following equation:(40)

From this point onward, the soil is already fully saturated, and the saturation front begins to move down the arable layer.

An important practical implication of the solution described above is the establishment of the total volume of water that has entered the soil from the surface of a unit area during the precipitation period , replenishing the reserves of productive moisture , as well as the volume initially lost to crops due to surface runoff into natural catchments. However, such losses may be temporary if surface runoff can be at least partially accumulated and used for irrigation purposes during the dry season. In general, the value of is determined as follows:

(41)

Equation (41) was transformed by considering

In the considered special case, the integral in (41) is calculated and then

(42)

where is determined based on (39) at .

CALCULATION OF EXAMPLES AND DISCUSSION OF RESULTS (DEFORMED SOIL)

The methodology developed in this section for calculating the wetting of surface-deformed soil as a result of storm rainfall is illustrated using a number of test examples. Particular attention was paid to the role of the newly formed interlayer in the distribution between subsurface and surface runoff. Therefore, the subject of the quantitative analysis was mainly the ratio, which characterizes the proportion of precipitation to groundwater recharge. This relative value was determined in the dynamics and depended on the relative seepage parameters of the interlayer and the rain intensity. In several examples, a rise in the water level on the soil surface has been observed. Given the considerable difficulties in obtaining reliable detailed information on surface runoff, the area with the soil in question was considered flat, so that $q_s = 0$. Finally, the influence of capillary forces on the inflow of moisture into the unsaturated soil was assumed to be insignificant (= 0). The calculations of the relative variables , in time were strictly limited to a maximum relative value of 0.07, which, with = 1m/day, = 0.3 m, corresponds to a real time of 30 min. Simultaneously, an additional restriction was imposed on them because the deformed soil wetting was analyzed only with its incomplete saturation. Therefore, the calculations were interrupted in most cases when the level reached the value .

It should be noted that the developed methodology allows us to accurately assess the effect of surface deformations on the development of the seepage process (in a broad sense) at the first stage formally and adequately, given reliable initial information. This stage is characterized by soil wetting owing to the low permeability of the swelling compacted layer and, as a result, the inflow of water from the outside. In the second stage, the soil was intensively moistened because of the retention of a large volume of water on its surface. From a physical point of view, the fundamental difference between infiltration and percolation is the significant impact of soil seepage properties on soil wetting, which occurs only in the first case. Theoretical studies on infiltration in the second stage will continue this work logically.

On flat terrain, the water retained due to the low permeability of the interlayer gradually and completely (except for the evaporated water) enters the soil after the rain stops. The time for the surface water to fully enter the soil depends significantly on the parameters of the interlayer , and the corresponding maximum water level that is reached at time . Various situations are possible here, which deserve separate consideration. For example, with prolonged heavy precipitation and significant initial soil moisture, it is possible that the soil may be flooded. If there was infiltration at the end of the rain, then as level decreased, there would be a time , when it was replaced by percolation.

First, the current values of were determined sequentially using equation (39) and using the equation derived from (36),

(43)

where , for four examples with typical initial data. In the first example, = 3, = 0.05, = 0.005. In the other examples, these parameters were changed alternately, namely, = 0.001 (Example 2), = 6 (Example 3), = 0.01 (Example 4). The rain continued with a corresponding constant intensity until the above-mentioned moment (0.07). The data obtained in this manner for are presented in Figure 7, and for - in Figure 8. The final values of the transient time in the set of current calculations were determined based on the values of according to (19) using (20) and differed significantly in the examples. The maximum values of the ratio was equal to (0.3333 and 0.1667, respectively). Naturally, soil wetting with incomplete saturation was replaced by infiltration much faster, with a five-fold decrease in interlayer thickness (Example 2). The corresponding value of was an order of magnitude less than the duration of the rain and corresponded to a small value of (0.019), which was approximately equal to 5.7 mm. Under such conditions, the pore space within the zone limited by the saturation front from below will be completely filled with water (excluding the small part with trapped air) for almost the entire duration of rain.

The saturation zone expands over time, and the speed of movement of this front depends on the initial moisture content of the unsaturated zone, its permeability, and the depth of the water on the surface. A detailed calculation in the presence of a swelling interlayer in the infiltration process, which changes the percolation, should be carried out in the future. The percolation process lasts significantly longer when the intensity of precipitation is doubled (Example 3). In this case, full saturation of the soil at the boundary with the interlayer was observed after 0.017 at the level of = 0.095 (approximately 2.85 cm). In the baseline case, the second stage began long before the rain stopped, and the depth of the retained water increased five times compared to Case 2 by time . The greatest impact on the dynamics of both characteristics was caused by a similar deterioration in the permeability of the interlayer. In this case, the increase in the hydraulic resistance of the interlayer and the resulting slow percolation of water into the undeformed soil caused a relatively low rate of moisture transfer (infiltration into the interlayer) at the end of the rain (= 0.4). Obviously, further water absorption, which deserves separate consideration, will also take place for a long time and with partial filling of the pores. Figures 7 and 8 provide an initial understanding of the possible effects of surface deformation on the water exchange between drained lands and the atmosphere.

Figure 7. Rise of the relative water level on the soil surface over time: 1 - example 3; 2 - example 4; 3 - example 1; 4 - example 2

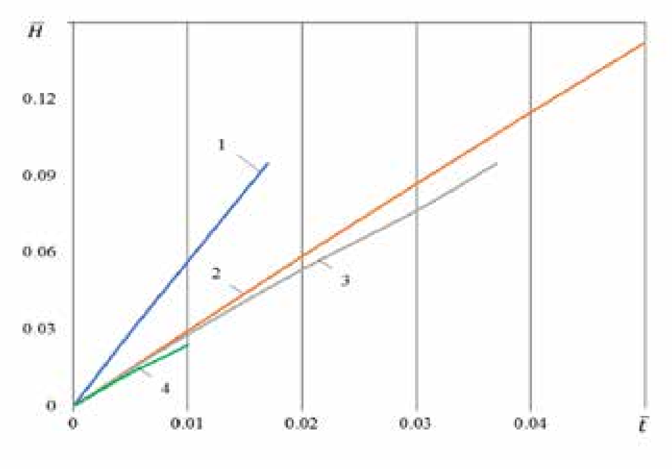
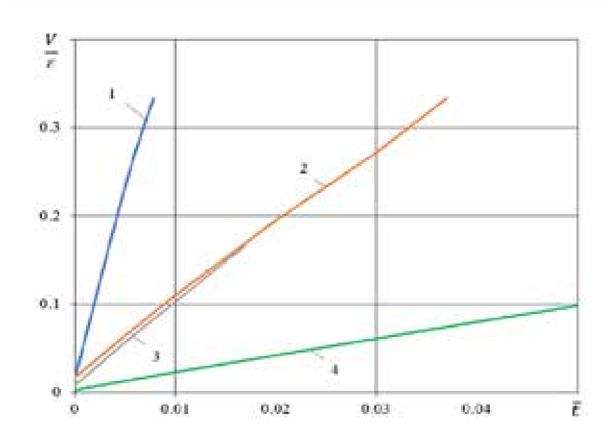


Figure 8. Increase in the fraction of subsurface runoff over time: 1 - example 2; 2 - example 1; 3 - example 3; 4 - example 4



The clearer idea of the importance of the interlayer for the atmospheric feeding of flat agricultural land during heavy precipitation can be obtained by calculating the ratio as a function of special arguments. In the second set of examples, the relative parameters of the interlayer () and precipitation () varied continuously or discretely and within a wide range. The calculations were performed at a strictly defined time point (0.07) until rain continued with a constant intensity . The arrays of data obtained according to (43) are shown graphically. Thus, Figure 9, first of all, illustrates the behavior of the desired ratio depending on , as an argument, as well as , for which three characteristic values were taken. The value of was fixed (3) so that the calculation of in this case was carried out up to the maximum value of 0.3333 allowed by the developed methodology. This corresponds to three different (depending on) values of . These characteristic values of separate the two intervals by argument. If , then the soil is wetted with incomplete saturation at the selected time; if , then the wetting will be fully saturated, and the new methodology cannot be used yet. In general, it is natural that the portion of precipitation directly spent on soil wetting increases with the increasing permeability of the interlayer and reducing its thickness. Simultaneously, as increased, the wetting characteristics changed at proportionally higher values of . In addition, Figure 9 shows a curve that describes the dependence of height on and corresponds to all three values of .

Figure 9. Dependencies : 1 – ; 2-4 – ; 2 – ; 3 – ; 4 –

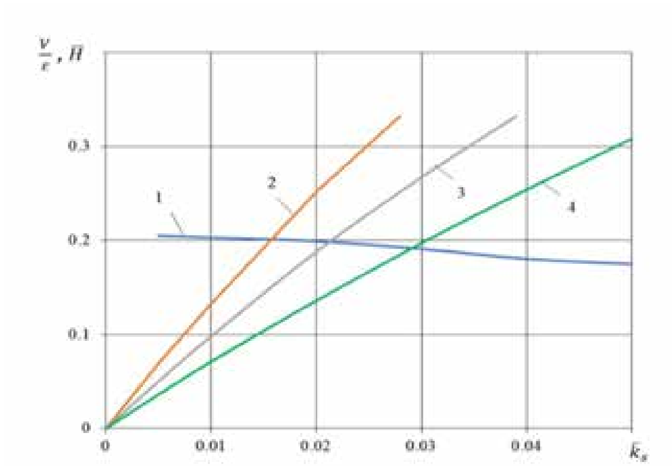
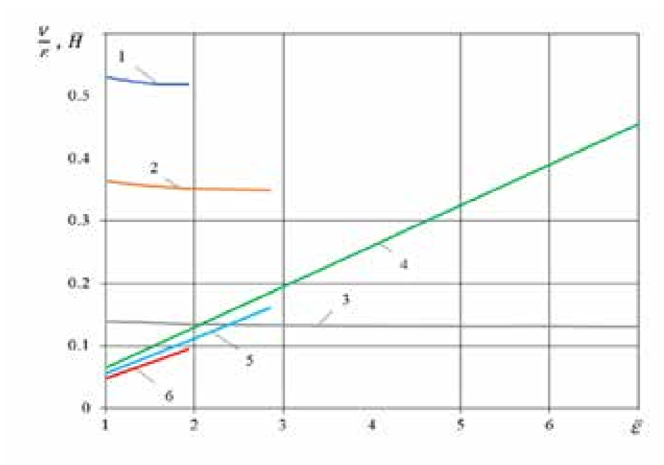


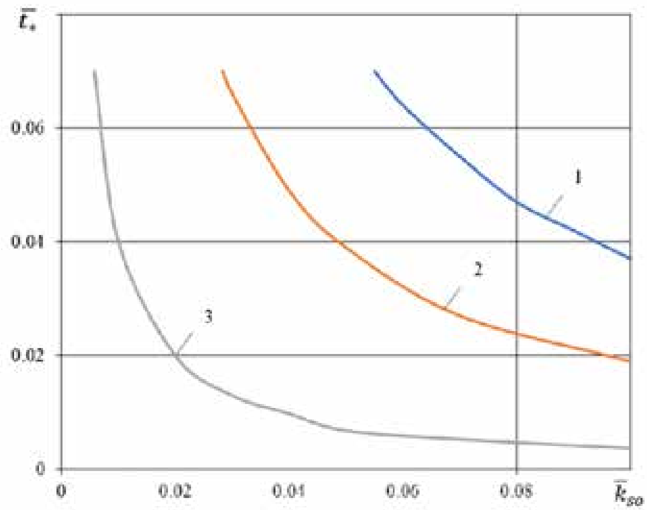
Figure 10 is also indicative. It presents the data on and, simultaneously, on at = 0.005 and the permissible change in precipitation intensity from moderate to extremely high values (approximately 0.7 to 5.0 mm/min). The graphs of and versus differ for a fixed value of . It should be noted that the increase in the volume of water retained as a result of strong surface deformation of the soil () was similar to the increase in . In this case, a prolonged heavy rain can lead to severe environmental consequences owing to the formation of a surface water layer of considerable height. Obviously, such situations, given their exceptionality, are interesting only from a methodological perspective. The stability of the ratio as a function of only means that increases synchronously with . Here, by analogy with , it is advisable to distinguish a characteristic value of , which depends on and divides the range of possible values of into two intervals. In the case of , the above methodology is justified to be used only up to a time point of 0.07 when and longer () when . If , then the corresponding value of is less than 0.07 and the infiltration process begins before the end of rain.

Figure 10. Dependencies : 1-3 – ; 2-4 –



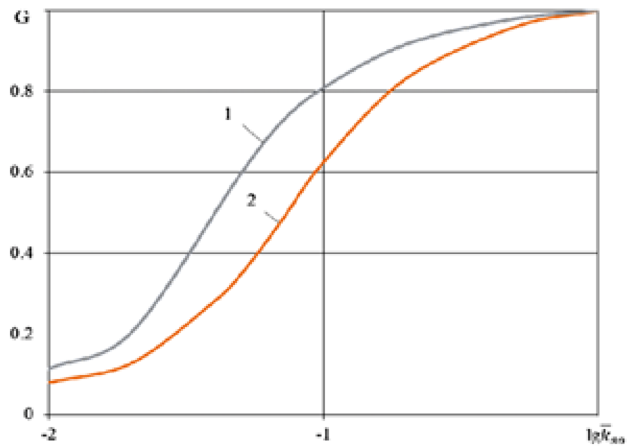
In the following series of examples, attention was focused on the relative transient time , as it strictly limits the time (– by level) and area of correct application of the calculation methodology for soil wetting. The calculation curves in Figure 11 are limited by the value of = 0.07. This is the duration of the precipitation. Therefore, these curves reflect a variety of time values at which soil soaking was replaced by infiltration before the end of rainfall. In such cases, the methodology developed above for calculating the wetting of surface-deformed soil is correct only up to the moment . In addition, when the new technique is used to calculate infiltration from the surface layer of water through a low-permeability interlayer, it will be possible to analyze its natural wetting in the first and second stages consistently over the entire possible range of water-physical states, from the overdried to flooded state. The time was determined based on . The value (3) was previously fixed, and the largest and smallest values of differed by an order of magnitude. In general, the time of transition from partial saturation of the arable layer with rainwater to full saturation demonstrates a high sensitivity to key model parameters. Indeed, an increase in , , and a decrease in by an order of magnitude resulted in approximately the same reduction in .

Figure 11. Dependence : 1 – ; 2 – ; 3 –



In accordance with the main goal of this study, Figure 12 can be considered as a summarized figure. It shows curves on a semilogarithmic scale that reflect the reduction in the maximum volume of rainwater by the time precipitation ends () due to its delay on the soil surface caused by the low-permeability interlayer. The subject of the calculations was the lack of atmospheric soil feeding , namely, the ratio of to its potential value , which characterizes the feeding in the absence of surface deformations.

Figure 12 Dependence : 1 – ; 2 –



The desired value was considered as a function of the relative coefficient , which varied by two orders of magnitude. The value of was assumed to be three, which is not important for the estimations being conducted. Two characteristic values of were selected. In the case of flat terrain, surface deformations only slow down the flow of water into the soil, but over time, the water temporarily accumulated on the soil surface replenishes the groundwater reserves. The situation can change dramatically if a territory has a noticeable slope. In this case, it is likely that a significant portion of the retained precipitation flows down the slope to lower areas. As a result, the elevated areas will absorb a minimal amount, whereas the lower areas will be waterlogged or even flooded. In such cases, special measures should be taken to locally drain the area. If there are natural reservoirs, part of the precipitation will be irretrievably lost. Therefore, when regulating the water conditions in agricultural land with a slope, it is crucial to establish the proportion of precipitation spent on surface runoff. The value of) can be taken as the base value () for comparison in the absence of surface deformation. For a given , , the value of is approximately 0.14. Obviously, the accumulation of water on the surface will increase infiltration, and the saturation front lowering, in contrast, will decrease infiltration. These factors partially compensate for each other, justifying the choice of this value for .

THE DIRECTION OF FUTURE RESEARCH

In future research endeavors, there is a plan to delve deeper into theoretical studies that will account for the two-dimensional nature of changes in hydrological characteristics, considering both longitudinal and vertical directions as well as the variable nature of surface runoff rates. This approach aims to provide a more accurate determination of the proportion of precipitation contributing to subsurface and surface runoff.

Furthermore, future studies should address the differences between the water retention curves formed after prolonged soil drainage and wetting. Strict expressions for these moisture distribution functions will be presented in a subsequent article, focusing on optimizing the soil water conditions in humid zones.

This study primarily focused on the infiltration process, particularly in the presence of a swelling compacted interlayer, during the initial stage initiated by rainwater from the surface water layer. Future research will entail detailed calculations of the subsequent stages, including the formation of a drainage front and the final stage of infiltration before soil flooding.

Moreover, the methodology developed for calculating the wetting of surface-deformed soil will be expanded to include the calculation of infiltration from the surface layer of water through a low-permeability interlayer in the subsequent stages. This expansion will enable the analysis of natural wetting across the entire spectrum of water-physical states.

CONCLUSIONS

1. A comprehensive theoretical analysis was conducted on the infiltration process initiated by storm precipitation, particularly on sloping terrain, where significant volumes of rainwater accumulate as a surface water layer, resulting in stable surface runoff.
2. This research employed analytical and numerical methods based on mathematical models describing the dynamics of precipitation, distinguishing between their effective parts (excluding surface runoff) in both undeformed and surface-deformed soils; the latter involves the formation of a low-permeability interlayer.
3. The numerical solution was augmented using approximate analytical solutions, which are more suitable for engineering applications, obtained by averaging the dependent or independent variables. Both analytical solutions demonstrated sufficient accuracy in calculating arable layer saturation, with one particularly accurate when calculated in full until the infiltration water reached the groundwater.

4. Through numerous calculations, patterns of effective precipitation distribution between the soil and the surface water layer were identified, supported by real (experimental site) and generalized (HYPRES database) data on soil hydrophysics and meteorological factors. The lack of saturation in the absence of actual moisture profiles is proposed to be formalized based on water retention curves (BHC), with corresponding recommended expressions.
5. This study investigated the influence of the thickness and permeability of layers formed due to soil compaction and flooding on surface dynamics during intense precipitation, illustrating the likelihood of significant redistribution of effective precipitation towards the accumulating component using an experimental site as an example.
6. A generalized approach was proposed to establish a new stable water-physical state of the soil, including the stable position of the water table and equilibrium moisture distribution in the aeration zone, following the conclusion of prolonged heavy rain.
7. Although the mathematical framework used in this study ensures the reliability of both numerical and analytical calculations, it is acknowledged that the calculated scenario may not fully reflect reality, primarily because of the simplified consideration of surface runoff as a stable component of precipitation. Therefore, future theoretical research plans should account for its initial uncertainty and variable nature based on the amount of accumulated rainwater on the soil surface and terrain slope.

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Chapter 6
Influence of Soil Tillage Methods on the Protective Role of Vegetation Cover

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ABSTRACT

This chapter presents opportunities to use vegetative plants or their residues on the soil surface as a primary main indicator that restrains the development of erosion processes. Technological measures of soil cultivation that create different levels of erosion control efficiency presented, directly affecting the presence of post-harvest residues on the surface and indirectly the conditions of growth and development of crops in the conditions of unstable and insufficient moistening of Left Bank Forest

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Steppe, which is especially pronounced in the spring period. The methods and types of soil cultivation to strengthen this indicator by preserving the post-harvest residues of the previous crop for a certain period of time are considered. The compensating ways for an inevitable weakening of plant development and a decrease in their yield against the background of minimal tillage are presented to solve a problem of the same values of erosion resistance in agrocenosis with different tillage options during the growing season of crops in the rotation.

BACKGROUND

The main task facing modern land users is to preserve soil cover properties used or affected by agricultural production (Kopittke P. M. et al., 2019; Kuzmych et al., 2022, 2023; Yakymchuk et al., 2022). In general, such a direction is called sustained or sustainable agriculture (CTIC, 1998; Smart Farming…, 2019). The preservation of soil cover is the main security challenge for civilization. It is estimated that agricultural activities on land provide 99.7% of the human food supply on a global scale (Pimentel D., 2006).

The concept of sustainable agriculture is aimed at preserving soil fertility. Among the factors that negatively affect fertility in a number of regions of the world, the leading role belongs to water erosion. So, in particular, in Ukraine, up to 40% of arable land (13 million ha) needs additional protection from it (Kutsenko M. V., Timchenko D. O., 2016). To mitigate the impact of this factor, a number of measures are being taken, including both amelioration and agrotechnical components. Of course, a complete list of such measures is used in basic models of erosion processes, such as USLE (Wischmeier W. H., Smith D. D., 1978). Their values at the local territorial level (field - a group of fields) can be regulated by the land users themselves - the length of the slopes, agrotechnical factors that determine the roughness of the soil surface and its vegetation cover (Castrignano A. et al., 2020).

Adequate assessment of the values of such factors is the correctness basis of the mathematical modeling results, which in turn is the basis for making management decisions in modern agriculture. Such solutions include both the management of the configuration of the working plots and, most importantly, in the management of the structure of the sown areas and agrotechnical measures. This changes both the nutrient regime of soils (Haruna S. I., Nkongolo N. V., 2020) and their ability to resist the effects of water flows and raindrops (Malézieux E. et all., 2009; Wallander S. et al., 2021).

In recent years, the problem of conducting a more accurate and more targeted system of anti-erosion measures has been determined both by the requirements of precision farming technologies and by the action of the global climate change process. The most accessible for carrying out such measures are agrotechnical, which include the protective effect of two subfactors: plant residues on the soil surface and cultivated vegetation. Such an impact, which is estimated using tabular data, also puts forward requirements for the accuracy of its determination. The introduction of new technologies in agriculture creates new combinations of the influence of each of the subfactors in space and time. This requires conducting regional studies to clarify them.

According to Czech researchers, the distribution of the R factor value varies with a minimum in April and October and a maximum in June (Janeček M. et al., 2012). Optimum use of vegetation cover positively involves such properties of the soil as its structure, soil erosion resistance, humidity, moisture capacity and saturation of surface runoff (Choden T., Ghaley B. B., 2021). That is why it is considered that an effective management system of plant residues should be implemented both for erosion-prone lands and in areas affected by drought (Smil V., 1999). Often, overestimation of the value of C-factor leads to significant changes in potential soil losses, especially in ultra-detailed modeling of erosion processes (Prasuhn V. et al., 2013). Climate changes cause changes in the time ranges of C factor values, often narrowing them (Auerswald K. et al., 2021). Such changes caused not only the redistribution of erosively dangerous precipitation during the year, but also extended the terms of application of anti-erosion measures, including the protective role of vegetation (Auerswald K., Menzel A., 2021).

Protection of the soil surface from the action of heavy rainfall is one of the main goals of creating a management system for plant residues and vegetation cover (Basic F., 2004). This system is two-component - the calculations involve the residues accumulated during the past seasons and the potential vegetation coverage of vegetative plants. Sometimes postharvest crops are included in the calculations (Gholami L. et al., 2013). In addition, crop residues are intended to play an indirect role in reducing soil losses, positively influencing the formation of its anti-erosion properties (Valenzuela H., 2020). Thus, infiltration increases significantly when the surface is covered with mulch, especially during high-intensity rainfall (Huffman R. L. et al., 2013). It is believed that the layer of mulch significantly reduces evaporation, the level of which increases under the influence of global climate change (Eekhout J. P. C. et al., 2018).

In Ukraine, values averaged across calendar months are used to calculate the protective effect of vegetation cover (Morgun F. T. et al., 1988). These values correspond to the values of factor C of the USLE model and its modifications. The calculation of the values of the agrotechnical factor P were provided for in the already canceled standard GOST 17.4.4.03:1986 (Okhrana prirody, 1986). It should be noted that the set of values given here is quite limited. More general works covering the entire post-Soviet territory are known (Zharkova Y. G., 1987). In addition, as a result of global climate changes, the introduction of a number of new agricultural technologies is noted, the impact of which on the value of the mentioned factors is not foreseen by the existing regulatory documents. Thus, the sowing dates of spring grain crops and corn in some regions have shifted by 1-3 weeks, which requires certain adjustments (Olesen J. E. et al., 2012). That is why specialized scientific institutions of the state conduct research taking into account the influence of modern technologies on the value of agrotechnical factors (Ulko Ye. M., 2021). Similar problems arise when using the C factor for the evaluation of the remote sensing results for vegetation. One of the ways to overcome the problem is the need to conduct research on a regional scale (Alexandridis T. K. et al., 2013).

The purpose of such works is to characterize the influence of certain technologies on the anti-erosion properties of the projective vegetation cover of land sites on the example of experimental fields in the Left Bank forest-steppe of Ukraine. In this case the impact of different types of main tillage on the characteristics of the protective effect of mulch and vegetation should be analyzed. Their total protective effect during the year have to be calculated.

Calculating the anti-erosion properties of plants and agrotechnical measures is carried out within the framework of the regulation of mathematical erosion models. Both average annual values and those associated with certain periods of the agricultural season are used. Obviously, such values should be maximally adequate to the real state. The need for research in this direction is also related to the uneven distribution of rainfall intensity depending on the season.

The purpose of research is the characterization of the influence of certain technological operations on the anti-erosion properties of the vegetation cover of land sites on the example of experimental fields in the Left Bank forest-steppe of Ukraine.

SOIL TILLAGE METHODS AND PROTECTIVE ROLE OF VEGETATION COVER

In order to achieve this goal and considering the rather large number of methods for calculation of the soil protective vegetation efficiency, we selected the method included in the Universal Soil Loss Equation (USLE):

Mathematic structure of USLE method can be written as follows:

$$A = RKLSCP,$$

where A – soil erosion rates (ton/ha yr.),

R – rainfall and/or runoff erosivity factor (mm/ha h yr.),

K – soil erodibility factor (t ha h/ha mm),
LS – topographic factor combined of slope length and slope gradient-slope steepness,
C – cropping management factor,
P – soil conservation practices factor (Wischmeier W. H., Smith D. D., 1978).

According to this guide to conservation planning, we consider the factor of anti-erosion effect of vegetation cover (sub-factor of factor C) as a combination of the protective effect of actually growing cultivated crops and plant residues of past harvests located on the surface of the soil. The use of C-factor indicates how the conservation schemes will affect the average annual soil erosion loss and how that soil-loss potential can be transformed in time during agrotechnical activities, crops vegetation cover or other management technics.

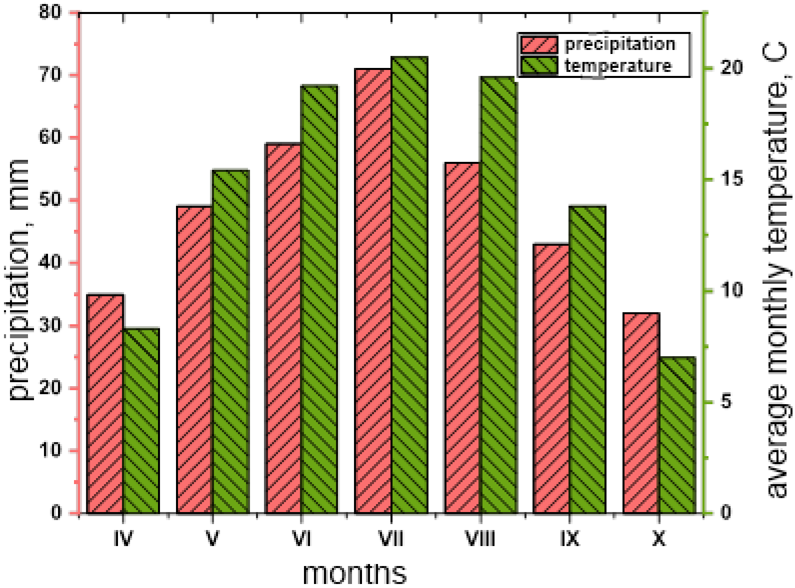
The calculations were based on the USLE methodology, which involves the use of nomograms. Projective cover means the value of the indicator of the relative area of the crops projection or their remains on the surface of the soil. Projective coverage was determined using the photographic grid method (Laflen J. M. et al., 1978).

The value of projective soil cover with post-harvest residues was determined by the method of intersecting lines (Shelton D. P., 1998). The protective effect of vegetation is best manifested when the majority of the biomass is in the 0-100 cm layer. It decreases with higher plant heights (Khan M. J. et al., 1988).

There have been attempts to estimate the degree of projective cover of mulch based on its quantitative data (Yan Xin et al., 2023). For example, American researchers believe that when the value of 4.5 tons of straw per 1 ha is reached, the protective effect of mulch becomes maximal (Khan M. J. et al., 1988). It should also be noted that exact values of the influence of the C factor are necessary when calibrating erosion models (Jetten V. et al., 2003).The research sites are located in the Left Bank Forest-Steppe zone of Ukraine (1 – 49.9000 N, 36.4572 E and 2 – 49.6744 N, 32.7465 E). The sites are located on the flat part of the watershed plateau, the steepness of the slope does not exceed 1%. The first section is the main one, multi-year field experiments are laid here, the second section is a production experiment of the first year of the rotation. On the territory of site 1, a 5-field crop rotation with such crops has been introduced: 1 –fallow; 2 – winter cereals (wheat); 3 – corn for grain; 4 – winter cereals (rye); 5 - sunflower.

Soil cover is typical chernozem. The thickness of the humus layer is about 80 cm. The content of organic carbon in the processed layer is up to 3%. The territory has been cultivated for more than 100 years. The climatic characteristics of the warm period of the year, as the most erosion-prone, for the territory of site 1 is presented in Figure 1 (average for 8 years).

Figure 1. Values of average temperature and monthly rate of precipitation on experimental site 1

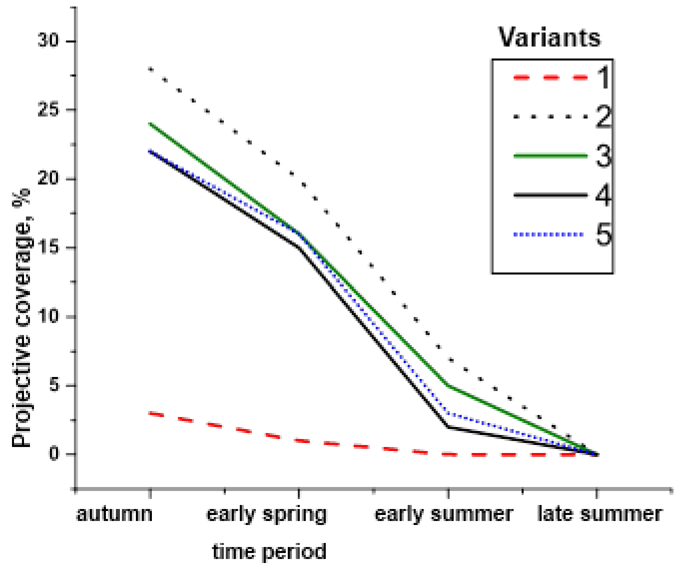


The research area is characterized by significant values of the monthly rate of precipitation, especially in the period of May - September, when it often falls in the form of heavy rains, especially in the first part of it. This fact necessitates the implementation of erosion control measures during this time period. In the same period, the greatest damage from the influence of strong winds is also noted.

The peculiarities of the climatic conditions of the research area determine the obtaining of one harvest per year. Sometimes stubble or post-cut sowing is used. The main (deep) cultivation of the soil is carried out mainly in the autumn period. Soil cultivation is carried out in the period from the third decade of March to the second decade of November. It is believed that the main factors affecting the parameters and configuration of the surface layer of crop residues are agrotechnical tillage (Bechmann M. E., Boe F., 2021). We evaluated this parameter using the example of site 1.

The nomenclature of soil cultivation methods included: 1 –moldboard plowing at 20-27 cm; 2 – deep local loosening with a chisel plow PM-2.5 at 33-35 cm; 3 - moldboardless tillage with PRN 31000 at 33-35 cm; 4 – disc tillage with DMT-4A at 10-12 cm; 5 –entire tillage with PCh-2.5 at 20-27 cm. Figure 2 shows the results of determining the degree of vegetation coverage during the growing season when carrying out the indicated methods of soil cultivation. In addition, early spring harrowing and pre-sowing cultivation (8-10 cm depth) were carried out.

Figure 2. Projective coverage of the surface with crops residues under different tillage methods



As we can see, the soil surface after plowing is characterized by the lowest protection indicators (without taking into account the vegetation cover). Moldboardless options show approximately the same values, the indicator is slightly lower against the background of disking. After the first spring harrowing with tooth harrows, the value of the coefficient of projective soil cover with residues decreased for all options by an average of 40-50%, with preservation of trends and differences between tillage methods. Its value at the level of 15-25% (from the initial) was maintained until the first continuous cultivation (on average, the end of April - beginning of May), and gradually decreased until it disappeared at the end of summer for all variants of the experiment.

The obtained result was confirmed by the observation carried out on the area of site 2. A different set of tillage was adopted here: 1 – plowing, 2 – deep subsoiling, 3 – Salford vertical tillage, 4 – shallow disking, 5 –direct sowing. The options are of various depths, the depth of cultivation decreases from 1 to 5 options from 27 cm to 0 cm. The results of determining the vegetation coverage of crop residues (corn for grain) and agricultural crops (corn in phase 40-44).

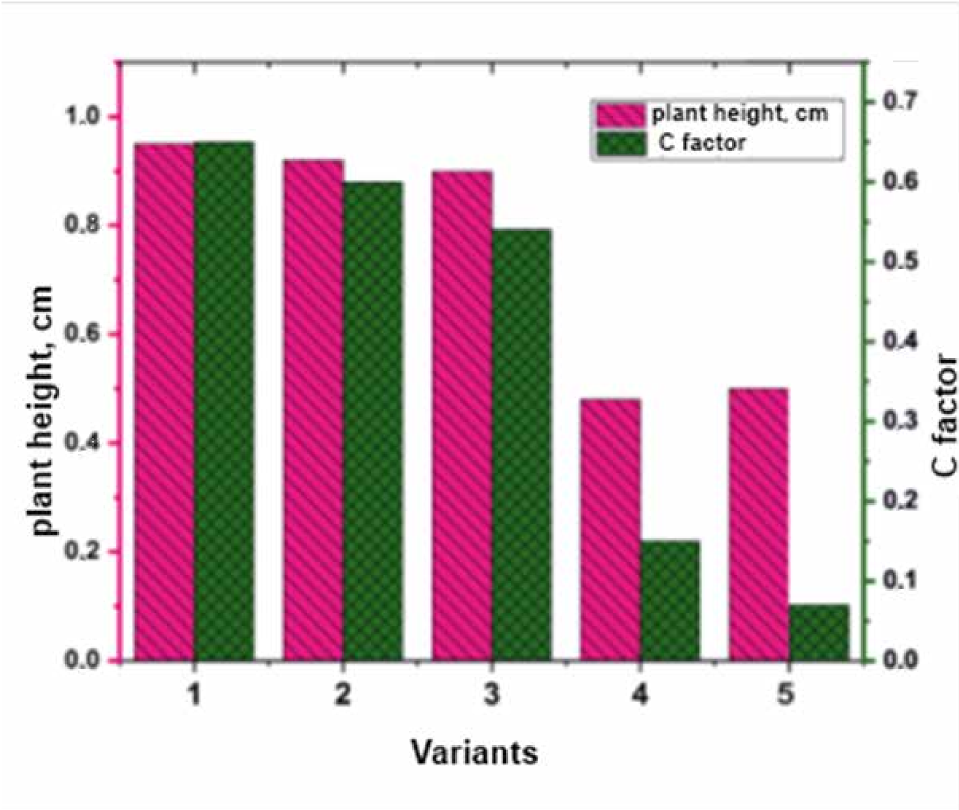
Table 1. Dependence of the projective coverage on soil cultivation in the territory of experimental site 2

Tillage type	**Surface coverage, %**	
	Crop residues	**Vegetative crops**
1. Plowing	3	40
2. Deep loosening	10	35
3. Vertical disking	15	35
4. Shallow disking	70	10
5. Direct sowing	90	5

From the data in Table 1, it can be concluded that the density of the plant residue layer on the background of moldboard plowing as of the first decade of July decreases to zero values. On options with moldboardless deep chiseling, it decreases to 10-15%, practically correlating with the data of Figure 2. Shallow tillage also reduces this indicator compared to its absence but keeps it significantly higher compared to the deep options.

At the same time, the conditions created on deeper variants are more favorable for the development and growth of corn plants. The vegetation coverage of vegetative crops on them is 2 times higher than on shallow discing ones. The total protective effect was calculated for the variants of the experiment (Figure 3).

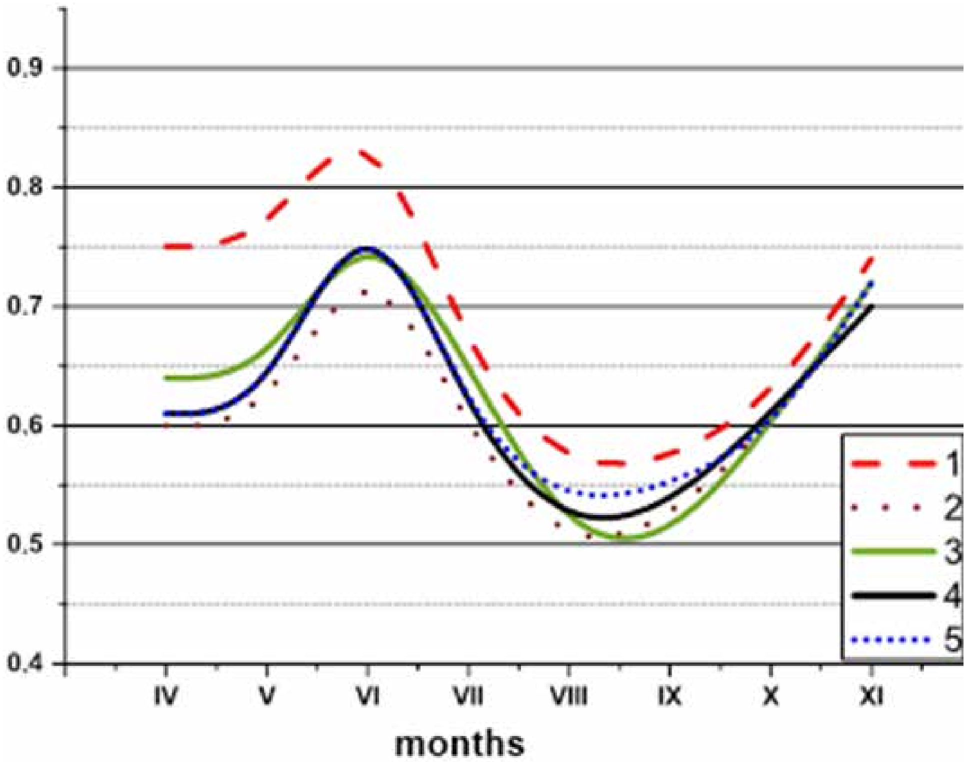
Figure 3. Height of corn plants and value of subfactor C for experimental site 2



The results presented in Figure 3 indicate that a dense mulch cover provides a sufficient level of subfactor C, despite a significant difference in the assessment of the impact of vegetative crops. Thus, the value of the vegetation impact subfactor of options 4 and 5 is approximately 3 times more effective than options 1-3. A similar trend of the leading role of crop residues is described by many authors, including the classic work of American specialists (Pimentel D., 2006, Abrantes J. R. C. B. et al., 2018).

On the area of experimental site 2, the value of the protective effect of vegetation in the dynamics of the fields occupied by grain maize, winter wheat and sunflower was determined (Figures 4-7). The black fallow field is characterized by the values of this subfactor similar to those shown in Figure 2. Soil tillage here included continuous cultivation of 8-10 cm every three weeks. This mode does not allow to form a more or less significant volume of vegetative mass of plants. The winter rye field characteristics are similar to the values obtained in the winter wheat field. In the figures, tillage options are shown in the order similar to the explanations in Figure 2.

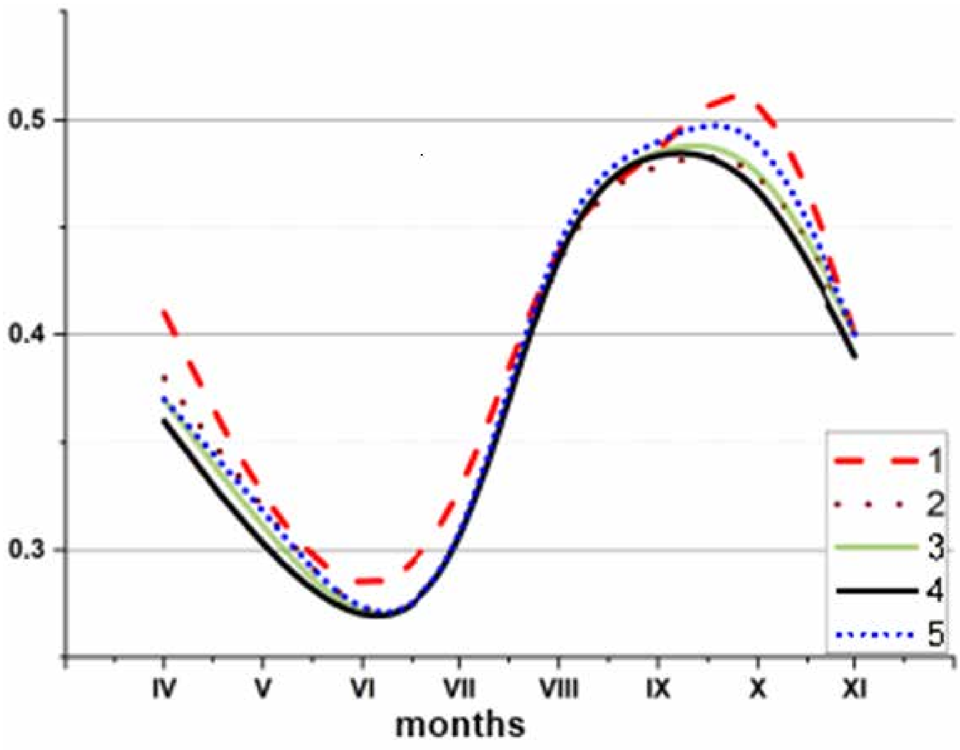
Figure 4. The value of subfactor C in the maize field of experimental site 1



For the entire observation period, the values of the subfactor for options 2-5 are almost identical. Only the variant with moldboard plowing stands out, the value of the subfactor here is on average 10% higher, it is most fixed in the first period of crop vegetation, while at the end of it there is no fundamental difference. Local maxima of this difference are observed in the phase of 3-5 leaves of the crop and in the phase of full maturity.

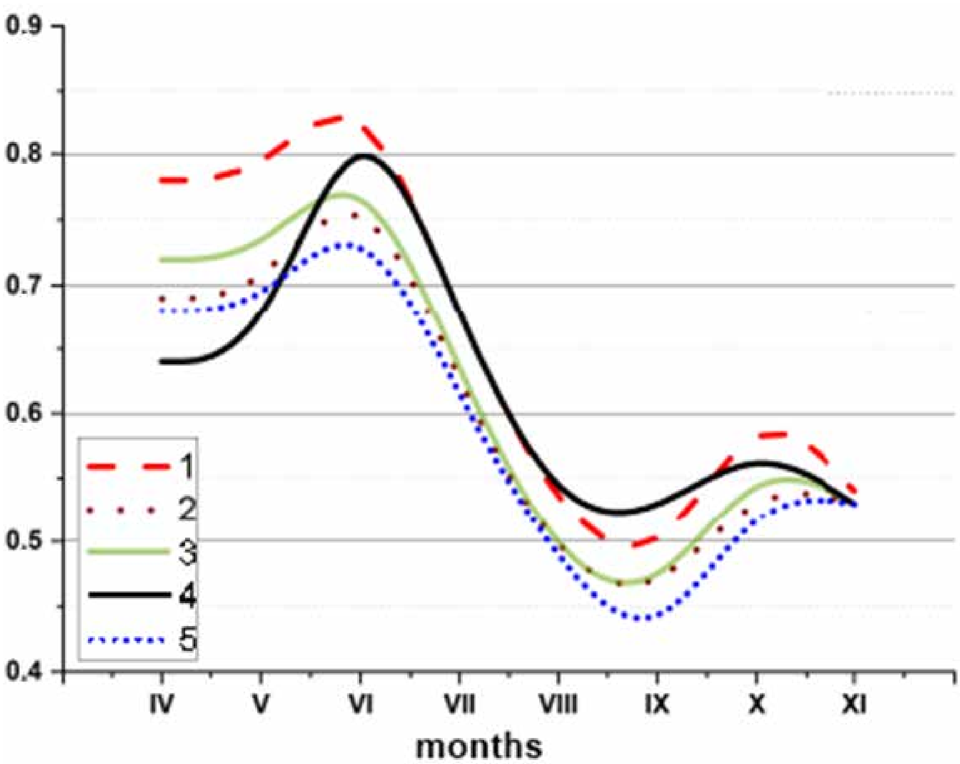
The difference between the indicators of soil protection efficiency of the test options on the winter wheat field is minimal, rising to significant data only in option 1 (moldboard plowing) in the initial period of plant growth: seedlings - the beginning of tillering (Figure 5).

Figure 5. The value of subfactor C in the winter wheat field of experimental site 1



In general, the graphs show the same trends of changes in the values of the subfactor in the field of winter cereals. The values of the studied indicator are the same during the harvest period - the post-harvest period with a tendency to increase. It should also be noted that the range of such values is substantially smaller compared to other cultures. The highest values of subfactor C are characteristic of the variant with plowing. In the field with sunflowers, the differentiation of values according to the variants of the experiment is more pronounced (Figure 6).

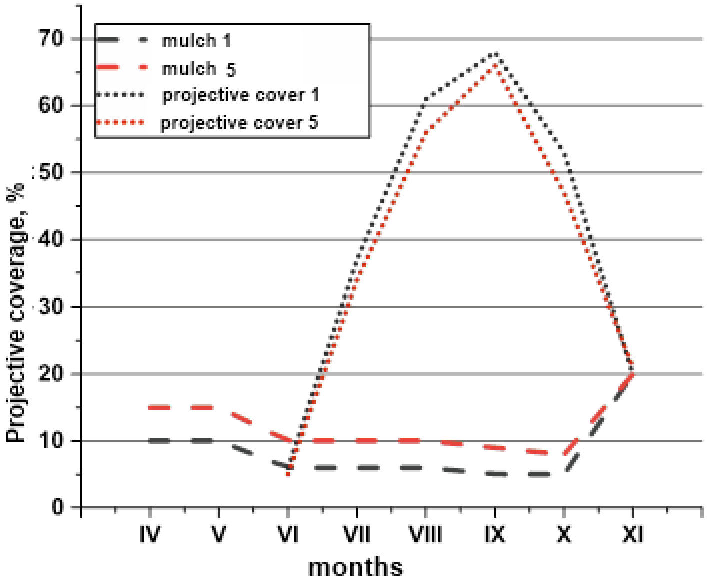
Figure 6. The value of subfactor C in the sunflower field of experimental site 1



This difference is most pronounced in the first two months of crop vegetation, minimizing on plowing. In the phase of the beginning of flowering of the crop (end of June), the values of the subfactor are almost the same. Again, a significant differentiation appears at the end of summer after drying of the crops before harvesting, which levels off by the end of the observation period. Minimum values are characteristic for option 5 at the beginning of September.

In general, common to all plants is the increased differentiation of subfactor C values in the sowing-seedling period, where it is determined mainly due to surface residues. Figure 7 shows the dynamics of the values of the projective cover by vegetative plants. This graph is based on sunflower field measurements (options 1 and 5). The maximum value of the design coverage of vegetative plants is reached at the end of the flowering phase, remaining practically unchanged until harvesting. Currently, sunflower hybrids are in production with harvest dates from the end of August to mid-October, which also requires adjustments.

Figure 7. Dynamics of the vegetation coverage of sunflower (options 1 and 5)



The trend shown in Figure 7 is characteristic of all crop rotations. During the entire vegetation period, a higher level of vegetation coverage is observed for option 1 (moldboard plowing). The same result is observed on the example of experimental site 2 (Figure 3), although there the difference between plowing and deep cultivation options is less pronounced, compared to shallow ones. Thus, the yield of the ground mass of crops in the experimental area is inversely related to the amount of mulch, i.e. It causes the growth and development of plants. Similar conclusions were reached by an international group of experts, who stated that, in conditions of a moderate climate, the negative impact of the level of projective mulching on the nitrogen and temperature regimes of the soil, especially when using the no-till technology, under drought conditions, it is observed "interception" of insignificant precipitation (Turmel M.-S.et al., 2015). However, unequivocal conclusions cannot be drawn here, as American researchers have shown that these processes depend not only on the type of cultivation, but also on the species composition of the mulch itself (Hunter M. C. et al., 2019; Abrantes J. R. C. B., 2018). The fluctuation and range of the calculated values of the C-factor are close to those shown by German researchers on the example of Central China (Schönbrodt S. et al., 2010). The most interesting, in our opinion, is the situation that has developed with the recently widespread practice in Ukraine, when sunflowers are sown repeatedly, and the mulch is represented by chopped stems of this crop.

On the contrary, Iranian researchers, in arid climate conditions, showed a positive effect of the projective cover on the corn yield both with traditional technologies and with the use of no-till (Mirzaei M. et al., 2021). It is obvious that the moisture-retaining role of mulch under these conditions is dominant, compared to the negative processes caused by it. This determines the need for studies of the impact of mulch on various factors of plant life, conducting them in different climatic conditions (Al-Kaisi M., Lowery B., 2017).

In our work, we did not differentiate the level of plots productivity, like American researchers did (Wischmeier W. H. and Smith D. D., 1978). In their opinion, the difference of subfactor C values significantly (more than 20%) depends on this level, with better erosion-prone properties inherent in areas with higher indicators of plant productivity.

Based on the graphs in Figures 3-6, it is possible to conclude about the possibility of making corrections to the values of the coefficients of the protective effect of vegetation (such as factor C of the USLE model).

Such corrections are more relevant in the initial period of spring crops vegetation (March - May), or the SB period (Soil erosion, 1984). Thus, in the sunflower field, the total protective effect against the background of option 5 is 22% more pronounced, decreasing to a difference of 11% during the first three months.

In general, during the growing season, the total value of subfactor C for options 2-5 did not differ significantly. This corresponds to the trends described by American experts on the example of a site in Nebraska: the ratio of soil loss between different tillage options shown by them corresponds to the ratio of the projective cover with harvest residues that we obtained, indicated in Table 1 (Dickey E. C. et al. 1981).

The difference between the values of subfactor C at the end and at the beginning of the growing season is significant for the various studied crops. This confirms the opinion that the sequence of crop alternations over time is also of significant importance (Auerswald K. et al., 2021).

The C- factor is considered as the main indicator for the process of soil erosion protection. The wide range of types of soil treatment, including new ones, is due to the availability of reliable information for effective work in the field of soil protection. Particularly valuable is the two-factor nature of the C - factor, which provides greater possibilities when combining other subfactors.

CONCLUSIONS

1. The primary factor that restrains the development of erosion processes is the presence of vegetative plants or their residues on the soil surface. The duration of the period and the degree of plant development determine the value of the

surface roughness and the buffering capacity to counteract the destructive force of water. Technological measures of soil cultivation create different levels of erosion control efficiency, directly affecting the presence of post-harvest residues on the surface and indirectly the conditions of growth and development of crops.

2. In this regard, in the conditions of unstable and insufficient moistening of Left Bank Forest Steppe on typical chernozems, there is a differentiation in the impact of different crop rotation and technological measures of the basic tillage, which is especially pronounced in the spring period.
3. The methods and technologies of soil cultivation are able to strengthen this factor by preserving post-harvest residues of the previous crop for a certain period of time.
4. In particular, the replacement of plowing with moldboardless tillage and the absence of tillage from harvesting the precursor to sowing the crop ensure the presence of surface coverage in the early spring period by approximately 20%, which is especially important for growing spring crops with a low intensity of vegetative mass development. In general, this, compensating for an inevitable weakening of plant development and a decrease in their yield against the background of minimal tillage, determines practically the same values of erosion resistance of agrophytocenoses with different tillage options during the growing season of crops in the rotation.

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Chapter 7
Plant Tolerance to Soil Acidity in the Era of Climate Change:
Biotech and Breeding for Sustainable Agriculture

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ABSTRACT

The crucial topic of soil acidity and its effects on global food security are the main focus of this chapter. Owing to its immediate effects on plant growth, development, and productivity as well as its capacity to fend off biotic stresses, such as diseases and insect pests, soil acidity, an abiotic stress, has gained significant attention in the agricultural community. Although the effects of aluminum (Al) toxicity on plants have received considerable attention, few studies have examined the harmful effects of low pH on plants. Low pH in agricultural soil can cause oxidative stress and electrolyte leakage through increased generation of reactive oxygen species (ROS), hinder CO2 assimilation, and impact plant water intake. This study delves into the mechanisms underlying plant growth under acidic conditions and highlights the strategies employed by plants to withstand and adapt to acidic stress. This chapter offers valuable insights into strategies for enhancing plant resistance to acidic soils and ensuring food security in the face of increasing water scarcity.

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INTRODUCTION

Over 3.95 billion ha of the world's soils are acidic, with pH < 5.5, and finding an appropriate approach to increase crop production in these soils is critical (Knežević et al., 2022). The growth and productivity of crops can be severely hampered by this acidity. Soil is crucial for successful crop production because it is a reservoir of essential nutrients, including carbon and minerals, organic matter, water, and microbes. Soil also serves as a supportive environment for plant roots while facilitating gaseous exchange and soil aeration. Additionally, soil ecosystems and natural biodiversity are necessary to encourage agricultural sustainability. Safeguarding soil properties, such as physical (soil structure, texture, and porosity), chemical (pH, cation exchange capacity, nutrient availability), and biological (microbial activity, organic matter content) properties is highly important for crop development (Cardoso et al., 2013). In recent years, research shows that soil health is deteriorating owing to issues such as soil erosion (loss of top soil due to wind and water), compaction (reduction in soil porosity, often due to heavy machinery), salinization (accumulation of soluble salts in the soil, acidification (decrease in soil pH, contamination, and pollution (introduction of harmful substances to the soil) which have a significant negative impact on the development of crops such as rice, wheat, maize, sorghum, and many others (Brevik, 2013).

In recent years, many countries, such as China, Australia, India, Malaysia, and Brunei Darussalam, have reported highly acidic conditions in agricultural soils. Soil acidification, defined as a reduction in acid-neutralizing capacity (ANC) or a boost in base-neutralizing capacity (BNC), has accelerated and become a major global environmental and economic concern. Studies have shown that the major constraint of soil acidity is Al toxicity, which leads to the inhibition of root growth (Chauhan et al., 2021). Therefore, understanding the mechanisms underlying plant responses to soil acidity can aid in developing plant tolerance strategies for these stressors.

Climate change is one of the main factors that contribute to increased soil acidity. The impact of climate change is estimated to trigger greater intensity and frequency of rainfall catastrophes in certain geographic regions, causing the weakening of soil and nutrient leaching (Reyes-Díaz et al., 2023) by washing away topsoil and exposing deeper, often more acidic layers and as water percolates through the soil, it carries away essential nutrients, mainly base cations like magnesium and calcium. As vital nutrients required by plants are eliminated through leaching or excessive plant uptake without replenishment from the soil, this may culminate in elevated soil acidity (Gunadasa et al., 2023). As global temperatures rise due to climate change, increasing temperatures can hasten organic matter decomposition in the soil due to increased microbial activity, releasing organic acids and increasing soil acidity (Jiao et al., 2016).

Climate change can also shift vegetation patterns, which can in turn affect soil acidity. For example, deforestation can cause soil acidity to increase due to the loss of plant residues that help maintain soil pH (Wamelink et al., 2019). Certain types of plants that grow well in a particular region can change due to changes in climate since the effects of various plant species on the chemistry of the soil vary. Additionally, modifications to the vegetation may have an indirect impact on soil acidity by modifying rates of evapotranspiration and water uptake. The occurrence of longer dry spells and more frequent droughts due to global warming can stimulate changes in precipitation patterns, leading to increased soil acidity because plants cannot take up sufficient water and nutrients from the soil (Prakash et al., 2022). Drought causes reduced plant growth causing less uptake of nitrates, which eventually accumulate and lead to acidification of soil due to leaching and this stress can alter plant root exudates, increasing soil acidity. Moreover, the increase in atmospheric carbon dioxide (CO_2) due to climate change is causing the oceans to become more acidic, affecting the chemical composition of coastal soils and increasing soil acidity since ocean absorb more CO_2 and gets further spread to soils due to sea spray, tidal influences, and groundwater interactions (Renforth & Campbell, 2021).

Few research shows that rising atmospheric CO_2 in non-coastal regions may cause higher levels of carbonic acid to develop in rainfall, which could eventually cause the acidity of the soil to rise (L. Zhang et al., 2018). Carbon sequestration, soil acidity, and climate change are interconnected since carbon sequestration in the soil can help mitigate climate change, which reduces global warming, maintains optimum soil pH, and maximizes the potentiality of carbon sequestration by releasing CO_2 (Das et al., 2021). The impact of climate change on soil properties may have negative consequences for agricultural productivity and ecosystem health; thus, coping with soil pH levels has become increasingly important as the effects of climate change on the environment and food security continue to worsen (Brevik, 2013; Bäurle et al., 2023).

This chapter will address the current state of soil acidity, as well as the mechanisms underlying it and its long-term consequences for the environment, the economy, microbes, and plants. Soil acidity has long-term effects that go beyond the surrounding agricultural landscape to affect water quality and the overall health of bigger ecosystems. Despite its significance, little is known about the mechanisms by which different crops are impacted by acidity in the soil. This review seeks to summarize the state of the art on plants' physiological and molecular reactions to acidic environments, highlighting the necessity of holistic approaches. The study also looks at how cutting-edge biotechnological techniques and breeding initiatives that might be used to create crop varieties that are resistant to acidity, which is essential for maintaining food security in the face of climate change.

GLOBAL STATUS OF SOIL ACIDITY

Acid soils are common in high-rainfall areas with annual precipitation exceeding 600-800 mm (Decker et al., 2019). More acidic elements are left behind as a result of the parent materials weathering and basic cations (potassium, magnesium, and calcium) leaching due to the heavy rainfall. On a global scale, there are two main geographic belts of acid soils: one in the humid northern temperate zone, where coniferous forests predominate with soils primarily consisting of Spodosols (highly leached, acidic forest soils), Inceptisols (young soils that can be acidic in high rainfall areas), Histosols (organic soils, often acidic sue to organic acid accumulation), Entisols (young soils that can be acidic if formed from acidic parent material), and Dystric Alfisols (soil with low base saturation), and one in the humid tropics, where Oxisols (highly weathered) and Ultisols (strongly leached) dominate tropical rainforests. Countries in the Asian, European, and Oceanic regions deal with acidic soil problems that destroy agricultural crop growth. Soil acidity, for example, is a significant issue in Brunei Darussalam, affecting crop production, particularly in lowland areas, and reduces the availability of essential macronutrients such as calcium, magnesium, and potassium, necessary for plant growth and development (Zin et al., 2015). In addition, the development of highly acidic soil ($pH \leq 5.50$) may also affect plant growth and soil health due to factors such as aluminum (Al) and heavy metals toxicity and loss of soil microbes (Naz et al., 2022).

In Ethiopia, land degradation is a perilous issue that significantly impacts agricultural productivity and rural livelihoods. This problem is particularly severe in the highlands, which comprise 44% of the country's total area and are under heavy human and livestock pressure (Sisay Golla, 2019; Warner et al., 2023). Sreelakshmi et al. (2022) studied soil acidity and its distribution in laterite soils of Northern India by analyzing rice wetlands in Kerala. They reported that effective forms of acidity such as exchangeable acidity, potential acidity, and pH-dependent acidity were high, indicating an increasing demand for the soil management system. Acid sulfate soils are also a common problem in oil palm plantations in Malaysia, thus reducing oil palm yields, oil quality, and economy (Abdul Halim et al., 2018). Similarly, soil acidity is a significant constraint to crop production in China, particularly in areas with high rainfall and intensive agricultural practices (Guo et al., 2010). A study assessing soil acidity in tea plantations in China concluded that soil pH in each province varied from pH 3.96 to 5.48, with an average pH of 4.50 nationally and dominated by exchangeable Al^{3+}, indicating an increasing demand for soil amendment to obtain sustainable tea plantations (Yan et al., 2018). In contrast to other drylands, Australian dryland soils are acidic, nutrient-poor, and have distinctive microbial communities (Eldridge et al., 2018). Agricultural soils of the UK and Europe have soil pH between 5 and 7 which is caused by factors such as acidic precipitation, the deposition from the acidifying gases, the application of acidifying fertilizers, nutrient uptake by crops and root exudates, and the mineralization of organic matter, therefore, usage of ground limestone as a common liming material (Goulding, 2016; Zeng et al., 2017).

Soil acidity can have significant economic impacts on farmers, communities, and countries due to decreased agricultural productivity (Zeng et al., 2017). Acidic soils can lower crop yields which directly impacts farmers' incomes because they restrict the availability of vital nutrients and increase plant stress. Acidic soils can also impact crop quality, lowering market value and decreasing consumer appeal. Farmers may need to spend money on expensive soil amendments like agricultural lime to lessen the effects of acidic soil which shows immediate effect but are found to have only short-term effects on the improvement of soil quality. Their profit margins may be affected and their production costs may rise (Shoghi Kalkhoran et al., 2019). Acidic soils can also reduce the value of agricultural land, making it less attractive to investors and lowering property values in rural areas.

Another drawback includes food security, which may be negatively impacted by soil acidity, particularly in areas where agriculture serves as a significant food source and supports economic growth (Kopittke et al., 2019). Acidic soils can also have environmental impacts, such as increased soil erosion and nutrient runoff, leading to water pollution and other ecological problems. Low acidity leads to the release of heavy metals into the soil that can cause health risks due to its bioaccumulation in different parts of the plant. A case study by Orton et al. (2018) discussed the effects of soil limitations on wheat yield and quantified the economic impact on Australian agriculture, concluding that the acidity of the soil cost the country's wheat producers approximately USD$1000 million annually lost in wheat production. Therefore, it is important to address soil acidity through sustainable agricultural practices and soil management strategies to maintain soil health and support long-term economic growth.

ACIDIFICATION OF THE SOIL

A soil's pH buffering activity determines its capacity for resistance, or susceptibility, to pH modification (Gentili et al., 2018). Soil pH is the master variable of soil due to its impact on biological, physical, and chemical properties that influence plant growth and development (Neina, 2019; Rengel, 2011). The pH spectrum ranges from 0 to 14, with pH 7 corresponding to neutrality, and values less and more than seven indicate an acidic environment and alkaline (basic) condition, respectively. All living tissues have the ideal pH needed for appropriate physiological and biochemical activities, for example, the pH range of 5.5 to 6.5 is suitable for plant growth because nutrients are readily available. Most soil microbes also flourish in this range partly because plants thrive and produce more root exudates, which serve as a carbon source for microbial growth and survival. The Rhizobia-legume symbiotic relationship is disrupted in soils with pH below 6, which harms nodulation and N fixation in Leguminosae (Goyal et al., 2021).

Acid sulfate soil is a severe case of acidic soil with unique characteristics such as an extremely low pH (< 3.5) and the presence of jarosite or $KFe_3^{+3}(OH)_6(SO_4)$, a yellowish mineral formed when pyrite is exposed to the atmosphere (Enio et al., 2020). Pyrite oxidation causes acid to be released into the soil, lowering pH and increasing Al concentration. Excess Al^{3+} and Fe^{2+} solubilized in the soil environment give rise to nutrient deficiency while being toxic to plants and stunting plant growth. The root tip is the target of Al phytotoxicity, in which Al exposure inhibits cell elongation and cell division, leading to stunted root growth associated with reduced water and nutrient uptake (Shamshuddin et al., 2017).

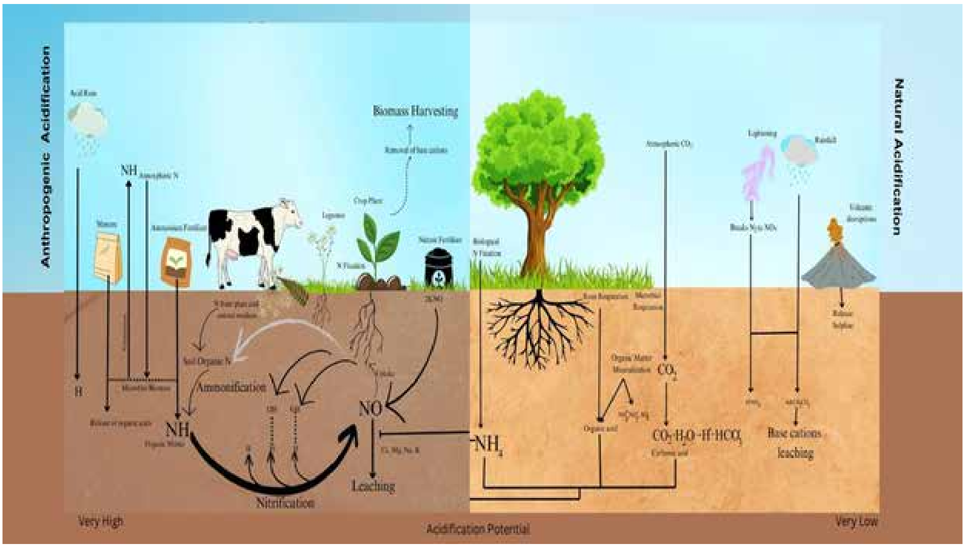
MECHANISM OF SOIL ACIDIFICATION

Soil acidification is a complex phenomenon that can be influenced by a variety of natural processes. Understanding the mechanisms of soil acidity is vital for developing effective strategies to manage and prevent soil acidification. Here are some of the mechanisms that contribute to soil acidity (Fig. 1.):

i. Decomposition of organic matter: Organic acids are released when plant residues or other organic matter decompose, lowering the soil pH. Although this organic phenomenon benefits soil fertility, excessive decomposition or a shortage of nutrient cycling is capable of causing soil acidification (Averill & Waring, 2018).
ii. Mineral weathering: The chemical disintegration of minerals in the soil may unleash hydrogen (H^+) ions into the soil solution, thereby dropping the pH level. This mechanism occurs naturally over time but can be accelerated due to variables such as erosion or modifications to land use (Alekseeva et al., 2011). The mobility and availability of heavy metals in plants are influenced by soil pH, which results in the enhancement of leaching due to increased solubility of metals (Zunaidi et al., 2021). Soil formation from parent materials such as granite and alluvial sediments contributes to soil acidification by causing a sharp shift in the pH buffering capacity and exchangeable acidity (Wen et al., 2023).
iii. Nitrogen-deposition: Nitrogen-based fertilizers have the potential to raise soil acidity due to the production of nitrates, which can release H^+ ions into the soil solution, and they can also have considerable effects on the ecosystem due to the gradual reduction in the pH of the soil (Tian & Niu, 2015; Padhi et al., 2020).

iv. Acid precipitation: Acid rain or acid snow can result from acid deposition caused by the release of sulfur dioxide and nitrogen oxides into the atmosphere because of the combustion of fossil fuels. Acid rain, fog, and snow can directly acidify soils by lowering pH and disrupting soil respiration (Bhargava, 2013). Soil acidification can be exacerbated by irrigation water that is naturally acidic or has become acidic due to anthropogenic causes (He et al., 2015).

Figure 1. Natural and anthropogenic mechanisms of soil acidification



UNDERSTANDING THE EFFECTS OF SOIL ACIDITY ON PLANT GROWTH AND PRODUCTIVITY

Soil acidity and its impact on parts of plants

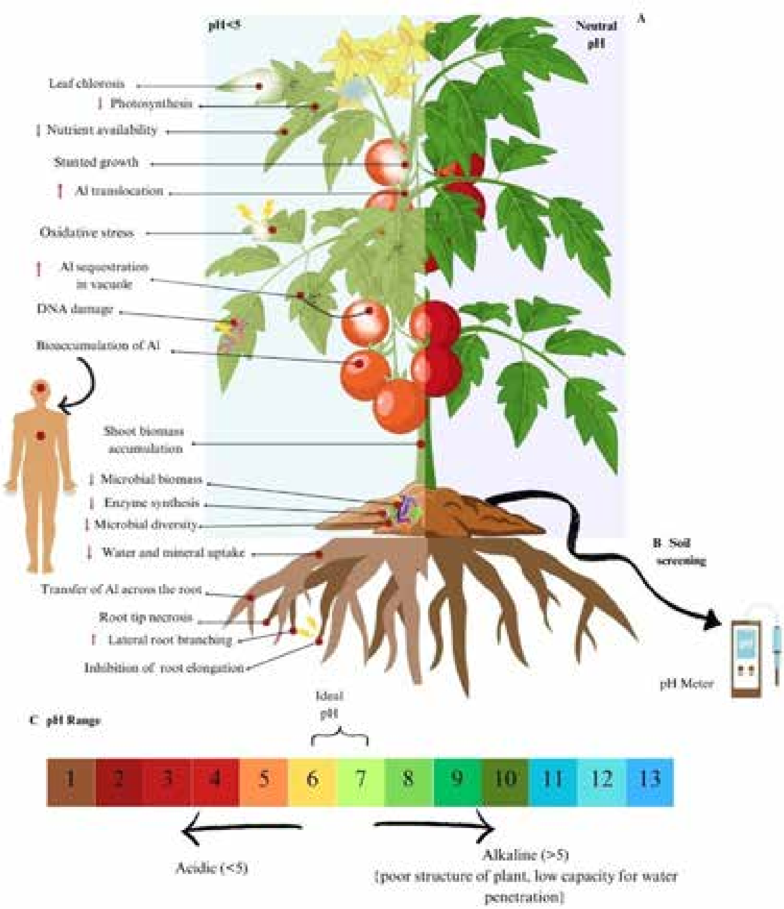
Soil acidity significantly impacts root growth and development by diminishing the availability of essential plant nutrients such as phosphorus (P), calcium (Ca), and magnesium (Mg) (S. Kumar et al., 2017). At low pH levels, these nutrients can become less available for plant uptake, limiting root growth and development and reducing plant water uptake. Another major issue is that soil acidity can cause toxic levels of Al^{3+} ions to be released, inhibiting root growth and causing root tip necrosis. Aluminum toxicity can impair root nutrient uptake efficiency (Rahman & Upadhyaya, 2021). Figure 2a. demonstrates that acidic soils lead to lower microbial diversity and activity and negatively affect root morphology, limiting nutrient availability and potentially reducing plant growth and yield (Haling et al., 2011).

Aluminum (Al^{3+}) and manganese are two toxic ions that can be released from acidic soil and inhibit shoot growth, and these ions may readily accumulate in plant tissues, causing toxicity symptoms, such as chlorosis and necrosis (Bojórquez-Quintal et al., 2017). Soil acidity can affect the balance of plant hormones involved in shoot growth and development, such as auxins and gibberellins. High acidity levels can prevent these hormones from being produced or transported, stunting shoot growth (Reyes-Díaz et al., 2023). Like roots, acidity in the soil can limit plant water uptake, limiting growth and shoot development (Figure 2a).

Soil acidity screening facilitates agriculturalists in making decisions about the best crop management methods for their soils (Shoghi Kalkhoran et al., 2019). Farmers may employ limestone to enhance soil pH and boost crop productivity if soil acidity is too high or sulfur to lower soil pH to enhance nutrient accessibility for crop production if soil acidity is excessively low (Turmel et al., 2015). Soil acidity screening entails analyzing soil samples for pH and exchangeable acidity, such as exchangeable H^+ and aluminum (Al^{3+}) ions, using portable or bench pH meters or laboratory analysis (Sisay Golla, 2019). The first step is collecting soil samples from the field at various locations and depths. After sieving, the samples are air-dried or oven-dried to remove rocks and other debris. A soil-water or soil-salt suspension is prepared in the laboratory, and the pH is measured using a pH meter (Figure 2b) or colorimetric methods. Portable soil pH meters can be used to measure soil pH in the field quickly, but they may not be as accurate as bench pH meters. Laboratory analysis methods such as atomic absorption spectrophotometry, inductively coupled plasma spectroscopy, or titration can measure the acid cations (Mangosongo et al., 2019; Yi et al., 2017).

Soil acidity alters the availability of essential nutrients in the soil, leading to nutrient deficiencies, which can indirectly affect the growth and development of leaf tissues (Neina, 2019). Acidic soils can cause Al^{3+} and manganese ions to become more soluble in the soil, which can be taken up by plant roots and transported to the leaves. These ions may turn toxic to plant cells, causing chlorosis and necrosis in leaves, and reduced photosynthesis (Mukhopadyay et al., 2012). Furthermore, soil acidity can promote the growth of soil-borne pathogens such as fungi and bacteria, which can infect plant roots and cause diseases that can spread to the leaves, leading to leaf discoloration, necrosis, and reduced growth (M. Yang et al., 2015). Overall, the effects of soil acidity on plant leaves can be complex and multifaceted and depend on factors such as plant species, soil type, and nutrient availability (Figure 2a). Managing soil acidity levels and ensuring that plants have sufficient nutrients is paramount for maintaining healthy leaves while optimizing plant growth and productivity.

Figure 2. (a) Effect of soil acidity on plant growth and development; (b) Soil screening using pH meter; C. Soil pH ranges



SOIL ACIDITY AND ITS IMPACT ON SOIL MICROBES

Long-term soil acidification may hinder soil diversity in bacterial species (Lu et al., 2014), while fungal communities exhibited little response to soil acidification (T. Wang et al., 2022). When soil becomes more acidic, it may create a hostile environment for certain bacteria. Consequently, certain species of bacteria may become extinct, while other kinds may flourish and dominate the soil microbial community (Lewis et al., 2018). Aluminum toxicity could mediate stress symptoms in soil microorganisms, thereby affecting microbial-mediated nutrient cycling causing suppression in nitrification, soil respiration, and NH_4^+ uptake, leading to low functional microbial diversity in acidic soils. Kunito et al. (2016) studied the soil enzymatic activities and microbial biomass in acidic forest soils in Japan and the results showed a sharp reduction in the exchangeable Mg and Ca. In contrast, an increase in the exchangeable and soluble Al levels with decreasing pH, moreover, highly elevated KCl-Al and $CaCl_2$-Al levels, have been demonstrated to inhibit β-d-glucosidase and polyphenol oxidase enzyme activity in lower pH soils. As an outcome of Al toxicity, this reduction in enzyme activity may be related to a dropped rate of enzyme synthesis and possibly a decline in several enzyme-producing microorganisms.

SOIL ACIDITY AND ITS IMPACT ON CROPS

Ongoing soil acidification reduces soil fertility and can lead to crop failure and production loss of important crops such as rice, wheat, maize, barley, and soybean in many parts of the world (Zhou et al., 2016; Ngoune Tandzi et al., 2018; Reis et al., 2018). For instance, model-based research showed that flooding and drainage lead to changes in paddy soil's pH affecting the growth and development of rice (C. Ding et al., 2019). Soybean is one of Ethiopia's most important crops and contributes to 18% of the country's oilseed production. Like many other crops, soybeans are sensitive to soil acidity, which can limit their growth, development, and yield. Low soil pH is exacerbated by the region's high rainfall and soil weathering that leaches out soil nutrients, leading to soil degradation (Bedassa et al., 2022).

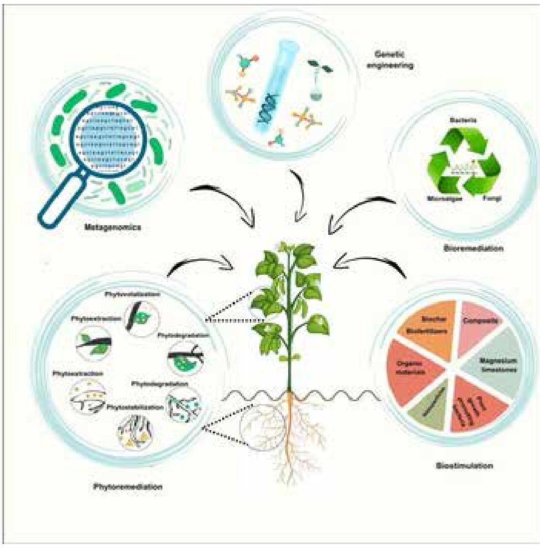
Aluminum toxicity severely constrains agricultural production in acidic soil worldwide, primarily due to excessive soil acidification accelerated by intensive agriculture and altered environmental conditions linked to global climate change (Rahman & Upadhyaya, 2021). Most soils contain aluminum naturally, however, Al solubility rises in acidic soils, contributing to high exchangeable Al concentration entering the soil environment (S. Singh et al., 2017). In general, aluminum can harm the aerial and belowground parts of the plant, for example, decreasing root elongation and shoot growth, inhibiting root growth and development, and reducing biomass production. The aluminum phytotoxicity also has the potential to create a nutrient and water imbalance by reducing nutrient and water uptake, thus altering physiological and metabolic processes, which are responsible for stunted growth, lower yield, and poor crop quality and therefore, decreased land productivity. Aluminum also initiates a series of toxic symptoms in plants, such as reduction of photosynthetic capacity, accumulation of reactive oxygen species (ROS), damaging cellular and nuclear DNA, and disruption of the cytoskeleton in major crops (Ofoe et al., 2023). Rapid production and accumulation of ROS induce oxidative stress in plants by facilitating cellular damage, such as harming DNA, enzymes, and membrane lipids and proteins. Imbalanced ROS production may result in tissue necrosis and cell death, further hampering plant growth (Siecińska & Nosalewicz, 2017).

There are varying degrees of aluminum toxicity tolerance among various plant species. While some plants have naturally developed defenses against or detoxification mechanisms for aluminum, others are extremely vulnerable to its toxic effects (Chauhan et al., 2021). Along with plant genetics, variables like soil pH, soil type, and nutrient availability can also impact how toxic aluminum is to plants. To manage aluminum toxicity in crops, it is important to correct soil pH to a level where aluminum becomes less soluble and therefore less available to plants. Agricultural liming, or adding calcium carbonate, calcium hydroxide, calcium oxide, or magnesium carbonate to the soil, is an effective way to mitigate soil acidity, raise soil pH and nutrient availability, enhance microbial activities, and reduce aluminum toxicity (Mesfin et al. 2021). Lime applications have a short-term and temporary stimulating effect on soil, mainly if the acidity problem lies in the topsoil horizon. However, lime needs to be applied regularly, thus this agricultural practice can be less affordable and effective if it concerns the subsoil region (Grover et al., 2017). Therefore, several biotechnological methods, such as the use of plant varieties that are acid-tolerant, are a better approach to mitigating the effects of soil acidity and aluminum toxicity in the long run.

BIOTECHNOLOGICAL ADVANCEMENTS FOR ENHANCING PLANT TOLERANCE TO SOIL ACIDITY

The vast discipline of biotechnology blends biological sciences with engineering technologies to modify and use living creatures or their parts for useful purposes. Liming is one of the traditional techniques for improving soil acidity, however, it has few drawbacks (Gurmessa, 2021), including slow response times (Li et al., 2019), high costs, unsuitability for some crops, increased CO_2 emissions (Y. Wang et al., 2021), nutrient imbalances (Burke & Raynal, 1998), and damage to indigenous species (Lawrence et al., 2016). Moreover, there are not much studies on how different agricultural practices (e.g. tillage, fertilizer type) interact with liming to understand the overall effects on crop production. Developing long-term remedies for soil acidity problems using biotechnological methods can reduce the requirement for expensive soil additions while enhancing soil health. However, these approaches require careful evaluation to ensure they are safe, effective, and socially and ethically acceptable. It is crucial to consider the potential environmental and economic impacts of biotechnological technologies and engage stakeholders in their developmental and implementation stages. Some of the biotechnological approaches that can be used to address problems with soil acidity is described as follows (Figure 3).

Figure 3. Different biotechnological approaches for soil amelioration



METAGENOMICS

Metagenomics involves the study of genetic material recovered directly from environmental samples, such as soil (Na et al., 2022). This approach can be used to analyze soil microbial communities using metagenomics to identify potential soil acidity-degrading microorganisms or enzymes. In the latest research conducted on *Eleusine coracana* (finger millet), RNA sequencing (RNA-seq) and gene expression evaluation identified that a total of 322 genes were significantly varied in expression when compared between Al-tolerant and Al-susceptible genotypes, with 40.7% being upregulated and 59.3% being downregulated in Al-tolerant genotypes (Brhane et al., 2022). Several new genes governing aluminum tolerance in Arabidopsis thaliana accessions were found by transcriptome analysis such as T-DNA Knockout of 5 aluminum-inducible genes, including TAO1 and At5g22530, increased aluminum sensitivity in Arabidopsis (Kochian et al., 2015).

GENETIC ENGINEERING

Genetic engineering involves the introduction of genes from other organisms into crops to confer desirable traits such as soil acidity tolerance (Babiye et al. 2020). This technique can be used to develop crop varieties with enhanced soil acidity tolerance or microbial strains with enhanced soil acidity degradation capabilities (Agegnehu et al., 2021). This approach is still in its early stages and is subject to regulatory oversight. Aluminum and aluminum-induced signals regulate and trigger resistance gene expression, as does the regulation of proteins encoded by these functional genes (Kochian et al., 2015). According to findings by Chen et al. (2013), *Holcus lanatus* plants adapt to acidic soil due to increased cis-acting elements that regulate the expression of the ALMT1 gene, providing insight into the molecular mechanism of plant adaptation to acidic soil. The following are the types of genes responsible for tolerance to acidity in plants:

i. Acid tolerant genes: Researchers are actively studying acid-tolerant genes to develop crop varieties with improved acid tolerance, which could help to improve crop productivity in acidic soils (Kochian et al., 2015). However, breeding for acid tolerance is a complex process and requires a long-term commitment from plant breeders and farmers. Plant species naturally adapted to grow in acidic soils possess genes to confer acid tolerance. Acid soils are typified by a P deficit as well as Al, Mn, and Cd toxicity, which restrict agricultural yields. Al, Mn, and Cd toxicities can be significantly mitigated by phosphorus. In order to generate crop types adapted to acid soils, further research is required to comprehend regulatory components and signaling pathways, particularly the involvement of intracellular Pi signaling (X. Wang et al., 2023).
ii. Drought and salt tolerance genes: Some drought and salt tolerance genes can also confer acid tolerance (Iqbal et al., 2022). For example, the overexpression of HaASR2 from the desert shrub *Haloxylon ammodendron* significantly affects plant adaptability to salt stress and drought. It might serve as a potential gene for crop tolerance to abiotic stresses through genetic improvement (Cao et al., 2023). Other similar genes and their expression should be studied for acidic stress tolerance.
iii. Aluminum tolerance genes: These genes help plants to tolerate high levels of aluminum in acidic soils, which can cause toxicity and inhibit root growth (Ryan et al., 2011). There are mainly three key characteristics of Al resistance gene expression which are firstly resistance gene expression appears to be greater in resilient germplasm, secondly, gene expression has been confined to the root tip, which is the epicenter of Al toxicity and finally, gene expression is frequently enhanced by Al stress (Chauhan et al., 2021). Al resistance genes TaALMT1,

TaMATE1B, and HvAACT1 have constitutively higher gene expression in wheat and barley (Pereira & Ryan, 2018). Aluminum tolerance genes include the Aluminum-activated Malate Transporters (ALMT) gene in wheat (Oliveira & Pinto-Maglio, 2020) and the STAR1 (Sensitive to Al Rhizotoxicity 1) gene in rice (Asheed et al., 2020). The aluminum tolerance locus in wheat encodes an aluminum tolerance mechanism based on malic acid excretion stimulated by aluminum. The amount of malic acid excreted from the root apices depended on the external aluminum concentration and its presence in nutrient solutions defended Al-sensitive seedlings from commonly phytotoxic Al concentration levels (Liu et al., 2017). Some of the other Al-tolerant genes include MATE (Multidrug and Toxic Compound Extrusion), ART1 (Aluminum Resistance Transcription Factor 1), ALS3 (Aluminum Sensitive 3), and TaSTOP1 (*Triticum aestivum* STOP1). Table 1 shows the different gene targets for Al-tolerance in different plants.

Table 1. Gene targets conditioning for Al-tolerance in different plants

Plants	**Gene**	**Function**	**References**
Arabidopsis thaliana	H^+-ATPase	Decreased vacuolar H1 pump activity and Al resistance	Zhang et al. 2019
Glycine max (Soyabean)	GmALMT1	Malate exudation	Liang et al. 2013
Hordeum vulgare (Barley)	TaALMT1	Malate efflux and Al tolerance	Delhaize et al. 2004
Oryza sativa (Rice)	STAR1	Al tolerance	Zhang et al. 2019
Solanum lycopersicum (Tomato)	SIFDH	Positive regulation of SISTOP1 Reduction of NAD^+ to NADH	He et al. 2023
Sorghum bicolor (Sorghum)	MATE	Aluminum-activated citrate transporter	Ribeiro et al. 2017
Triticum aestivum L. (Wheat)	ALMT	Al-tolerant	Sasaki et al. 2004
	TaMATE1B	Introgression of a large fragment of the 4D chromosome	Han et al. 2016
	WRKY46	T-DNA insertion increase Root malate secretion Negative regulation of ALMT1	Ding et al. 2013
		Inhibition of transcription in NUDX9 Inhibiting ammonium efflux in root elongation zone	Di et al. 2021
	TaSTOP1	Al tolerance	Garcia-Oliveira et al. 2013
Zea mays (Maize)	ZmAT6	Scavenging of Reactive Oxygen Species	Du et al. 2020

iv. Proton pump genes: These genes encode proteins that pump hydrogen ions (H^+) out of root cells, maintaining a favorable pH environment for root growth. Plants react to high concentrations of protons (H+) in two ways: first, they use defensive signals and proton pumps to respond short-term, and then they use genes for ROS detoxification to respond longer-term (Shavrukov & Hirai, 2016). Examples of proton pump genes include the H^+-ATPase gene in *Arabidopsis* (Zhang et al. 2019) and the P-ATPase gene in wheat (Hamilton et al. 2001).
v. Organic acid synthesis genes: Harvesting more crops on acid soils may be possible if the genes governing organic acid efflux are identified. These genes help plants to synthesize and secrete organic acids, such as citrate, malate, and oxalate, which can increase soil pH and chelate Al^{3+} ions, making them less toxic (Ma, 2000) and examples include the OsALMT gene in rice (Heng et al., 2018) and the TaALMT1 gene in wheat (Silva et al., 2018). A study shows that Alfalfa exhibits enhanced synthesis of organic acid and aluminum tolerance in acidic soils due to the overexpression of malate dehydrogenase (Tesfaye et al., 2001).

BIOREMEDIATION

Bioremediation uses microorganisms to degrade or transform soil contaminants (Enerijiofi, 2021). This approach can be used to create microbial strains with improved degradability of soil acidity compounds (Neina, 2019). Marble quarry waste (MQW) and marble cutting waste (MCW) have also been used as soil conditioners to remediate acidic soils which in turn helped in minimizing the negative impact of marble waste on the environment (Tozsin et al., 2014). An intriguing possibility for the bioremediation of Al-contaminated acidic red soils is the bacterium *Burkholderia sp.* SB1, which was isolated from acidic red soil. It demonstrates moderate to high Al tolerance, acid resistance, and multi-antibiotic tolerance (Huang et al., 2018).

The amount of aluminum in the agroecosystem continues to rise, and research shows that certain bacteria have the ability to modify their metabolic pathways to endure in environments impacted with the metal by generating organic acids and other substances that chelate and immobilize it (J.-L. Yang et al., 2019). This emphasizes the significance of comprehending microbial metabolic networks in the development of the bioremediation technological innovations. (Auger et al., 2013) demonstrated that microorganisms like *Pseudomonas fluorescens* have developed mechanisms to resist aluminum toxicity by reworking metabolic pathways and can chelate, immobilize, and exude aluminum, making it unavailable for biological uptake.

PHYTOREMEDIATION

Phytoremediation is a cost technique which involves using plants to remove, degrade, or stabilize soil contaminants (Chakraborty et al., 2019). Biotechnological approaches can be used to develop crop varieties with enhanced phytoremediation abilities to address soil acidity issues (Osman et al., 2022). Lebrun et al. (2022) studied the phytoremediation for metal-contaminated soil using biochar to reduce soil acidity.

The application of advantageous microorganisms, such as mycorrhizal fungi (Aguilera et al., 2015) and plant growth-promoting rhizobacteria (PGPR) (Dutta & Bora, 2019), can improve the nutrient uptake, aluminum tolerance in acidic soil, and general health of the agroecosystem, hence augmenting the phytoremediation capacities of agricultural plants (Seguel et al., 2013). Other modifiers such as rice husk, compost (Abdul Halim et al., 2018), cow-dung (Ashraf et al., 2022), and nanomaterials (Song et al., 2019) can also help in enhancing phytoremediation efficiency. In very acidic soil situations, the incidence of ginger bacterial wilt may be significantly influenced by the level of aluminum toxicity in regions used for ginger cultivation. An increased use of PGPRs, particularly bacteria like *Arthrobacter, Bacillus, Serratia, and Pseudomonas*, and may be crucial in removing ongoing cropping challenges and averting the possibility of ginger bacterial wilt in stressful aluminum conditions, according to a research study conducted by (S. Zhang et al., 2020).

BIOSTIMULATION

Biostimulation involves the addition of nutrients or other substances to the soil to enhance microbial activity and improve soil health (Aparicio et al., 2022). This approach can be used to develop microbial strains or enzymes that can enhance biostimulation and improve soil acidity conditions. Biostimulants such as biochar, compost, basalt, biofertilizers, nanoparticles, magnesium limestone (GML), organic materials, or plant growth–promoting bacteria are applied for soil amelioration (Panhwar et al. 2014; 2016). Recently, the efficacy of Chinese medicinal herbal residue (CMHRs) compost for its anti-pathogenic properties against *Alternaria solani* and *Fusarium oxysporum* during tomato and cabbage plant growth in acidic soil (pH ~4) was studied and showed to be an effective soil amendment method (Zhou et al. 2023). In recent research, the combined usage of compost and lime can help enhance the wheat and soil properties of Northwestern Ethiopia compared to individual amendments (Ejigu et al., 2023). Plant growth-promoting microbes (PGPM) have the potential to support plant growth under a variety of environmental stresses and have shown promise as sustainable plant growth enhancers (Msimbira & Smith, 2020). *Burkholderiia thailandensis*, *Burkholderia seminalis*, and *Sphingomonas pituitosa* are good acid-tolerant plant growth-promoting microbes for boosting the root volume and seedling dry weight of rice in acid sulfate soil with a pH range of 3.3 to 4.7 (Panhwar et al. 2014).

One of the common biostimulants for soil amelioration is biochar (Bolan et al., 2023; D. Wang et al., 2023). Biochar is charcoal produced by pyrolysis, which is the thermal conversion of organic materials, such as wood, agricultural waste, or manure, in a low-oxygen environment (Van Nguyen et al., 2022). While pyrolysis also produces renewable energy through biofuel and syngas, the other pyrolytic product, biochar can help reduce acidity and improve health in several ways when added to the soil (Kumar Mishra et al., 2023). High pH levels of biochar can help neutralize soil acidity and improve the pH buffering capacity of the soil. The biochar addition can help reduce the effects of acid rain and other acidic inputs on the soil. Biochar has a high surface area and can absorb nutrients, such as Ca, Mg, and K, which are essential for plant growth (Ghorbani et al., 2022). By retaining these nutrients in the soil, it can be help to reduce nutrient leaching and improve soil fertility.

Biochar have also shown to help support microbial activity in the soil, promoting the growth of beneficial microorganisms that help break down organic matter and release nutrients for plant uptake and help improve soil structure and fertility (Xiang et al., 2022). The most significant benefit of biochar is its ability to improve soil water retention and, reduce the effects of drought and water stress on plants. However, the effectiveness of biochar as a soil amendment can vary depending on biotic and abiotic factors such as the type of biochar used, application rate, and soil and environmental conditions (Qian et al., 2023). For instance, Cornelissen et al. (2018) have concluded from their research that cacao shell biochar has a robust positive effect on maize crop yield and can help alleviate acidity in ultisol soil but needs reapplication after 3 to 5 seasons. Therefore, it is important to carefully evaluate biochar as a soil amendment and conduct soil testing to ensure that soil pH and nutrient levels are optimized for plant growth.

BREEDING STRATEGIES TO DEVELOP ACID RESILIENT PLANTS

Crop acidity tolerance breeding is a long-term strategy aimed at developing crop varieties that can grow and yield well in acidic soils (Agegnehu et al., 2021). It encompasses recognizing and choosing plant genetic characteristics capable of enduring or adapting to acidic conditions in the soil. Breeding for soil acidity tolerance can result in crop varieties that can produce high yields in acidic soils, reducing the need for costly soil amendments such as lime. However, breeding programs for soil acidity tolerance are complex and require a long-term commitment from plant breeders, farmers, and policymakers. It is important to consider the genetic, environmental, and socioeconomic factors that affect crop performance in acidic soils when developing new crop varieties (Aparicio et al., 2022). Listed below describe a few various approaches adopted for soil acidity tolerance breeding:

i. Screening of germplasm: Plant breeding endeavors display many plant genetic materials (germplasm) for desirable traits like soil acidity tolerance (Kuswantoro, 2015). These plants are subsequently utilized in breeding programs for developing new varieties of crops. In 2017, 50 fava bean genotypes were investigated to determine the genetic variability of grain production and associated traits under soil acidity stress. Except for the number of seeds per pod, there were statistically substantial variations between genotypes for all agronomic traits, contributing to a reduction in yield of 32.34%. Mean selection would be productive for enhancing traits with substantial heritability (Mesfin et al. 2021). (Kuswantoro, 2015) identified two soybean germplasm lines, MLGG 0471 and MLGG 0064, as promising sources for developing soybean varieties tolerant to low soil pH (pH=4) and another study conducted by (Arévalo-Hernández et al., 2022) screened cacao germplasm (normal pH=4.46 and amended pH=5.8) and identified 10 genotypes potentially tolerant to soil acidity and could be used for breeding acid soil-tolerant varieties. A recent study identified two acid-tolerant coffee genotypes, Timor Hybrid and Rume Sudan, that could be used as progenitors in a breeding program for an acid-tolerant coffee variety (Acuña-Zornosa & Sadeghian-Khalajabadi, 2020).
ii. Marker-assisted selection: Marker-assisted selection (MAS) involves using genetic markers linked to specific genes associated with soil acidity tolerance (X. F. Zhu & Shen, 2023). This approach can help breeders identify plants with desirable traits more efficiently, reducing the time and cost of developing new crop varieties. TaMATE2 homolog cloning, specifically TaMATE2-D, provides an attainable potential candidate for Al tolerance in bread wheat that could be employed for producing more Al-tolerant cultivars of this staple crop (Garcia-Oliveira et al. 2018). The identification and introgression of genes or genomic areas linked to aluminum tolerance in cereals has been made possible through the use of MAS techniques, DNA markers, and bioinformatics tools (Inostroza-Blancheteau et al., 2010). (Tang et al., 2000) identified RFLP markers linked to the barley aluminum tolerance gene Alp. These markers can be used to select barley for aluminum tolerance with marker assistance, obviating the necessity for soil bioassays, solution culture analysis, or field testing. In a malting barley variety, a novel allele of the acid soil tolerance gene HvMATE

was found, opening the door to marker-assisted selection for acid soil tolerance (Bian et al., 2015). A study conducted by (Froese & Carter, 2016) identified 55 genetic loci associated with wheat tolerance to acidic soils (Caldwell–Thatuna complex and Larkin–South-wick complex) and aluminum toxicity, which could be used for marker-assisted selection.

iii. Recurrent selection: Recurrent selection involves repeatedly selecting and crossing plants with desirable traits over multiple generations (Baertschi et al., 2021). This approach can help improve the frequency of desirable traits in a breeding population. Individual/phenotypic selection and family-based selection are the two primary techniques used in recurrent selection. In breeding populations of maize, recurrent selection have shown to increase the frequency of desired features (Hallauer & Carena, 2012). In addition to progeny effects, generation and population effects can also be taken into account to optimize recurrent selection in self-pollinated crops (de Paula et al., 2020). This technique is used in oil palm breeding to improve desirable traits by repeatedly selecting and crossing plants over multiple generations (Rafii et al., 2020). And also help concentrate genes for resistance to *Helminthosporium turcicum* leaf blight in corn (Jenkins et al., 1954).

iv. Cropping techniques: Developing new cropping techniques to decrease the impact of acidic soil on crop development is essential. The Very Simple Dynamic (VSD) model is a single-layer dynamic model comprised of charge and mass balances used to calculate changes in pH and element concentrations in soil solution and, as a result, element outputs from the root zone (Vašát et al., 2015). Recent studies indicate that acidification of non-calcareous soils may result in a pH drop of 1.1-2.5 units in all double cropping systems before 2050 due to Al release (Q. Zhu et al., 2018). A more recent investigation screened 67 genotypes for aluminum tolerance in the northeastern (NE) regions of India where rice was produced adopting the jhum cultivation technique and reported a detrimental influence on the crop's agronomic traits considering excessive precipitation in the northeastern part of the country has been accountable for flushing out basic cations gradually (A. Kumar et al., 2013). Crop diversification can improve soil pH in acidic soils (Ghimire & Bista, 2016). The detrimental impact of acidic soils on crop growth can be lessened by creating maize cultivars that are acid-tolerant and implementing them into sustainable cropping systems (Horst, 2000).

FUTURE DIRECTIONS AND CHALLENGES IN ADDRESSING SOIL ACIDITY IN THE ERA OF CLIMATE CHANGE

i. Future direction for soil acidity includes examining in greater detail the particular Al-tolerant microbial species and their possible uses in reducing Al toxicity and enhancing crop growth in acidic soils.
ii. Developing a reliable screening procedure for aluminum toxicity tolerance in crop plants to minimize the gap between data and model plants. This can be approached by standardization of screening conditions like consistent growth conditions, optimal growth stages and duration. Assessment of multi-parameter such as shoot growth and biomass accumulation, root growth inhibition, physiological markers and biochemical indicators and high-throughput phenotyping can be used to accelerate the process of developing aluminum-tolerant crop varieties.
iii. Investigating the numerous ways in which soil pH influences the relationships that Al-tolerant microorganisms have with one another and consider how managing microbial populations in acidic soils used in farming might benefit. By investigating the relationship between adaptability to other soil stresses (such as salinity, flood and drought) and microbial Al-tolerance strategies and the interaction of climate change drivers on acidic soil microbial populations.
iv. To comprehend the wider application of the findings, expanding the study to include agricultural soil types other than paddy fields. Investigating soil acidity and resilience to aluminum in various agricultural practices, including agroforestry, pastures, orchards, and highland crops and looking into how various intercropping as well as crop rotation strategies impact the dynamics of soil acidity is necessary. And designing soil acidity control plans that take into account the geographical variations seen in various farming environments.
v. Assessing the functionality and effectiveness of several bacterial strains as bioinoculants for crops cultivated in acidic soils through field trials and further examining the specific mechanisms by which the bacteria respond to the combined stresses of Al toxicity and P deficiency, and how this knowledge can be leveraged to improve crop performance.
vi. Also exploring the interplay between root and leaf responses to Al stress, and how the coordination between these two tissues contributes to the overall Al tolerance. Different approaches such as root-to-shoot signaling by analyzing ROS signaling and hormone signaling, metabolite translocation including in-detailed study on organic acid transport, and nitrogen metabolism, and physiological coordination in root-to-shoot system such as water relations, growth regulation, and nutrient homeostasis can be used. Molecular approaches such as identifying

transcriptional networks and proteome changes, and studying epigenetic regulation in coordinating root-shoot responses can be performed. Also, experimental approaches such as split-root experiments, grafting experiments, mathematical modeling and microscopy and imaging can be performed.

vii. Conducting further molecular and physiological research to advance the understanding of the mechanisms underlying Al tolerance in crops using molecular approaches such as genomic studies, transcriptomics, proteomics, metabolomics and physiological approaches such as changes in root system architecture, cellular compartmentalization, and analyzing antioxidant systems and ROS signaling pathways.

viii. And most importantly, utilizing the new molecular resources to improve crop Al tolerance through advanced biotechnology techniques such as molecular-assisted breeding, live-cell imaging single-cell sequencing, bioinformatics and machine learning.

CONCLUSION

Soil Acidity in changing climate is complex and involves numerous interactions between the plant and its environment. To gain understanding of the possible escape/avoidance/tolerance mechanisms, all aspects of acid tolerance have to be investigated. In order to comprehend the long-term effects on agricultural and natural ecosystems, experts are actively researching the relationship that exists between soil acidity and climate change and moreover, the negative effect of climate change on agriculture is a constraint to achieving the Sustainable Development Goals. The possibility for creating plant varieties resistant to acidity through breeding programs and biotechnological breakthroughs is highlighted in this chapter. It is essential to comprehend the variety of Al resistance mechanisms that extend beyond the malate and citrate efflux transporters and to clarify the ways in which Al controls the expression and functionality of Al resistance genes and proteins. Finding helpful characteristics and criteria to screen traditional crops for tolerance will not only yield valuable information for future breeding endeavors but also enable the screening of current germplasm for tolerance. Multidisciplinary efforts combining agronomy, microbiology, and genetics will lead to resilient crop types in the face of climate problems. Future research can help create conditions for plants to flourish in acidic surroundings and promote soil health, paving the way for sustainable agriculture in a changing global landscape.

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Chapter 8
Environmentally Safe Technologies for Leaching Saline Soils in Rice Systems to Enhance Their Productivity

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ABSTRACT

Rice systems in Ukraine are built on territories with saline soils, and with a complex hydrogeological situation. A method of calculating ecologically safe periods for growing dryland crops on saline soils is proposed, which will help to optimize the structure of rice rotations and prevent soil degradation. The considered technologies for leaching of saline soils, which make it possible to ensure qualitative soil desalination, to shorten the duration of leaching, to lower the level of groundwater, to improve the oxygen regime of the soil. The methods for calculating the technological parameters of capital and preventive soil leaching of saline soils have been developed. These methods allow improving the water permeability of the soil, attracting a natural thermal effect, reducing the volume of freshwater, and preventing the restoration of salts. It can be an important step in restoring fertility and increasing the productivity of rice systems in the face of water scarcity and climate change.

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BACKGROUND

The problem of salinization of soils, including rice systems, is one of the most pressing issues in modern agriculture, especially in view of the expected increase in global warming, prolonged droughts and shortages of water resources. This problem is expected to worsen in the coming years. The main agroecological feature of saline soils is the presence of harmful salts in the root zone in an amount that exceeds the permissible amount for the development of agricultural plants or leads to a significant decrease in their productivity. According to the Food and Agricultural Organization (FAO), the world area of saline soils is 424 million hectares (Montanarella L., et al., 2015; Global Map of Salt-affected Soils, 2024; Kuzmych, 2023; Yakymchuk et al., 2022). Factors influencing the salinization process include climatic conditions, soil type, irrigation, depth of groundwater, mineralization of irrigation water, as well as land use methods and technologies (Kuzmych et al., 2022; Pessarakli M., et al., 2019; Rahman M.M., et al., 2015; Stashuk V.A., et al., 2014; 2016). Various measures are used to counteract soil salinity, including various leaching methods, chemical amelioration, soil loosening, salt collection, and amelioration using halophytes. Often, a comprehensive approach involving several methods is necessary for the restoration of saline soils (Shaygan M., et al., 2022).

A distinctive feature of the rice systems of Ukraine and a limiting factor in planning their agricultural use is that they are located mainly in territories with complex hydrogeological conditions, saline soils of the aeration zone, and a shallow level of mineralized groundwater. The repurposing of rice systems to conventional crop rotations or the reduction of rice crops threatens the salinization of the soils of rice systems and the deterioration of the agrochemical composition of soils and groundwater, since in the absence of a leaching regime, salinization is restored. In addition, weather and climate changes, characterized by an increase in air temperature in the summer and a decrease in the amount of precipitation, increase the processes of evaporation from the fields, especially in conditions of shallow occurrence of mineralized groundwater. This contributes to the activation of secondary salinization processes, which deepens the problematic state of agricultural lands.

Preservation of rice systems has become critically important in Ukraine, as two of the three rice-growing regions (the Autonomous Republic of Crimea and the Kherson region) are currently under temporary occupation. These systems are located in areas that were previously exposed to salinization and have nearby weakly mineralized groundwater. The destruction of the Kakhovka reservoir, the main source of freshwater, led to the shutdown of 94% of irrigation systems in the Kherson region (Economic Consequences, 2023). This, together with the destruction of canals and hydraulic structures, makes it difficult to carry out the necessary remedial measures in a short time after the restoration of control over the territory. The analysis of Earth remote sensing data (NDVI and NDMI) shows the lack of vegetation and potential soil degradation in a significant part of the Skadovsk district of the Kherson region, where rice fields are located (Klimov S., et al., 2023).

During the last fifty years, the soils of rice irrigation systems in the south of Ukraine were in a periodic leaching regime, which led to the formation of complex complexes of water and soil processes. The cessation of irrigation due to the active hostilities of the Russian Federation and the occupation of the territory led to changes in the water-salt balance, as a result of which the hydrogeological and melioration of these territories deteriorated (Vargas R., et al., 2018; Irrigation and Drainage Strategy in Ukraine until 2030).

The restoration of soils can be significantly complicated due to the lack of the necessary volume of water for traditional washing, which will lead to the activation of secondary salinization processes, loss of soil productivity, and ecological disaster.

The purpose of the research is to develop environmentally safe and resource-saving technologies for leaching saline soils of rice systems in order to increase their productivity. Leaching technologies must take into account the peculiarities of natural-climatic, soil, hydro-geological improvements and economic conditions. They must provide the necessary parameters of water, salt and air regimes of the soil, optimal conditions for soil formation, rational use of water resources and meet ecological requirements for the preservation of the environment.

To achieve the goal, technologies for regulating the water-salt regime of the soil during the cultivation of rice and related crops on saline lands have been developed, which take into account the peculiarities of the accumulation of salts during the growing season, which makes possible to justify the structure of rice crop rotation.

A method of calculating leaching norms has been developed, which is based on the complex application of deep loosening and periodic irrigation, the maximum involvement of soil moisture in the leaching process, and the use of the natural thermal effect.

The implementation of these technologies for leaching saline soils can be an important step in restoring fertility and increasing the productivity of rice systems in conditions of water scarcity and climate change.

THE SALINITY BALANCE OF THE RICE SYSTEM

Studying the water and salt regime of rice irrigated areas is important for general control of land reclamation conditions and prevention of secondary soil salinization processes, deterioration of land reclamation conditions on newly developed land massifs, as well as for the development of scientifically based measures for the reclamation of lands already salted and removed from agricultural production.

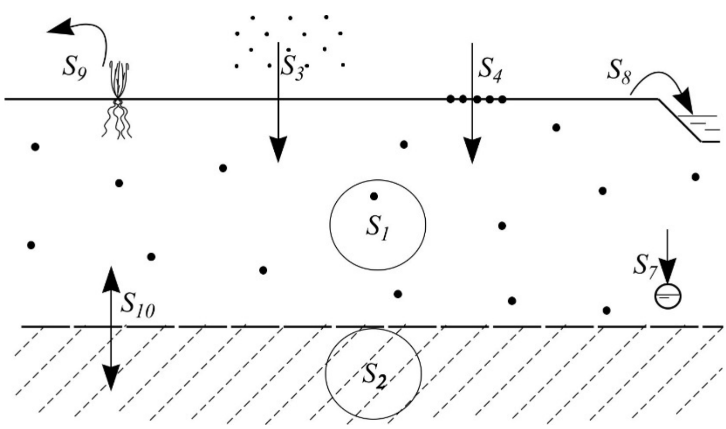
The main agroecological feature of saline soils is the presence of harmful salts in the root zone in quantities exceeding the permissible levels for the development of agricultural plants, or leading to a significant reduction in their productivity.

The intensity of soil salinization in rice systems during prolonged cultivation of flooded rice was determined by the initial salinity and the chemistry of readily soluble salts, water permeability, the location of the investigated areas relative to the irrigation and drainage network, and the ability of drainage to actively influence the level and salt regime of groundwater, primarily depending on the construction and parameters of the latter.

The forecast of changes in the salt regime can be made based on the analysis of components of the salt balance equation (Stashuk V.A., et al., 2017). Solving this equation helps answer the question of how the salt content in the soil layer will change by the end of the calculation period.

The salt balance is usually calculated for a layer that includes the aeration zone and the upper layer of groundwater. It is precisely in this layer that a relatively intensive redistribution of salts occurs, significantly affecting the yield of agricultural crops (Figure 1).

Figure 1. Salinity balance of irrigated lands



The calculation of the salt balance is carried out using the equation

$$S_1 + S_2 + S_3 + S_4 = S_5 + S_6 + S_7 + S_8 + S_9 \pm S_{10}, \quad (1)$$

where S_1 – the reserves of salts in the soils of the aeration zone of the balance layer at the beginning of the calculation period; S_2– the reserves of salts in the groundwater of the balance layer at the beginning of the calculation period; S_3 – the influx of salts from irrigation water; S_4 – the influx of salts from fertilizers; S_5 – the reserves of salts in the soils of the aeration zone of the balance layer at the end of the calculation period; S_6 – the reserves of salts in the groundwater of the balance layer at the end of the calculation period; S_7 – the removal of salts with drainage water; S_8 – the removal of salts with runoff water; S_9 – the removal of salts with the harvest; S_{10}– the salt exchange with lower horizons. All components are measured in kg/ha.

The reserves of salts in the soils of the aeration zone and in the groundwater of the balance layer are determined based on the results of soil salinity surveys, which are conducted twice a year in Ukraine.

The salt reserves in the aeration zone are calculated using the formula

$$S_{1(5)} = 0{,}1 \cdot \alpha_i \cdot \rho_i \cdot h_i, \text{ kg/ha} \tag{2}$$

where α_i – the total salt content, % of the dry soil mass; ρ_i – the average bulk density of the soil, t/m^3; h_i – the thickness of the aeration zone, m.

The salt reserves in the groundwater of the balance layer are calculated using the expression

$$S_{2(6)} = 10 \cdot \alpha_i \cdot n_i \cdot h_i, \text{ kg/ha} \tag{3}$$

where α_i – the mineralization of groundwater, g/l; n_i – the active soil exchangeability, parts per unit; h_i – the thickness of the groundwater layer in the balance layer, m.

The influx of salts from irrigation water is calculated using the equation

$$S_3 = 1000 \cdot \alpha_{\text{av}} \cdot M, \text{ kg/ha} \tag{4}$$

where α_{av}– the average mineralization of irrigation water during the growing season, g/l; M – the irrigation norm, m^3/ha.

The influx of salts from fertilizers is determined based on data provided by land users regarding the quantity of fertilizers applied per hectare.

The removal of salts with drainage water is calculated using the formulas:

$$S_7 = \sum_{i=1}^{n} S_{7(i)}, \text{ kg/ha} \tag{5}$$

$$S_{7(i)} = 1000 \cdot \alpha_{dr(\text{i})} \cdot F_{dr(i)}, \text{ kg/ha} \tag{6}$$

where $\alpha_{dr(i)}$ – the average mineralization of drainage water for the decade, g/l; $F_{dr(i)}$ – the volume of drained drainage water for the decade, m^3/ha.

The calculation of salt removal with runoff water is conducted using the formulas:

$$S_8 = \sum_{i=1}^{n} S_{8(i)}, \text{ kg/ha} \tag{7}$$

$$S_{8(i)} = 1000 \cdot \alpha_{rn(\text{i})} \cdot S_{rn(i)}, \text{ kg/ha} \tag{8}$$

where $\alpha_{rn(i)}$ – average mineralization of runoff water for the i-th discharge, g/L; $S_{rn(i)}$ – volume of water discharged during the i-th discharge, m^3/ha.

Sampling of runoff water to determine its mineralization is conducted during each of the technological discharges. The value of $S_{rn(i)}$ is determined through direct measurements.

The displacement of salts from the balance layer into the lower horizons is calculated as the difference between the incoming and outgoing parts of the salt balance

$$S_{10} = S_1 + S_2 + S_3 + S_4 - S_5 - S_6 - S_7 - S_8 - S_9, \text{ kg/ha.} \tag{9}$$

The value of S_{10} allows us to assess the efficiency of the rice system in terms of soil leaching.

The pattern of salt accumulation and distribution in the vertical profile of the aeration zone imposes different requirements on the irrigation and leaching regimes, which should ensure the desalination process with minimal water consumption.

The mechanism of soil leaching is quite complex. Sorption, capillary, and gravitational forces play a key role in this process, which depend on the physical properties, degree, and chemistry of soil salinity and groundwater.

The selection of irrigation parameters should consider upward and downward moisture flows in the aeration zone, ensuring the improvement of the reclamation status of irrigated lands. According to Averianov S.F., if groundwater is mineralized or even lacks upward movement, salts, through their mobility and filtration diffusion, migrate and salinize the upper soil horizons up to 40-70% of groundwater mineralization (Averyanov S.F., et al., 1971).

This indicates the necessity of maintaining constant downward water movement during the operation of rice systems, as the creation of such groundwater flows ensures favorable levels of readily soluble salts in the soil.

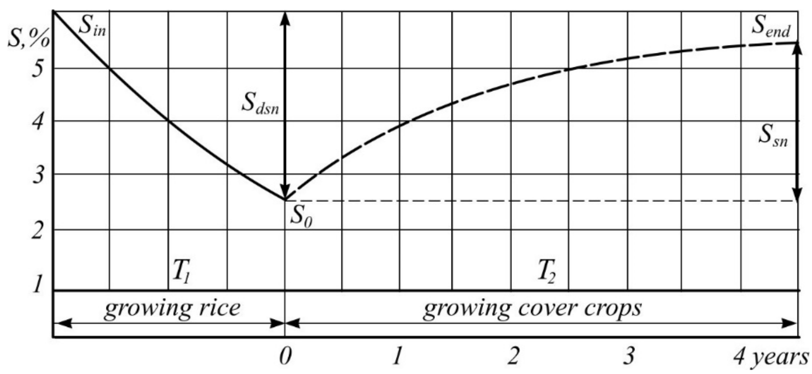
The intensity of the leaching regime in rice fields is determined by both the irrigation regime and the hydro-physical properties of saline soils.

JUSTIFICATION OF ENVIRONMENTALLY SAFE CULTIVATION PERIODS FOR CROPS ON SALINE SOILS

Reprofiling rice systems to conventional crop rotations or reducing rice plantings threatens secondary soil salinization in rice systems and deterioration of the agrochemical composition of soils and groundwater. Therefore, determining the permissible duration of cultivating companion crops after rice cultivation is relevant and allows for the proper regulation of rice rotations with rice and companion crops.

The dynamics of salt content in the active soil layer during rice and companion crop cultivation can be represented graphically (Figure 2).

Figure 2. Dynamics of salt content in the active soil layer during rice and companion crop cultivation: S_{in} *– initial soil salinity,* S_0 *– salt content at the end of the leaching period,* S_{end} *– salt content at the end of companion crop cultivation,* S_{dsn} *– soil desalination magnitude,* S_{sn} *– soil salinity magnitude,* T_1 *– leaching period,* T_2 *– period of soil salinization*



The magnitude of desalination during one year of rice cultivation depends on the initial soil salinity, grain size composition, type of soil salinity, and soil drainage (Table 1). A correlation has been established between the magnitude of desalination of the one-meter soil layer per year of rice cultivation and the aforementioned factors against the backdrop of satisfactory operation of the drainage-discharge network in soils of different granulometric compositions with chloride-sulfate and hydrocarbonate types of salinization. For other types of soil salinity, an adjustment should be made, which is 1.2 for chloride salinization and 0.85 for sulfate salinization (Kyrienko T.N., 1984). To determine the magnitude of desalination of a one-meter soil layer, a nomogram has been constructed (Figure 3).

Table 1. The value of desalination of a one-meter layer of soil during 1 year of rice cultivation with chloride-sulfate and bicarbonate soil salinization (rice system of the Kherson region, Ukraine)

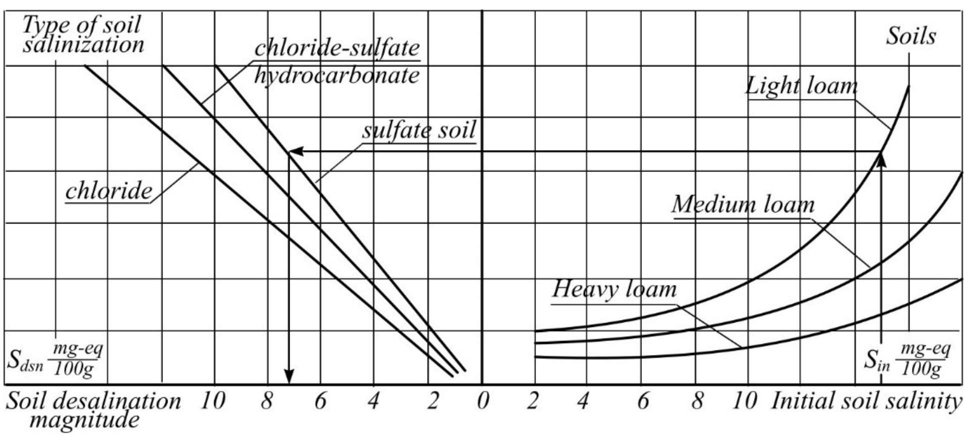
Granulometric composition of the soil	**Initial soil salinity S_{in}, mg-eq/100g of soil**		
	4	**10**	**15**
Soil desalination norm S_{dsn}, mg-eq/100g of soil			
Light loam	2.0	4.0	9.0
Medium loam	1.5	2.0	5.0
Heavy loam	0.8	1.0	2.0

Once the desalination norm is determined, the salt content at the end of the leaching period can be calculated

$$S_0 = S_{in} - S_{dsn}, \text{mg} - \text{eq}/100\text{g of soil} \quad (10)$$

where S_0 – the salt content at the end of the leaching period, in mg-eq/100 g of soil; S_{in} – the initial soil salinity, in mg-eq/100 g of soil; S_{dsn}– the amount of soil desalination, in mg-eq/100 g of soil.

Figure 3. Nomogram for determining the magnitude of desalination of a one-meter soil layer within one year of rice cultivation in the conditions of the Kherson region, Ukraine



During the non-irrigation period T_2, the salt reserves are restored in the soil due to upward water currents, the values of which depend on the intensity of salinization. At the end of period T_2, the salt content in a one-meter soil layer can be determined by the formula

$$S_{end} = S_0 + S_{sn}, \text{mg} - \text{eq/100g of soil} \quad (11)$$

where S_{end} – the salt content at the end of the companion crop cultivation, mg-eq/100 g of soil; S_{sn} – is the magnitude of secondary soil salinization, mg-eq/100 g of soil.

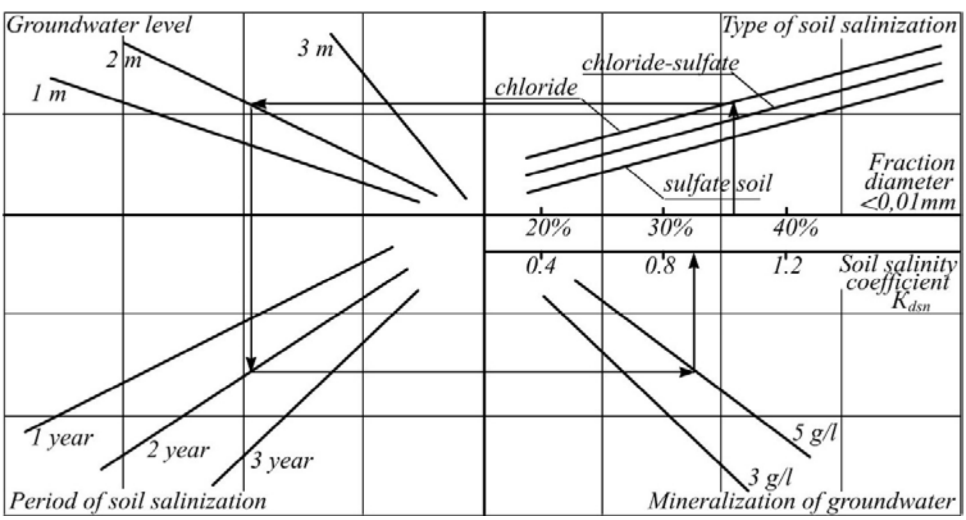
The magnitude of secondary soil salinization depends on several factors, the main ones being: the salt content at the end of the leaching period, the depth of the groundwater table, the particle size distribution, and the type of soil salinity, the mineralization of groundwater, and the duration of salinization.

The magnitude of secondary soil salinization of a meter-thick soil layer can be determined based on the aforementioned factors using the following expression

$$S_{end(i)} = S_0 + S_0 \cdot K_{dsn}, \text{mg} - \text{eq/100g of soil} \quad (12)$$

where $S_{end(i)}$ – the degree of soil salinity at the end of the companion crop cultivation period, mg-eq/100g of soil; K_{dsn} – the soil salinity coefficient during the period of cultivation of companion crops, the value of which can be determined using a nomogram (Figure 4).

Figure 4. Nomogram for determining the soil salinity coefficient during the period of cultivation of companion crops (rice system of the Kherson region, Ukraine)



The possible period of non-rice cultivation in rice systems is limited by the magnitude of secondary soil salinization, which should not exceed the permissible level

$$S_{end(\mathrm{i})} = S_0 + S_0 \cdot K_{dsn} < S_{per}, \text{ mg} - \text{eq/100g of soil} \tag{13}$$

where $S_{end(i)}$ – the permissible amount of salts in a meter-thick soil layer, mg-eq/100g of soil.

To prevent the development of secondary salinization processes during the cultivation of dryland crops, the groundwater level should be below a critical depth, which is determined in each specific case by the hydro-physical properties of the soil, its salinity, lithological structure, and climatic factors. The salt content in the soil depends on weather conditions, the groundwater level, their mineralization, the type of intercrop, and the level of agronomy practices.

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To ensure environmentally safe conditions for the functioning of rice systems, it is necessary to scientifically justify the structure of rice crop rotations and the selection of companion crops, apply periodic leaching regimes, and adhere to permissible levels of groundwater on saline lands of rice systems.

Introducing dryland crops into rice crop rotations will improve soil water-air regimes, increase soil fertility, and rid fields of specific rice weeds, diseases, and pests.

The application of such crop rotations allows for reducing the volume of irrigation water without allowing secondary soil salinization, using organic and cover crop fertilizers, implementing agronomic practices, maintaining proper phytosanitary and ecological-ameliorative conditions of the soil, and increasing the economic efficiency of the rice system.

Currently, there are several environmentally safe irrigation technologies for rice cultivation and companion dryland crops in rice rotations (Shereen A., et al., 2002; Xu Z., et al., 2020; Zhu C., et al., 2023; Stashuk V.A., et al., 2023, Turcheniuk V.O., et al., 2020, 2023; Dudchenko V.V., et al., 2011). This necessity arises from the projected climate changes in rice-growing areas, which anticipate decreased precipitation and increased air temperatures, potentially leading to increased moisture deficit and reduced moisture supply coefficient, necessitating significant increases in water supply volumes for rice crop cultivation.

However, in complex hydrogeological conditions of rice irrigation systems, the implementation of resource-saving irrigation regimes for rice rotations may lead to intensified evapotranspiration water regimes and the development of secondary salinization processes on irrigated lands, as observed in the 1990s in southern Ukraine (Kovaliov S.V., et al., 2002).

Thus, there is a need to optimize irrigation regimes and techniques for irrigating companion dryland crops in rice rotations based on ecological and economic principles. It is necessary to develop organizational, economic, technical, and constructive measures that will contribute to the creation of an effective system for rational use of the rice irrigation fund and improvement of the ecology-ameliorative state of agro-landscapes in rice-growing areas.

Therefore, maintaining the necessary water-salt regime of the soil is a prerequisite for the effective functioning of rice irrigation systems. This is achieved through the use of environmentally safe leaching technologies.

ILLUSTRATIVE EXAMPLE

An example of the calculation of salt content and dynamics over three years for the conditions of the Kherson region is given in the Table 2.

Table 2. Dynamics of salts in the 1-meter soil layer and possible periods of using rice fields for companion crops (rice system of the Kherson region, Ukraine)

Granulometry composition of soils	**medium loam**											
Type of soil salinization	**chloride-sulfate-hydrocarbonate**											
Initial soil salinity, mg-eq/100 g	2				3				4			
Removal of salts for 1 year of rice cultivation, mg-eq/100 g	0.8				1.2				2.0			
Salt content at the end of the leaching period, mg-eq/100 g	1.2				1.8				2.0			
Permissible amount of salts, mg-eq/100 g	4.1				4.1				4.1			
Groundwater level, m	1.0		2.0		1.0		2.0		1.0		2.0	
Mineralization of groundwater, g/l	3	5	3	5	3	5	3	5	3	5	3	5
Salinity coefficient (year 1)	0.56	0.73	0.46	0.60	0.56	0.73	0.46	0.60	0.56	0.73	0.46	0.60
Salt content at the end of the 1st year, mg-eq/100 g	1.88	2.08	1.75	1.92	2.80	3.11	2.63	2.88	3.12	3.46	2.92	3.20
Salinity coefficient (year 2)	0.88	1.11	0.72	0.92	0.88	1.11	0.72	0.92	0.88	1.11	0.72	0.92
Salt content at the end of the 2nd year, mg-eq/100 g	2.25	2.53	2.06	2.30	3.38	3.80	3.10	3.46	3.76	4.22	3.44	3.84

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Table 2. Continued

Granulometry composition of soils	medium loam											
Type of soil salinization	chloride-sulfate-hydrocarbonate											
Salinity coefficient (year 3)	1.08	1.32	0.87	1.10	1.08	1.32	0.87	1.10	1.08	1.32	0.87	1.10
Salt content at the end of the 3rd year, mg-eq/100 g	2.50	2.78	2.24	2.52	3.75	salin.	3.37	3.79	salin.	salin.	3.74	salin.

According to the obtained data, the implementation of dryland crop rotation in rice systems leads to the restoration of the water-salt regime and soil salinization already at the end of the third year of growing companion crops. This can lead to soil degradation and a sharp decrease in yields.

To prevent secondary soil salinization in rice systems and deterioration of the agrochemical composition of soils and groundwater, it is necessary to determine the permissible duration of cultivating companion crops after rice cultivation in advance. In our case, this amounts to two years.

METHODS OF LEACHING SALINE LANDS OF RICE SYSTEMS

Rice systems in Ukraine are predominantly located in areas with complex hydrogeological conditions, saline soils in the aeration zone, and shallow levels of mineralized groundwater. Therefore, when developing new territories for rice systems or after prolonged cultivation of companion crops, there may be a need for intensive leaching of saline lands.

Moreover, recent weather and climatic conditions differ from previous years and long-term averages, with an increase in air temperatures during the summer period. Increased evaporation from the surface of fallow rice fields with shallow mineralized groundwater undoubtedly activates salinization processes.

The effectiveness of leaching depends on the soil's hydro-physical properties, its salinity level, and the depth of groundwater.

Norms and timing of leaching. Leaching is carried out by applying a specific volume of water (leaching norm) to saline lands, which dissolves salts and displaces them as a solution into groundwater intercepted and discharged by the drainage network.

The leaching norm is the amount of water required to remove excess salts in the calculated soil layer per hectare. It consists of two components: the amount of water needed to saturate the calculated soil layer to field capacity and the amount needed to leach out dissolved excess salts.

Various methods exist for determining the leaching norm. The formula proposed by V.R. Volobuyev is commonly used to determine the leaching norm in drained rice territories (Volobuyev V.R., 1974)

$$M = 10000 \cdot \alpha \cdot \lg\frac{S_0}{S_{per}},\ m^3/ha \quad (14)$$

where M – the leaching norm, m^3/ha; S_0 – the initial soil salinity content (1.0 m), %; S_{per} – the permissible soil salinity content after leaching, %; α – the empirical salt yield coefficient (Table 3).

Table 3. The value of the salt yield coefficient α depending on the type of salinity and the granulometric composition of soils (according to V.R. Volobuyev)

Soils	**Type of salinity**		
	chloride	**chloride-sulfate**	**sulfate**
Sandy and sandy loams	0.62	0.72	0.82
Medium loam	0.92	1.02	1.12
Heavy loamy	1.22	1.32	1.42

Depending on the granulometric composition, type and degree of soil salinity, the leaching norm can be from 1.0 to 10 thousand m^3 or more (Table 4).

Table 4. Leaching norms depending on the granulometric composition, type and degree of soil salinity (according to V.R. Volobuyev)

Initial content of salts in the soil, *So*, %	**Leaching norm depending on the type of salinity, *M*, m^3/ha**		
	chloride	**chloride-sulfate**	**sulfate**
Sandy and light loams			
0.4	2700	2200	1100
0.6	3800	3500	2500
0.8	4500	4400	3500
1.0	5100	5100	4300
Medium loam			
0.4	4000	3100	1400
0.6	5600	4900	3400
0.8	6700	6200	4800
1.0	7600	7200	5900
Heavy loamy			

continued on following page

Table 4. Continued

Initial content of salts in the soil, *So*, %	**Leaching norm depending on the type of salinity, *M*, m³/ha**		
	chloride	**chloride-sulfate**	**sulfate**
0.4	5200	4000	1800
0.6	7400	6300	4300
0.8	8900	8000	6100
1.0	10100	9300	7500

Leaching of the soil is best conducted during the autumn period when the soils are dry, and the groundwater is at greater depths, maximizing the soil's salt discharge.

Soil leaching is carried out in two stages. During the first stage, the soil layer is moistened to its minimum (field) capacity. Salts present in the soil dissolve during this stage. The second water application is carried out 4-5 days after the first. During the second stage, further dissolution of salts in the soil occurs, and they are displaced from the leaching layer into the groundwater and then into the drainage network. Each subsequent application is made after the previous one has soaked through.

The most effective leaching action of water is observed when the leaching norm corresponds to 30-40% of the maximum field capacity of the calculated soil layer. For a one-meter soil layer, this amounts to: on light soils – 700-900 m^3/ha; on medium soils – 900-1100 m^3/ha; on heavy soils – 1100-1500 m^3/ha.

A significant resource of washing water is the use of drainage and discharge water of rice fields. The suitability of these water for leaching is assessed by their general mineralization, chemical composition, concentration of individual ions and their ratio and combinations.

The use of drainage effluents for leaching salt-affected rice fields will enhance water use efficiency, reduce the volume of water drainage, and preserve and improve the ecological conditions of water bodies (Koltsov A.V., et al., 1994; Makovsky V.Y., 2002; Lukyanchuk O.P., et al., 2019).

Traditional flooding is a common method for leaching salt-affected soils, but it has both advantages and disadvantages. More efficient soil desalination methods have been proven through research, including periodic flooding, surface irrigation, and sprinkler irrigation, which require smaller leaching norms compared to constant flooding. Technologies for leaching heavy soils during restructuring are known, and new methods for leaching salt-affected soils, such as using polymers, are under study (Pessarakli M., et al., 2019, Stashuk V.A., et al., 2014; Oleynik, A.Y., et al., 1987; Tanton, T.W., et al. (1988, Vidal J., et al., 2021).

The dynamics of salt movement in the soil during leaching is a complex process influenced by natural and agricultural factors. Analyzing this process is essential for justifying land improvement measures aimed at the effective utilization of salt-affected lands. The theoretical foundations of the salt removal process during soil leaching have been adequately studied, enabling the effective resolution of tasks related to reducing excess salt content through physicochemical hydrodynamics (Letey J., et al., 2011; Tanton T.W., et al., 1988; Marcos M., et al., 2018; Kozishkurt S.M., et al., 2003). This primarily applies to sulfate and chloride salinization, prevalent in the rice grown regions of Ukraine.

Types of leaching of saline lands. The field (check) of the rice system according to its design features is prepared for leaching, does not require additional earthworks or other works, or special equipment. The check is limited by earthen embankments, water supply is carried out through channels of the irrigation network, drainage is carried out through an open or closed drainage and discharge network with the help of hydraulic structures.

The leaching of saline lands in rice fields varies in terms of water volumes, duration, and frequency, depending on the type of salinization and the construction of the rice system.

In most cases, leaching involves flooding areas with freshwater for several days, weeks, or even months. This method requires a significant amount of irrigation water, and the leaching depth roughly equals the depth of water infiltration during the leaching period.

The timing of continuous flooding for leaching is determined considering the maximum possible salinization. Therefore, the optimal period for Ukraine is from August to September when the soils are dry, groundwater is at greater depths, and salt release from the soil is highest. During this period, the expanded zone of soil aeration allows excess salts to be flushed into deeper soil layers or the drainage network, reducing the duration of leaching. The duration of leaching is determined based on the initial degree of salinization, water infiltration intensity, and the norm of salt dissolution in water within the soil.

The criterion for initiating the next stage of leaching on soils with hydromorphic properties is the depth of the groundwater level. For light soils, it should be between 1.0 to 1.5 m, while for heavy soils, it should range from 0.8 to 1.0 m (Stashuk V., et al., 2020).

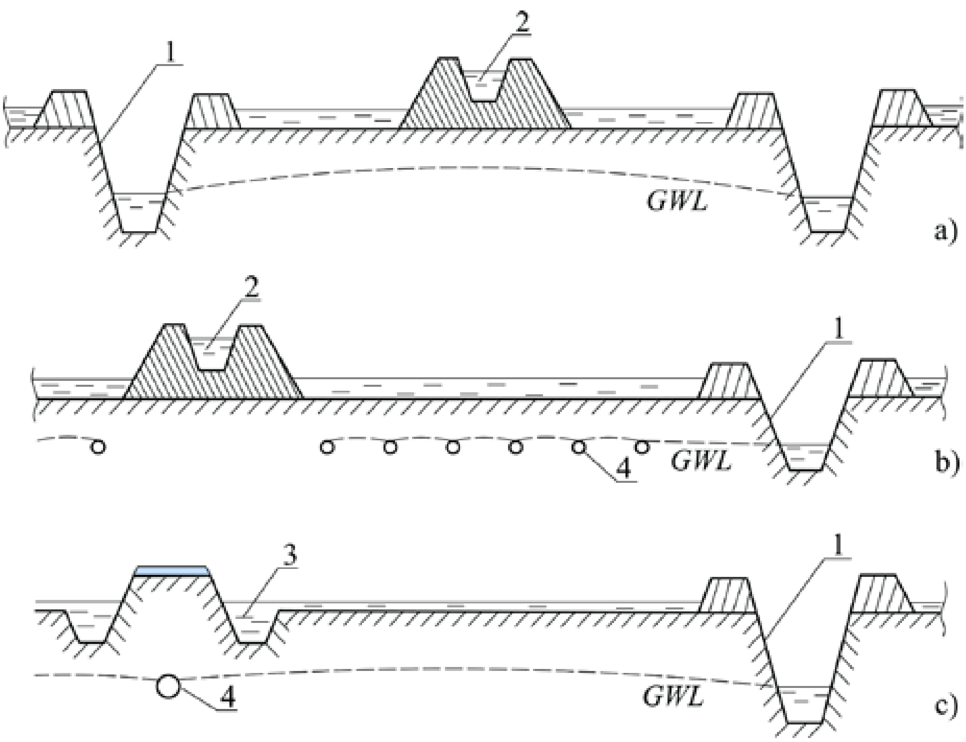
Leaching activities are categorized into capital and operational (preventive) leaching based on organizational and economic purposes. Capital leaching involves the primary removal of salts from the soil to acceptable levels. Operational (preventive) leaching aims to maintain acceptable salt levels in the soil after capital leaching, ensuring subsequent leaching of deeper horizons and reducing the mineralization of groundwater.

Depending on the quantity and duration of leaching, they can be classified as one-time (applying the entire leaching norm at once) or cyclical (leaching with reduced leaching norms). It is known that salt removal from the soil occurs more intensively under conditions of unsaturated flow, which occurs during periodic short-term flooding. This is due to the slow process of salt diffusion between soil pores during continuous flooding. Therefore, continuous flooding requires a larger volume of water for leaching compared to periodic flooding.

Leaching with norms exceeding 8000 m^3/ha typically occurs over two to three years. If the leaching norm reaches 15000 m^3/ha, it can be combined with rice cultivation in floodplain and deltaic areas, as demonstrated in Ukraine (the Danube Delta).

Depending on the construction of the rice system, leaching is carried out against the backdrop of open (Figure 5, a) or closed (Figure 5, b, c) drainage systems. In rice systems, closed drainage can be systematic or selective.

Figure 5. Leaching of salt-affected soils against the background of: a) open drainage network; b) closed drainage network with selective drainage; c) closed drainage network with systematic drainage; 1 – drainage channel; 2 – irrigation channel; 3 – irrigation-discharge channel; 4 – drain



With the aim of ensuring the necessary desalination of the soil's calculated layer, preventing salt restoration during the non-rice period, creating optimal soil formation conditions, and increasing the efficiency of the drainage network, scientists have proposed various implementation options for leaching taking into account the designs of rice irrigation systems.

The existing (traditional) method of leaching saline soils of rice systems involves prolonged flooding of checks during rice cultivation on rice field constructions against the background of check drainage with minimum distances between drains of 200-500 m and depths of 1.3-1.5 m.

Water consumption using this technology is associated not only with significant recommended irrigation norms but also with potential drawbacks in conducting flushes. Among such drawbacks, insufficient drainage of leaching areas and poor field surface planning for flooding can be noted.

Research have shown that the features of the movement of filtration flows on irrigation maps during the period of maintaining the water layer are that a zone of groundwater bulging (along irrigation canals) and a stagnant zone in the center of the check is formed on part of their areas. While the active movement of groundwater occurs only on part of the area directly adjacent to the drainage and discharge channels (Kovaliov S. V., et al., 2002).

The total area that is practically not drained exceeds 60% of the irrigated field area. This results in unstable soil and groundwater desalination, allowing for the cultivation of companion crops without significant salt restoration but only for a short period.

Leaching against the background of systematic closed internal check drainage. The proposed method involves leaching the soil during rice cultivation while maintaining the optimal soil salt regime against the background of systematic closed internal check drainage with the output of drainage runoff into a closed collector (Oleynik A.Y., et al., 1987).

This method will reduce the duration of leaching, which is particularly relevant when the proportion of rice in the crop rotation is reduced to 30%. It will ensure uniform irrigation and soil aeration across the entire area of the irrigation field, including the strips along the irrigation channels, creating safe conditions for growing companion crops in a short time, and increasing rice yield by 10-15 q/ha. This leaching method requires the implementation of a capital reconstruction of the rice system and significant material resources.

Leaching of saline soils against the background of selective drainage with the application of deep tillage. The drawback of the traditional leaching method is the uneven and shallow leaching of soils across the rice field, especially in its central part and in areas influenced by irrigation channels. Deterioration of the water-physical properties of soils, primarily their permeability, as a result of prolonged flooding, slow filling of checks with a water layer leading to the rise of mineralized groundwater to the active soil layer, slow drying of checks in the post-irrigation period due to large distances between drainage channels (200-500 m), and correspondingly low drainage of checks. Therefore, this leaching method is applied to checks with selective closed drainage, which reduces the distance between open drainage channels to 100-125 m (Lukyanchuk O.P., et al., 2019). Deep tillage is carried out as a highly effective measure to increase the water permeability of heavy soils before their leaching.

Deep ameliorative tillage will create conditions for rapid and uniform irrigation of soils across the rice field, ensure sufficient depth of desalination, and accelerate the drying of rice checks in the post-irrigation period. Deep tillage significantly improves the aggregate composition and water permeability of soils in the upper layer with a thickness of not less than 0.6 m, thereby positively influencing their water-physical properties and agro-ameliorative condition overall.

The advantage of the proposed method of leaching saline soils in rice irrigation systems against the background of previous deep tillage is the uniform desalination of soils across the entire rice field area and to a greater depth, reduction in leaching duration, rapid lowering of groundwater levels in the post-irrigation period, accelerating harvest and autumn soil processing, improving soil oxygen regime, and consequently increasing rice and other crop yields in crop rotation.

Soil leaching against the background of an open drainage network with periodic irrigation.

Capital leaching. The mechanism of soil leaching is quite complex, with sorption, capillary, and gravitational forces playing a key role, which depend on the physical properties, degree, and chemistry of soil and groundwater salinization.

In simplified terms, moisture and salt transport in the soil can be represented as follows. The soil has a porous environment in which, when filled with water, salts dissolved in it occur. Under the action of gravitational forces, a portion of this solution flows into lower layers (or drainage systems), resulting in the desalination of the upper soil layers.

However, not all water in the soil participates in dissolving and transporting salts. Part of it is retained by the soil particles' surface with considerable force, resulting in the high density of this water, preventing salt dissolution and participation in moisture and salt transport. This water constitutes 5-8% of the soil mass and is called its maximum hygroscopicity.

Soil moisture occupying porous environments with diameters up to 600 microns is retained in the soil by meniscus forces, moves under the influence of moisture gradients, and is unaffected by gravitational forces, known as capillary, with its volume being the least water-retentive capacity of the soil.

Moisture occupying soil pores with diameters greater than 600 microns is not retained in the soil and moves as a filtration flow, driven by gravitational forces when moistening the soil above the capillary moisture reserve. Such moisture is called gravitational, with its volume being the water conductivity volume. The maximum water conductivity volume is determined as the difference between the total and minimum soil water-retentive capacities.

The volumes of capillary water and water conductivity constitute the soluble volume of soil moisture, determined by the difference between total moisture content and the volume of hygroscopic moisture in the soil. However, the actual soluble volume will be 7-10% less than determined due to the presence of trapped air in the soil pores. In calculations, this reduction can be accounted for by a coefficient of 0.9 (Kozishkurt S.M., et al., 2001).

Upon moistening the leaching soil layer to full moisture capacity, soluble salts transition into the soil solution. As a result of mixing, collision of different pore diameters, and the diffusion process, the concentration of this solution becomes approximately equal in both capillary and gravitational waters.

Therefore, during the leaching process, the active (calculated) soil layer needs to be saturated with leaching water to full moisture capacity through successive irrigation, equivalent to the water conductivity volume. With each successive irrigation, salts will be leached from the soil in an amount accommodated by the water conductivity volume. With each subsequent irrigation, the salt content in the leaching soil layer will decrease.

Certainly, mineralization and the volume of salt input with leaching water should be taken into account.

Mathematically, this can be represented as

$$S_{lch} = S_{in} - \frac{S_{in} + m \cdot C}{W_{sol}} m = \frac{S_{в}(W_{sol} - m)}{W_{sol}} - \frac{m^2 \cdot C}{W_{sol}}, \text{ kg/ha} \tag{15}$$

where S_{lch} – the stock of salts in the leaching layer of the soil after applying the leaching norm, kg/ha; S_{in} – the initial stock of salts in the soil at the beginning of leaching, kg/ha; W_{sol} – the soluble volume of water in the soil, m^3/ha; m – the leaching norm, m^3/ha; C – the mineralization of leaching water, kg/m^3.

If the expressions of constant values for specific soil conditions are marked $\frac{W_{sol} - m}{W_{sol}} = \beta$ and $\frac{m^2 \cdot C}{W_{sol}} = \gamma$, then equation (15) takes the form

$$S_{lch} = S_{in} \cdot \beta - \gamma, \text{ kg/ha} \tag{16}$$

Similarly, it is possible to determine the reserves of salts in the leaching layer of the soil after the second, third, etc. introduction of the leaching norm. Substituting the initial values of salt reserves into equation (16) as the final reserves after the previous irrigation, the general equation of the final salt reserve in the leaching layer of the soil through "*n*" leaching will be

$$S_{end} = S_{in} \cdot \beta^{n} - \gamma \cdot \beta^{n-1} - \gamma \cdot \beta^{n-2} - \ldots - \gamma \quad (17)$$

where S_{end} – the reserve of salts in the leaching layer of the soil at the end of leaching, which should not exceed the permissible reserve, kg/ha (t/ha).

With a certain number of contributions of separate leaching norms "*n*", the general norm of soil leaching will be

$$M = n \cdot m + \Delta W, \text{ m}^3/\text{ha}, \quad (18)$$

where ΔW – the volume required to saturate the estimated soil layer to the lowest moisture content at the beginning of leaching $\Delta W = W_{low} - W_{in}$, m^3/ha; W_{low} – the lowest moisture content of the soil, m^3/ha; W_{in} – initial moisture reserve in the soil, m^3/ha.

Preventive leaching. In addition to capital leaching during the cultivation of companion crops, autumn preventive irrigation is carried out to leaching the root zone of the soil from the seasonal accumulation of salts. Preventive leaching of saline lands is an important measure to preserve soil fertility and ensure high yields.

The accumulation of salts in the root zone of the soil during the vegetation period is determined by the equation

$$S_{grw} = \left(W_{g.w.} \cdot S_{g.w.} + M \cdot S_{ir.w.}\right) - S_{cr}, \text{ kg/ha} \quad (19)$$

where S_{grw} – accumulation of salts in the root layer of the soil during the growing season, kg/ha; $W_{g.w.}$ – volume of groundwater that participated in plant evapotranspiration, m^3/ha; $S_{g.w.}$ – salinity of groundwater that participated in plant evapotranspiration, kg/m^3; M – irrigation norm, m^3/ha; $S_{ir.w.}$ – mineralization of irrigation water, kg/m^3; S_{cr} – removal of a part of salts by the crop of companion crops (5% of the mass of salts can be accepted), kg/ha.

The amount of washed salts from the estimated soil layer during the growing season can be determined by the volume of water that filtered through the root layer and dissolved soil salts

$$S_{grw} = \rho \cdot W_{fil}, \text{ kg/ha} \quad (20)$$

where S_{grw} – amount of washed salts, kg/ha; ρ – saturation of the soil solution with salts, kg/m^3; W_{fil} – volume of water filtered through the estimated soil layer, m^3/ha.

The value of ρ is determined from the conditions of accumulation and dissolution of salts in the leaching layer of the soil

$$\rho = \frac{S_{grw} + M \cdot S_{ir.w.}}{M}, \text{ kg/m}^3 \quad (21)$$

The leaching norm is determined as the sum of the volume of water that has filtered through the leaching layer of the soil and the volume needed to saturate the soil to its minimum moisture content at the beginning of leaching:

$$M = W_{fil} + \Delta W, \text{ m}^3\text{/ha} \quad (22)$$

where ΔW – the volume required to saturate the estimated soil layer to the lowest moisture content at the beginning of leaching, m^3/ha.

Substitute the obtained formulas into formula (20)

$$S_{grw} = \frac{S_{grw} + \left(\Delta W + W_{fil}\right) \cdot S_{ir.w.}}{\Delta W + W_{fil}} \cdot W_{fil}, \text{ kg/ha} \quad (23)$$

Hence, the volume of water required to remove the accumulated salts during the growing season from the root layer of the soil will be

$$W_{fil} = \frac{-S_{ir.w.} + \sqrt{S_{ir.w.}{}^2 + 4 \cdot \frac{S_{ir.w.}}{\Delta W} \cdot S_{grw}}}{2 \cdot \frac{S_{ir.w.}}{\Delta W}}, \text{ m}^3\text{/ha} \quad (24)$$

ILLUSTRATIVE EXAMPLE

The example of the calculation of the volume of capital leaching under the same initial conditions according to two methods for the conditions of the Kherson region is given in Table 5.

Table 5. Calculation of the volume of capital leaching (on the example of the rice system of the Kherson region, Ukraine)

Type of soils	**dark chestnut**
Granulometric composition of soils	medium loamy
Type of soil salinization	sulfate-chloride

Type of soils	dark chestnut
Estimated soil layer	1.0 m
Initial salting	0.38% or 49.5 t/ha
Permissible salting	0.10% or 13.0 t/ha
Hygroscopic humidity	7% or 910 m^3/ha
Lowest moisture content of the soil	19% or 2470 m^3/ha
Full moisture content of the soil	30% or 3900 m^3/ha
Initial moisture reserve in the soil	16% or 2070 m^3/ha
Mineralization of irrigation water	0.4 g/l
Calculation of the leaching norm according to the method of V.R. Volobuyev	$M = 10000 \cdot 1.02 \cdot lg\frac{0.38}{0.10} = 5942$ m^3/ha
Calculation of the leaching norm according to this method	$W_{sol} = (3900 - 910) \bullet 0.9 = 2691$ m^3/ha
	$m = (3900 - 2470) \bullet 0.9 = 1287$ m^3/ha
	$\Delta W = 2470 - 2070$ m^3/ha
	$\beta = \frac{2691 - 1287}{2691} = 0.52$, $\gamma = \frac{1287^2 \cdot 0.0004}{2691} = 0.25$
	$S_{end} = 49.5 \cdot 0.52^2 - 0.25 \cdot 0.52^1 - 0.25 \cdot 1 = 13$ t/ha
	$M = 2 \cdot 1280 + 400 = 2960$ m^3/ha
Saving water	$5942 - 2960 = 2982$ m^3/ha or 50%

Comparison of the results of determining the norms of capital leaching of saline soils indicates that the proposed methodology allows for a more rational use of water resources. According to this methodology, water savings amount to 2982 m^3/ha or 50% of the leaching norms determined by V.R. Volobuyev's method.

The example of the calculation of the volume of preventive leaching for the conditions of the Kherson region is given in Table 6.

Table 6. Calculation of the volume of preventive leaching (based on the example of the Kherson region, Ukraine)

Type of soil	dark chestnut
Granulometric composition of soils	medium loamy
Type of soil salinization	sulfate-chloride
Estimated soil layer	1.0 m
Lowest moisture content of the soil	19% or 2470 m^3/ha
Initial moisture reserve in the soil	16% or 2070 m^3/ha
Irrigation norm	3000 m^3/ha
The share of soil water in evapotranspiration	15%

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Table 6. Continued

Type of soil	dark chestnut
Mineralization of ground water	2.0 g/l
Mineralization of irrigation water	0.4 g/l
Seasonal accumulation of salts in the estimated soil layer	$S_{grw} = (0.15 \cdot 3000 \cdot 2 + 3000 \cdot 0.4) \cdot 0.95 = 1995$ kg/ha
The volume of irrigation water for filtration, which will ensure the removal of salts from the root layer	$W_{fil} = \frac{-0{,}4 + \sqrt{0{,}4^2 + 4 \cdot \frac{0{,}4}{400} \cdot 1995}}{2 \cdot \frac{0{,}4}{400}} = 1227$ m^3/ha.

Therefore, during the prolonged cultivation of companion crops with small irrigation norms, absence of filtration losses during vegetative irrigation, and participation of mineralized groundwater in evapotranspiration, there is a seasonal accumulation of salts in the soil's root zone.

According to calculations, the volume of water required to remove accumulated salts during the vegetative period from the soil's root zone will amount to 1227 m^3/ha.

Conducting autumn preventive flushes will prevent soil salinization and eliminate the need for capital leaching.

IMPROVING THE EFFICIENCY OF LEACHING SALINE SOILS UNDER CONDITIONS OF WATER RESOURCE SCARCITY

The leaching regime on the soils of rice crop rotations, which have salinization properties or are prone to this process, not only have prevented its spread but also improved their physicochemical characteristics. The absence of irrigation due to the active military actions of the Russian Federation and the occupation of the territory led to the deterioration of the hydrogeological and land reclamation state of rice fields (Klimov S., et al., 2023).

Measures need to be taken to restore agricultural use of rice fields, halt degradation processes in the soils, and prevent salinization restoration within the shortest period possible. The restoration of irrigation systems and the Kakhovka reservoir will take a longer time. Therefore, given the limited water resources, it is necessary to actively seek new approaches to organizing the leaching of saline lands.

It is known that the most intensive removal of salts from the soil occurs under conditions of unsaturated flow, which is formed during periodic short-term flooding. Today, soil leaching using periodic flooding is quite common. Water for leaching is supplied at a specified frequency, with intervals ranging from 3 to 4 days at the beginning and from 7 to 8 days at the end of the leaching period, taking into account the seepage of previously supplied water.

However, the drawbacks of these methods include the fact that slow groundwater level decline, high evaporation norms, and inadequate drainage capacity lead to the re-salinization of the soil. This results in increased water consumption for salt removal.

When studying the advantages and disadvantages of known leaching methods, a comprehensive approach incorporating hydraulic and agronomic measures was proposed. The implementation of this method allows for a reduction in the volume of leaching water.

This method differs from standard periodic leaching in that, for more effective desalination of soils, a reasoned algorithm for performing technological operations of flooding, loosening, and drying of the soil is implemented.

Initial flooding of the area partially dissolves salts and carries them away in the form of a solution into the soil water or drainage network. The next stage involves measures to displace salts from the soil and accumulate them on the surface.

After each water application, once the soil reaches physical maturity, deep loosening is performed. This prevents the restoration of salts during the period between periodic flushes and enhances the effectiveness of heat action on soil desalination. During loosening, the size of gaps increases, porosity rises, and the contact area of leaching water with the soil expands.

Following deep loosening, the soil drying stage occurs, the duration of which depends on weather conditions. With rising soil temperatures, water evaporates from the soil solution in clods, depths, and shallow gaps, and salts are brought to the surface. These salts are easily leached out by subsequent water applications.

The intensive removal of salts from the soil observed when using the proposed method is explained by changes in some of its indicators (Table 7). For example, the porosity of the soil increases from 24% to 47%.

From the table, it can be seen that deep soil cultivation leads to an increase in fissuring, an enlargement of crevice dimensions, and consequently an increase in the contact area of leaching water with the soil.

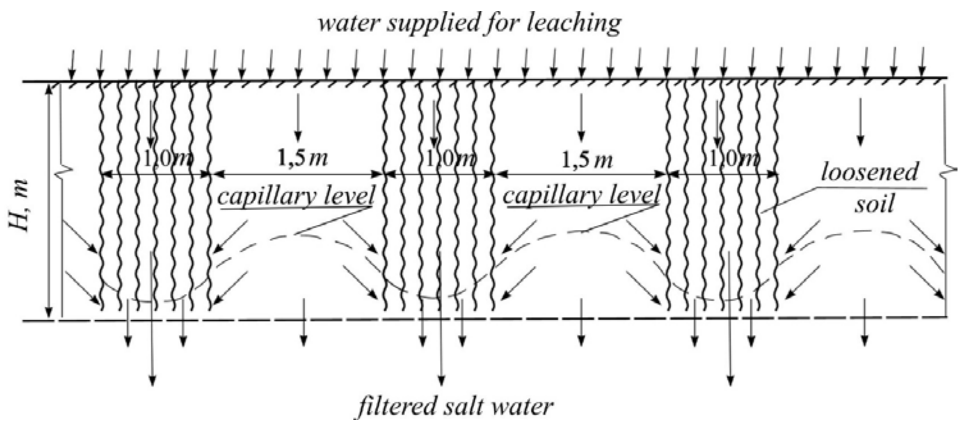
Table 7. Changes in soil indicators due to deep loosening, which affects the effectiveness of its desalination during leaching

Indicators	**Soil condition**	
	compacted soil	**loose soil**
Cross-sectional area of gaps, mm^2	$f=0,16 \cdot R^2$	$f=0,86 \cdot R^2$
Effective radius of gaps, mm	$r=0,23 \cdot R$	$r=0,52 \cdot R$
Soil porosity, %	$A = \frac{0.84 \cdot R^3 \cdot 100}{2\sqrt{3} \cdot R^3} = 24$	$A = \frac{3.8 \cdot R^3 \cdot 100}{8 \cdot R^3} = 47$
Height of capillary rise, mm	$h = \frac{15}{0,23R}$	$h = \frac{15}{0,52R}$

here R – the mean-weighted radius of soil particles, mm.

This soil leaching method involves conducting deep soil cultivation in strips to a depth of 0.6-1.0 m, with a distance of 1.0-1.5 m between the strips (Figure 6). The width of each strip should be 0.5-1.0 m. It is recommended to perform cultivation alternately perpendicular to the previous direction. With crosswise cultivation, soil blocks are formed, arranged in a checkerboard pattern. Drying of these blocks occurs faster due to contact with the loosened soil, which has better aeration properties than the non-loosened soil.

Figure 6. Movement of moisture during soil leaching against the background of deep band loosening



The peculiarity of the proposed method lies in achieving soil desalination not only through the gravitational transport of salts by water flow but also includes the mechanism of leaching salts, which accumulate on the surface of soil structural elements as a result of moisture evaporation.

After conducting deep strip tillage of the soils, clod-like elements are formed in the treated layer, between which monolithic areas are located, which intensely evaporate moderately mobile moisture in the range between field capacity and the moisture content at the capillary break. Moderately mobile moisture does not participate in salt transport during leaching, but it exhibits noticeable mobility during evaporation (Rode A.A., 1965).

Since the mineralization of moderately mobile moisture is higher than that of slightly mobile moisture, the salt content in the internal volume of soil elements and in monolithic layers of untreated areas decreases during evaporation, as salts concentrate on their surface.

Upon subsequent water application after soil drying, salt leaching occurs through gravitational water flow, moving them beyond the boundaries of the leaching layer. Part of the salts is carried down to lower layers, while the rest mixes with water towards drainage elements, including loosened strips, and is carried out beyond the flushed area.

Thus, the function of moderately mobile moisture lies in carrying salts to the surface of soil clods, from which they are flushed away by leaching water. Less water is required for this leaching compared to leaching salts through the soil layer via filtration. It is important to note that moderately mobile moisture, although part of the total leaching water volume, is inert and considered unproductive in land improvement practices.

After completing the initial stage of leaching and achieving the physical maturity of the soil, a repeated deep strip tillage is conducted, but across the direction performed during the previous tillage.

During the subsequent drying of the soil, a salt crust will re-form on the surface of soil clods and aggregates, which will be washed away by water during the next round of leaching.

Thus, this method of soil desalination is based on repeating cycles of tillage, drying, and leaching the soil until a certain level of desalination is achieved.

It is worth noting that the tillage process weakens the salt uplift from deeper layers, preventing re-salinization, as it leads to the destruction of capillaries.

The height of capillary rise depends on the composition of the soil, its physical and chemical properties, as well as external conditions such as atmospheric pressure and temperature. Therefore, by altering the density of the soil through deep tillage, we change the height of capillary rise.

The regularity of this change can be determined by Laplace's equation, according to which the capillary pressure of water wetting the soil gap equals

$$P = 2 \cdot \frac{a}{r}, \text{Pa} \tag{25}$$

where P – the capillary pressure of water, Pa; a – the surface tension, which at a water temperature of 10…15°C is equal to 74 N/m; r – the radius of the meniscus, which can be assumed to be equal to the radius of the capillary, m.

Under the pressure, water in the soil crevice rises to a height where the mass of the lifted column of soil water equals the force of capillary pressure and amounts to

$$P = h \cdot \rho \cdot g, \text{Pa} \tag{26}$$

where h – the height of capillary rise of soil water, m; ρ – the density of soil water, kg/m^3; g – the acceleration due to gravity, m/s^2.

By equating expressions (25) and (26), we obtain the equation

$$h \cdot \rho \cdot g = 2 \cdot \frac{a}{r}. \quad (27)$$

Hence, the height of capillary rise of groundwater will be equal to

$$h = \frac{2 \cdot a}{\rho \cdot g \cdot r}, \text{ m} \quad (28)$$

The quantity $\frac{2 \cdot a}{\rho \cdot g}$ is called the capillary constant, denoted as a^2, and its value can be taken as 15

$$\left(a^2 = \frac{2 \cdot 74}{1 \cdot 9{,}81} \approx 15\right)$$

Therefore, the height of capillary rise of groundwater will be equal to

$$h = \frac{a^2}{r} = \frac{15}{r}, \text{ mm} \quad (29)$$

where r – the effective radius of the soil fissure, mm.

As a result of a significant increase in fissure radius in loosened soils compared to compacted ones, the capillary rise decreases (Table 7). This phenomenon is observed not only in loosened soils but also in adjacent monolithic blocks (Figure 6).

Therefore, deep loosening prevents the restoration of salts between periodic leaching, reducing the height of capillary rise. And the proposed algorithm for performing technological operations will allow to increase the efficiency of washing saline lands in conditions of shortage of water resources.

THE DIRECTION OF FUTURE RESEARCH

Given that the research data are based on theoretical statements, further field experimental studies and clarification of some indicators depending on the specific conditions of the object are needed for implementation in reclamation practice.

CONCLUSIONS

1. In order to solve modern problems in managing the water-salt regime of soils in rice systems and to preserve their productivity under conditions of natural moisture deficit and limited water resources, scientific developments and

implementation of resource-saving and environmentally safe technologies for leaching saline soils are necessary.

2. Since the rice systems in Ukraine are predominantly built on territories with complex hydrogeological situation, salinized soils in the aeration zone, and shallow levels of mineralized groundwater, the need arises to establish a leaching water regime to maintain favorable ecological and reclamation conditions.
3. The introduction of dryland crops into rice crop rotations and the reduction of rice cultivation in them occurs due to the deficit of water resources in the rice sowing zone, which leads to the processes of secondary salinization of irrigated lands. Calculation of ecologically safe periods for growing dryland crops on saline soils will help to optimize the structure of rice crop rotations and prevent soil degradation. According to forecast calculations, restoration of soil salinity in the rice systems of the Kherson region is expected in the third year of cultivation of companion crops, therefore this period should be no more than 2 years.
4. In order to ensure the necessary desalination of the estimated soil layer and create optimal soil formation conditions, various variants of implementing soil leaching of rice irrigation systems were proposed, taking into account their design features. The proposed technologies for leaching saline soils will allow providing soil desalination evenly over the area and to a greater depth, reduce the duration of washing, quickly reduce the level of groundwater in the post-irrigation period and improve the oxygen regime of the soil.
5. A methodology for calculating the technological parameters of the thorough leaching of saline soils and its comparison with the existing method (V.R. Volobuyev's method) has been developed. According to the calculation, the standard for capital leaching is reduced by 50%.
6. Research has established that when growing companion crops during the growing season, salts accumulate in the root layer of the soil in the amount of 2.1 t/ha. To remove such a quantity of accumulated salts, the required volume of water for leaching will be 1227 m^3/ha, which will avoid the increase of initial salinity.
7. The proposed technology of soil desalination in conditions of shortage of water resources, which includes alternating processes of deep loosening, drying and leaching of the soil. Deep loosening improves the agrophysical parameters of the soil, increases the porosity of the soil from 24% to 47%, reduces the height of capillary rise. Drying of the soil by means of a natural thermal effect allows attracting medium-moving moisture to bring salts to the surface of soil lumps, from which they are washed away with irrigation water. This method requires less water for leaching compared to the removal of salts through filtration across a soil layer.

8. The introduction of these technologies and approaches to leaching saline soils can be an important step in restoring fertility and increasing the productivity of rice systems in conditions of water scarcity and climate change.

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Chapter 9
Predictive Assessment of Changes in Water Needs of Accompanying Crops of Rice Crop Rotation in Changing Modern Conditions

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ABSTRACT

The chapter considers an approach for assessing and forecasting the water needs

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of accompanying crops of rice crop rotation in changing modern conditions of rice irrigation system's functioning. The obtained results can be effectively used in the development of adaptive measures to the climate changes in the context of water, energy, and food crises, as well as in the justification of resource-saving regimes and technological solutions in projects of reconstruction and modernization of rice systems aimed at achieving the goals of optimizing the use of water and energy resources during their functioning. The chapter presents the results of a machine experiment on the predictive assessment of the water needs of accompanying crops in variable natural-agro-melioration conditions of the Danube area. The conditions of the water needs formation for various types of accompanying crops were determined according to accepted schemes of technologies and water regulation regimes on irrigated lands of rice systems. A comparison of the obtained results with real production data was carried out.

BACKGROUND

The existing global problems associated with climate change, food, water and energy crises pose a need for the world community, including Ukraine, to adapt to existing challenges and threats and to increase the efficiency of all spheres of economic activity, including the efficiency of agricultural production in the face of modern changing conditions and requirements (IPCC, 2020; FAO, 2019; Recovery Plan, 2022; Siddique, K. H. et al, 2016; Sourour, A., et al, 2017; Zhou, X. et al, 2017).

It is well known that melioration, and especially irrigation, is one of the most effective tools for reducing the negative effects of climate change on agricultural production, and irrigated lands harvest in 2–3 times higher harvest compared to rainfed lands.

In order to achieve the goals of restoring melioration in 2019 the Cabinet of Ministers of Ukraine approved the Irrigation and Drainage Strategy in Ukraine until 2030 (Irrigation and Drainage Strategy, 2019), and in 2020 adopted a plan for its implementation. In addition, to identify the existing needs for adaptation of economic sectors to climate change, in October 2021, the Cabinet of Ministers of Ukraine adopted the Strategy on Environmental Security and Climate Change Adaptation until 2030 (Strategy for Environmental Security, 2021), the first national document that creates a legislative framework for adaptation measures for systematic and long-term work on climate change adaptation.

According to the Institute of Water Problems and Land Reclamation of the National Academy of Sciences of Ukraine (Dehydration, 2020), while today about 62% of Ukraine's arable land belongs to areas with a natural water supply deficit of 150 mm or more, in 2050 there will be 67% of such land, and by 2100 their share will reach 80%. This means that more than 25 million hectares of arable land will be practically unsuitable for growing crops without artificial irrigation. In addition, there is a significant imbalance between the need for water resources and their availability in the regions, which is significant and catastrophic for the southern regions of the country, the zone of irrigated agriculture.

Given that under the conditions of climate change, water shortages in Ukraine's irrigation zone are expected to further worsen due to a decrease in the amount of water available and suitable for irrigation, there is an urgent need to review water policy and water management strategies to adapt to existing and projected changes.

Since the beginning of the full-scale war, the loss of Ukraine's sown areas caused by the temporary occupation and hostilities has amounted to more than 25% of the total amount, and the main part of these losses are highly productive irrigated lands. After Russia's terrorist attack on the Kakhovka Hydroelectric Power Plant, which led to a further reduction in sown areas, the problem of water shortages for irrigation, which is already relevant at both regional and global levels, reached a critical level (The destruction of the Kakhovka, 2023).

The most acute need for sustainable water management exists in the rice sector, which is one of the most water- and energy-intensive, due to the use of traditional surface irrigation by flooding in the cultivation of the leading crop – flooded rice, as well as the need to create and maintain a flushing water regime for saline soils, as a prerequisite for the effective functioning of rice irrigation systems (RIS) in the complex hydrogeological conditions of the rice growing area of Ukraine. Therefore, the implementation of effective water management on RIS requires, first of all, the improvement of water regulation technologies during cultivation of rice crop rotation, which has so far been considered mainly from the point of view of flooded rice cultivation (Stashuk, V. et al, 2016; Stashuk, V. et al, 2018). At the same time, the issue of improving irrigation techniques and irrigation regimes for the accompanying crops of rice rotation is still unresolved.

Thus, climate change leads to an increase in total evaporation and total water needs for the cultivation of both the leading crop flooded rice and the accompanying crops of rice crop rotation. The data on which are the basis for the development of design and formation of operational regimes of water regulation, which is carried out by managing water resources in the face of increasing water resource shortage through the justification and application of resource-saving methods and regimes of water regulation on irrigated lands of rice systems (Chen, Z. et al, 2021; Humphreys, E. et al, 2005; Liang, Hao et al. 2021; Nawaz, A. et al. 2022).

Since resource-saving technologies and methods of rice cultivation have been a priority so far and have already been developed, and the rational share of the accompanying crops in rice rotation should be 40–50% (Stashuk, V. et al, 2016; Stashuk, V. et al, 2018), the aim of our research is to assess changes in water needs for the accompanying crops in rice crop rotation on irrigated lands of the RIS to justify appropriate adaptive solutions.

Analysis of recent research and publications. The presented materials are an additional result obtained by us in the development of previous studies on the formation of water needs on drained lands, carried out within the framework of the joint project of the Institute of Water Problems and Land Reclamation of the National Academy of Sciences of Ukraine and the National University of Water and Environmental Engineering "Assessment of the impact of climate change on plant moisture supply and development of a GIS system for irrigation and water management".

Our studies of the weather and climatic conditions in the rice-growing zone of Ukraine confirm the presence of their changes and indicate a steady dynamics of increasing aridity of the region's climate (Romashchenko, M. et al, 2020). Assessing the situation as a whole, it is important to note that the current vegetation values of the main meteorological characteristics are close to or already in the zone of their predicted changes (Rokochynskiy, A. et al, 2020). At the same time, recent years have been characterized by record temperature highs and an increase in seasonal unevenness of precipitation, which negatively affects the natural soil moisture reserves available for crops.

The basis for determining the water needs of crops is total evaporation, the values of which depend primarily on the weather and climatic conditions of the area (Stashuk, V. et al, 2016; Stashuk, V. et al, 2018). Due to its complex dependence on numerous other factors, there are currently many models of evaporation intensity and its influencing factors that vary in complexity. Such models have been developed by I.A. Sharov, G.K. L'gov, S.I. Kharchenko, A.R. Konstantinov, M.I. Budyko, M.V. Danilchenko, D.A. Shtoyko, H.L. Penman, L. Turk, and others. Among foreign developments, the most popular are the Blaney and Kriedl, Thorntwain, and Penman-Monteith methods. At the same time, in Ukraine, the bioclimatic method of A.M. and S.M. Alpatyev is widely used for irrigated lands.

Thus, solving the problem of assessing changes in the water needs of crops grown under multiple variable conditions of a real object requires the use of an appropriate set of forecasting and simulation models implemented according to a long- term forecast.

To effectively implement such tasks, the Department of Water Engineering and Water Technologies of the National University of Water and Environmental Engineering has developed a set of forecasting and simulation models for assessing climatic conditions and meteorological regimes, water regime and water management technologies for drained lands, as well as their productivity. The practical application of forecasting and simulation models is regulated by the relevant sectoral regulations of the State Agency of Water Resources of Ukraine (Rokochinskiy, A. et al, 2008;

Rokochinskiy, A. et al, 2011; Rokochinskiy, A. et al, 2006). We have adapted these models for use in irrigation conditions.

The purpose of research is to estimate the changes in water needs for irrigation of the accompanying crops of rice crop rotation in the variable natural-agro-ameliorative conditions of rice system functioning. To achieve this goal, the was implemented a large-scale computer experiment, based on a complex of predictive-simulation models, which basing on a long-term forecast, allow to estimate weather and climatic conditions, water regime, water regulation technologies and the productivity of reclaimed lands. During the experiment the conditions of total evaporation formation were investigated, the water needs of different types of the accompanying crops of rice crop rotation were determined for the technology and regime of water regulation on the irrigated lands of rice systems for the typical groups of vegetation periods of target years in view of general heat and moisture provision. It was evaluated technological efficiency of irrigation of the accompanying crops of rice crop rotation in the variable natural-agro-ameliorative conditions of rice system functioning and obtained results with the actual production data were compared.

Research methods and materials. The research methods are based on the application of systems theory with the basics of the system approach, system analysis and modelling, focused on the widespread use of computers, and appropriate methodological, software and information software in the development of modern approaches to substantiating technical and technological solutions for water management of irrigated lands in changing natural-agro-ameliorative conditions.

To achieve this goal, we planned and carried out a large-scale computer-based machine experiment to substantiate the water needs of the accompanying crops of rice crop rotation under the studied conditions.

The object of the research is the group of rice systems in the Danube Delta in Odesa region – Danube RIS (Figure 1) with a total area of 13.6 thousand hectares, the constructive, natural-agro-ameliorative conditions of which are typical for most rice systems in Ukraine. The Danube River is the source of irrigation and the water recipient of drainage and discharge waters of the systems.

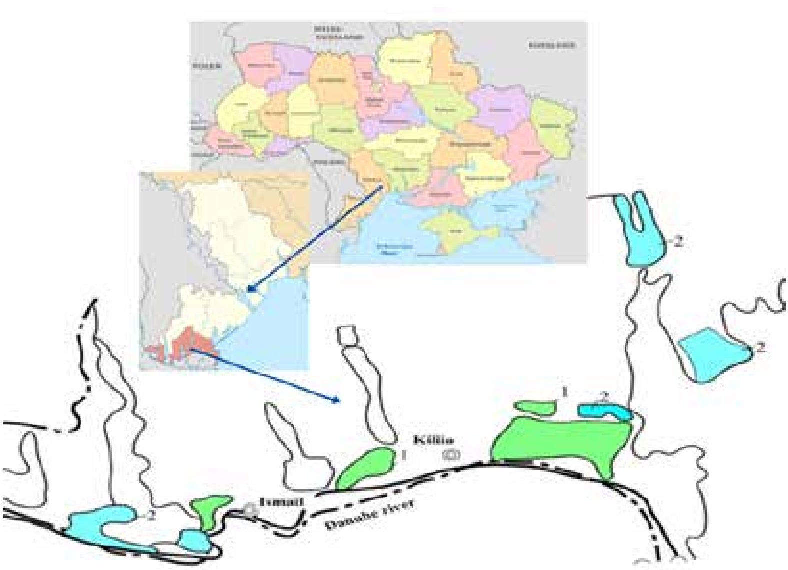
Among the operating rice systems of the Danube RIS group for the research was chosen the Kiliia RIS that by its conditions and characteristics is typical for the studied region. Kiliia RIS located on the previously saline East Kiliia floodplain territory of the Danube delta (Turcheniuk, V. et al, 2023).

Soils in the Kiliia RIS are mainly represented by loamy. Before the construction of the Kiliya RIS, the depth of the groundwater level ranged from 0.0 to 2.5 m, and its general slope was directed towards the Danube River.

The salt content of the groundwater ranged from 10 to 30 g/l, in some cases reaching 70 g/l. The mineralization of the groundwater increased from the waterlogged part of the floodplain to its central part.

For a long period of rice cultivation in the Kiliya RIS, desalination of groundwater occurred, resulting in a decrease in mineralization to 1.5–15.0 g/l that created favorable conditions for the accompanying crops cultivation.

Figure 1. Location of rice irrigation systems in the Odesa region of Ukraine (coordinates: 45°28′59′N 28°55′43′E): 1 – operating (existing) systems; 2 – planned future systems



Regarding the state of weather and climate conditions and their changes in Figure 2 presented comparative assessment of normalized values of basic meteorological characteristics of the zone of the Danube RIS for the period of 1981–2023 along with their retrospective and prospective rates.

To research the changes in weather and climate conditions (from the retrospective to the recent conditions and perspective) were implemented the following variants of research for the average conditions of the rice-growing zone of Ukraine (for the conditions of Danube RIS in Odessa region):

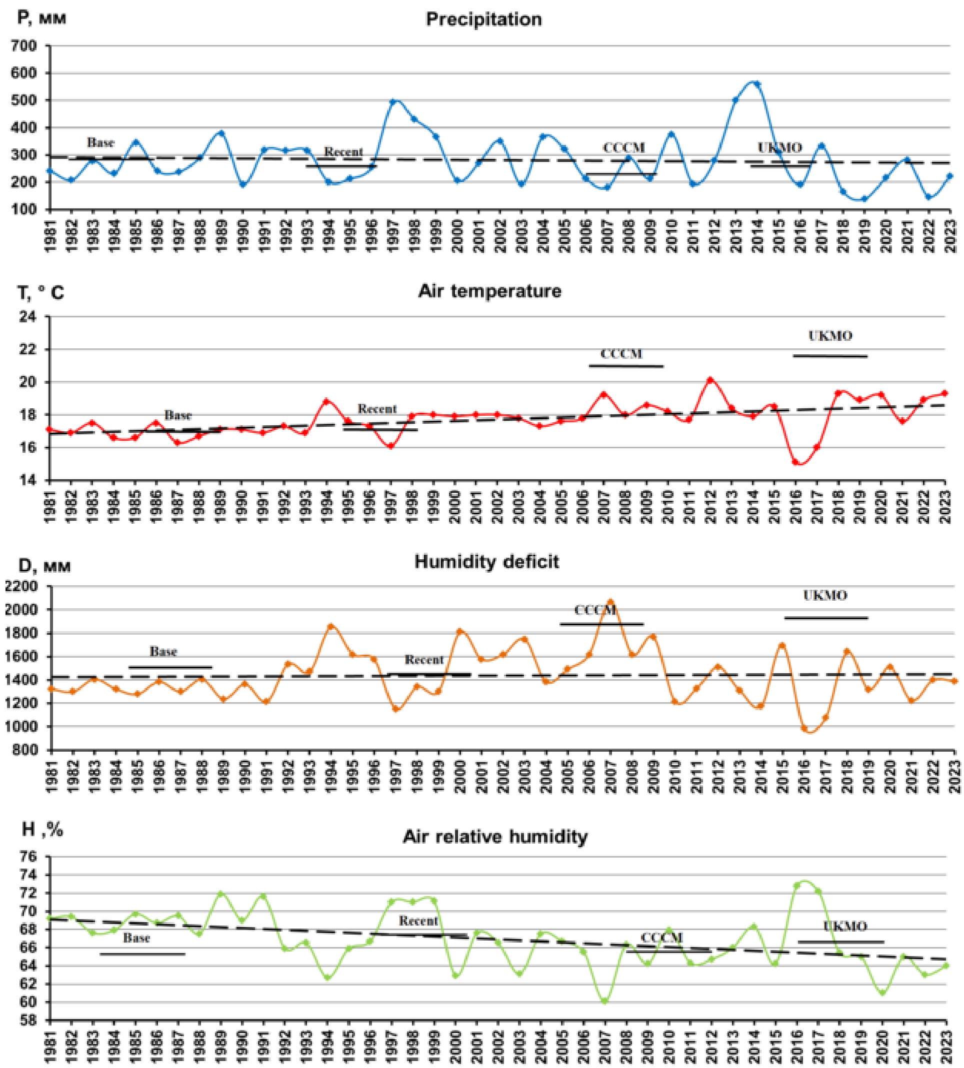
- ***"Base"***: characterization of the meteorological characteristics over a period of vegetation (months IV-X), obtained on the base of long-term retrospective data (1891–1964) (Hydrometeoyzdat, 1990);
- ***"Recent":*** characterization of the dynamics and standardized average long-term values of the variables of basic meteorological characteristics and their

distribution over the vegetation period, obtained under recent conditions over the years of 1981–2023;

- ***"CCCM"***: characterization of standardized average long-term values of the variables of basic meteorological characteristics and their distribution over the vegetation period, obtained in view of current and predicted climate change, in accordance with the recommendations (Romashchenko, M. et al, 2003), by the model of Canadian Climate Center "CCCM" – as a more favorable forecast, that foresee an increase in average annual temperature up to 4° C – provided that the doubling CO_2 in atmosphere occurs (Romashchenko, M. et al, 2003; Shevchuk, V. et al, 2001).
- ***"UKMO"***: characterization of standardized average long-term values of the variables of basic meteorological characteristics and their distribution over the vegetation period, obtained in view of current and predicted climate change, in accordance with the recommendations (Romashchenko, M. et al, 2003), by the model of the United Kingdom Met Office "UKMO" – as a less favorable forecast, that foresee an increase in average annual temperature up to 6° C relatively – provided that the doubling CO_2 in atmosphere occurs (Romashchenko, M. et al, 2003; Shevchuk, V. et al, 2001).

Practicability of the application of "CCCM" and "UKMO" models is proved by their capabilities to involve both less and more critical scenarios of changing weather patterns, and they perfectly comply with the predictive estimate of the rationing of basic meteorological characteristics in the long-term and one-year vegetation context (Rokochinskiy, A. et al, 2008).

Figure 2. Comparative assessment of normalized values of basic meteorological characteristics by the variants of research regarding the dynamics of their valid values in conditions of the rice-growing zone of Ukraine



The obtained results enable to make the following statements:

- **as to precipitation (P, mm)**: there is a significant amplitude of their change for the considered period from 180 to 550 mm at the rate of 287 mm with clearly pronounced maxima in 1997 and 2014 and relatively stable changes in their values in subsequent years after 2017. The average annual rate of precipitation for the model "Recent" is less than the average annual norm of the "Base" model;

- **as to air temperature (T, ° C)**: there is a different picture since 1981 the amplitude of changes reaches the first maximum in 1994 – 18.9° C, and rapidly drops to 15.9° C in 1997, after there is a gradual increase of air temperature to the second maximum in 2007 – 19.3°C, and the third in 2012 – 20.2° C. There is a clearly pronounced trend of temperature rise over recent years, but their average annual values are much lower than their forecasted norms by the models "CCCM" and "UKMO", although the average annual rate for the model "Recent" is somewhat higher than the average annual rate for the model "Base";
- **as to air humidity deficit (D, mm)**: the dynamics of changes in air humidity deficits, in general, reflect the characteristic features of the change for precipitation and temperature. The air humidity deficit reaches the first maximum in 1994 – 1850 mm with the average vegetative value of 8.69 mm, after it is similarly reduced to 1150 mm or 5.40 mm in 1997, and then gradually rises to the second and third maximums in 2000 and 2007 – respectively 1810 mm or 8.50 mm and 2150 mm or 10.1 mm. The gradual decrease to the second group of minima takes place in 2010 and 2014 – respectively 1215 mm or 5.70 mm and 1175 mm or 5.52 mm. At the same time, its average annual norm according to the model "Recent" is lower than the average annual norm for the model "Base", and its corresponding norms for models "CCCM" and "UKMO" are already within the limits of modern changes;
- **as to air relative humidity (H, %)**: there is an opposite situation to the dynamics of change of the air humidity deficit, here the first two maximums (about 72%) in 1989 and 1991, after which there is a rapid decrease to the first minimum of 62.9% in 1994. A similar increase to the other highs of about 72% occurs in 1996–1999 with the gradual decrease the amplitude of changes to the second group of minimums ≈ 63% in 2000 and 2003. Since the next minimum (≈ 60%) in 2007, there has been a tendency to further increase of the air relative humidity value. At the same time, the average annual norm of air relative humidity for the model "Recent" is much higher than its average long-term norm for the model "Base", and its corresponding norms for models "CCCM" and "UKMO" are already within the limits of modern changes.

In whole the forecasted values of studied meteorological characteristics for the models "CCCM" and "UKMO" in the rice-growing zone of Ukraine, except air temperature, are already within the limits of modern changes and even exceed them by separate positions, which indicates a steady trend of weather and climate change in the region.

The obtained results of the comparative estimation of weather and climatic conditions in the rice-growing zone of Ukraine testify to the fact that for almost all basic meteorological characteristics (except air relative humidity) are already undergoing changes. In the near future, these changes may exceed the 10 percent critical ecological threshold (first it concerns air temperature as the determining factor of modern climate change, as well as FAR, as its derivative), that according to N.F. Reimers will lead to corresponding irreversible changes in the environmental state of the region.

Accordingly, all these changes in weather and climate conditions have a direct impact on the conditions of agricultural production and the need for water resources for crop irrigation.

As experience and practice have shown, the most widely used for irrigation of the accompanying crops of rice crop rotation are traditional surface irrigation by flooding (similar to rice irrigation) and sprinkler irrigation in the context of modern technological, economic and environmental requirements are not sufficiently effective.

Therefore, among the options for water management technologies, we have considered an improved version of surface irrigation by flooding, which is structurally provided for implementation in rice systems (Rokochinskiy, A. M. et al, 2018). It involves irrigation of the accompanying crops of rice crop rotation by flooding them with a layer of water of 2–4 cm cyclically and only in the dark. The irrigation rate varies according to the dynamics of total evaporation and precipitation during the growing season and is 200–400 m^3/ha. If the daily water needs of crops is 5–7 mm, the irrigation rate is 2–6 thousand m^3/ha. The irrigation rate for one cycle is provided and controlled by water outlets equipped with hydraulic automatons that supply the calculated flow rate from the irrigation canal of the rice system at night. The advantages of such cyclic irrigation at night are a reduction in unproductive losses of irrigation water due to evaporation from the soil surface and total evaporation, and more rational use of water and energy resources in the system.

The new patented technology is aimed at maintaining a favorable ecological and reclamation condition of the irrigated lands of the RIS in accordance with modern ecological and economic requirements in general, which will improve the growth conditions and productivity of related crops in the rice rotation.

In addition, in the rice-growing areas and adjacent territories, there is a so-called supported groundwater level (GWL) with a depth of 0.8–1.2 m. That is, about 60% of the system operates in this regime, while the rest of the system and areas with elevated ground surface elevations operate in the unsupported water level regime with a depth of 1.4–2.0 m. Since the supported and unsupported DGW regimes significantly affect the formation of moisture exchange, water regime and productivity of irrigated lands, it is necessary to make their forecasts taking into account the corresponding background GWL regime.

Based on the above, the predictive calculations in the machine experiment were performed under the following multiple variable conditions:

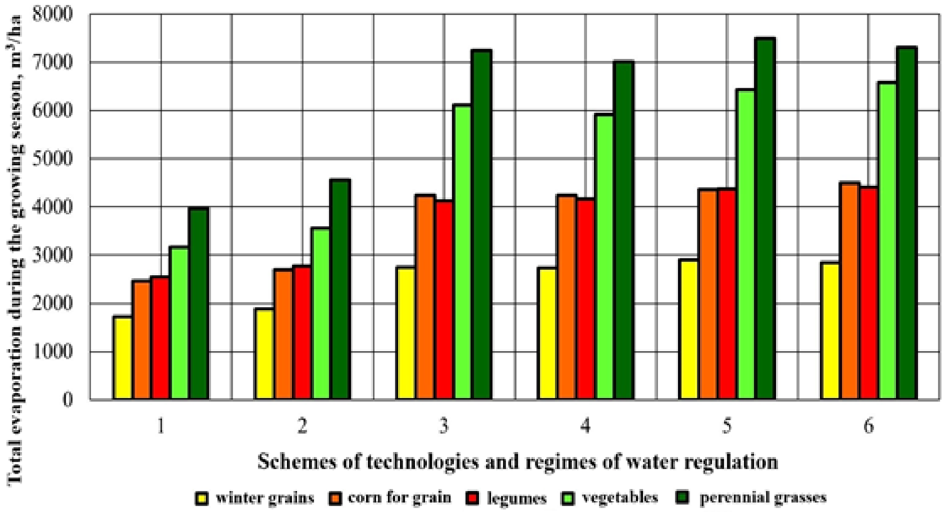
- for soils *(g)*: loamy soils according to the particle size composition, k_{ϕ} = 0.6 m/day;
- for the accompanying crops of the project rice crop rotation set {k}, $k = \overline{1, n_k}$ with their total content of 50% and the corresponding share of cultivated areas under each of them on the system,:
  - 1 – perennial grasses, potential yield 800 centner/ha, $f_k = 0.25$;
  - 2 – winter grains – 75 centner/ha, $f_k = 0.1$;
  - 3 – vegetables (tomatoes) – 800 centner/ha, $f_k = 0.05$;
  - 4 – corn for grain – 90 centner/ha, $f_k = 0.05$;
  - 5 – legumes (soy) – 38 centner/ha, $f_k = 0.05$;
- according to typical (estimated) years regarding the conditions of heat and moisture provision during the growing season of the set, {p}, $p = 1, n_p$ ($n_p = 5$):
  - 1 – very wet *($p = 10\%$);*
  - 2 – wet *($p = 30\%$);*
  - 3 – middle ($p = 50\%$);
  - 4 – dry ($p = 70\%$);
  - 5 – very dry ($p = 90\%$);
- according to different technologies of water regulation of the set {*s*}, $s = \overline{1, n_s}$: without irrigation, sprinkler irrigation and improved surface irrigation by flooding, which are implemented under two background regimes of GWL – supported and unsupported regimes:
  - 1 – unsustained regime of GWL without irrigation;
  - 2 – sustained regime of GWL without irrigation;
  - 3 – sprinkler irrigation under the unsustained regime of GWL;
  - 4 – sprinkler irrigation under the sustained regime of GWL;
  - 5 – improved surface irrigation by flooding under the unsustained regime of GWL;
  - 6 – improved surface irrigation by flooding under the sustained regime of GWL.

RESEARCH RESULTS AND DISCUSSION

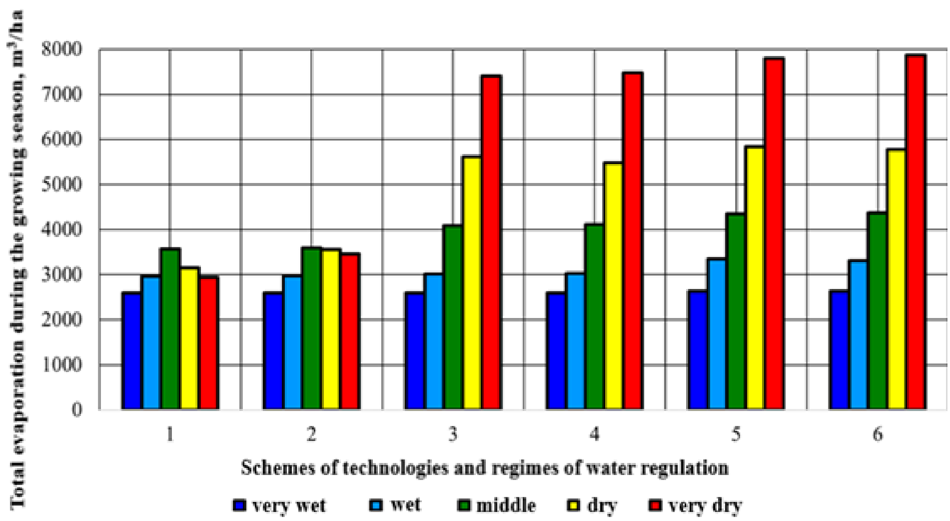
The results of the predictive calculations based on the machine experiment were processed according to the following scheme and presented in the appropriate sequence:

1. Research and analysis of the conditions for the formation of total evaporation in rice systems with regard to the types of associated crops grown, schemes of technologies and water management regimes, conditions of heat and moisture supply during the growing season (Figure 3).

Figure 3. Formation of total evaporation under different schemes of technologies and regimes of water regulation on irrigated lands of the RIS: a) in relation to various types of the accompanying crops in the conditions of the estimated dry year (p=70%); b) in relation to the conditions of estimated years for values averaged over the set of cultivated accompanying crops



a



b

These results reflect a clear differentiation of total evaporation in rice systems under the studied conditions regarding the types of the cultivated accompanying crops, schemes of technologies and regimes of water regulation, of heat and moisture provision during the growing season. The value of total evaporation here varies in a fairly wide range from 1800 m^3/ha for winter grains in the conditions of an estimated dry year (p=70%) without irrigation (Figure 3a) to 7500–7800 m^3/ha for the averaged values according to the set of cultivated accompanying crops in conditions of a very dry year (p=90%) under sprinkler irrigation and improved surface irrigation by flooding (Figure 3b).

The obtained results are the basis for further determination the values of water needs of the accompanying crops on irrigated lands of rice systems.

2. Determining the water needs of the accompanying crops on irrigated lands in relation to the natural-agro-ameliorative conditions of the RIS functioning.

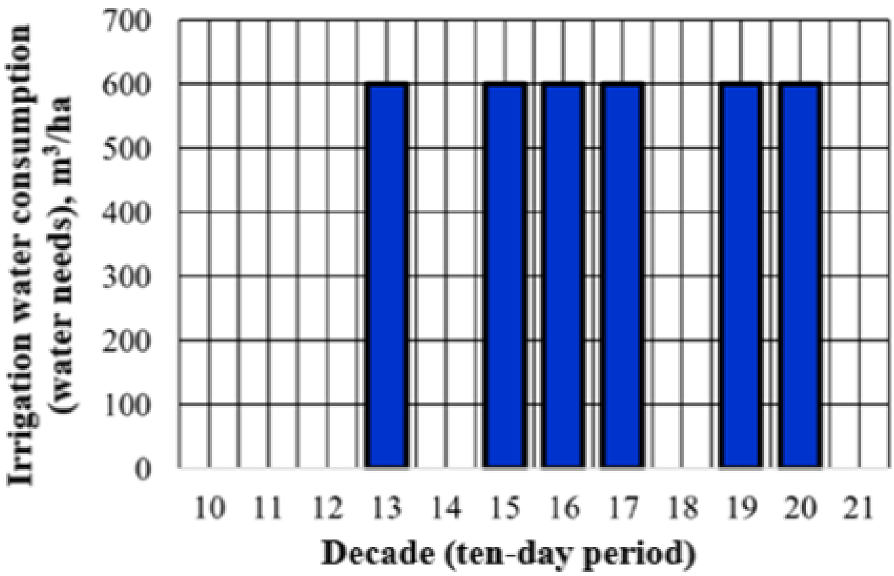
Corresponding results of predictive regime calculations are presented, first of all, for perennial grasses as a crop that plays an extremely important role in the structure of rice crop rotation. They are the best recovery crop after the cultivation of flooded rice and a good predecessor for other crops. Perennial grasses characterized by the highest amount of water consumption and occupy the largest sown area compared to other accompanying crops.

Predicted values of the irrigation regime, irrigation water consumption (water needs) and the harvest of perennial grasses in the studied changeable weather and climate conditions, irrigation technologies and background regimes of GWL on the system are presented for comparison in tabular (Table 1) and graphical (Figure 4) form.

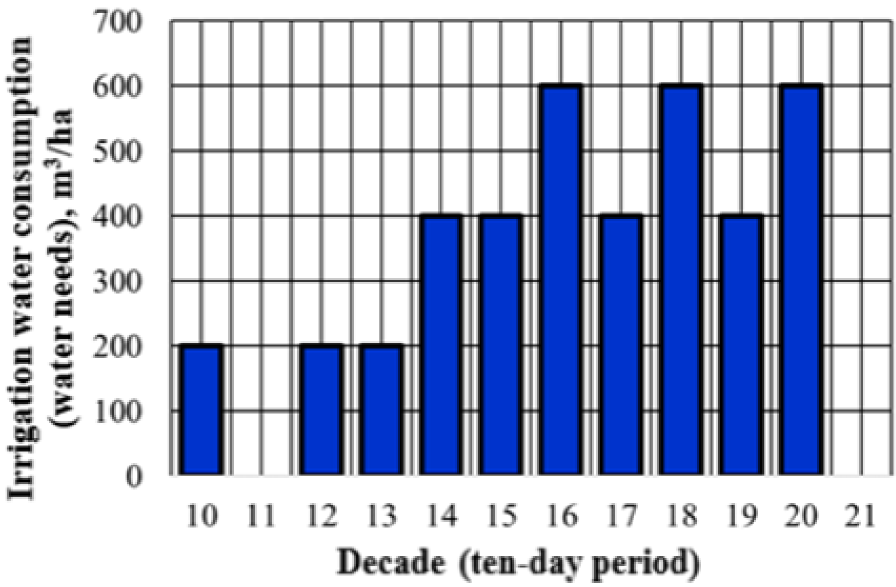
Table 1. Irrigation regime, water needs and productivity of perennial grasses in relation to different irrigation technologies with the sustained regime of GWL on the system and different weather and climate conditions

Typical groups		**Sum of positive**	**Sum of humidity deficits, mm**	**Irrigation water consumption (water needs) in a decade section (ten-day period), m³/ha**												**Total irrigation water**	**Yield, centner/ha**
				10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**		
Sprinkler irrigation																	
10%	360	3542	1214													0	490
30%	265	3602	1307													0	474
50%	260	3622	1433						600			600				1200	520
70%	185	3735	1582					600		600	600		600	600		3000	528
90%	167	3867	1814				600	600	1200	600	600	1200	600			5400	611
Improved surface irrigation by flooding																	
10%	360	3542	1214													0	49.0
30%	265	3602	1307				200		200		200		200			800	54.9
50%	260	3622	1433			200		200	200	200	200	200		400		1600	61.2
70%	185	3735	1582		200		400	200	400	400	400	400	400	400		3200	64.3
90%	167	3867	1814	200		400	400	600	800	1000	800	1000	800			6000	69.8

Figure 4. Irrigation water consumption (water needs) for watering perennial grasses in a decade section in the conditions of dry year (p=70%): a) in relation to sprinkler irrigation under the unsustained regime of GWL; b) in relation to improved surface irrigation by flooding under the unsustained regime of GWL



a



b

The presented dynamics of irrigation water consumption (water needs) for watering perennial grasses in a decade section showed that, in contrast to sprinkler irrigation, which is widely used in rice systems, the implementation of improved surface irrigation by flooding requires the implementation of a larger number of watering, but with smaller watering rates. This shows that under using improved surface irrigation by flooding for irrigating the accompanying crops of rice crop rotation, the use of water and, accordingly, energy resources is more uniform in time.

3. Estimation of technological efficiency of irrigation of the accompanying crops in relation to natural-agro-ameliorative conditions of the RIS functioning.

Such an assessment was carried out and reflected on the set of forecast values of the main indicators that reflect the technological efficiency of various technologies of irrigation of the accompanying crops in the studied conditions of the estimated dry year (p=70%): vegetation values of irrigation water consumption (water needs) and electricity, yield of cultivated crops, as well as specific indicators derived from them (Table 2).

Table 2. Comparative characteristics of the main indicators of the technological efficiency of irrigation of the accompanying crops in relation to various schemes of technologies and regimes of water regulation on the system in the conditions of the estimated dry year (p=70%)

Schemes of technologies and regimes of water regulation	Accompanying crops	Indicators of the technological efficiency				
		Irrigation rate, m^3/ha	Electricity	Yield, centner/ha	Specific of irrigation water	Specific of electricity
sprinkler irrigation under the unsustained regime of GWL	perennial grasses	3600	0.18	533.5	6.75	0.34
	winter grains	1200	0.06	49.5	24.24	1.21
	vegetables	3600	0.18	566.4	6.36	0.32
	corn	2000	0.10	58.1	34.42	1.72
	legumes	3000	0.10	31.7	94.63	3.16
Weighted average value:		***2800***	***0.14***	***-***	***21.76***	***0.93***
sprinkler irrigation under the sustained regime of GWL	perennial grasses	3000	0.15	528.7	5.67	0.28
	winter grains	1200	0.06	54.2	22.14	1.11
	vegetables	3000	0.15	503.3	5.96	0.30
	corn	2000	0.10	68.9	29.03	1.45
	legumes	2800	0.08	34.0	82.35	2.35
Weighted average value:		***2400***	***0.12***	***-***	***19.00***	***0.77***

continued on following page

Table 2. Continued

Schemes of technologies and regimes of water regulation	Accompanying crops	Indicators of the technological efficiency				
		Irrigation rate, m³/ha	Electricity	Yield, centner/ha	Specific of irrigation water	Specific of electricity
improved surface irrigation by flooding under the unsustained regime of GWL	perennial grasses	4000	0.20	678.4	5.90	0.30
	winter grains	1600	0.08	65.0	24.62	1.23
	vegetables	3800	0.19	628.1	6.05	0.30
	corn	2200	0.11	68.6	32.07	1.60
	legumes	3200	0.11	32.2	99.07	3.41
Weighted average value:		***3140***	***0.16***	-	***21.59***	***0.93***
improved surface irrigation by flooding under the sustained regime of GWL	perennial grasses	3200	0.16	642.7	4.98	0.25
	winter grains	1400	0.07	59.3	23.61	1.18
	vegetables	3600	0.18	691.3	5.21	0.26
	corn	2200	0.11	74.3	29.61	1.48
	legumes	3000	0.10	35.6	84.27	2.81
Weighted average value:		***2660***	***0.13***	-	***19.12***	***0.82***

The obtained and presented results (Table 1, Figure 3, Table 2 and Figure 4) show that the vegetative values of water consumption (water needs) during the irrigation of the accompanying crops of rice crop rotation fully correspond to the conditions and the nature of the formation of total evaporation on the irrigated lands of the RIS in relation to the types of cultivated crops, schemes of technologies and regimes of water regulation, conditions of heat and moisture provision during growing seasons. They vary from 1 200 m^3/ha for winter cereals to 6 000 m^3/ha for perennial grasses and can cover up to 70–80% of total evaporation in dry growing seasons. In addition, water consumption for irrigation in the conditions of the sustained GWL regime is 20–30% less than in the conditions of the unsustained GWL regime. And although the given data on the technological efficiency of various schemes of technologies and irrigation regimes testify to the prospects of using the improved technology of surface irrigation of accompanying crops, the final decision on their implementation must be made taking into account the conditions of implementation and construction of each specific rice system, as well as necessarily economic and ecological efficiency its functioning in accordance with modern requirements.

To compare and contrast the results of the predictive assessment of water demand and technological efficiency of irrigation of the accompanying crops under production conditions used their averaged values for traditional surface irrigation by flooding during cultivation of both leading crop flooded rice and accompanying crops, which are obtained based on the results of the Danube RIS functioning over the last years during 2013–2023 (Table 3).

Table 3. Averaged values of the technological efficiency indicators obtained based on the results of the Danube RIS functioning during 2013–2023 (according to the data of the Kiliya Administration of Water Management and State Agency of Water Resources of Ukraine)

Nº	Indicators	Rice	Accompanying crops	For system
1	Sown area, thousand ha	4.0	2.9	6,9
2	including grain and legumes crops (winter, spring, corn), thousand ha	-	2.1	-
3	Gross harvest, thousand centner	222.9	93.9	-
4	Average yield, centner/ha	55.1	45.6	-
5	Water consumption, million m^3	79.2	6.1	85.3
6	Electricity consumption, million kWh	3.58	0.56	4.14
7	Average irrigation rate, m^3/ha	19533	1872	21.4
8	Specific of irrigation water consumption per production unit, m^3/centner	355.6	64.9	-
9	Specific of electricity consumption: - per production unit, kWh/centner - per unit area, kWh/ha	16.7 895.0	5.9 193.1	- 600.0

The presented results show that when the yield of the leading crop flooded rice is reached, 55.1 centner/ha on an area of 4.0 thousand hectares, compared to 45.6 t/ha on an area of 2.9 thousand hectares for accompanying crops, among which by area grain crops prevail (up to 70%), the indicators of water consumption of rice, as well as other indicators of the technological efficiency of its cultivation, significantly exceed similar values for accompanying crops. This is the case in general throughout the system under the conditions of the Danube RIS functioning at the current stage. At the same time, it should also be noted the high level of comparability of the forecast values of the considered set of indicators of water consumption and technological efficiency of irrigation obtained for accompanying grain crops with their production characteristics.

Thus, the existing threats of food, water and energy crisis, as well as the level of changes in weather and climate conditions, the impact of which is already felt in agricultural production, primarily in the rice growing zone, require adaptation to the increase in water needs for cultivating crops of rice crop rotation on irrigated lands of the rice irrigation system in the conditions of growing scarcity of water resources. In addition, we have a significant deterioration of the quantitative and qualitative state of water resources as a result of Russia's military aggression. Under such conditions, the modern development of irrigation should be based on the introduction of new and progressive technologies of water regulation, taking into account the natural and ameliorative conditions of a specific object, which should ensure the saving of water and energy resources, as well as the improvement or maintenance of a favorable ecological and reclamation state of irrigated lands of the rice irrigation system.

THE DIRECTION OF FUTURE RESEARCH

Prospects for further research lie in the need to research this issue with a long-term forecast of possible changes in the weather and climatic conditions of the rice-growing zone of Ukraine. The obtained results can be effectively used in the development of adaptive measures to the predicted climate changes in the context of water, energy, and food crises, as well as in the justification of resource-saving regimes and technological solutions in projects of reconstruction and modernization of existing irrigation systems aimed at achieving the goals of optimizing the use of water and energy resources during their functioning as nature-based and resource-efficient solutions for achieving the goals of sustainable development of agricultural production on irrigated lands of rice systems of Ukraine.

CONCLUSIONS

1. Recent studies of weather and climatic conditions of the rice-growing zone of Ukraine indicate a steady tendency to increase the aridity of the climate in the region. Further increase in air temperature and decrease in natural water availability of these territories will lead to the increase in total evaporation and water needs for irrigation of the crops of rice crop rotation. Under such conditions a significant exacerbation of the existing problem of water deficit is expected in the region.
2. The availability of water resources directly affects the efficiency of agricultural production on the irrigated lands of rice systems. In this regard, there is an objective need to adapt agricultural production on the irrigated lands of rice systems to the existed and predicted climate change, which, first of all, requires the assessment of water needs for irrigation both the leading crop of flooded rice and the accompanying crops of rice crop rotation.
3. In this way, research aimed at estimating the changes in water needs for irrigation of the accompanying crops of rice crop rotation in the variable natural-agro-ameliorative conditions of rice system functioning becomes extremely important. To achieve the set goal was implemented a large-scale computer experiment, based on a complex of predictive-simulation models, which basing on a long-term forecast, allow to estimate weather and climatic conditions, water regime,

water regulation technologies and the productivity of reclaimed lands, the results of which are presented in this chapter.

4. The research was carried out for the conditions of the Danube rice irrigation systems of the Odesa region of Ukraine. On the example of the Kiliya rice irrigation system. It's constructive, natural-agro-ameliorative conditions are typical for most rice systems in Ukraine
5. Obtained results reflect a clear differentiation of total evaporation in rice systems under the studied conditions regarding the types of cultivated accompanying crops, schemes of technologies and regimes of water regulation (without irrigation, sprinkler irrigation and improved surface irrigation by flooding, which are implemented under two background regimes of ground water level – supported and unsupported regimes) and general provision of heat and moisture during the growing season. The value of total evaporation here varies in a fairly wide range from 1800 m^3/ha for winter grains in the conditions of an estimated dry year (p=70%) without irrigation to 7500–7800 m^3/ha for the averaged values according to the set of cultivated accompanying crops in conditions of a very dry year (p=90%) under sprinkler irrigation and improved surface irrigation by flooding.
6. Determining the water needs of the accompanying crops on irrigated lands in relation to the natural-agro-ameliorative conditions of the rice irrigation systems functioning presented as dynamics of irrigation water consumption (water needs) in a decade section showed that, in contrast to sprinkler irrigation, which is widely used in rice irrigation systems, the implementation of improved surface irrigation by flooding requires the implementation of a larger number of watering, but with smaller watering rates. This shows that under using improved surface irrigation by flooding for irrigating the accompanying crops of rice crop rotation, the use of water and, accordingly, energy resources is more uniform in time.
7. The results of the conducted estimation of technological efficiency of various schemes of technologies and irrigation regimes testify to the prospects of using the improved technology of surface irrigation of the accompanying crops, however the final decision on their implementation must be made taking into account the conditions of implementation and construction of each specific rice system, economic and ecological efficiency its functioning in accordance with modern requirements.
8. The obtained results show that the vegetative values of water consumption (water needs) during the irrigation of the accompanying crops in the research conditions are quite vary. For example from 1 200 m^3/ha for winter cereals to 6 000 m^3/ha for perennial grasses and can cover up to 70–80% of total evaporation in dry growing seasons. Such results are fully correspond to the conditions and the

nature of the formation of total evaporation on the irrigated lands of the RIS in relation to the types of cultivated crops, schemes of technologies and regimes of water regulation, conditions of heat and moisture provision during growing seasons.

9. A comparison of the predictive assessment results concerning to water consumption (water needs) and the technological efficiency of irrigation of rice crop rotations with production data in the case of irrigation with traditional flood irrigation of both the leading rice crop and accompanying crops (according to the results of the Danube rice irrigation systems functioning during the period from 2013 to 2023) was made. The results of the predictive assessment have a high the level of comparability with their production characteristics.
10. These materials can be effectively used for justification of regime and technological decisions in the projects of reconstruction and modernization of existing rice systems and developing adaptive measures to the predicted climate change in the region.

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Chapter 10
Analysis of Moisture Deficit in the Kherson Region Within the Context of Climate Change

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ABSTRACT

Developing a predictive system for water deficit analysis in the Black Sea Lowland, especially in climate change, involves integrating various data sources, modeling techniques, and technological tools to forecast water availability and demand. The analysis of the change in moisture deficit in the Kherson region is provided for the period from 1955 to 2022. A description of temperature gradients across the Kherson region is provided. The distribution of precipitation throughout the years in terms of quantity and intensity is provided. As part of the Black Sea Lowland, the Kherson region is critically important for southern Ukraine's agriculture and water security. Given the region's reliance on irrigation and the challenges posed by climate change, developing a predictive system for water deficit analysis is essential.

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Such a system can help stakeholders make informed decisions to ensure sustainable water management and mitigate the adverse effects of water scarcity.

BACKGROUND

As part of the Black Sea Lowland, the Kherson region is critically important for southern Ukraine's agriculture and water security. Given the region's reliance on irrigation and the challenges posed by climate change, developing a predictive system for water deficit analysis is essential (Korobiichuk et al, 2017; Kravchenko et al, 2017; Kuzmych et al, 2022a,, 2023f; Land reclamation, 2015; Romaschenko, 2019; Yakymchuk et al, 2022).

The agricultural production in the Kherson region, particularly its irrigated agriculture sector, faces challenges due to complex soil and climatic conditions. The region experiences insufficient and unstable natural moisture, with low precipitation levels and high evaporation rates leading to a moisture deficit. This results in frequent droughts, long periods without rain, and significant yield fluctuations, impacting agricultural productivity (Kravchenko et al, 2017; Kuzmych et al, 2022b, 2022c,, 2023a; Land reclamation, 2015; Rakushev, 2017).

The Kherson region, located in the Steppe agro-climatic zone, covers an area of about 27.5 thousand km^2. It is characterized by an arid and moderately hot climate, with a flat relief and limited water bodies. The region relies on irrigation to improve agricultural conditions in the face of inadequate natural moisture.

The region's economy heavily depends on agriculture, focusing on grains, vegetables, and fruits. Water resources, including the Dnipro River and canals, are crucial in irrigation and municipal water supply. However, overuse of groundwater resources and the impact of climate change, such as rising temperatures and changing precipitation patterns, pose challenges to water availability for agriculture (Kuzmych et al, 2022e,, 2023b, 2023c; Shevchenko et al, 2019; Zima, 2010),

Efficient water management and predictive systems for water deficit analysis are essential to sustain agricultural productivity, ensure food security, and support economic development in the Kherson region. Proactive planning and strategies to address water scarcity risks are necessary to mitigate the impact of water shortages on agriculture and the economy.

METHODS AND TECHNIQUES

It is proposed the structured approach to designing the predictive system for water deficit analysis consists of the following steps (Schroder al, 2010; Bakhovets et al, 1989; Chernyuk, 2017; Instruction on accounting and assessment of the condition of reclaimed lands and land reclamation systems. VND 33-5.5-13-2002, 2002; Kvasnikov, 2023; Kuzmych et al, 2022d, 2023a, 2023d, 2023e, 2022f; Methodology of field surveys of pumping stations and hydrotechnical structures on main canals of reclamation systems, 2013; Onanko, A. et al, 2022a, 2022b, 2023; Rokochinskiy et al, 2019, 2020, 2023a, 2023b; Rus et al, 2006; Turcheniuk et al, 2022a, 2022b; Yakymchuk et al, 2022):

1. Data Collection and Integration:
   1.1. Climate data - collect historical data on temperature, precipitation, humidity, and wind patterns.
   1.2. Hydrological data:

      - River flows: data on river discharge rates, particularly for major rivers like the Dnipro River;
      - Reservoir levels: historical and current water levels in reservoirs and major water bodies;
      - Groundwater levels: data from groundwater monitoring wells.

   1.3. Water Usage Data:

      - Agricultural Demand: Information on crop types, irrigation practices, and water usage patterns;
      - Domestic and Industrial Use: Data on municipal and industrial water consumption.

2. Modeling Framework:
   2.1. Climate models - apply regional climate models to downscale global climate projections to the Black Sea Lowland region for more accurate local predictions.
   2.2. Hydrological models:

      - Rainfall-runoff models - use models like SWAT (Soil and Water Assessment Tool) to simulate the conversion of rainfall to runoff and river flow;

- Water balance models - implement models that account for inputs (precipitation, river inflows) and outputs (evaporation, water extraction) to estimate water availability.

2.3. Demand models:

- Agricultural demand - develop models to estimate future irrigation needs based on crop types, planting schedules, and climate conditions;
- Municipal and Industrial demand - use demographic and economic projections to forecast changes in water demand for domestic and industrial uses.

3. System Design:

3.1. Data integration platform:

- GIS integration - use a Geographic Information System (GIS) to integrate spatial data on climate, hydrology, and land use;
- Database Management - implement robust databases to store and manage large volumes of data from various sources.

3.2. Predictive Analytics / Scenario Analysis - develop tools to simulate different scenarios (e.g., varying levels of water usage, different climate change scenarios) and assess their impact on water deficit.

4. Application and Use Cases:

4.1. Agricultural planning:

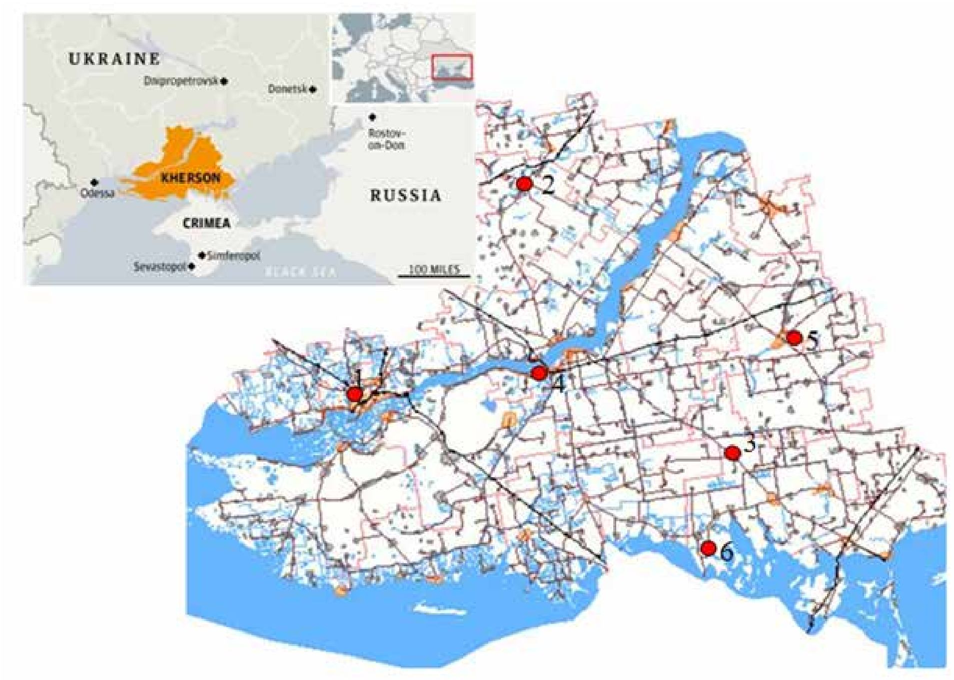
- Crop planning - assist farmers in planning crop types and irrigation schedules based on predicted water availability;
- Water allocation - help water managers allocate water resources efficiently during dry periods.

4.2. Urban and industrial water management:

- Demand management - support municipalities and industries in managing water demand and implementing conservation measures;
- Infrastructure planning - guide investment in water infrastructure, such as reservoirs and pipelines, to mitigate future water deficits.

To characterize the climatic features of the object, data from the weather stations Askania-Nova, Velyka Oleksandrivka, Kherson, Nova-Kakhovka, Nizhny Sirogozy, Khorly (Figure 1) and the relevant sources were used (Corcoran et al, 2007; Field Wiring and Noise Considerations for Analog Signals, 2014; Klassen,2000; Onanko, Yu et al,, 2022; Ruban, 2008; S. Kuzmych et al,, 2023; Turcheniuk et al, 2023).

Figure 1. Scheme of the map of the Kherson region and the location of weather stations: 1 – Kherson; 2 – Velyka Oleksandrivka; 3 – Askania-Nova; 4 – Nova Kakhovka; 5 – Nizhny Sirogozy; 6 – Khorly



III. RESULTS AND DISCUSSION

According to the Köppen climate classification, the classification of climates Alisova et al. this territory belongs to the Black Sea sub-region of the Atlantico-continental steppe region. The climate is typically continental with a high heat resource and insufficient humidity.

The change of seasons occurs gradually without sharp temperature fluctuations, the average annual air temperature ranged from 8.1°C (1976) to 11.4°C (1966), with an average annual value of 9.7°C. The coldest month is January, with an average monthly temperature ranging from -11.2°C (1972) to 1.9°C (1966) and an average annual value of -3.5°C. The winter period does not exceed 100 days. Winter is short, moderately cold, mild, with frequent thaws. The snow cover usually appears in November-December, characterized by instability, and melts in February-March.

The snow depth does not exceed 5-10 cm. Snow is not the main source of spring moisture accumulation in the soil in this area. The instability of the temperature regime is due to frequent soil thawing in winter, affecting soil moisture in the aeration zone during the winter period.

The spring increase in average daily temperature in March leads to the complete thawing of the frozen layer. The increase in evaporation of moisture in spring, along with rising air temperatures, causes a sharp increase in moisture deficit. The warmest month is July, with an average monthly air temperature ranging from 20.5°C (1969) to 24.3°C (1972) and an average annual value of 23.2°C.

By the degree of humidity, the northern and central parts of the territory belong to the zone of insufficient humidity with a humidity coefficient greater than 0.5 (for Askania-Nova - 0.68), while the southern part (Prisivashshya) belongs to the coastal arid zone with a humidity coefficient of approximately 0.4. The annual precipitation varied from 238.5 mm (1984) to 640.8 mm (1966). According to the book "Climate of Ukraine," on average in the northern hemisphere, the surface air temperature increased by only 0.5°C from 1961-1990, and globally by 0.4°C. The change in annual temperature over a 100-year period in the Steppe region is 0.2-0.3°C towards warming. Winter warming is 1.2°C, in spring - 0.8°C, with minor changes in summer and autumn.

From 1900 to 2020, the annual amount of precipitation in Ukraine varied unevenly. In some regions, there was an increase in precipitation by 7-10% (over 40 mm) from the climatological norm, while in the rest of the territory, it remained within the norm. During the period of maximum global warming, starting from 1975, a decrease in the amplitude of precipitation fluctuations from year to year was observed almost throughout Ukraine. This means that the moisture regime stabilized and is within the climatological norm. It is known that seasonal unevenness in precipitation, an increase in average annual precipitation in recent decades, and the amplitude of precipitation in certain years are natural factors contributing to flooding.

The distribution of precipitation throughout the year is uneven both in quantity and intensity. The highest amount of precipitation falls during dry months when evaporation is high. Summer rainfall (35-40% of the annual total) occurs in the form of short downpours and heavy rains, often accompanied by thunderstorms. The main spatial distribution pattern of precipitation in Ukraine, determined by general circulation factors, is their decrease from the northwest to the southeast.

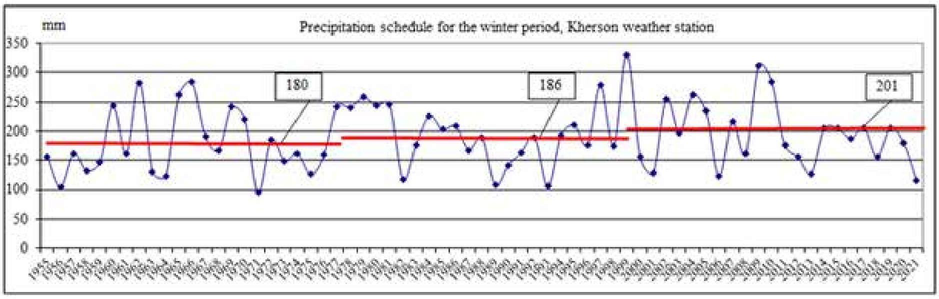
In the Kherson region, the average annual precipitation decreases from 450 to 300 mm and less from northwest to southeast, reaching 230 mm on the coast of the seas. The distribution of precipitation throughout the year is uneven both in quantity and intensity. The highest amount of precipitation falls during dry months when evaporation is high. Summer rainfall (35-40% of the annual total) occurs in the form of short downpours and heavy rains, often accompanied by thunderstorms. The most significant increase in precipitation is observed in the observation zone of the Kherson and Velyka Oleksandrivka weather stations, with slightly less growth in the observation zone of Nova Kakhovka and Nyzhni Sirohozy weather stations, and very slight increase in the observation zone of Askania-Nova and Khorly weather stations.

An analysis of the long-term dynamics of precipitation at the Kherson and Velyka Oleksandrivka weather stations was conducted for the periods 1955-1975, 1976-1995, and 1996-2022. Comparison of the long-term seasonal unevenness of precipitation at the Kherson weather station indicates a gradual increase in the average precipitation over twenty years, especially in the last forty-five years (41 mm), indicating a gradual increase in overall natural loading. In the winter period (most critical for replenishing groundwater with atmospheric precipitation), the overall increase in average precipitation was 21 mm, while in the summer period, precipitation increased by 19 mm (Figure 2).

A comparison of the long-term seasonal unevenness of precipitation at the Velyka Oleksandrivka weather station was carried out in a similar way (Figure 3). The analysis shows a gradual increase in the average rainfall over sixty-five years (44 mm), which indicates a significant increase in the total natural load. Moreover, in the winter period (the most threatening, in terms of replenishment of groundwater by atmospheric precipitation), the total increase in average precipitation was 8 mm, in the summer period precipitation increased by 48 mm.

Taking into account the conducted analysis and the location of the weather stations, there is reason to say that the significant cause of flooding in the area covered by the weather stations Kherson (western part of Kherson region) and Velyka Oleksandrivka (north-western part of Kherson region) is precisely the natural factor - an increase in atmospheric precipitation. Particular attention should be paid to the increase in the amplitude of precipitation in the summer period in 2005, which exceeds the average value by 360 mm, which was practically not observed in previous years.

Figure 2. Precipitation schedule according to Kherson weather station data: a) winter period; b) summer period; c) for a year



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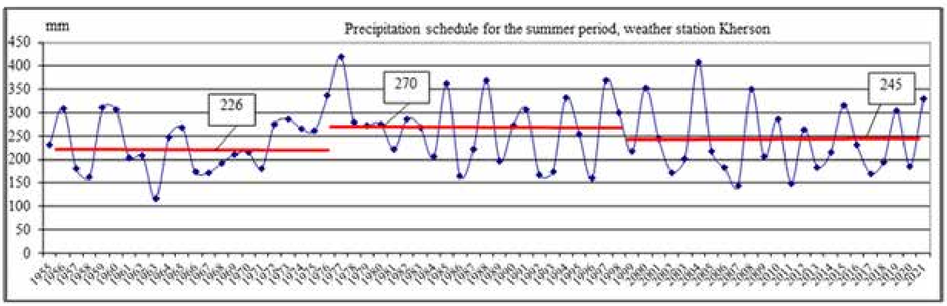

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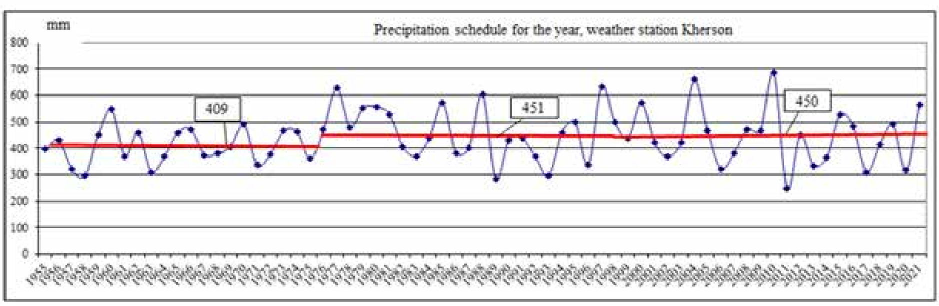
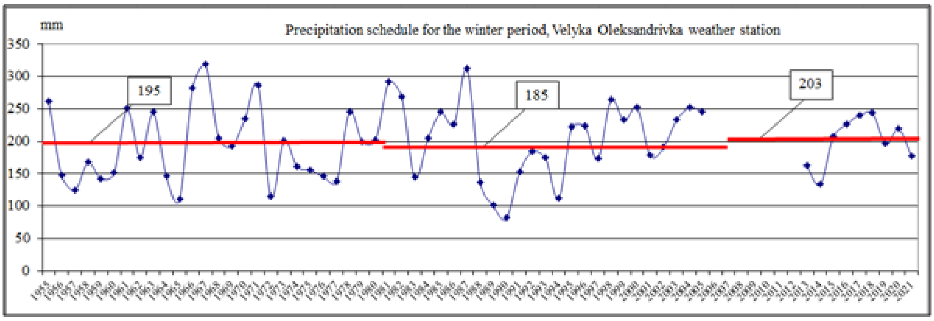


c)

Analysis of the multi-year dynamics of precipitation at the Nova Kakhovka and Nizhni Syrogoza weather stations. A comparison of the long-term seasonal irregularity of precipitation at the Nova Kakhovka weather station (Figure 4) shows an increase in the average annual precipitation from 416 mm in the period 1946-1975 to 420 mm in 1996-2022. Moreover, in the winter period (the most threatening, in terms of the replenishment of groundwater by atmospheric precipitation), the total increase in average precipitation was 14 mm, and in the summer - 24 mm.

Figure 3. Precipitation schedule according to data from the Velyka Oleksandrivka weather station: a) winter period; b) summer period; c) for a year



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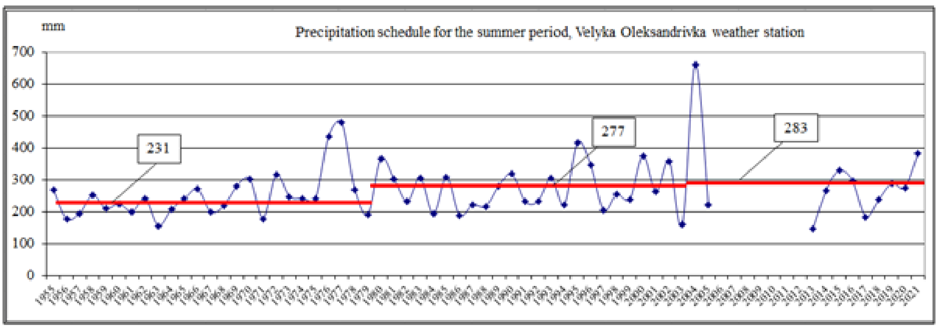

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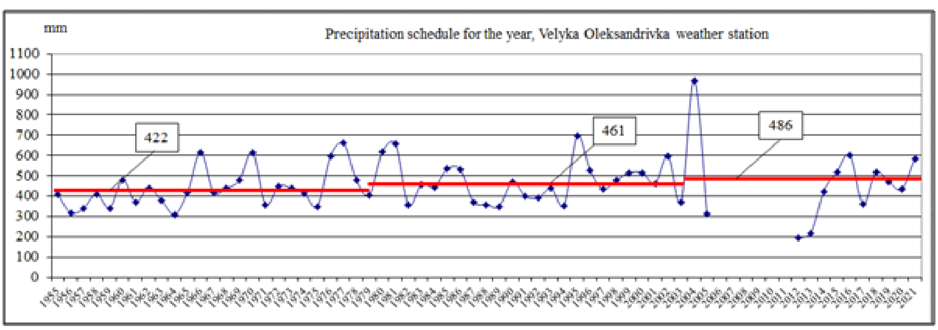
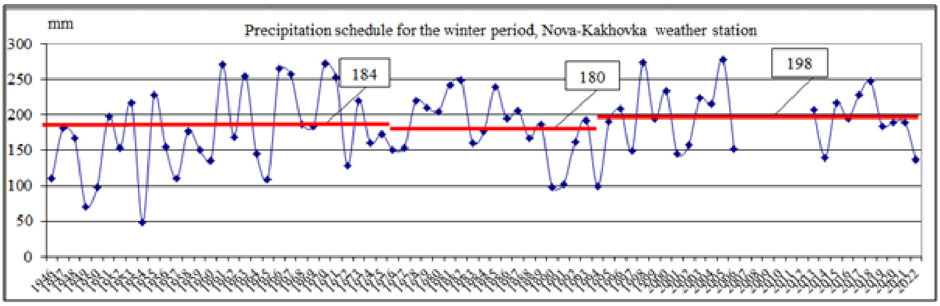


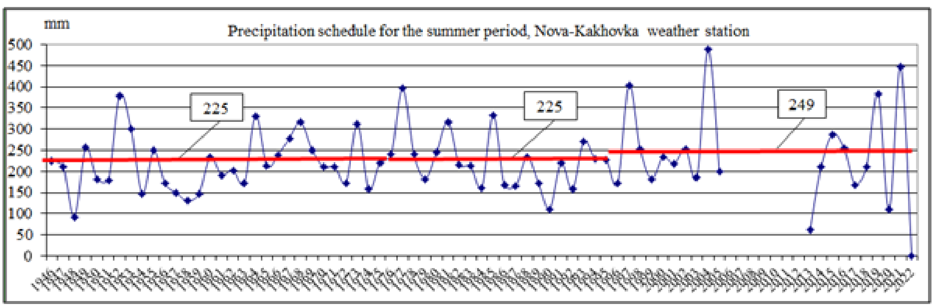
c)

A comparison of the long-term seasonal unevenness of precipitation according to the data of the Nizhny Sirogoza weather station (Figure 5) shows a gradual increase in the average amount of precipitation over seventy-five years (98 mm), which indicates a slight increase in the total natural load. Moreover, in the winter period (the most threatening, in terms of replenishment of groundwater by atmospheric precipitation), the total increase in average precipitation was 24 mm, in the summer period the increase was 54 mm.

Figure 4. Precipitation schedule according to the data of the Nova Kakhovka weather station: a) winter period; b) summer period; c) for a year.



a)



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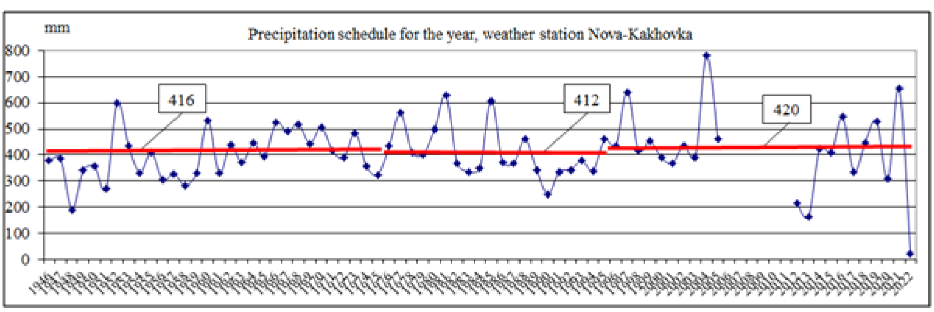

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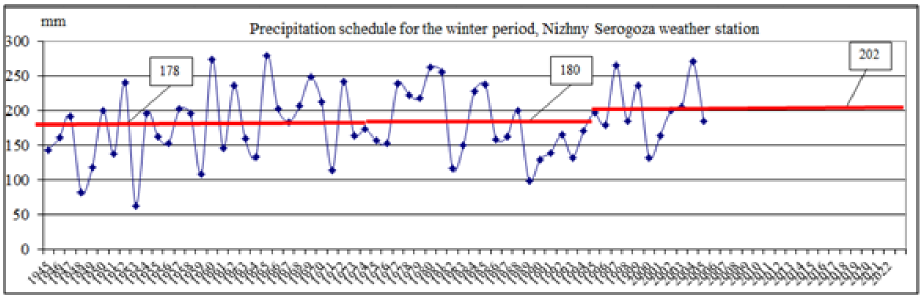
Figure 5. Precipitation schedule according to the data of the Nizhny Sirogoza weather station: a) winter period; b) summer period; c) for a year



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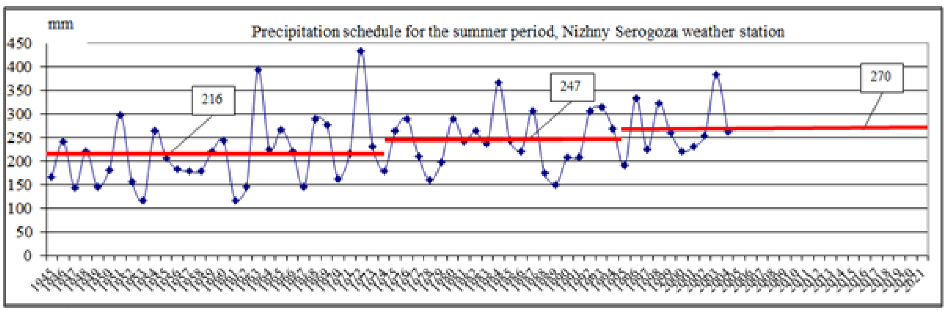

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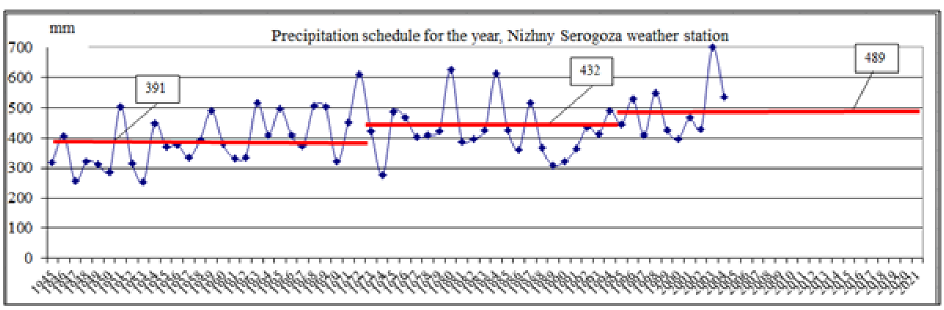


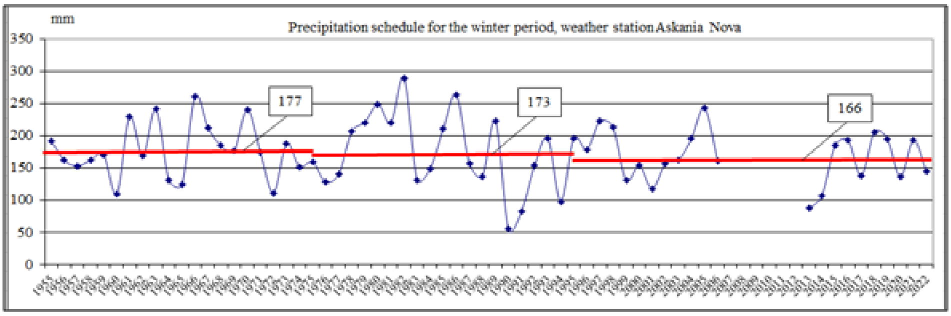
c)

Taking into account the conducted analysis and the location of weather stations, there is reason to say that one of the reasons (natural factors) of flooding in the area covered by the Nova Kakhovka and Nizhni Syrogozy weather stations in the recent period (1996 - 2022) is also an increase in atmospheric precipitation. At the same time, the amplitude of precipitation in the summer period in 2005 is increasing, which exceeds the average value by 240 mm, which was practically not observed in previous years.

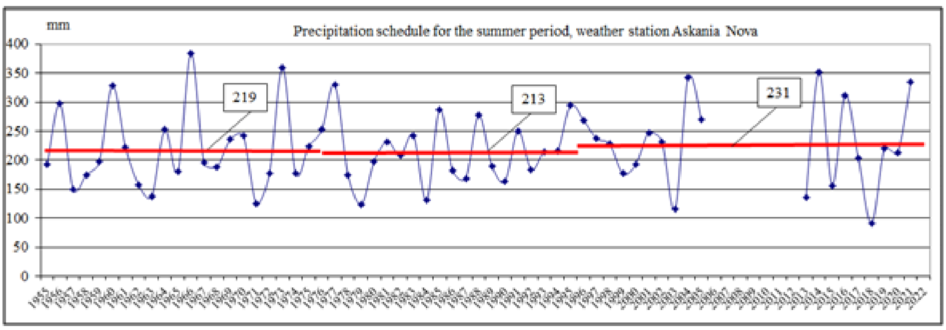
The analysis of long-term precipitation dynamics of the Askania-Nova and Khorly weather stations. Weather stations Askania-Nova and Nizhny Sirogozy are located in the Kherson region, on the left bank of the Dnipro River.

The analysis of long-term precipitation dynamics was carried out for the following periods: 1955-1975, 1976-1995, 1996-2022.

Figure 6. Precipitation schedule according to the data of the Askania-Nova weather station: a) winter period; b) summer period; c) for a year



a)



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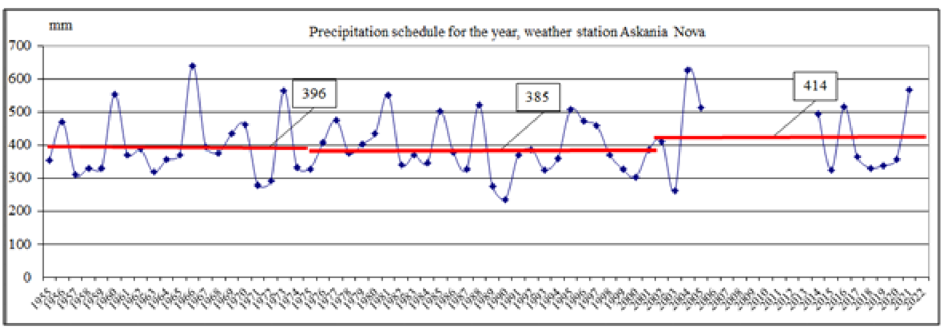
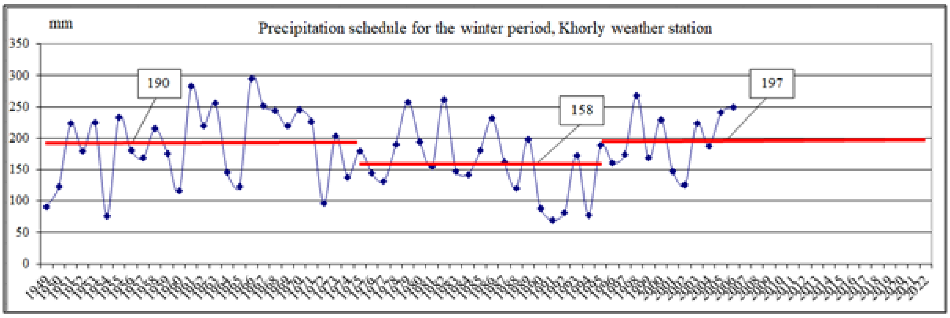


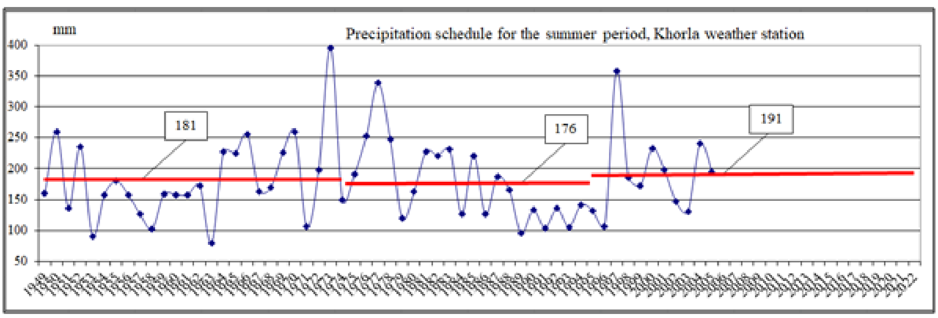
c)

A comparison of the long-term seasonal unevenness of precipitation according to the data of the Askania-Nova weather station (Figure 6) shows a slight increase in the average amount of precipitation over twenty years (18 mm), which indicates an increase in the overall atmospheric load. Moreover, in the winter period (the most threatening, in terms of replenishment of groundwater by atmospheric precipitation), there was a slight (11 mm) decrease in average precipitation, in the summer period the increase was 12 mm.

Figure 7. Precipitation schedule according to data from the Khorly weather station: a) winter period; b) summer period; c) for a year.



a)



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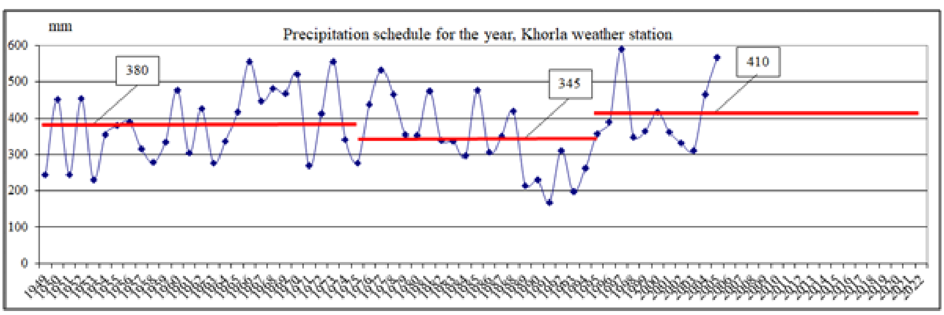

c)

Analyzing the comparison of precipitation according to the data of the Khorla weather station (Figure 7), we can see that in the period 1976-1995, there was a decrease in the average amount of precipitation for many years by 35 mm. In the last period (1996 - 2022), the reverse process is observed (an increase in the average annual rainfall by 65 mm). Moreover, in the winter period (the most threatening period, in terms of replenishment of groundwater by atmospheric precipitation), the total increase in average precipitation compared to the period 1976-1995 was 34 mm, and in the summer - 15 mm.

Taking into account the conducted analysis and the location of the Askania-Nova and Khorly weather stations, there are reasons to say that a small increase in the average amount of precipitation is not able to significantly affect the acceleration of flooding processes in this area.

CONCLUSIONS

Long-term analysis of precipitation in the Kherson region indicates an increase in natural load on the right bank of the Dnieper River (weather stations Kherson, Velyka Oleksandrivka) and in the north of the Kherson region (Nova Kakhovka, Nyzhni Sirohozy), which is one of the important natural factors increasing the risk of flooding. At the same time, on the left bank in certain areas (weather stations Askania-Nova, Khorly), there has not been a significant increase in the average amount of precipitation, which suggests the possibility of long-term anthropogenic influence on the flooding process.

Analysis of precipitation showed in some cases an increase in their amplitude in recent years (Kherson weather station 1998, 2004, 2010; Velyka Oleksandrivka weather station 2004, Askania-Nova weather station 2004). This leads to years with an increased risk of flooding and inundation of corresponding areas, as observed in the Kherson region in 1997-1998 and 2004-2005.

Analysis of seasonal unevenness of precipitation revealed an increase in the average amount of precipitation in the winter period over twenty years (Kherson weather station by 33 mm, Velyka Oleksandrivka weather station by 29 mm), which is the most threatening in terms of groundwater replenishment through infiltration.

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Chapter 11
The Methodology of Technical and Economic Justification for the Construction of Irrigation Systems to Prevent and Reduce Risks in Agriculture

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ABSTRACT

The methodology for developing the technical and economic justification for the construction of irrigation systems is presented, based on a multidisciplinary approach. The goal of this approach is to provide a thorough and persuasive rationale for the implementation and construction of irrigation systems to reduce risks in agricultural practices and enhance agricultural productivity, considering a complex array of influencing factors. This approach involves quantitative modeling of various scenarios with different sets of parameters that characterize the state of irrigation management taking into account the increased level of agricultural production considering climate changes, natural moisture conditions, soil characteristics, crop structures, irrigation methods, types of irrigation equipment, efficiency coefficients of irrigation systems, etc. The development of the technical and economic justification is considered using the example of land use by the State Enterprise "State Farm "Pioneer" in the Kherson region.

BACKGROUND

Amidst the ongoing armed aggression by Russia, Ukraine is confronted with a serious challenge of escalating threats, demanding immediate action not only to protect the lives of the population and the environment but also to establish stability and food security in the country. This course of action aligns with the overall direction of the UN Food and Agriculture Organization (FAO) Strategic Program for the period 2022-2031 (Strategic Program 2022-31, 2021). This vision entails joint efforts to achieve the Sustainable Development Goals by 2030 through transitioning to more efficient, inclusive, resilient, and sustainable agrifood systems (Agrifood Systems Transformation, 2023; FAO Report, 2023), with a primary focus on improving production quality, ensuring better nutrition, preserving the environment, and enhancing the quality of life for all. The Water-Energy-Food approach underscores the interconnectedness of water, energy, and food resources, highlighting the synergy between water, environmental, and agricultural policies (Kuzmych L. et al., 2022a; Romashchenko M. et al., 2023).

Modern conditions and prospects for irrigation use in Ukraine require a comprehensive approach to solving the problem of efficient use of water and land resources within integrated technological modules of irrigation systems. The issue of ensuring resource efficiency in irrigation needs addressing both when using irrigation within existing irrigation systems and when developing plans to restore former irrigation areas. Currently, farmers place high hopes on the government's program for the restoration of on-farm irrigation systems and attracting investments for this purpose

(Irrigation and Drainage Strategy in Ukraine, 2019; Action Plan for the Implementation of the Irrigation and Drainage Strategy in Ukraine, 2020; On Amendments to Certain Acts of the Cabinet of Ministers of Ukraine, 2022). High profits from irrigated lands can only be achieved under conditions of optimal sustainable water and land use within the modules (irrigated plots) of irrigation systems.

Making managerial decisions regarding the feasibility of investing funds in the restoration and development of hydro-technical reclamation in Ukraine is a complex process dependent on various factors and conditions. Therefore, for potential investors there is a need to develop a specialized tool to make balanced decisions on investing in the reconstruction, modernization, or new construction of irrigation systems. This tool is called a technical and economic justification (feasibility study). Feasibility study (FS) is one of the design stages (DBN A.2.2-3-2014, 2022; Shen L.Y. et al., 2010). FS determines the project's potential, the costs associated with its implementation, and the expected benefits from its realization. During the development of FS, economic, legal, technical, financial, operational, and time factors that may affect the project are considered. A feasibility study is advisable to combine with SWOT analysis and risk assessment of project implementation (Zakia Z. et al., 2022; Carrêlo I.B. et al., 2020; Ashebir H.T., 2021). Developing a methodology for technical and economic justification of the construction or modernization of irrigation systems based on an interdisciplinary approach and involving quantitative modeling of options is relevant now.

The Institute of Water Problems and Land Reclamation of NAAS of Ukraine has vast experience in developing technical and economic justification in hydrotechnical reclamation. For instance, an annual water demand planning system for irrigation was developed (Zhovtonoh O.I. et al., 2015a), operational irrigation planning information systems were implemented (Polishchuk V. et al., 2021; Matiash T. et al., 2022), and several projects for restoring irrigation and drainage systems were fulfilled (Technical and economic justification (feasibility study) of the Construction of an Irrigation System, 2019). Also, different methodological approaches were developed for this purpose (Zhovtonoh O.I. et al., 2015b; Zhovtonoh O.I. et al., 2011; Kuzmych Lyudmyla et al., 2022b). For making management decisions on plans of long-term restoration and development of irrigation, a scenario approach is proposed, where a scenario is an alternative vision of the system's future functioning considering a complex of variable influencing factors (driving forces) (Meijer et al., 2007).

METHODOLOGY OF TECHNICAL AND ECONOMIC JUSTIFICATION FOR IRRIGATION SYSTEM CONSTRUCTION

The methodology presented in this chapter involves the systematic development of technical and economic justification (feasibility study) using a scenario-based interdisciplinary approach. This approach provides a thorough and compelling justification for implementing and constructing irrigation systems to reduce risks in agriculture and enhance agricultural productivity given influencing factors. During the development of FS, the following key technical decisions and recommendations affecting the project cost are thoroughly assessed:

-selecting water sources and assessing water volumes; determining water quality and its suitability for irrigation (Usatyi S. et al., 2022; Usatyi Serhii et al., 2023);
-assessing soil cover; determining soil properties and estimating the changes in soil health influenced by water quality and irrigation methods (sprinkler irrigation, drip irrigation, etc.) (Usata L.G. et al., 2017; Trofymenko P. et al., 2018; Ryabkov S. et al., 2021);
-determining crop water consumption rates and calculating available water supply for irrigation systems (Zhovtonoh O.I. et al., 2015a; Romashchenko M.I. et al., 2020c);
-considering climate change in the future (Romashchenko M.I. et al., 2020a; Tararico Y. et al., 2020);
-substantiating irrigation equipment options: different types and modifications of irrigation equipment and irrigation network (Romashchenko M.I. et al., 2020b);
-evaluating the possibilities of partial cost compensation for irrigation systems produced domestically by the state (Polishchuk V. et al., 2021; Romashchenko M. et al., 2021; Romashchenko M. et al., 2023).

Furthermore, the issues of water consumption, selection of irrigation methods and techniques, cost estimation for the reconstruction of existing or construction of new irrigation systems, and assessment of all costs and revenues are substantiated in detail. The justification of water consumption begins with developing crop structure options, listing planned crops and their proportions within the irrigation module, and options with different irrigation machines or systems providing crop irrigation. Seasonal dynamics of water supply for irrigation are calculated based on the developed crop list and the meteorological data from a nearby weather station, covering over 25 years. These data include temperature, relative humidity, and precipitation. Calculations are made using mathematical models for selected crops and periods with defined precipitation probability, considering crop water demand at different growth stages. The capacity of the irrigation network, i.e., its operational hydromodule, is evaluated. This module is the amount of supplied water in dm3/s per hectare of irrigated area required for sufficient water supply to the irrigation system in the year of chosen natural water probability. The operational hydromodule is calculated given the seasonal dynamics of hydromodules for individual crops requiring water supply and the structural coefficient of field area in the crop rotation structure.

The justification of irrigation methods and techniques is based on analyzing the existing irrigation network capability to connect other irrigation systems. Layout schemes for intra-farm irrigation networks and the placement of irrigation equipment are developed depending on their types and modifications (e.g., center-pivot or linear sprinkler machines, surface or sub-surface drip irrigation, etc.). Hydraulic calculations are made to justify the use of selected irrigation machines based on their pressure-flow characteristics. When selecting irrigation equipment, the preference is given to machinery most adapted to the natural-agricultural and soil-topographical conditions of the irrigation area and meets agro-soil requirements.

A technical audit is conducted to estimate the costi of reconstruction and modernization of the existing irrigation system intended to be used for providing water supply for the constructed new irrigation system. Costs for reconstructiтng and modernizing pumping equipment and the main network to increase the capacity of water supply and distribution, are determined. The costs for constructing a new irrigation system are calculated based on current prices for each type of pipeline and irrigation machinery. The costs and profits from implementing the planned measures are assessed based on calculating the cultivation efficiency for each crop when applying the developed technically substantiated irrigation. The results of the calculations for each option will allow the client to choose the most efficient variant, which can be used as the primary option for designing and constructing the irrigation system on the farm.

The developed methodology for the technical and economic justification (feasibility study) of irrigation system construction was tested on the lands of the State Enterprise "State Farm "Pioneer" (SE "SF "Pioner") in the Novovorontsovsky district of the Kherson region (Technical and economic justification (feasibility study) of the construction of an irrigation system, 2019), the analysis of the natural and climatic conditions of which revealed that profitable crop cultivation is possible only when applying irrigation. The Zolotobalkivska irrigation system was considered as a source of irrigation, where water was sourced from the Kakhovka reservoir as of 2019 when the work was performed. On June 6, 2023, the Kakhovka Reservoir was emptied due to the destruction of the Kakhovka HPP dam (Zheleznyak M., 2024). This reservoir, which supplied up to 40% of southern Ukraine's water needs (Snizhko Sergiy et al, 2023), was transformed into the Dnipro River bed. The lack of the required water volumes made it impossible to implement irrigation by the options within the FS, the methodology of which is presented in this chapter. Nevertheless, this study serves as an example of the methodology for developing FS for irrigation system construction aimed at preventing and reducing risks in agriculture and increasing agricultural productivity. Despite the specific conditions changed due to the reservoir's depletion, the methodology can still guide similar projects under different conditions or with alternative water sources.

EXAMPLE OF METHODOLOGY IMPLEMENTATION

General Information About the Territory

In 2019, the technical and economic justification of irrigation system construction was developed for the area located in Lyubymivka village (Novovorontsovsky district, Kherson region, Ukraine), with the coordinates 47.361656, 33.756559. Currently, this area is de-occupied, but it is partially destroyed due to the hostilities caused by the full-scale invasion of the Russian Federation into Ukraine. The projected capacity of the future irrigation array included eight land plots, numbered sequentially from 37 to 44. The schematic location of these plots is shown in Figure 1. The area of these plots ranged from 137.96 to 382.83 hectares (Table 1). The total area of the territory was 2770.05 hectares (Table 1). During the study, it was found that there was a power transmission line passing across plot N°40, the area of which with the protective zone was 0.05 hectares. So, that area was excluded from further calculations, and the calculated area became 2770 hectares.

Figure 1. Plot locations within the irrigation array (plot boundaries is shown in red, plot numbers - in white)

Table 1. The area of plots within the farm land suitable for irrigation

Plot number within the farm land	Plot area, hectares	Note
37	137.96	-
38	380.18	-
39	366.93	-
40	371.31	Along the western side a power transmission line (PTL) runs, the area of which with a protective zone (0.05 hectares) was excluded from the calculations
41	376.66	-
42	375.03	-
43	382.83	-
44	379.15	-
The total area:	2770.05	-
The calculated area:	2770.00	-

Natural and Climatic Conditions of the Territory

The climate of the studied territory is moderately continental with pronounced dry and drought phenomena, characterized by moderately hot summers and mild, unstable winters (Climate data for the weather station Velyka Oleksandrivka, 2019). The average annual air temperature across the territory is +9.5°C.

The general climatic feature of the region is the continental type of annual precipitation with a maximum in spring and summer and a minimum in winter. The average annual precipitation is 466 mm, of which 234 mm falls in the growing season and 151 mm in the summer. During the year, up to 110 days may have precipitation to 0.1 mm and more, and up to 10 days - to 10 mm. In summer, precipitation falls unevenly across the territory. Eliminating the deficit of natural moisture supply through irrigation is one of the effective measures that will create the necessary prerequisites for highly efficient farming if it is designed and built based on a feasibility study, which is the initial stage of works on the implementation of irrigation on land plots.

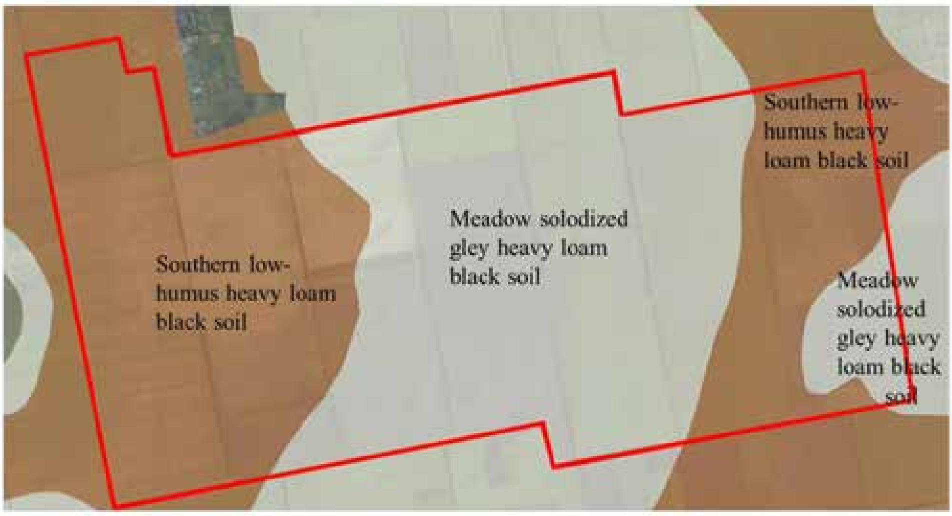
Data on Existing Resources and Networks Within the Agricultural Enterprise

A storage pond was chosen as the source of water for irrigation. Water will flow to it from the Zolotobalkivska irrigation system, which is supplied with water from the Kakhovka reservoir. The water will be supplied from the storage pond to the main and irrigation network of irrigation systems, the construction of which is also justified in this study.

The Zolotobalkiv irrigation system has been in operation since 1980. The advantages of this irrigation system are the presence of a network of canals, main pipelines, and pumping equipment, which allow for minimizing capital investments without solving additional settlement works. In addition, it has a favorable territorial location to the fields of State Enterprise “State Farm “Pioneer” (SE “SF “Pioner”). The distance from the storage pond to the nearest field N° 44 is about 3 km.

In the structure of the land holding of SE “SF “Pioner”, southern low-humus heavy loam black soil and meadow solodized gley heavy loam black soil (Fig. 2) prevail. Black soil has a thick humus horizon, which contains 4.0% of humus (Fig. 2). Southern black soil has a neutral and slightly alkaline reaction of the soil environment (pHH2O = 6.7-7.6). Meadow black soil is different by a differentiated profile . The humus horizon contains 3.75% organic matter. This soil has a very weak alkaline reaction (pHH2O=7.4). This soil has worse physical and water-physical properties responsible for the accumulation, filtration, and distribution of moisture than the black soil, so it can slightly complicate the control of irrigation water regime by one protocol per plot. Therefore, before starting to apply irrigation, it will be necessary to perform reclamation measures to improve the water and physical characteristics of the soil.

Figure 2. Soils of the plot of SE "SF "Pioner" (Soil map from the Public Cadastral Map of Ukraine, adjusted according to the Soil Map of Ukraine Scale 1:200000)



In this study, water samples were taken near the water intakes (the Kakhovka Reservoir) of the Zolotobalkivska irrigation system, located near the villages of Zolota Balka and Mykhailivka in the Novovorontsovsky district of the Kherson region. The quality of irrigation water was evaluated by its chemical composition (Figure 3, Table 2) to predict the possible impact of irrigation on soil properties and the technical condition of irrigation systems. In Ukraine, a lot of effort is made to study and protect soils (Baliuk S. et al, 2024). Therefore, forecasting changes in soils under irrigation is mandatory, which allows for improving the control of the ecological and reclamation state of irrigated soils. The quality of irrigation water is also one of the main factors in ensuring the reliable and long-term operation of irrigation systems (Nakayama F.R. et al, 1991; Capra A. et al, 1998; Rokochinskiy A. et al, 2020; Usatyi S.V., 2021), which is controlled and regulated in Ukraine by state standards. The chemical and biological compositions of water during the irrigation period are influenced by external and internal water exchange and water velocity (Khilchevskyi V.K. et al, 2024) during transportation to irrigation systems, so it is important to control the quality of such water in different periods.

Figure 3. Content of main ions in the water of the Kakhovka Reservoir depending on the sampling location (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, and K^+, meq/dm3)

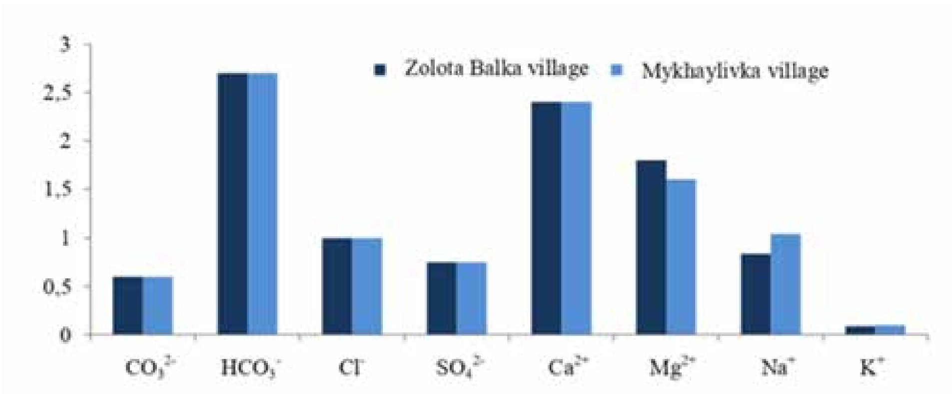


Table 2. Indicators of water quality and suitability for irrigation in the Kakhovka reservoir

Nº	Indicator	Water indicator at the sampling point	
		Zolota Balka village	Mykhaylivka village
1	Concentration of toxic ions, meq/dm3	1.65	1.65
2	Toxic alkalinity, meq/dm3	0.70	0.70
3	The ratio of alkaline cations to all cations, %	17.97	22.18
4	Total mineralization, g/dm3	0.35	0.35
5	Total hardness, meq/dm3	4.20	4.00
6	pH, units	8.30	8.35

By agronomic criteria following DSTU 2730 (State Standard of Ukraine DSTU 2730:2015, 2016), the irrigation water from the Kakhovka Reservoir does not meet the normative standarts, and it can be limited in use due to the danger of soil alkalizing and toxic effects on plants. By technical criteria, the irrigation water is suitable by the total mineralization (0.35 g/dm3) and moderately suitable by the pH degree (8.30-8.35 units). The total water hardness (4.0-4.2 meq/dm3) is permissible for use in irrigation systems. The efficiency of irrigation is determined by how accurately the ecological and productive functions of soils will be assessed, substantiated, and improved under irrigation to increase crop yields (Soil Reclamation, 2015).

Audit of the Technical Condition of the Zolotobalkivska Irrigation System

The technical audit of the Zolotobalkivska irrigation system allowed for assessing the technical condition of its main components and developing the options for including the planned areas in irrigation. The irrigation system consists of the main pumping station "Zolota Balka", and three booster pumping stations: BPS Nº1 "Zolota Balka", BPS Nº2 "Zolota Balka", and BPS Nº3 "Zolota Balka".

The main canal of the irrigation system extends for 7750 meters and, according to the technical passport, should have a capacity of 3 m3/s. However, as determined by the audit, its conveyance capacity varies in different sections. Part of the main canal is in good working condition, and another part is in a satisfactory condition.

The main pumping station supplies water for crop irrigation and has additional technical capacities to supply water to the planned area. The building of the MPS is in satisfactory condition, where pumping equipment consisting of three pumps with a total capacity of 9950 m3/hour is located. The pumps are in good working condition. The booster pumping station BPS Nº1 has been out of operation since 1998, but its pumping equipment is in working condition. After repair works, the operation of BPS Nº1 can be restored to perform its functions. The main issue identified during the audit is the absence of a power transmission line with a capacity of 10000 kW and a length of 3000 meters, which prevents the operation of the pumping stations. Therefore, it is necessary to develop a new project for constructing and restorating the power transmission line.

Despite its satisfactory condition, the audit results have revealed that the Zolotobalkivska irrigation system has unused capacities with a productivity of 3000 m3/hour for supplying water to the irrigation areas planned by the SE "SF "Pioner".

Assessment of Crop Water Consumption

Calculation of crop water consumption rates under irrigation was performed using the equation of a water balance for the root zone of the soil:

$$Di = E_i - (P_i - \Delta P_i), \quad (1)$$

where: Di - deficit of crop water consumption for the i-th decade of the growing season, m3/hectare; E_i - total evaporation, m3/hectare; P_i - precipitation; ΔP_i - part of precipitation for surface runoff and filtration;

The calculation of total evaporation is performed using the formula:

$$E_i = \phi_i \cdot k^{\kappa}_{б_i} \cdot E_{0_i} + (1 - \phi_i) \cdot k_{\Pi_i} \cdot E_{0_i}, \quad (2)$$

where: E_i - total evaporation, m3/hectare; φ_i - the ratio of the field vegetation cover at a given stage of its development to its critical value, when the evaporation from the soil surface is practically absent; E_{0_i}- evapotranspiration, m3/hectare, calculated using the formula:

$$E_{0_i} = 0,0006 \cdot (25 + t_i)^2 \cdot (100 - r_i), \tag{3}$$

where: t_i and r_i - average daily temperature, °C, and relative air humidity, %; k_{∂_i} - biological plant evaporation coefficient; k_{Π_i} - evaporation coefficient from the bare part of the field depending on its moisture degree:

$$k_{\Pi_i} = 0,33 + 0,01 \cdot P_i + 0,04 \cdot n_{P_i}, \tag{4}$$

where: P_i - total precipitation for the decade, m3/hectare; n_{P_i}- number of days in the decade with precipitation P > 10 m3/hectare.

When calculating the crop water consumption rates, the total deficit of water consumption *Di* for all decades of the irrigation period is reduced by the amount of available moisture in the soil root zone at the beginning of growing season (W_o).

$$M_{j_n} = \sum_{i=1}^{i=J} D_i^{\kappa} - W_{0_j}, \tag{5}$$

where: M_{j_n}- crop water consumption rate, m3/hectare; D_i^{κ} - deficit of crop water consumption, m3/hectare; W_{0_j}- amount of available moisture in the soil root zone at the beginning of growing season, m3/hectare.

Developing the existing climate change trend for the next 20-50 years (COP28, 2023) involves an increase in water consumption rates by 10-20% when developing plans to modernize irrigation systems compared to the rates, which have been calculated considering climate change over the last 20 years. Accordingly, assessment should be made for worse natural moisture conditions - for moderately dry years with 75% probability and dry (extremely dry) years with 95% probability.

The crop water consumption rates used in the study were calculated, considering the natural moisture coefficient, which for the land of the SE “SF “Pioner” is more than 0.45, and the natural moisture supply of the year, which is for moderately dry years is 75% and dry (extremely dry) years is 95% (Table 3).

Table 3. Water consumption rates of maib crops in the years of different natural moisture supply in Ukraine

Crop	Coefficient of natural moisture	Water consumption rates, m3/hectare	
		for years with 75% probability	for years with 95% probability
Soybeans	<0.40	3000	3400
	0.40-0.45	2900	3300
	>0.45	2800	3100
Corn	<0.40	3900	4100
	0.40-0.45	3600	3900
	>0.45	3400	3600
Winter wheat	<0.40	1900	2300
	0.40-0.45	1700	2100
	>0.45	1500	1900
Sunflower	<0.40	2500	2800
	0.40-0.45	2300	2500
	>0.45	2000	2300
Winter rapeseed	<0.40	1500	1800
	0.40-0.45	1400	1600
	>0.45	1200	1500

The technical and technological capacity of the irrigation system must ensure the supply of the necessary water volumes to the fields, determined by the actual cropping system, irrigation network capacity, production capacity of the irrigation equipment and pump-power units, the technical condition of the irrigation network and hydraulic structures, and the efficiency of water control. The substantiation of the statistical reliability of the calculated hydromodules for irrigated crops is the basis for designing the irrigation network and determining its capacity to ensure high irrigation efficiency. The net hydromodule required to irrigate any crop (*k*) is calculated by the formula:

$$q^k = \frac{a^k m}{86,4 \cdot t}, \qquad (7)$$

where: q_i^K - average ten-day hydromodule value, dm3/s/hectare; a^k - crop structural coefficient - the share of the area occupied by a crop; *m* - net irrigation rate, m^3/ hectare; *t* - irrigation duration, days; 86,4 - unit agreement factor (days to seconds and m3/hectare to liters).

To determine the hydromodules of the planned irrigation system, the decadal water consumption deficits were calculated using the following formula:

$$D_i^K = E_i^K - (P_i - \Delta P_i) - G_i^K, \quad (8)$$

where: D_i^K- decadal water consumption deficit, mm or m3/hectare; E_i^K- total evaporation from a crop field (*κ)* for the *i-th* decade; P_i, ΔP_i - precipitation and precipitation share for surface runoff and filtration; G_i^K - feeding of the root zone with groundwater, the level of which is less than 3.5 m (capillary inflow).

The average ten-day hydromodule was calculated using the formula:

$$q_i^K = \frac{D_i^K}{86,4} = 0,116 D_i^K, \quad (9)$$

where: q_i^K - average ten-day hydromodule, dm3/s/hectare; D_i^K- decadal water consumption deficit, mm or m3/hectare.

Selection of Crop Rotation Systems and Irrigation Equipment Tailored to the Water Supply Limit and Operational Hydromodule

The farm planned to implement three options of cropping system in the irrigated area of 2700 hectare (Table 4). Option 1 involved cultivating 60% soybeans, 20% winter wheat, and 20% corn, respectively (Table 4). Option 2 involved cultivating 40% soybeans, 30% winter wheat, and 30% corn, respectively (Table 4). Option 3 involved cultivating 40% soybeans, 20% winter wheat, and 40% corn, respectively (Table 4).

Table 4. Cropping system used in calculations of maximum hydromodule and decadal water supply volumes for an area of 2700 hectares

Option	Cropping system (%)		
	Soybeans	Winter wheat	Corn
1	60	20	20
2	40	30	30
3	40	20	40

Having calculated the maximum hydromodule for the cropping system by options 1-3 (soybean-corn-winter wheat), the need for irrigation water supply, which was 3489-4005 m3/hour, was specified. That significantly exceeds the technical capabilities of the Zolotobalkivska irrigation system, which can provide a water supply of no more than 3000 m3/hour. Such a capacity lack will not provide irrigation with the calculated rates for soybean-wheat-corn in the planned cropping systems (Table 4). Therefore, a different cropping system was substantiated, which includes five crops (soybean-corn-winter wheat-sunflower-winter rapeseed) when having a water supply limit of 3000 m3/hour focusing on dry (extremely dry) (95% natural moisture supply) and moderately dry (75% natural moisture supply) years and four options of their ratio.

Maximum hydromodule was calculated and the irrigation network discharge was specified for each cropping system option. A model range of irrigation equipment was selected, based on the existing water supply limit of 3000 m3/hour, and the placement schemes of irrigation equipment were made. The list of selected irrigation equipment for the planned irrigation area is given in Table 5. When using selected irrigation equipment, the net irrigation area for the "Fregat" linear sprinkler will range from 2400 to 2700 hectares, the "Fregat" linear and center pivot (combined action) sprinkler – from 2400 to 2666 hectares, the "Fregat" center pivot sprinkler – 2208 hectares, and for the "Zimmatic" center pivot sprinkler – 1976 hectares (Table 5).

Table 6 presents the selected options of cropping system given the water supply limit of 3000 m3/hour focusing on an moderately dry years with 75% probability for the "Fregate" linear sprinklers, the net area of which is 2700 hectares, center pivot sprinklers - 2208 hectares, linear and center pivot (combined action) sprinklers - 2666 hectares and the "Zimmatic" center pivot sprinklers - 1976 hectares, respectively. Table 7 presents the options of a cropping system given a water supply limit of 3000 m3/hour focusing on a dry (extremely dry) years with 95% probability. The irrigated area or the share of moisture-loving crops was reduced, because the presence of moisture-loving crops (soy, corn) in the cropping system at the level of 60% or more does not allow for meeting their optimal water demands. Therefore, the cropping system options were optimized in terms of reducing the share of moisture-loving crops in the cropping system, so the net irrigation area was reduced. The net irrigation area was optimized to 2500 hectares for the "Fregat" linear sprinklers, 2208 hectares - for the "Fregat" center pivot sprinklers, 2400-2500 hectares - for the "Fregat" linear and center pivot (combined action) sprinklers, and 1976 hectares - for the "Zimmatic" center pivot sprinklers.

Table 5. List of selected irrigation equipment for irrigation of the planned area

Sprinkler modification	Sprinkler manufacturer	Principle of sprinkler operation	Irrigated area served by the sprinkler equipment, hectare
DMF-F-B8 (456 m)	PJSC "The Plant "Fregat", Ukraine	linear	2400-2700
DMF-F-B9 (504 m)			

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Table 5. Continued

Sprinkler modification	Sprinkler manufacturer	Principle of sprinkler operation	Irrigated area served by the sprinkler equipment, hectare
DMF-F-B8 (456 m)	PJSC "The Plant "Fregat", Ukraine	linear and center pivot (combined action)	2400-2666
DMF-F-B9 (510 m)			
DMF-K-B10 (550 m)			
DMF-K-B8 (444 m)	PJSC "The Plant "Fregat", Ukraine	center pivot	2208
DMF-K-B9 (504 m)			
DMF-K-B10 (550 m)			
DMF-K-B11 (589 m)			
Zimmatic NTCP (540 m)	Lindsay Corporation, Nebraska, USA	center pivot	1976
Zimmatic NTCP (460 m)			

Zimmatic NTCP (460 m) - PC

Table 6. Options of cropping system given a water supply limit of 3000 m3/hour focussing on a moderately dry years with 75% probability

Nº	Crop	Crop share in the cropping system by options, % of the total area focusing on an moderately dry years with 75% probability			
		Option 1	Option 2	Option 3	Option 4
For the "Fregat" linear sprinklers					
1	Soybeans	35	35	35	25
2	Corn	25	30	30	25
3	Winter wheat	15	20	10	10
4	Sunflower	10	-	-	20
5	Winter rapeseed	15	15	25	20
For the "Fregat" center pivot sprinklers					
1	Soybeans	50	30	40	-
2	Corn	20	50	40	80
3	Winter wheat	-	20	-	20
4	Sunflower	15	-	-	-
5	Winter rapeseed	15	-	20	-
For the "Fregat" linear and center pivot (combined action) sprinklers					
1	Soybeans	35	35	35	25
2	Corn	25	30	30	25
3	Winter wheat	15	20	10	10
4	Sunflower	10	-	-	20

continued on following page

Table 6. Continued

Nº	Crop	Crop share in the cropping system by options, % of the total area focusing on an moderately dry years with 75% probability			
		Option 1	Option 2	Option 3	Option 4
5	Winter rapeseed	15	15	25	20
For the "Zimmatic" center pivot sprinklers					
1	Soybeans	60	40	45	55
2	Corn	30	50	45	30
3	Winter wheat	10	10	5	5
4	Sunflower	-	-	-	10
5	Winter rapeseed	-	-	5	-

Table 7. Options of cropping system given a water supply limit of 3000 m3/hour focussing on dry (extremely dry) years with 95% probability

Nº	Crop	Crop share in the cropping system by options, % of the total area focusing on a dry (extremely dry) years with 95% probability			
		Option 1	Option 2	Option 3	Option 4
For the "Fregat" linear sprinklers					
1	Soybeans	35	35	35	25
2	Corn	25	30	30	25
3	Winter wheat	15	20	10	10
4	Sunflower	10	-	-	20
5	Winter rapeseed	15	15	25	20
For the "Fregat" center pivot sprinklers					
1	Soybeans	40	20	30	-
2	Corn	20	50	40	70
3	Winter wheat	-	30	-	30
4	Sunflower	15	-	-	-
5	Winter rapeseed	25	-	30	-
For the "Fregat" linear and center pivot (combined action) sprinklers					
1	Soybeans	35	35	35	25
2	Corn	25	30	30	25
3	Winter wheat	15	20	10	10
4	Sunflower	10	-	-	20
5	Winter rapeseed	15	15	25	20
For the "Zimmatic" center pivot sprinklers					
1	Soybeans	35	40	40	35
2	Corn	35	40	40	35
3	Winter wheat	15	10	20	-

continued on following page

Table 7. Continued

Nº	Crop	Crop share in the cropping system by options, % of the total area focusing on a dry (extremely dry) years with 95% probability			
		Option 1	Option 2	Option 3	Option 4
4	Sunflower	15	-	-	15
5	Winter rapeseed	-	10	-	15

Table 8 presents the general results water network consumption, and net irrigation area for various types of sprinkler machines under a water supply limit of 3000 m3/ hour for an moderately dry and dry (extremely dry) years with 75% and 95% natural moisture supply, respectively.

Table 8. Irrigation network discharge, and net irrigated area for different types of sprinklers, selected to a water supply limit of 3000 m3/hour for a moderately dry years (75% probability) and dry (extremely dry) years (95% probability)

Options	Irrigation network discharge, and net irrigated area for different types of sprinklers, selected to a water supply limit of 3000 m3/hour							
	"Fregat" linear sprinkler		"Fregat" center pivot sprinkler		"Fregat" linear and center pivot (combined action) sprinkler		"Zimmatic" center pivot sprinkler	
	irrigation network discharge, m^3/hour	net irrigated area, hectare	irrigation network discharge, m^3/hour	net irrigated area, hectare	irrigation network discharge, m^3/hour	net irrigated area, hectare	irrigation network discharge, m^3/hour	net irrigated area, hectare
For a moderately dry years (75% probability)								
Option 1	2964.6	2700.0	2926.0	2666.0	2909.3	2208.0	2902.3	1976.0
Option 2	2867.4	2700,0	2830.1	2666.0	2893.4	2208.0	2909.5	1976.0
Option 3	2867.4	2700.0	2830.1	2666.0	2885.4	2208.0	2909.5	1976.0
Option 4	2848.0	2700.0	2811.0	2666.0	2901.3	2208.0	2973.5	1976.0
For a dry (extremely dry) years (95% probability)								
Option 1	2963.5	2400.0	2963.5	2400.0	2869.5	2208.0	2952.1	1976.0
Option 2	2988.0	2500.0	2988.0	2500.0	2885.4	2208.0	2909.5	1976.0
Option 3	2988.0	2500.0	2988.0	2500.0	2861.6	2208.0	2909.5	1976.0
Option 4	2988.0	2500.0	2988.0	2500.0	2933.1	2208.0	2994.8	1976.0

Specifications of the Proposed Irrigation System Options

For the placement of sprinkler equipment in the irrigated area, three scheme options were developed, taking into account the sizes of the fields, the land area of the SE "SF "Pioner" and the specifications of the sprinkler equipment. In Figures 4-6, schemes for placing center pivot and linear and center pivot (combined action) sprinklers are proposed, sprinkler modifications are indicated, irrigation zones, sprinkler flow rates, and the required pressure at the point of connection to the hydrant of the irrigation network are shown. Based on hydraulic calculations, types, diameters, and lengths of pipelines, flow rate, and head losses along the length of the irrigation network pipelines were determined. In addition, the location of the irrigation network, main and regional pipelines, and hydrants are grounded (Fig. 4-6). The recommended irrigation network schemes consist of main and regional pipelines made of polyethylene of PE 100 brand. Pipelines were selected by type (SDR 17 (10 atm.) – SDR 26 (6 atm.)) and diameter (200-900 mm) for each irrigation network scheme.

Figure 4. Scheme of the irrigation network when using the "Frigate" center pivot sprinkler (net irrigated area - 2208 hectares; number of sprinklers - 24 units)

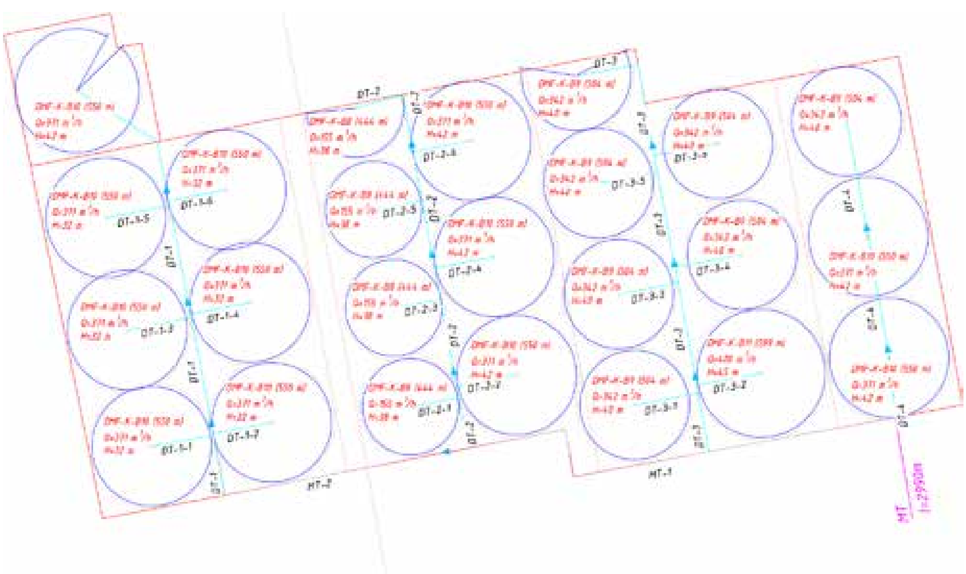


Figure 5. Scheme of the irrigation network when using the "Frigate" linear and center pivot (combined action) sprinklers (net irrigated area - 2666 hectares; number of sprinklers - 29 units)

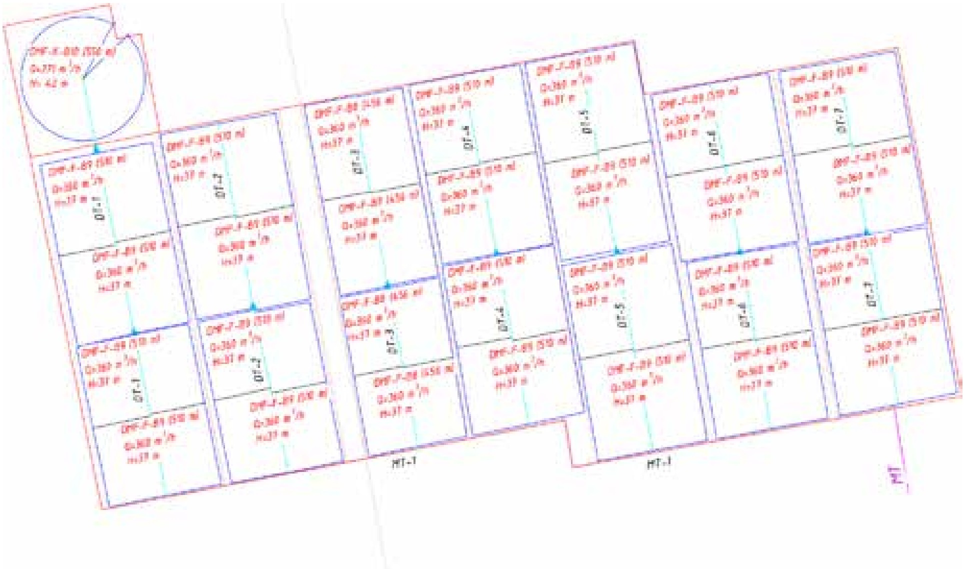
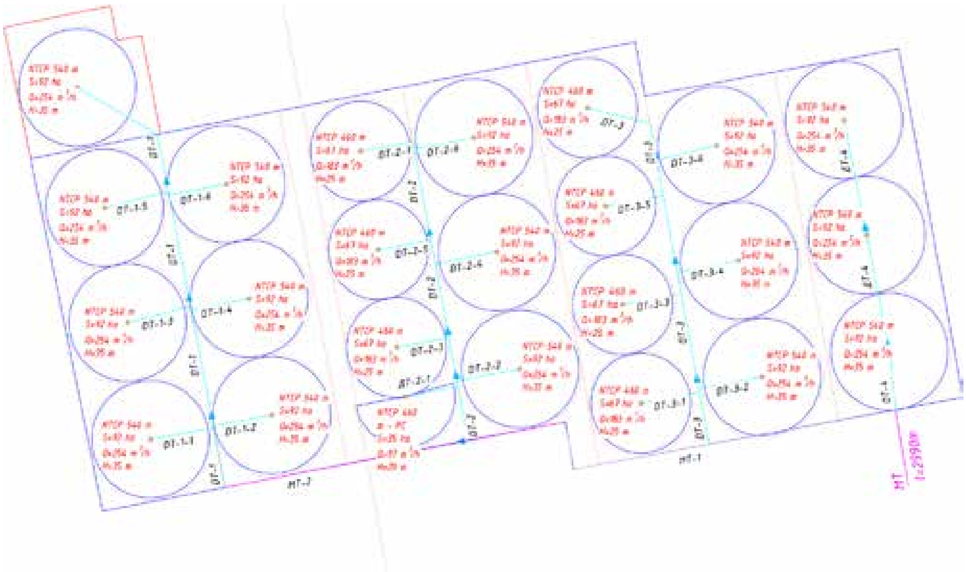


Figure 6. Scheme of the irrigation network when using the "Zimmatic" center pivot sprinkler (net irrigated area - 1976 hectares; number of sprinklers - 24 units)



The cost calculation for the sprinkler equipment was based on commercial proposals provided by the representatives of PJSC "The Plant "Fregat" (Pervomaisk town, Mykolaiv Region), which is a manufacturer of sprinkler equipment in Ukraine (Table 9). Additionally, the cost of domestic sprinkler equipment was calculated and presented, assuming a partial state compensation of 20% of the total cost for domestically produced sprinkler machines.

Wholesale and retail prices were used when calculating the cost of polyethylene pipelines. However, these prices are approximate because they depend on the cost of imported raw materials (polyethylene) and, accordingly, on fluctuations in the national currency exchange rate against the US dollar. The cost of the irrigation system, in addition to the cost of sprinkler equipment and irrigation pipeline, also includes the cost of an electrical transmission line needed to be restored with a length of 3000 meters to supply electricity to the pumping station. The total cost of the components of the irrigation system is presented in Table 10.

Table 9. Calculation of the sprinkler equipment cost

Nº	Sprinkler modification	Number, pcs.	Cost per unit, $	Cost per unit, UAH	Total cost, UAH	Total cost with partial compensation for domestic-produced irrigation equipment (20%), UAH
Irrigation with the”Fregat” linear and center pivot (combined action) sprinklers						
1	DMF-F-B8 (456 m)	4	91880.00	2176269.68	8705078.72	6964062.98
2	DMF-F-B9 (510 m)	24	99662.00	2360594.13	56654259.17	45323407.33
3	DMF-K-B10 (550 m)	1	96377.00	2282785.62	2282785.62	1826228.50
Total:		29	-	-	67642123.51	54113698.81
Irrigation with the “Fregat” center pivot sprinklers						
1	DMF-K-B8 (444 m)	4	81208.00	1923492.69	7693970.75	6155176.60
2	DMF-K-B9 (504 m)	7	88793.00	2103151.00	14722056.99	11777645.59
3	DMF-K-B10 (550 m)	12	96377.00	2282785.62	27393427.46	21914741.97
4	DMF-K-B11 (589 m)	1	104061.00	2464788.85	2464788.85	1971831.08
Total:		24	-	-	52274244.05	41819395.24
Irrigation with the “Zimmatic” center pivot sprinklers						
1	Zimmatic NTCP (540 m)	16	105695.00	2503491.77	40055868.32	Not compensated
2	Zimmatic NTCP (460 m)	7	93295.00	2209785.37	15468497.59	Not compensated
3	Zimmatic NTCP (460 m) - PC	1	94795.00	2245314.37	2245314.37	Not compensated
Total:		24	-	-	57769680.28	-

Note: The prices in the table are given in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD.

Table 10. Total cost of the irrigation system components for the SE “SF “Pioner”

Irrigation system components	Cost of the irrigation system components by different options, UAH				
	Option 1	Option 2	Option 3	Option 4	Option 5
	“Zimmatic” center pivot sprinkler	“Fregat” center pivot sprinkler		“Fregat” linear and center pivot (combined action) sprinkler	
	without cost compensation	without cost compensation	with partial cost compensation*	without cost compensation	with partial cost compensation*
Sprinklers	57769680	52274244	41819395	67642124	54113699
Irrigation network	90825000	131685000	131685000	134386250	134386250
Power transmission line	5000000	5000000	5000000	5000000	5000000
Total:	153594680	188959244	178504395	207028374	193499949

Note: * - partial compensation of the cost of Ukrainian-made irrigation equipment by the state

During the development of the feasibility study for the SE “SF “Pioner” probable costs and profits from the sale of products were determined and estimated, profitable purchase prices were calculated, and the “break-even point” indicator was determined. For example, Tables 11-14 show the calculations of these indicators for each option applying irrigation when using different modifications of sprinklers for two climate scenarios (with 75 and 95% precipitation probability). As a result of the work performed, a sufficiently large database was formed, which is the basis for selecting the cheapest and most profitable option.

By the cost and profit assessment, the most optimal irrigation option was the use of the “Fregat” linear and center pivot (combined action) sprinklers (Option 5) with partial compensation of their cost by the state. That allows achieving the highest profit from irrigation for corn, sunflower, winter rapeseed, and winter wheat, excluding soybeans. Therefore, given the existing water supply limit of 3000 m3/hour, it is advisable to consider using Option 5. However, if there are favorable fluctuations in purchase prices for agricultural products, all proposed options can be considered for use.

Tables 13-14 present the results of the assessment of probable costs and profits under Option 5, when using the “Fregat” linear and center pivot (combined action) sprinklers with partial compensation of the equipment cost by the state, which allows achieving the highest profit from irrigation in dry (extremely dry) years.

With increasing climate aridity, soybeans, sunflower, and winter rapeseed cultivation will not be profitable under sprinkler irrigation due to the low market prices for these crops. Soybeans have to be included in the cropping system if the predicted sale price will be higher than UAH 9370/t (Table 13).

An expert assessment established that using the diesel generator, which provides the movement of sprinklers, requires fuel, the cost of which is about UAH 1000/hectare, which amounts to UAH 2.0 to 2.7 million annually. Therefore, an economically viable option for driving sprinklers instead of diesel generators will be using electricity from the power transmission line, which has to be restored with a length of 3000 m and connected to each sprinkler.

Table 11. Probable costs and profits from applying irrigation for crop cultivation when using various equipment cost options

Indicator	Options by types and conditions of partial compensation for irrigation equipment				
	Option 1	Option 2	Option 3	Option 4	Option 5
	“Zimmatic” center pivot sprinklers	“Fregat” center pivot sprinklers		“Fregat” linear and center pivot (combined action) sprinklers	
	without cost compensation	without cost compensation	with partial cost compensation	without cost compensation	with partial cost compensation
Irrigated area, hectares	1976	2208	2208	2666	2666

Indicator	**Options by types and conditions of partial compensation for irrigation equipment**				
	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5**
	"Zimmatic" center pivot sprinklers	**"Fregat" center pivot sprinklers**		**"Fregat" linear and center pivot (combined action) sprinklers**	
	without cost compensation	**without cost compensation**	**with partial cost compensation**	**without cost compensation**	**with partial cost compensation**
Equipment cost, thousand UAH/ hectare	77.73	85.58	80.84	77.66	72.58
Depreciation expenses for the network and irrigation equipment, thousand UAH/ hectare	4.86	5.07	4.67	4.73	4.25
Profit from soybean irrigation, thousand UAH/hectare	-6.8	-6.5	-5.5	-6.2	-5.1
Profit from corn irrigation, thousand UAH/hectare	8.9	9.2	10.2	9.5	10.6
Profit from sunflower irrigation, thousand UAH/hectare	-0.5	-0.1	0.9	0.1	1.3
Profit from winter rapeseed irrigation, thousand UAH/ hectare	-0.4	-0.1	0.9	0.2	1.3
Profit from winter wheat irrigation, thousand UAH/ hectare	2.8	3.1	4.1	3.4	4.5

Note: The prices in the table are given in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD.

Table 12. Probable costs and profits from applying irrigation when using the "Frigate" linear and center pivot (combined action) sprinklers under Option 5 (with partial cost compensation of the Ukrainian-made irrigation equipment)

Crop	Irrigation																Without irrigation (winter wheat)					Profit from irrigation, thousand UAH/hectare
	Irrigation rate, thousand m3/hectare		Irrigation costs, thousand UAH						Cultivation costs, thousand UAH/hectare	Overhead exenses	Total costs, thousand UAH/hectar	Yield, cent /hectare	Sale price, UAH/cent	Income, thousand UAH/hectare	Profit, thousand UAH/haectare	Cost price for 1 cent, thousand UAH	Yield, cent /hectare	Sale price, UAH/cent	Income, thousand UAH/hectare	Cultivation costs, thousand UAH/hectare	Income, thousand UAH/hectare	
	Net	Gross	Water	Electricity	Depreciation expenses for the network and irrigation equipment	Fuel and lubricant cost	Maintenance	Sum														
Soybeans	3.3	3.795	1.90	7.59	4.3	1.48	1.7	16.97	11.2	8.4	36.6	40	870	34.8	-1.8	0.91	18	540	9.72	8.8	0.92	-2.7
Corn	3.0	3.45	1.73	6.9	4.3	1.34	1.7	15.97	15.2	9.3	40.5	120	450	54	13.5	0.34	18	540	9.72	8.8	0.92	12.6
Sunflower	2.3	2.645	1.32	5.29	4.3	1.03	1.7	13.64	13.1	8.0	34.8	40	985	39.4	4.6	0.87	18	540	9.72	8.8	0.92	3.7
Winter rapeseed	1.5	1.725	0.86	3.45	4.3	0.67	1.7	10.98	8.5	5.8	25.3	30	1000	30	4.7	0.84	18	540	9.72	8.8	0.92	3.8
Winter wheat	1.9	2.185	1.09	4.37	4.3	0.85	1.7	12.31	11.0	7.0	30.4	70	540	37.8	7.4	0.43	18	540	9.72	8.8	0.92	6.5

Note: The electricity cost for supplying 1 m3 of water is UAH 2/m3.
The cost of water supply services is UAH 2/m3.
The cost of diesel fuel for irrigation is 17.7 dm3/1000 m3.
The cost of fuel is UAH 22/dm3.
All calculations in the table are presented in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD.

Table 13. Breakeven Point (sale price for crops) when applying irrigation with the "Frigate" linear and center pivot (combined action) sprinklers (Option 5) (given the required purchase prices with partial cost compensation of the Ukrainian-made irrigation equipment)

Crop	**Break-even point (sale price for crops), UAH/t**
Soybeans	9370
Corn	3450
Sunflower	8930
Winter rapeseed	8750
Winter wheat	4470

Note: All calculations in the table are presented in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD

Table 14. Assessment of the breakeven point when applying irrigation with the "Frigate" linear and center pivot (combined action) sprinklers in dry (extremely dry) years under Option 5 (given required purchase prices with partial cost compensation of the Ukrainian-made irrigation equipment)

Crop	Irrigation																Without irrigation (winter wheat)					Profit from irrigation, thousand UAH/hectare
	Irrigation rate, thousand m3/ hectare		Irrigation costs, thousand UAH						Cultivation costs, thousand UAH/hectare	Overhead exenses	Total costs, thousand UAH/hectar	Yield, cent/hectare	Sale price, UAH/cent	Income, thousand UAH/hectare	Profit, thousand UAH/haectare	Cost price for 1 cent, thousand UAH	Yield, cent/hectare	Sale price, UAH/cent	Income, thousand UAH/hectare	Cultivation costs, thousand UAH/hectare	Income, thousand UAH/hectare	
	Net	Gross	Water	Electricity	Depreciation expenses for the network and irrigation equipment	Fuel and lubricant cost	Maintenance	Sum														
Soybeans	3.3	3.795	1.90	7.59	4.3	1.48	1.7	16.97	11.2	8.4	36.6	40	937	37.48	0.9	0.91	18	540	9.72	8.8	0.92	0.0
Corn	3.0	3.45	1.73	6.9	4.3	1.34	1.7	15.97	15.2	9.3	40.5	120	345	41.4	0.9	0.34	18	540	9.72	8.8	0.92	0.0
Sunflower	2.3	2.645	1.32	5.29	4.3	1.03	1.7	13.64	13.1	8.0	34.8	40	893	35.72	0.9	0.87	18	540	9.72	8.8	0.92	0.0
Winter rapeseed	1.5	1.725	0.86	3.45	4.3	0.67	1.7	10.98	8.5	5.8	25.3	30	875	26.25	0.9	0.84	18	540	9.72	8.8	0.92	0.0
Winter wheat	1.9	2.185	1.09	4.37	4.3	0.85	1.7	12.31	11.0	7.0	30.4	70	447	31.29	0.9	0.43	18	540	9.72	8.8	0.92	0.0

Note: All calculations in the table are presented in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD.

9 CONCLUSIONS REGARDING THE OPTIMAL OPTION OF THE PROPOSED SOLUTIONS AND PROPOSALS

The optimal option of the proposed solutions and proposals for SE "SF "Pioner", which allows for obtaining the highest profit from irrigation given the existing limit of the water supply of 3000 m3/hectare from the Zolotobalkivka irrigation system, is the option of applying irrigation when using the "Fregate" linear and center pivot (combined action) sprinklers providing a partial compensation of their cost by the state (Option 5) (Table 10).

Analysis of calculations using the sale prices for crops as of December 2019 showed that the most profitable crops in moderately dry years with 75% probability and in dry (extremely dry) years with 95% probability when irrigating with the "Fregate" linear and center pivot (combined action) sprinklers is corn, which in cropping system have to occupy up to 58% of the total irrigated area, and winter wheat - up to 42% of the total irrigated area, respectively. To prove that, calculations of the maximum hydromodule and ten-day volumes of water supply, the economic efficiency of new construction of the irrigation network using the "Fregat" linear and center pivot (combined action) sprinklers were performed (Table 15). The probable costs and profits from the irrigation under such an option were assessed (Table 16).

The calculation of the economic efficiency of new construction of an irrigation network for irrigating profitable crops in dry (extremely dry) years (95% probability) is given in Table 17. The payback period of the new construction of an irrigation network when using the "Fregate" linear and center pivot (combined action) sprinklers providing a partial compensation of their cost by the state will be 7.2 years (Table 17). An increase in the sale prices for agricultural products by 20% will reduce the payback period of constructing the irrigation system to 3.7 years (Table 17).

Table 15. Calculation of the maximum hydromodule and ten-day water supply volumes when using the "Frigate" linear and center pivot spinkler for irrigating profitable crops on in dry (extremely dry) years (95% probability) with partial cost compensation of the Ukrainian-made irrigation equipment

Crop	Area, hectare / structural coefficient, %	Параметр	Month, ten-day period															In total
			April		May			June			July			August			September	
			2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	
Corn	1546.28/58	Deficit of water consumption, D, m3/ hectare	-	-	182	163	216	201	250	282	383	455	435	433	-	-	-	3000
		Crop hydromodule, q, dm3/s per hectare	-	-	0.21	0.19	0.25	0.23	0.29	0.33	0.44	0.53	0.50	0.50	-	-	-	-
		Crop hydromodule in the proposed cropping system, Q, dm3/s per hectare	-	-	0.042	0.109	0.145	0.135	0.168	0.189	0.257	0.305	0.292	0.291	-	-	-	-

continued on following page

Table 15. Continued

Crop	Area, hectare / structural coefficient, %	Параметр	Month, ten-day period															In total
			April		May			June			July			August			September	
			2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	
Winter wheat	1119.72/42	Deficit of water consumption, D, m3/per hectare	193	250	462	459	573	471	-	-	-	-	-	-	-	-	-	1900
		Crop hydromodule, q, dm3/s per hectare	0.22	0.29	0.54	0.53	0.66	0.55	-	-	-	-	-	-	-	-	-	-
		Crop hydromodule in the proposed cropping system, Q, dm3/s per hectare	0.094	0.121	0.225	0.223	0.278	0.229	-	-	-	-	-	-	-	-	-	-
∑Q, dm3/s per hectare for the proposed cropping system			0.057	0.063	0.094	0.121	0.267	0.332	0.423	0.364	0.168	0.189	0.257	0.305	0.292	0.291	-	-
Maximum value of ∑Q, dm3/s per hectare for the proposed cropping system			-	-	-	-	-	-	-	-	-	-	-	0.305	-	-	-	-

Note: The irrigation network discharge, necessary to ensure water supply (the maximum hydromodule value ∑Q (dm3/s per hectare)) for the proposed cropping system, is Q = 2927.3 m3/hour.

Table 16. Assessment of probable costs and profits when applying irrigation with the "Frigate" linear and center pivot (combined action) sprinklers in years with 95% probability (with partial cost compensation of the Ukrainian-made irrigation equipment)

Crop	Irrigation																Without irrigation (winter wheat)					Profit from irrigation, thousand UAH/hectare
	Irrigation rate, thousand m3/ hectare		Irrigation costs, thousand UAH						Cultivation costs, thousand UAH/hectare	Overhead exenses	Total costs, thousand UAH/hectar	Yield, cent/hectare	Sale price, UAH/cent	Income, thousand UAH/hectare	Profit, thousand UAH/haectare	Cost price for 1 cent, thousand UAH	Yield, cent/hectare	Sale price, UAH/cent	Income, thousand UAH/hectare	Cultivation costs, thousand UAH/hectare	Income, thousand UAH/hectare	
	Net	Gross	Water	Electricity	Depreciation expenses for the network and irrigation equipment	Fuel and lubricant cost	Maintenance	Sum														
Soybeans	3.3	3.795	1.90	7.59	4.3	1.48	1.7	16.97	11.2	8.4	36.6	40	1044	41.76	5.2	0.91	18	540	9.72	8.8	0.92	4.3
Corn	3.0	3.45	1.73	6.9	4.3	1.34	1.7	15.97	15.2	9.3	40.5	120	540	64.8	24.3	0.34	18	540	9.72	8.8	0.92	23.4
Sunflower	2.3	2.645	1.32	5.29	4.3	1.03	1.7	13.64	13.1	8.0	34.8	40	1182	47.28	12.5	0.87	18	540	9.72	8.8	0.92	11.6
Winter rapeseed	1.5	1.725	0.86	3.45	4.3	0.67	1.7	10.98	8.5	5.8	25.3	30	1200	36	10.7	0.84	18	540	9.72	8.8	0.92	9.8
Winter wheat	1.9	2.185	1.09	4.37	4.3	0.85	1.7	12.31	11.0	7.0	30.4	70	648	45.36	15.0	0.43	18	540	9.72	8.8	0.92	14.1

Note: The electricity cost for supplying 1 m3 of water is UAH 2/m3.
The cost of water supply services is UAH 2/m3.
The cost of diesel fuel for irrigation is 17.7 dm3/1000 m3.
The cost of fuel is UAH 22/dm3.
All calculations in the table are presented in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD.

Table 17. Economic efficiency of new construction of intra-farm irrigation network when using the "Frigate" linear and center pivot (combined action) sprinklers for irrigating profitable crops in dry (extremely dry) years with partial cost compensation of the Ukrainian-made irrigation equipment

Crop	Irrigation costs, thousand UAH	Profit from irrigation, thousand UAH/hectare	Profit from irrigation, thousand UAH	Payback period, years
Given the prices for crops as of December 2019				
Corn	193500.0	12.6	19483.13	7.2
Winter wheat		6.5	7278.18	
In total:	193500.0	19.1	26761.31	7.2
Given the prices for crops as of December 2019 with an increase of 20%				
Corn	204327.0	23.4	36182.95	3.7
Winter wheat		14.1	15788.05	
In total:	204327.0	37.5	51971.00	3.7

Note: All calculations in the table are presented in the national currency of Ukraine – Hryvnia. At the time of the FS development, the exchange rate was 23.7 UAH = 1 USD.

All proposed options for the cropping system and modifications of irrigation equipment can be promising options and can be considered during the design of new construction of an irrigation system, provided that the predicted market price for the sale of soybeans, corn, winter wheat, winter rapeseed, and sunflower is higher than the price established by the breakeven point, or highly profitable crops will be selected for cultivation.

CONCLUSION

1. The methodology for developing a feasibility study for constructing irrigation systems based on an interdisciplinary approach is presented. The goal of the approach is to provide a thorough and convincing justification for constructing irrigation systems to reduce risks in agriculture and increase crop productivity, given various influencing factors. This approach involves quantitative modeling of options with a different list of parameters characterizing the state of irrigation in terms of increased agricultural production, taking into account changes in climate, natural moisture supply, soils, cropping systems, irrigation methods, types of irrigation equipment, efficiency coefficients of irrigation systems operation, etc.

2. Developing a feasibility study was considered on the example of SE “SF “Pioner”, located in the Kherson region (Ukraine). When developing the feasibility study, key technical solutions and recommendations were substantiated in detail, which made it possible to select irrigation sources, assess water quality for irrigation, predict possible changes in soil quality affected by irrigation, calculate the capacity of irrigation systems and crop water consumption rates, take into account future climate change, propose options for selecting irrigation equipment modifications, irrigation network types and recommend to involve the mechanisms of partial cost compensation of the Ukrainian-made irrigation equipment.
3. The optimal option from the proposed solutions and proposals for the SE “SF “Pioner” which allows obtaining the highest profit from irrigation in the conditions of a water supply limit of 3000 m3/hour from the Zolotobalkivska irrigation system, was the option of constructing irrigation system when using the the “Fregate” linear and center pivot (combined action) sprinklers given the partial cost compensation of the irrigation equipment by the state. The payback period of the construction under this option will be 7.2 years. An increase in the sale prices for agricultural products by 20% will reduce the payback period of constructing the irrigation system to 3.7 years. The most profitable crops for this option in moderately dry years with 75% probability and dry (extremely dry) years with 95% probability will be corn, which in the cropping system has to occupy up to 58% of the total irrigated area, and winter wheat - up to 42% of the total irrigated area accordingly.
4. The methodology of a feasibility study for constructing irrigation systems presented in this work allows substantiating all scenarios of irrigation use aimed at timely preventing and reducing risks in agriculture and increasing the productivity of agriculture. It can be adapted to any conditions of use.

THE AREA FOR FURTHER RESEARCH

Future research will be aimed at improving the methodology of a feasibility study for constructing irrigation systems in terms of accounting for all losses and risks of agricultural production in the war-time conditions and post-war reconstruction of Ukraine.

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Chapter 12
Increasing the Economic Efficiency of Irrigation Restoration Investment Projects in the Face of Climate Change

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ABSTRACT

The chapter presents a scientific and methodological approach to justify investment projects for restoring irrigation systems in southern Ukraine that were not damaged

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by hostilities. It focuses on irrigation systems in the Odessa region covering up to 10000 hectares with water supply from local sources. The economic efficiency of investment projects for system restoration is analyzed under different agricultural scenarios. Proposals for modernizing a small irrigation system in Odessa are developed, considering legislative reforms for water user organizations. The chapter evaluates the technical condition of infrastructure, land use, legislative reforms, climate change, and water resources availability. Legal aspects of irrigation restoration are examined, and modernization plans are proposed with results mapping. Profitability indicators are calculated for various investment return scenarios, comparing them with the basic business scenario. Sensitivity analysis is conducted to assess project resilience to changes in key parameters.

BACKGROUND

Russia's war with Ukraine has caused instability in global food markets, for example, limited availability of food due to disruption of logistics routes and reduced production in Ukraine due to the ongoing war and the destruction of the Kakhovska Dam. This affected the export volumes of cultivated grains and led to an increase in prices on agricultural markets.Future challenges are expected to worsen due to the destruction and impairment of crucial hydrotechnical infrastructure that facilitates irrigation in water-demanding regions of Ukraine. This impending exacerbation is compounded by the ongoing impact of progressive climate change, particularly in Ukraine, where the average annual temperature is rising faster than the global average.

For example, data from the Institute of Water Problems and Reclamation of the National Academy of Sciences (IWPLR) and the Ukrainian Hydrometeorological Center shows a significant 1.2°C increase in the country's average annual air temperature over the past thirty years. This divergence in the rate of temperature rise in Ukraine compared to the broader European context during the period of 1975-2019 is noteworthy. Meanwhile, changes in the average annual amount of precipitation do not show a clear regularity over time, but there is a trend of increasing intensity of rainfall.

This climate analysis utilized data from the Ukrainian Meteorological Center's network of meteorological stations, along with information from IWPLR, the regional forecast projecting the average monthly air temperature and monthly precipitation amounts until 2050 and 2100. The forecast is based on the A1B scenario, anticipating a global warming of +2.8 °C by 2100.

Ukraine has six main moisture zones, with areas experiencing a significant deficit of natural moisture supply increasing by 7% from 1991 to 2015. These zones now cover over 29.5% of Ukraine's total land area, totaling 11.6 million hectares, which is 37% of the country's arable land. In contrast, regions with excessive and sufficient moisture supply saw a decrease of 10%, covering only 22% of the territory, equivalent to 7.6 million hectares of arable land (Romashchenko M. et al, 2020).

In the previous climatic period (1961-1991), when irrigation and drainage systems were intensively developed in Ukraine, the agricultural areas with excessive water supply were primarily used for meadows, perennial grass cultivation, pastures, and spring and winter cereals. However, due to climate change, there has been a shift of climatic zones to the north by 200-300 km. This shift has enabled the cultivation of row crops, such as grains (corn) and legumes (soybeans), as well as industrial crops (sunflower), which require deep plowing and soil overturning, exacerbating the negative impacts of climate change. In modern conditions, significant changes have occurred in agriculture. There has been a decrease in the number of cattle and pastures, while the cultivation of perennial grasses has declined. Crops that used to consume less water and promote its accumulation in the soil, which were predominant in crop rotation in the past, are cropped in much smaller areas.

The risks associated with extensive plowing and increased cultivation of row crops in Ukraine are exacerbated by the faster temperature increases. This risk is further heightened by the northward expansion of tillage crops into the Polissia zone, known for its low anti-erosion resistance soils (Zhovtonog O. et al, 2011; Bohaienko V. et al, 2023; Kuzmych L. et al, 2022).

Therefore, the modernization of irrigation systems in the southern regions of Ukraine, particularly in the Odesa region, is crucial to partially offset the agricultural territories affected by the war. The unoccupied Odesa region is expected to play a key role in addressing the food deficit resulting from the occupation of the southern part of the Kherson region (Zhovtonog O. et al, 2020).

Over the years, around sixty irrigation systems have been established in the Odesa region, serving nearly 250,000 hectares of agricultural land. The largest irrigation system in the Odesa region, the Danube-Dniester system, as of July 17, 2023, consists of 16 reservoirs, 274 pumping stations, and several thousand other hydrotechnical structures. As of the same date, six water user organizations have been established in the region.

Over the past thirty years, the irrigated land area in the Odesa region has decreased significantly by more than 200,000 hectares. In 2021, prior to the war, only 41,000 hectares were under irrigation compared to 243,000 hectares in 1991. According to State Agency of Water Resouces of Ukraine data, it is still possible to restore 187,000 hectares for irrigation. Recognizing the need to reform the reclamation system, the Ministry of Agrarian Policy had planned to implement 12 projects before the war to restore irrigation in the Odesa region, increasing the area of irrigated fields by an additional 35,000 hectares and attracting new investors and agricultural producers with planned financing of UAH 350 million.

The recent RDNA 3 report, a rapid assessment of the destruction and damage caused by the war conducted jointly by the World Bank and the Government of Ukraine, highlighted the urgent need to restore intact irrigation and drainage infrastructure, as well as invest in existing infrastructure to facilitate rapid economic recovery and compensate for damages from direct physical damage. The modernization of existing irrigation systems for Water User Organizations (WUO) and the restoration of damaged infrastructure in war-affected areas should be prioritized and carried out simultaneously in safer regions (World Bank, RDNA-3, 2022; Giordano, M. et al, 2023.).

Therefore, restoring relatively small irrigation systems in the southern part of the Odesa region will require a thorough analysis of the economic efficiency of such investment projects and an evaluation of various investment payback scenarios and profitability indicators (Perry C. et al, 2009; Shanono N. et al, 2023).

Numerous approaches and tools have been developed and practiced by various scientists in recent years to improve irrigation practices, which could be disseminated and scaled up in future irrigation investments. In this context, the Guidelines on Irrigation Investment Projects launched by FAO highlight experiences and lessons learned from global irrigation investment operations (FAO, 2018). These Guidelines were produced by an inter-agency team, including irrigation specialists from FAO, the World Bank, IFAD, ICID, and independent experts. The document introduce innovative approaches, tools and references, and provide practical guidance on how to incorporate or apply them at each stage of the investment project cycle.

The main challenge is to create the environment for increased and sustainable agricultural production through efficient management of the existing irrigated lands and expansion into new areas, to improve food security and livelihoods. This requires development planning and mobilization of investment resources for implementation and operation of many projects over the coming decades (Rogito O. et al, 2020; Burt C. et al, 1997, 2017; Morardet S. et al, 2005; Turral H. et al, 2010; Ayars J. et al, 1999).

In the case of the Odesa region, irrigation systems covering up to 10,000 hectares with water supply from local water sources for irrigation are considered. Different strategies to enhance the economic efficiency of investment projects aimed at restoration irrigation in the region are evaluated.

Proposals for investment projects have been developed to modernize the small-scale irrigation system in the Odesa region, considering legislative reforms and the formation of water user associations. An assessment of the technical condition of the irrigation infrastructure, land utilization, legislative changes related to climate change, and the availability of water resources was carried out to assess the feasibility and efficiency of irrigation system restoration (Shevchuk S. et al, 2022).

Various scenarios for investment returns were assessed, including cost-benefit analysis and profitability indicators, in comparison to the baseline business (Zhovtonog O. et al, 2011; Roerink G. J. et al, 2005).

MATHERIALS AND METHODS

The decision to select this specific irrigation system is based on various factors from both a scientific and practical perspective. These include the availability of infrastructure for recovery, significant impacts of climate change, and proximity to transportation routes. With the Kakhovska HPP suffering damage, there is an urgent need to shift agricultural production to areas of small irrigation systems that can be restored under the conditions of the establishment of water user associations.

This study evaluated two scenarios for restoring irrigation systems to assess the effectiveness of a future project. Economic efficiency calculations were carried out according to the Methodology for Ranking Irrigation Infrastructure Investment Projects (WB, 2013), according to the criteria proposed by the World Bank and adapted for the conditions of UkraineOne key criterion for evaluating the project's effectiveness is the Internal Economic Rate of Return (IRR). Typically, the profitability of irrigation restoration projects is compared to the cost of capital, which includes the cost of borrowed funds over the project's lifespan. If the IRR is lower than the cost of capital, the project should be carefully reviewed using other criteria. In this study, different refund scenarios were considered, in which each part can be covered by different investment approaches, the other part - in the form of non-refundable grants and subsidies from the state. During the study of the state of reclamation systems in the Odesa region, it became more and more obvious that the lack of priority for the restoration of irrigation systems, which applies not only to the irrigation and drainage system of the water sector as a whole, and the ongoing military operations in the country were an obstacle to the selection of investment project proposals. At the same time, covering the lost share of production at the expense of restoring the irrigation systems of the Odesa region is urgent in view of ensuring food security and preventing further destruction of the infrastructure. The project's advantage lies in establishing Water Users Associations within the Nagirnianska irigation system and the willingness of agricultural producers to invest in irrigation infrastructure.

Therefore, the calculation of the effectiveness of irrigation modernization projects is based on IRR - the interest rate that describes the profitability of the investment.

The Internal Rate of Return (IRR) calculated in the study is not the actual cost of the project in monetary terms. The definition of "internal" emphasizes the fact that this interest rate is a characteristic of the investment and does not depend on the environment, no, on market interest rates, cost of capital, inflation. The indicator that is taken into account when calculating IRR is the difference between the current values of expected future cash flows and the current value of invested funds. In fact, IRR is the discount rate that makes the net present value (NPV) of all cash flows equal to zero in a cash flow analysis.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0 \tag{1}$$

C_t - Net Cash Inflows during the period, C_0 - total initial investment costs for the period, IRR - Internal Rate of Return, t - number of time periods.

For the calculation of the cash flows that will be formed during the restoration of the Nagirnianska irrigation system, only the profit from the agricultural activities of the members of the WUO, namely the cultivation of agricultural products, is taken into account for the profitable part of the operational activity in this section. Providing related services will increase cash flow and accelerate return on investment.

Net Cash Flow (NCF) = Cash Flow from Operations (CFO) + Cash Flow from Investing (CFI) + Cash Flow from Financing (CFF).

$$NCF = CFO + CFI + CFF \tag{2}$$

To calculate the cost part of the cash flow, starting from the second year of the project, amortization deductions for the installed equipment in the amount of 2%, as well as the cost of cultivation, which during the implementation of the project changes depending on the crop rotation and the increase in the costs of cultivation technology with irrigation, are included.

Net Cash Flow is calculated using the formula as the difference in cash flows

Net Cash Flow = Total Cash Inflows – Total Cash Outflows.

$$NCF = TCI - TCO \tag{3}$$

Payback period is widely used when long-term cash flows are difficult to forecast, because no information is required beyond the break-even point. It may be used for preliminary evaluation or as a project screening method for high-risk projects in times of uncertainty. Payback period is usually measured as the time from the start of investment project to recovery of the capital investment. The payback period is the time taken for the cumulative net cash flow from start-up of the project to equal the depreciable fixed capital investment (CFC – S). It is the value of t that satisfies the equation:

$$\sum_{t=0}^{t=(PBP)} C_{CF} = (C_{FC} - S), \quad (4)$$

where C_{CF} - net annual cash flow, C_{FC} - fixed capital cost, S - salvage value

For the final year of calculation of the irrigation restoration investment project, it is assumed that the installed equipment has not amortized its initial cost (S is not equal to 0) and will remain usable for more than 25 years.

Thus, the higher the Internal Rate of Return, the more desirable the investment or the more attractive the business to the investor. IRR is uniform across investment types and as such can be used to rank several prospective investments or projects on a relatively even basis. In general, when comparing investment options with other similar characteristics, the investment in the scenario with the highest IRR is likely to be considered the best.

The theoretical basis for providing project development and operational irrigation planning in Ukraine began with the works of (Alpatyev, 1965). These works were based on the bioclimatic method of calculating of total evaporation.

The basis of the methodology for calculating water consumption rates is the water balance equation of the active soil layer:

$$D_i = E_i - (P_i - \Delta P_i) - G_i, m^3/ha, \quad (5)$$

where D_i – is the water demand deficit of agricultural crops for the i-th decade of the growing season; E_i – total evaporation; P_i– atmospheric precipitation; ΔP_i – discharge of a part of precipitation to surface runoff and filtration, G_i .– feeding the active layer of the soil with groundwater.

In our research, we used crop irrigation rates for a year with a 95% moisture deficit, as dry years have become more frequent in the Odesa region due to climate change.

GOALS AND OBJECTIVES

The aim of this study is to identify scenarios for the sustainable management of irrigated lands, ensuring sustainable cost recovery for the operation and maintenance of the irrigation infrastructure and the effective functioning of the WUO. Additionally, the study aims to assess scenarios for the modernization of irrigation systems to promote sustainable and profitable agricultural production under irrigation, with a focus on achieving optimal energy efficiency and managing production technologies across various production models. The economic model of the scenarios takes into account variables like climate change and fluctuations in market prices for energy and agricultural goods.

OBJECT OF RESEARCH

Due to the high energy consumption (lifting water up to 70 meters) and the potential risks to water quality and quantity posed by climate change in the water source (Lake Kagul), the proposed scenario of modernization of the Nagirnianska irrigation system in the Odesa region is designed to tackle these challenges. The scenario encompasses a range of integrated modernization objectives:

- Providing sustainable irrigation services for WUO members and other water users in the irrigation system's service area through technical upgrades to infrastructure (pumps, pipes, reservoirs), replacement of sprinklers and equipment, and implementation of water and energy-saving technologies.
- Introducing precision irrigated agriculture based on Green Deal principles to enhance crop productivity, maintain soil fertility, and promote ecological health.
- Strengthening the institutional capacities of WUO for effective management and high-quality service provision.
- Ensuring sustainable irrigation services for WUO “Nagirniansky Lan” members and other water users within the system's service area, with plans to establish 3-5 WUOs initially and eventually form an association of WUOs.

Location: The Nagirnianska irrigation system is located in the Odesa region, specifically in the Izmail district. The service area of the Nagirnyanska irrigation system (IS) includes Nagirnyanska IS (1203 ha), Orlovska IS (1820 ha), Khadzheyska IS (1041 ha), and Konstantinivska IS (1591 ha), totaling a project area of 5655 hectares. This irrigation system was built between 1980 and 1983.

Beneficiaries: The local population in the community area benefits greatly from this project as farming without irrigation in this region is nearly impossible. This includes both small-scale farmers and larger agricultural enterprises.

Climate: The climate in this area is humid and moderately continental, with a mix of continental and maritime characteristics. The average annual temperature ranges from 8.2°C in the north to 10.8°C in the south of the region. Total annual precipitation ranges from 340 to 470 mm. Winter winds mostly come from the north and south-west, while summer winds are primarily from the north-west and north.

Groundwater: Groundwaters of alluvial deposits are connected hydraulically with the waters of the Danube River and Lake Cagul. Water mineralization ranges from 0.5 g/dm3 to 1.3 g/dm3. Consequently, the type of groundwater changes from bicarbonate-chloride calcium-sodium to sulfate sodium-magnesium.

Soils: The main soil type in the Danube terrace plain is southern low-humus micellar-carbonate chernozems, which are found on medium-loamy loess rocks. These soils are highly fertile and can consistently produce high yields. Additionally, dark-chestnut soils are present in the area, showing physical salinity in their morphology and variations in mechanical composition and other characteristics typical of saline soils. These characteristics result in poor water-physical properties, such as low filtration capacity. The introduction of irrigation has further complicated the soil structure in all zones and subzones, leading to the development of secondary hydromorphic, saline, salinized, and surface-glazed soils. This requires a tailored approach to irrigation management and the implementation of agrotechnical and agromelioration measures on irrigated lands.

Environment: Lake Kagul is a significant source of pollution in the region, with the Kagul River, a tributary of the lake, contributing to its contamination. The lack of centralized sewerage systems in local communities has led to unregulated runoff. Lake Kagul is used for fish breeding, but periodic mass fish kills in the lake pose a risk of various epidemics. Additionally, economic activities have caused the siltation and drying of small rivers.

Characteristics of the irrigation source: Irrigation water is taken from Lake Kagul, which is replenished from the Danube River through three underpasses. Lake Kagul serves as the water source for the PS-1 Pumping Station (Table 1).

Table 1. Kagul Lake - reservoir passport

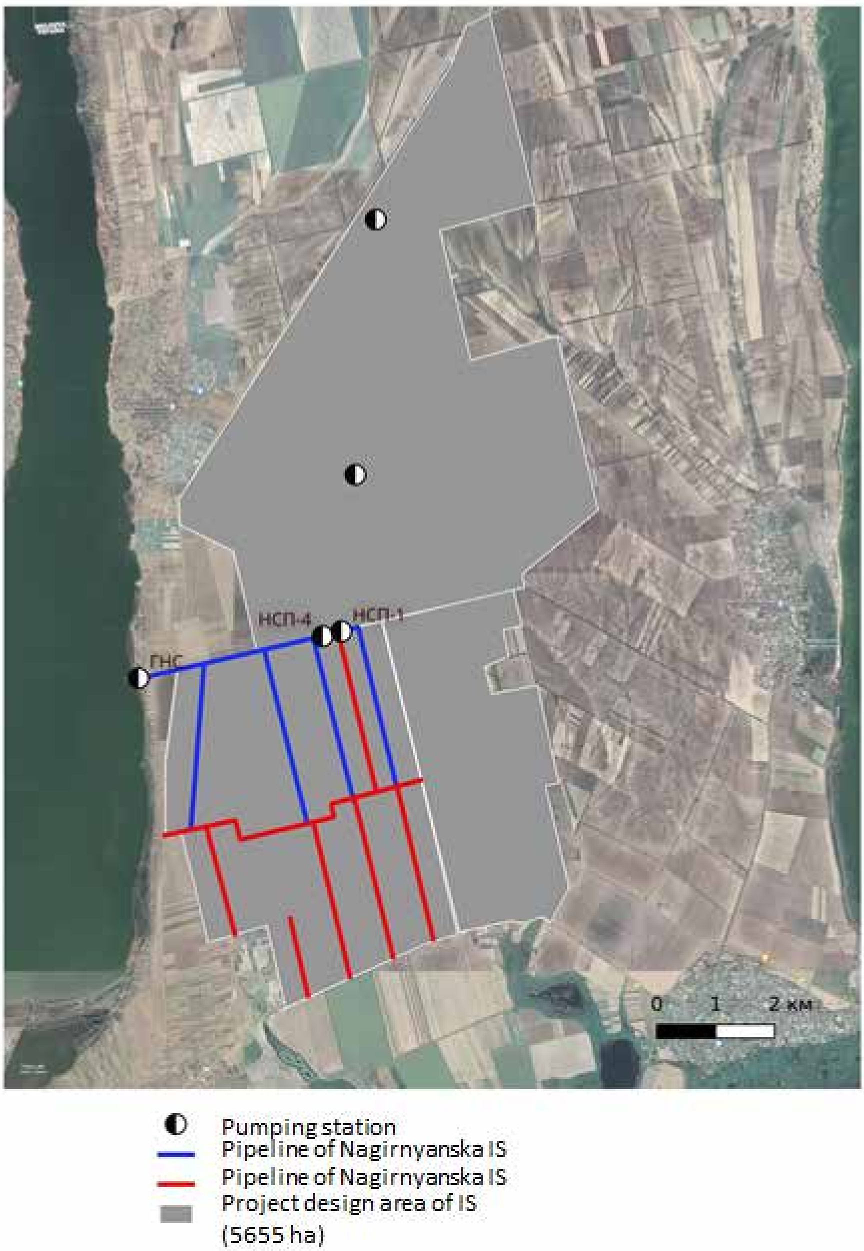
Length, km	Width, max/ average, km	Depth, max/ average, m	The area of the mirror at the forced supported level, km^2	Volume of water, mill m^3	Level marks, m		
					Normal supported level	Dead volume level	Forced supported level
20.30	10.15 4.99	3.50 2.47	101.34	250.67	3.50	2.00	3.70

Lake Kagul is the source of water supply for the Kostiantynivska, Khadzheyska, Orlovska, and Nagirnianska irrigation systems. Each of them is planned to be restored for irrigation purposes and, in the future, to create a WUA. The first stage of the project involves restoring irrigation within the Nagirnianska and partially Orlovska irrigation systems.

Irrigation Water Use: Currently, the irrigation system covers an area of 5,655 thousand hectares, but only slightly over 1000 hectares are actually irrigated. Water for irrigation is pumped from Lake Kagul, which is replenished by canals from the Danube River.

The main canal, 2600 meters long, needs reconstruction. A section of 1658 meters is in an earthen canal, causing water losses of up to 70%. Another 1000-meter section needs reinforced concrete lining plates replaced with an anti-filtration protective screen. Annually, water losses in the canal exceed 1.5 million cubic meters, costing over 500 000 UAH per year (Figure 1).

Figure 1. Nagirnianska IS



Irrigation can be expanded to cover an area of over 5655 hectares in Nagirnyanska irrigation system. Currently, only 1000 hectares are being irrigated due to significant losses and outdated infrastructure (Table 2).

Table 2. Irrigated areas

Name	According to the project, thousand hectares	It is possible to water thousand hectares	Actually irrigated, thousand hectares
Nagirnianska IS	5.655	5.655	1.000

ANALYSIS OF TECHNICAL STATE OF IRRIGATION INFRASTRUCTURE

The current assessment of the irrigation network indicates low efficiency, with main assets showing wear and tear of up to 60%. The main pumping station (MPS) and all pumping stations (PS) require replacement and modernization to enhance energy efficiency and enable the implementation of automated systems for continuous operation and water supply to meet demand.

The system functions as follows: water is sourced from Lake Kagul through MPS-1 at Nagirnianska Irrigation System via a pressurized pipeline into an open canal, and then to lift pump stations for further distribution for land irrigation (Figure 1).

PS-1 at Nagirnianska irrigation system, constructed over 50 years ago, sources water from Lake Kagul through a feeder channel. This pumping station, along with pressure pipelines, supplies water to Nagirnianska PS-1, PS-4, Konstantynivska PS-2, and Khadzeyska PS-3. The total capacity of the pumping units at PS-1 is 4445 m^3 per hour (Table 3).

Table 3. Capacities of pumping units at Nahirnianska IS

Name	Number of units	Type	Power, kW	Supply, m^3/s	Project area, ha
MPS	3	D5000-32	500	4.0	
	1	D1250-65	250		
PS-1	2	D4000-95	630	2.55	1203
	3	300D-70a	250		
PS-2	3	350D-70	250	0.97	1591
	1	VA350-23/2	75		

continued on following page

Table 3. Continued

Name	Number of units	Type	Power, kW	Supply, m^3/s	Project area, ha
PS-3	2	200D-90	250	0.89	1041
	2	D500-65	160		
	1	K290-30	40		
PS-4	Intra-farm PS				1820

Main pipelines: Main pipelines in the Nagirnyanska irrigation system are made of steel and asbestos-cement materials. These pipelines consist of steel pipes with diameters of 1020 mm, 820 mm, 530 mm, and 426 mm, as well as asbestos-cement pipes with a diameter of 500 mm. The internal economic network needs a complete replacement and a new laying scheme due to the outdated materials that are no longer in production.

Feeder canal: The feeder canal, which is 2600 meters long, is constructed in an embankment and lined with reinforced concrete slabs. It requires modernization to reduce infiltration losses by installing anti-filtration linings using advanced geomembrane materials. The main structures are worn, as shown in Figure 2.

Figure 2. Nagirnyanska IS - Technical condition of the main facilities

Pump station & building: The building housing the pump station is constructed with building blocks and has a substructure. It requires finishing touches such as whitewashing, painting, and lining the crane track with glazing rehabilitation. The building is in normal condition, but floor rehabilitation and wall repairs are needed. Upgrading the outdated, energy-efficient pump and power equipment at the main pumping stations and transfer stations with modern, energy-efficient equipment with adjustable drives is necessary. This includes implementing soft-start systems, frequency converters, and introducing an automation system for pump station operation.

Electric motors: The electrical equipment at the pump station has exceeded its operational life, necessitating the replacement of all existing switchgear with new equipment.

Penstock: Replacement of field pipelines with polymer pipes is needed.

Irrigation equipment: Currently, around 1000 hectares are irrigated, with 4 new front irrigation machines (IM) "Fregat" and approximately 600 hectares of subsoil drip irrigation. Plans include purchasing low-pressure IM with wheel drive (circular and front-mounted) and constructing drip irrigation systems for subsoil (1200 hectares - tomatoes, corn) and surface drip irrigation (300 hectares - vegetables, pumpkins).

Current O&M costs (water cost and operational expenses): The current cost of water supply services is approximately 6.0 UAH/m^3 (aprox 0.16 USD/ m^3) (including operating costs for the inter-farm network and electricity) for an area of 1000 hectares. During the first stage of system modernization, this cost will remain at 6.0 UAH/m^3 (aprox 0.16 USD/ m^3). In the second stage, with an increase in the irrigated area, the operational expenses for the inter-farm network will be reduced by 20%.

Land Use and Agricultural Production: Within the irrigation network service area, there are currently two middle-sized farms. The majority of the sown areas in these farms rely on rainfed cultivation without irrigation, primarily for grain crops such as wheat and barley. A smaller portion of the land is allocated for vegetables, melons, and orchards. Drip irrigation and sprinkler irrigation methods are employed for irrigated crops. The absence of irrigation poses a high risk to farming and hinders its development.

The modernization plan for the Nagirnianska irrigation system involves gradually shifting from the current crop rotation to a more economically viable one with a higher proportion of moisture-loving crops (vegetables). This transition will take place over the 2024-2025 periods. Two crop rotation options will be assessed in the economic analysis: Option 1, based on an economically justified approach, and Option 2 – traditional crop rotation, proposed by WUO members.

Scenario 1 (Option1) for agricultural producing is designed with a balanced selection of crops for a short-rotation cycle, considering optimal predecessors and high-yielding crops.

Scenario 2 (Option 2) includes traditional crops that require minimal changes to current farming practices or innovations.

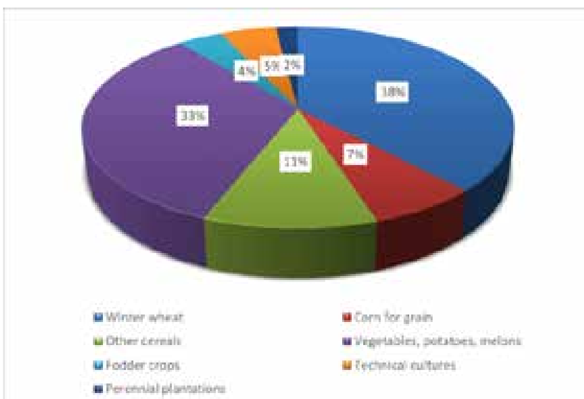
Data below shows that due to military conflicts in Ukraine, disruptions in logistics, and market sales, the gross income from the 2023 harvest has significantly decreased. Therefore, average prices from the last three years will be used for cost and benefit calculations in the scenarios (Table 4).

Table 4. Irrigation crop yields and gross income calculation in the selected area

No	Crop	% in crop rotation (16% is occupied by melons, vegetables, gardens)	Crop yield			Agricultural crop price			
			Potential yield, t/ha	Actual under irrigation, t/ha	Actual without irrigation, t/ha	2021	2022	2023	average for 2021-2023, $/t
1	Winter rapeseed	28	53	2.3	0.9	684	530	299	504
2	Watermelon	3	80	60	35	38	237	191	
3	Corn	50	175	107	5.5	260	203	109	191
4	Vegetables (tomato)	7	120	80	-	375	409	396	393
5	soybean	12	6	4.5	-	496	420	366	427

Option 1 of economically approved crop rotation is given on the diagram (Figure 3) and shows the list of crops in percentages, which, in addition to traditional crops, includes high-margin crops. This list is compiled on the basis of the best management practices in the Odesa region, those farms that successfully use irrigation. It contains a balanced set of crops for building a short rotation crop rotation and is also in accordance with the recommendations given in (Romashchenko M. et al, 2023; Tsyriulyk O. et al, 2021).

Figure 3. Economically approved crop rotation



The proposed option includes a gradual transition from traditional to an economically justified approach for crop rotation as part of the irrigation restoration investment project. In the second stage of modernization, a economically justified crop rotation will be implemented to promote soil ecological sustainability and improve the economic performance of farms (Polishchuk V. et al, 2021; Bohaienko V. et al, 2021).

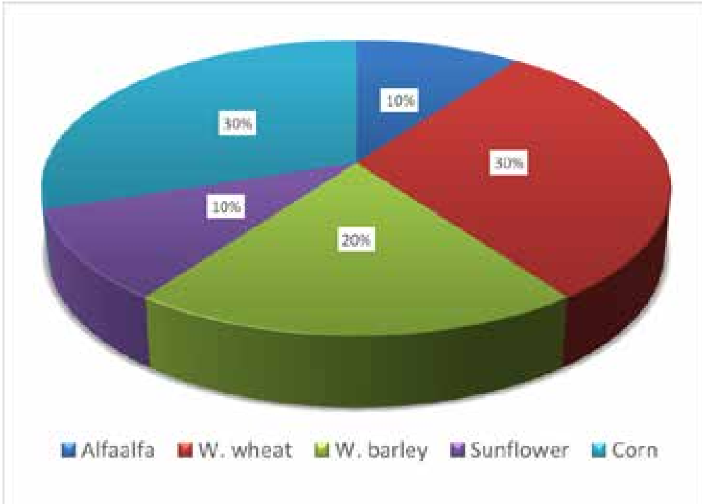
The economic indicators of the proposed crop rotation are presented in Table 5. The data used for the calculation of economic indicators has been obtained from official or reliable statistical sources, ensuring the accuracy and objectivity of the obtained results (https://tripoli.land/ua/kukuruza?cc=5; https://index.minfin.com .ua/ua/markets/).

Table 5. Economic indicators of the economically approved crop rotation Option 1

No	Crop	% in crop rotation (16% is occupied by melons, vegetables, gardens)	Crop yield			Agricultural crop price			
			Potential yield, t/ha	Actual under irrigation, t/ha	Actual without irrigation, t/ha	2021	2022	2023	average for 2021-2023, $/t, 8, 9, 10
1	Winter wheat	38%	5	2,3	0.9	684	530	299	504
2	Corn for grain	7%	17	10	5.5	260	203	109	191
3	Other crops (soyabean)	11%	6	4.5	-	496	420	366	427
4	Vegetables, potatoes, tomatoes, melons	33%	120	80	-	375	409	396	393
5	Fodder crops (alfalfa)	4%	23	20	10	104	-	51	
6	Technical crops Winter rapeseed	5%	5	2,3	0.9	684	530	299	504
7	Perennials, peach	2%	40	20	12	670	-	273	

Figure 4 illustrates the traditional crop rotation structure on the Nagirnianska irrigation system under Option 2. The proposed structure lacks moisture-loving crops in the rotation, with legumes acting as nitrogen accumulators in the soil. Leguminous crops are limited, and high-value, harvestable crops are not part of the agricultural practices.

Figure 4. Traditional crop rotation



To calculate economic indicators for Option 2, we consider the gradual expansion of irrigated areas without changing the traditional crops grown as part of the irrigation restoration investment project (Table 6).

Table 6. Economic indicators of the traditional crop rotation Option 2

No	Crop	% in crop rotation (16% is occupied by melons, vegetables, gardens)	Crop yield			Agricultural product price			
			Potential yield, t/ha	Actual under irrigation, t/ha	Actual without irrigation, t/ha	2021	2022	2023	average for 2021-2023, $/t
1	Winter wheat	30%	9	2.3	0.9	684	530	299	504
2	Corn for grain	20%	17	10	5.5	260	203	109	191
3	Winter barley	20%	9	6.6	4.5	275	230	111	205
4	Sunflower	10%	4	1.2	0.3	671	568	203	481
5	Pea	10%	4	3.1	1.8	260	164	179	201

Water consumption for the current and planned crop rotation at Nagirnianska irrigation system is calculated based on established water consumption rates. To account for current and anticipated future climate changes, water consumption norms were determined using values for the year of 95% deficit of natural moisture which represent water consumption levels for the driest years (Table 7).

Table 7. Range of rates of water consumption of the main agricultural crops with a deficit of natural moisture of 95%, m^3/ha

Irrigation type	Crop, Mn								
	Winter wheat	Winter rapeseed	Winter barley	Barley spring	Corn for grain	Medium ripe soybean	Sun-flower	Pea	Vegetables (tomato)
	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha	m^3/ha
Sprinkling	1800-2100	1000-1400	1100-1500	1200-1600	2900-3400	2900-3500	2100-2700	2000-2500	
Drip irrigation					3100-3700	3800-4400			3100-4100

ECONOMIC ASSESSMENT OF THE MODERNIZATION AND RESTORATION OF THE IRRIGATION SYSTEM

The first scenario for assessing the project's investment attractiveness involves maximizing the expansion of irrigated areas by implementing irrigation on land with an intra-farm network. This scenario considers utilizing the existing capabilities of the irrigation system with minimal changes of traditional cultivation practices. In the initial stages of WUO's power development, funding will be allocated to cover a part of the investment funds, equipment purchases, management, training costs, etc.

Key assumptions for the calculations in the first scenario include:

- Stable product prices throughout the calculation period (average 2021-2023)
- Project years 1 and 2: 3023 hectares of irrigated land
- Project years 3 and 4: 5652 hectares of irrigated land, stable thereafter
- Project management costs: 10% of investment funds and operating costs
- Amortization rate: 2% per year on infrastructure investments.

For the calculation of profitability, only the revenue from agricultural activities was considered to determine the return on investment. Additional income sources from the WUO may arise during the project implementation, which could accelerate the return on investment.

The project aims to invest in expanding irrigation on the current 3023-hectare area in the first year. Subsequent years will see an annual increase in the irrigated area, reaching 5652 hectares within 3-4 years. The irrigated area is expected to remain stable thereafter.

The operational conditions until project completion have not been factored into the calculations. The parameters are based on past experiences and assumptions about future expenses.

The investment structure for the Nagirnianska irrigation system is outlined in the Table 8, with a total cost of $36 248 500. This includes investments in infrastructure totaling $25 223 500, O&M costs of $7 725 000, and project management costs equivalent to 10 percent of investment funds and operating costs, amounting to $3 300 000

The estimated cost for modernization the existing irrigation system and extending the irrigated area to 5655 hectares is approximately $6410 per hectare.

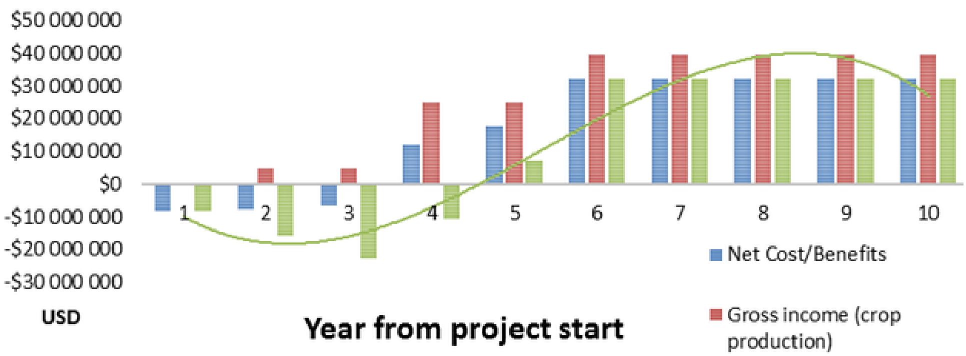
Table 8. Project components

Project Components WUO Nagirnyansky Lan		USD
Investment Costs:		
1	Modernization of the irrigation system	
	Modernization of pump stations ($200/ha)	1 131 000
	Replacement of pipes ($1400/ha)	7 917 000
	Modernization of main canal ($50/m2) (15m*2600m)	1 950 000
	Purchase of Irrigation machinery and Equipment (sprinklers, drip)	
	IM (4155 ha) ($2000/ha)	8 310 000
	Underground drip irrigation(1200 ha) ($3500/ha)	4 200 000
	Surface drip irrigation (300 ha) $2500/hà	750 000
	Implementation of reconstruction and modernization of shut-off and regulating fittings ($65.0/ha)	282 750
2	Purchase of equipment for O&M	100 000
3	Institutional strengthening of WUO (4 years)	300 000
4	Monitoring and water management technologies (agromonitoring) $50/ha	282 750
Total investment cost		**25 223 500**
Operational expenses		
6	4-Year O&M Costs - Main canals and pumping stations - Intra-farm network	**6 860 000** **865 000**
7	Project Management Costs (10.0 Percent), project development, etc	3 300 000
Total recurrent cost		11 025 000
Total Project Costs		**36 248 500**

The economic indicators for Option 1 (Figure 5) indicate a shift towards more productive crop rotation practices despite introducing the same amount of additional irrigated areas. This shift requires the same level of investment.

Although there are significant initial capital investments, the overall income from economic activities and subsequent profits are projected to increase annually due to the expansion of irrigated areas, reduced operating costs, and the implementation of a more productive crop rotation.

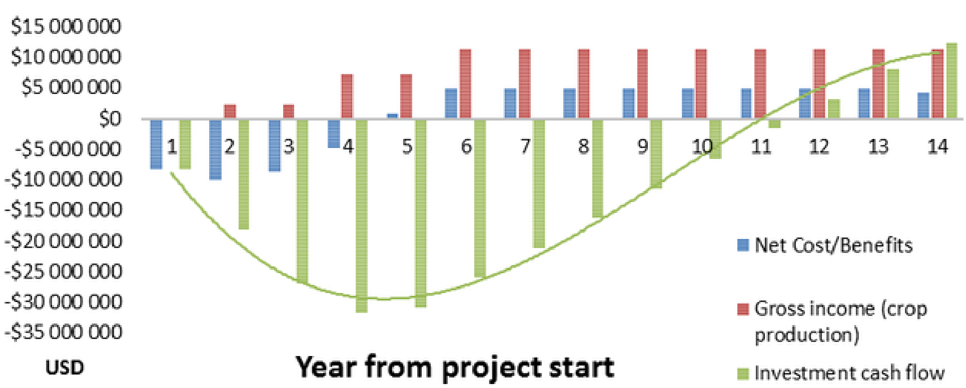
Figure 5. Economic inticators of the cost-benefit analysis Option 1



According to this scenario, implementing a productive crop rotation on an irrigation system results in a payback period of 5 years and an internal rate of return of 92% over 10 years.

Option 2 (Figure 6) does not require a shift from traditional agricultural practices to a more productive crop rotation.

Figure 6. Economic inticators of the cost-benefit analysis Option 2



In this scenario, with traditional crop rotation on an irrigation system, the payback period is 11 years (Table 9), and the internal rate of return over 14 years is - 154%, indicating a lack of profitability.

However, the investment project following the second scenario shows strong economic efficiency indicators, highlighting the overall profitability of the project.

Table 9. Project efficiency indicators

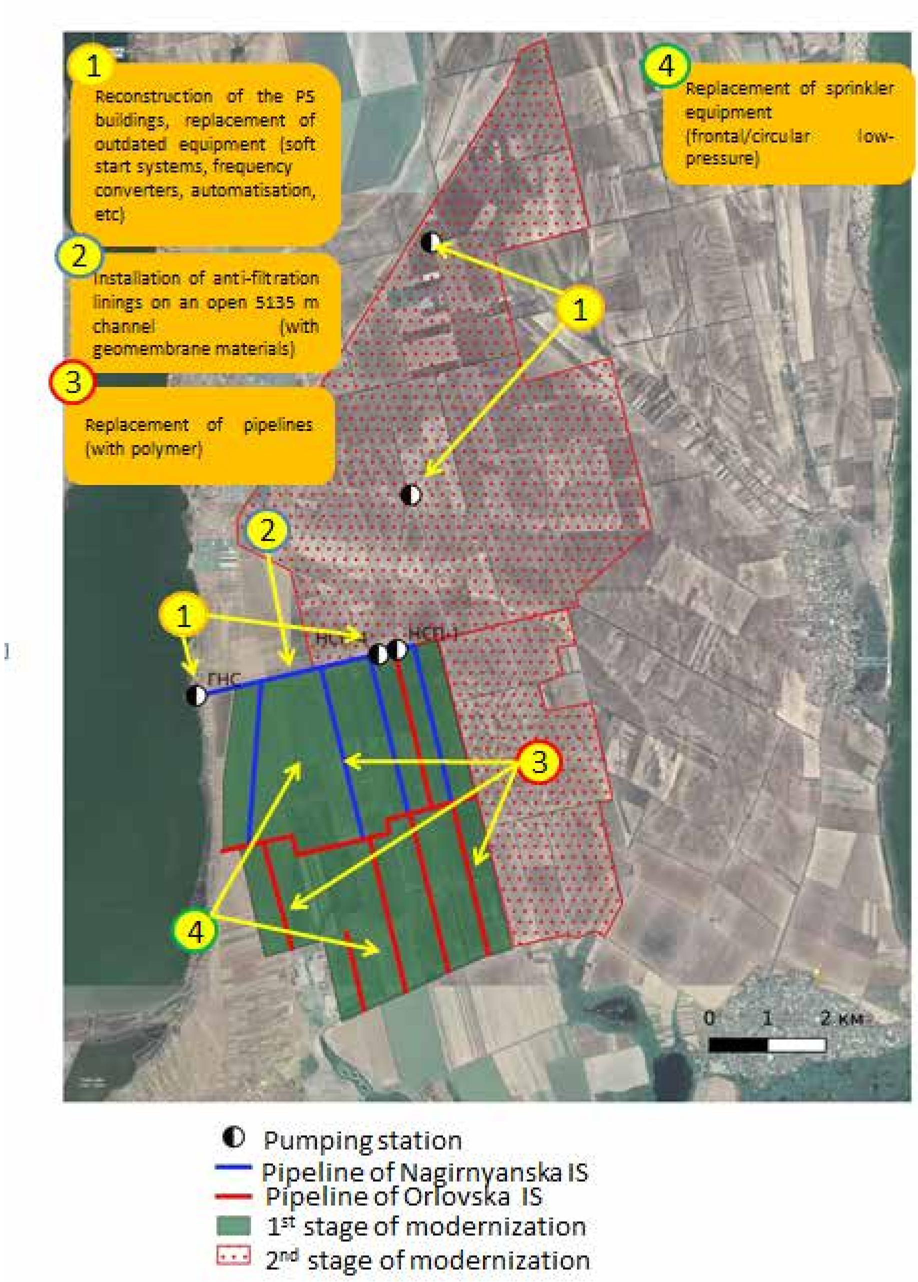
Indicator	Symbol	Value Scenario 1 Scientific based practice	Value Scenario 2 Traditional practice	Units
Gross income	NPV	7,008	2,005	Thous.USD/ha
Internal Rate of Return	IRR	92%	-154%	% annual
Regular Payback	RPB	5,1	11	years
Discounted Payback	DPB	10	22	years

The technical modernization project consists of two stages as shown in Figure 7:

1st stage (2 years): Reconstruction of the Main Pump Station (MPS), installation of anti-filtration lining on the open canal, restoration of the Nagirnianska and Orlovska irrigation systems, modernization of some units at Pumping Station (PS-4 and PS – 1), replacement of pipelines for the restoration of 3023 hectares (WUO members have a clear vision of the reconstruction and modernization directions).

2nd stage (2 years): Modernization of units at PS-2 and PS-3, replacement of pipelines for the restoration of 2632 hectares, replacement of sprinkler equipment with low-pressure (frontal and circular action), subsoil (1200 ha) and surface drip irrigation (300 ha), and land consolidation (red contour).

Figure 7. Nagirnyanska irrigation system modernization plan and stages based on a projet descision



The project aims to enhance the organizational structure, provide training for WUO personnel, and support WUO operations until the system is implemented in project areas with intensive agricultural cultivation.

Sensitivity analysis was conducted to assess the efficiency of irrigation water use, considering the significant contribution of irrigation management costs to total costs. The study examined the impact of varying economic costs and profits by adjusting the values of key indicators by +/- 40% from the 2023 values. The analysis focused on factors such as water prices (for water supply and electricity), product prices, productivity changes, and irrigation rate adjustments on the efficiency of irrigation water use, using corn for grain as an example.

The primary risks that could impact the project's effectiveness include:

- increasing costs of electricity and water supply services;
- decreasing prices of agricultural products;
- higher water consumption by agricultural crops;
- reduced productivity.

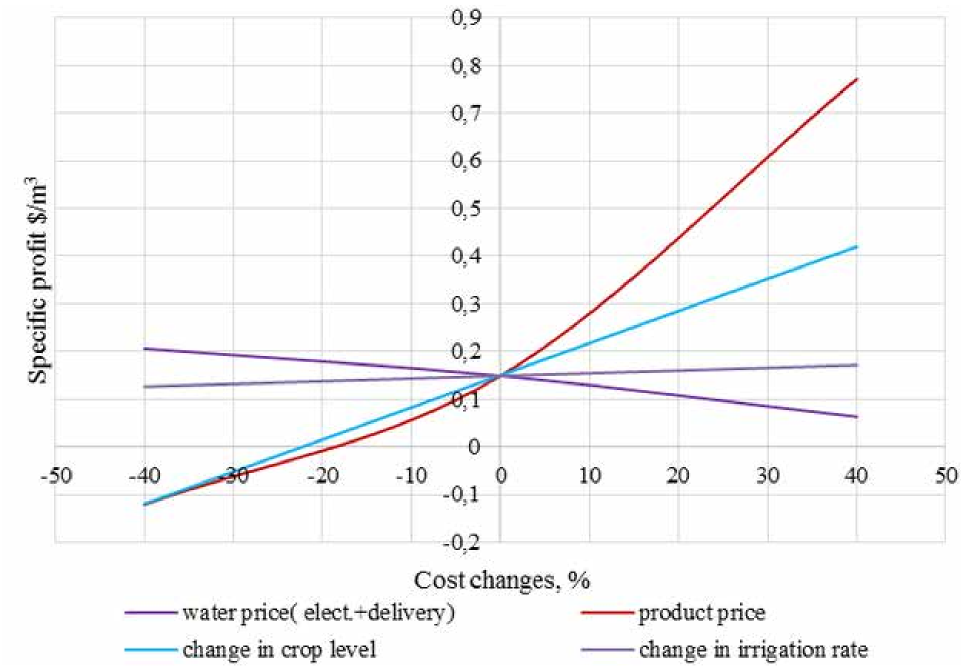
The analysis focused on the changes in indicators for the most profitable crops in both scenarios. The most profitable crops identified were corn for grain and tomatoes. The analysis included examining the efficiency of irrigation water use through factors such as water prices (water supply and electricity), product prices, changes in productivity, and changes in irrigation rates (Table 10), where the parameters of the NPV sensitivity analysis for individual factors, using tomato cultivation as an example are outlined.

Table 10. Parameters of NPV sensitivity analysis to individual factors for tomato

Variable	Units	-20%	Base level	20%
The cost of water supply	$\$/m^3$	0,176	0,22	0,264
Irrigation rate/ water consumption by agricultural crops	Thou. m^3	3,28	4,1	4,92
Agricultural products price (tomato)	$/t	104	130	156
Crop yield	t/ha	96	120	144

To analyze the individual impact of a specific variable on the project's performance, a sensitivity analysis was conducted for the specific profit (in $\$/m^3$). The specific profit per unit of irrigation water enables the assessment of irrigation efficiency for agricultural crops.

Figure 8. The graph of NPV sensitivity of a specific variable for tomato growing



The sensitivity analysis graph in Figure 8 highlights the importance of accurately forecasting agricultural product prices and crop yields in irrigated agriculture profitability analysis. These variables have a significant impact on the project's Net Present Value (NPV), while other factors have a less pronounced effect when varied by 20% from their base levels. This underscores the need for precise predictions of key variables to ensure the success of the project.

The irrigation water use efficiency indicator is more sensitive to criteria when it intersects the abscissa axis at a greater angle. The specific profit per 1 cubic meter of irrigated water serves as an indicator of irrigation efficiency. The NPV break-even analysis indicates that the tomato crop level can decrease to 32% or reach 81 tons per hectare in the year before the project's NPV drops to zero. A similar sensitivity analysis is conducted for corn, as shown in Figure 9.

Figure 9. The graph of NPV sensitivity of a specific variable for corn growing

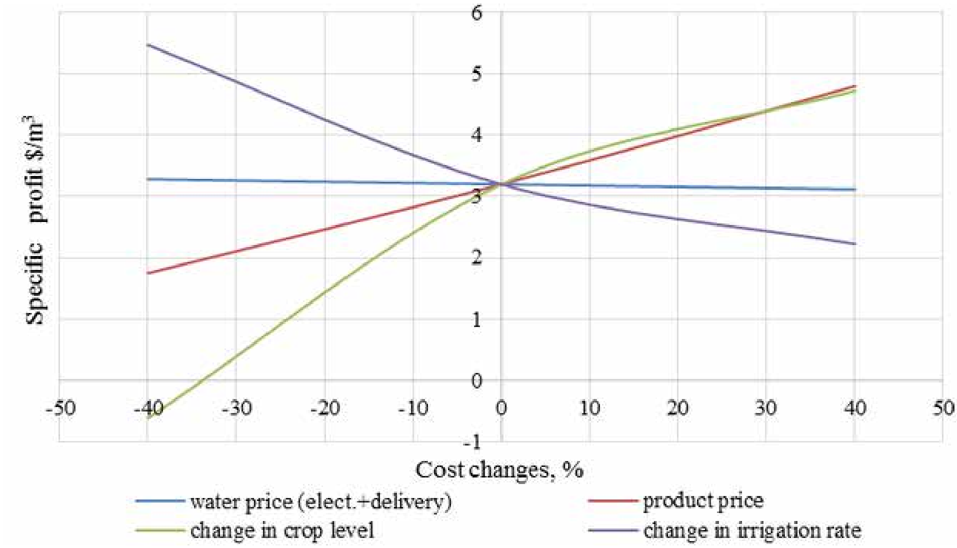


Figure 9 illustrates that the specific profit is most affected by fluctuations in market price and yield level. Changes in other factors within a 20% range from the base level have a lesser impact. For instance, an 18-20% decrease in product price would render corn cultivation under irrigation economically unfeasible. Similarly, a 23% decrease in corn yield (8.7 t/ha) would make corn cultivation under irrigation economically unviable.

Variations in other factors such as water cost and irrigation rate have a smaller influence on specific profit levels, but should still be considered in irrigation planning, particularly regarding fluctuations in water supply prices and the main component, electricity costs, which can vary significantly.

The combination of negative changes in model factors in the scenario suggests potential project inefficiency. It is important to note that the likelihood of all model factors experiencing simultaneous negative changes is low. Furthermore, the scenario analysis considers projected changes in service prices and resource costs over the forecasted period. Both scenarios are based on constant average prices and other variables.

RESULTS AND DISCUSSIONS

An integrated approach was implemented to assess the possibilities of irrigation restoration in the pilot area, considering the availability of water resources, crop water requirements, and agricultural practices under climate change conditions, as well as the stakeholders' view (WUO, farmers) regarding possible farming practices and management technologies. Ongoing consultations with local, regional, and national stakeholders were organized during the study.

With this approach, investments are provided simultaneously for several irrigation components (modernization and rehabilitation of infrastructure plus improvement of irrigation and agricultural management). At the same time, attention is paid not only to the renewal of infrastructure but also to the improvement of water resources management technologies, the implementation of environmental protection measures, and the introduction of innovations to provide profitable sustainable irrigated agriculture and strengthen the potential of water user organizations.

The authors studied and analyzed the successful experience of world-renowned scientists in the restoration of irrigation systems issues and project solutions of the World Bank using economic CBA models (cost-benefit analysis). The results obtained proved that without changing approaches to the crop rotation, implementation of measures to improve technologies and irrigation management, profitable agricultural production with an acceptable payback period is impossible.

The integrated investment project is developed according to several scenarios for irrigation technologies and crop rotation, as well as taking into account climate change. In addition to the net investment in irrigation, investment in alternative energy production and precision farming technologies, as well as IT support for the management of irrigated agriculture, is also required in the investment model. Additional costs for capacity building and consulting and advisory services are also necessary to ensure effective sustainable irrigation management with minimal environmental risks due to water losses or soil degradation.

CONCLUSIONS

1. The system is currently operating well beyond its cost-effectiveness due to outdated and worn-out fixed assets. Implementing investment projects will allow for the update of the main funds of the irrigation system for the next 50 years in forecasted climate change conditions. This will ensure increased system reliability and a stable water supply to users, while also reducing electricity and water losses and increasing irrigated areas.

2. Economically balanced approach is the most suitable scenario for implementing investment projects for the deep comprehensive modernization of the Nagirnyanska system. This scenario makes it possible to reduce the specific costs of water and energy per unit of grown products, which corresponds to the principles of the Green Deal. The proposed scenario for modernization and restoration of the irrigation system shows promising economic efficiency with a payback period of 5 years compared to 10 years for the alternative option of traditional growing. The economic internal rate of return for the proposed scenario is 92%. It also proves the financial viability of the investment project by the ability to attract credit funds.
3. Despite the substantial capital investment, the total income from economic activities and resulting profits are expected to increase annually as a result of the expanded irrigated areas and reduced operating costs. Increasing the actually irrigated agricultural land from 1000 hectares to 5655 hectares and modernizing the existing irrigation system, including extending the irrigated area to 5655 hectares, is projected to cost approximately US $6410 per hectare.
4. Analysis of net present value (NPV) sensitivity clearly demonstrates how changes in variables impact the profitability of irrigated agriculture. The project's NPV is highly influenced by fluctuations in agricultural product prices and crop yields. Accurate predictions of these variables are crucial for successful project implementation.
5. Under the proposed conditions for the established Water User Organization (WUO), the scenario of modernization would generate extra income and financial independence for the irrigation system and its users. This would enable sustainable cost recovery for the operation and maintenance of the irrigation infrastructure.

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Chapter 13
Simulation of Wetted Zones Under Subsurface Drip Irrigation

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ABSTRACT

Irrigation plays an important role in solving the food security problem. Hence, subsurface drip irrigation (SDI) becomes more and more widely used. Its expansion requires studies to determine the parameters of wetted zones for various conditions. We propose to study the process of wetted zones formation in soil using mathematical modeling by solving the initial-boundary value problem for moisture transport equation in vadose zone of soil. Using the proposed approach, the determination of wetted zones under SDI was performed for Ukrainian soils of different texture. Based on the results of mathematical modeling, the main parameters of wetted zones were determined. Empirical dependencies of wetted zone parameters on the structural parameters of SDI systems and pre-irrigation threshold were also established. With a decrease in the pre-irrigation threshold, all wetted zone parameters increased

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and the process of zone's formation for sands, sandy loams, and light loams can be described by linear dependencies, while for medium loams, heavy loams, and clays they have a polynomial form.

INTRODUCTION

The environmental and economic sustainability of agriculture is now mainly studied in the content of the so-called Water-Energy-Food (WEF) nexus (see, e.g., [Kuzmych and Yakymchuk, 2022]). This approach makes stress on multiple mutual influences of the issues of water, energy, and food securities and also the soil, water, and land ecosystems. Aiming at long-term economic, social, and environmental goal, the usage of the WEF nexus approach is, nevertheless, in the end bounded, in some aspects, to technical and technological solutions. It is specifically pronounces in the case of interconnections between water and food securities that rely on the decisions made in the field of irrigation and drainage.

In the case of Ukraine, these issues were brought up in the Strategy of Irrigation and Drainage in Ukraine until 2030, which was developed with the participation of the specialists of the Institute of Water Problems and Land Reclamation of NAASU and approved by the Cabinet of Ministers of Ukraine on August 14, 2019. It provides for the introduction of more than 1,180,000 ha of additional irrigated areas. While solving this problem the focus should be made on the application of the most novel methods and technologies of irrigation, which, thanks to the optimization of irrigation water consumption, ensure the economy of agricultural resources, energy conservation, and reduction of ecological burden on agrophytocenoses. Subsurface drip irrigation (SDI) most fully meets these requirements.

Under subsurface drip irrigation, water and nutrients are in many cases used much more efficiently than under other types of irrigation. This allows more complete use of the genetic potential of agricultural crops. Although this irrigation method is more efficient than traditional drip irrigation, it is mainly used on more valuable fruit crops due to higher capital costs. But in connection with the growing shortage of water resources and the constant increase in the cost of irrigation water, particularly due to the military aggression of the Russian Federation, the use of subsurface drip irrigation in the cultivation of other (vegetable, technical, etc.) crops will constantly increase.

The limited use of SDI systems is also explained by the lack of general theory and methods of mathematical calculation of systems' design parameters. Therefore, the development of a methodology for substantiating the structural parameters of subsurface drip irrigation systems and water supply regimes that ensure the optimal soil water regime for the development of irrigated plants is an extremely urgent problem.

The most important element of irrigation networks of SDI systems is irrigation pipelines, which are mainly produced in Israel (Metzerplas, Netafim, NaanDanJain), Italy (AgriPlastic, Toro), Turkey (Evci Plastik), as well as in Ukraine (Irrigator Ukraine).

In the process of choosing irrigation pipelines their technical characteristics are taken into account. The thickness of SDI pipeline walls is greater than for the surface drip irrigation to ensure the reliability of long-term operation (at least 8-10 years) of the network and should be at least 0.4 mm (16 mil). Pipelines with the wall thickness of 0.63-1.2 mm (25-45 mil) are usually used, preferably with compensating emitters and an anti-vacuum valve, which ensures equal flow along the entire length of plants row and the impossibility of absorbing impurities (particularly, soil particles) at the end of the watering.

The ends of subsurface irrigation pipelines are usually connected to flushing pipelines for convenient flushing of irrigation network during system maintenance. The depth of their installation is determined by the depth of soil freezing in winter. The ends of flushing pipelines are brought to soil surface.

The gradation of emitter discharge rates is 0.4; 0.6; 1.0; 1,2; 1.6; 2.0; 2.2; 3.8 dm^3/h. Evapotranspiration (ETc) has little influence on the choice of the discharge rate, because at the indicated rates, with typical distances between emitters and irrigation pipelines, it is possible to create irrigation rate that significantly exceeds the peak value of ETc. Some designers prefer higher flow emitters because they are less prone to clogging. During the selection of the discharge rate soil's mechanical properties must also be taken into account to avoid back pressure on emitters.

The depth of irrigation pipelines installation and the distance between them depend on the biological characteristics of the crop, the agrotechnology of its cultivation, climatic and soil conditions, irrigation techniques, especially the cost of drip irrigation, as well as the presence of soil pests, etc. [Gardner W. H., 1979]. It varies from 2-10 cm for watering seedlings and lawns, 30 cm for most vegetable, berry, and field crops, up to 30-70 cm for perennial fruit crops, depending on the type and age of plantings [Camp C. R., 1998]. The most common depth of irrigation pipelines installation for these crops is 40-45 cm [Lamm F.R., Camp C.R., 2007].

Although deeper placement of pipelines minimizes soil moisture losses due to evaporation, this aspect must be balanced with the threats of increased infiltration losses taking into account the depth of root-containing zone and the intensity of rooting [Gilley J. R., Allred E. R., 1974].

On heavy-textured soils with the deepest placement of irrigation pipelines, their wider installation is allowed. Bigger distances between pipelines can also be used in the areas with a sufficient amount of productive precipitation, since in these conditions the influence of irrigation on the formation of crop yield is reduced [Arbat G. et al, 2010].

Filtration properties of soil and emitters' discharge rates also influence the direction of soil water movement and its flow. If surface irrigation is not required for germination or for salinity management, a deeper installation of SDI system will help reducing evaporation. A decrease in annual evaporation losses (51 and 81%) was recorded on the SDI with the location of pipelines at the depths of 15 and 30 cm, respectively, compared to the surface irrigation system in field studies and in a simulation study for growing corn on loamy soil in Texas (USA) [Evett S. R. et al, 1995]. Models for calculating the minimum depth of irrigation pipeline installation, according to the criterion of minimizing moisture losses due to evaporation, were developed in [Lomen D. O., Warrick A. W., 1978; Philip J. R., 1991].

The distance between emitters usually depends on plants' location along the row and the type of soil. This distance, as a rule, varies from 10 to 75 cm or more. Most often, pipelines are used with a distance between emitters in the range from 30 to 60 cm [Lamm F.R., Camp C.R., 2007].

It is well-known that the greater the distance between emitters leads to the need for the greater duration of irrigation and larger wetted zones. However, an increase in wetted zones' area can lead to an increase in the consumption of water for irrigation, an increase in the investment cost of the SDI system, and water losses due to infiltration. Therefore, to determine the economically beneficial and ecologically safe distances between emitters, the studies of the processes of soil moisture redistribution, including its removal by plant roots, are important.

The choice of the distance between irrigation pipelines of SDI systems depends on the biological characteristics and agrotechnology of crop cultivation. For perennial orchards, nurseries, berry orchards, vineyards, nut crops irrigation pipelines are usually placed along the rows of plants, and for crop rotation crops: vegetables, melons, oil-protein and grain crops, etc., as well as perennial grasses, irrigation network is established with the distance between irrigation pipelines equal to or greater than twice the distance between emitters [Lamm F.R., Camp C.R., 2007].

The most widely used are the SDI systems with a distance between pipelines equal to 150 cm and a distance between emitters equal to 75 cm, which is sufficient for most agricultural crops on medium and heavy clay soils [Lamm F.R., Camp C.R., 2007]. A shorter distance between pipelines is used for highly profitable crops on sandy and loamy soils grown in rather small fields [Mmolawa K., Or D., 2000; Phene C. J., Sanders D. C., 1974].

Summing up we can state that a larger distance between pipelines can be useful for soils with a layered structure, which allows increasing the horizontal component of water redistribution, as well as in the regions that are less dependent on irrigation. But, in general, pipelines spacing of about 150 cm is usually recommended for crops like corn on medium and heavy-textured soils. These results are consistent with the findings of the review [Arbat G. et al, 2010] and historical discussion [Camp C. R. et al, 2000].

Additionally, for the review of irrigation practices, particularly drip irrigation, in Ukraine we refer the reader to the book [Romashchenko and Baliuk, 2000] in Ukrainian. The latest development of water-related sectors including irrigation due to military-related factors is covered in brief in [Hapich et al., 2024].

In general, the design of SDI systems is largely determined by hydro-physical properties of soils, on which they are installed, and the structure of soil profile. However, for the conditions of Ukraine, no dependencies were formed for determining the values of SDI systems' structural parameters such as the depth of installation and the distance between irrigation pipelines for different types of soil and agricultural crops.

In addition to experimental research, computer modeling is one of the effective methods for studying differences in the formation of wetted zones under SDI and for forming the aforementioned dependencies [Claire M. C. et al, 2003].

Classical physical models of moisture transport in the "soil-plant-atmosphere" system, in particular the SWAP (Soil-Water-Atmosphere-Plant) model [Keller J., Bliesner R. D., 2000; Thorburn P. J. et al, 2003], are mostly based on the Richards differential equation and may include equations describing mass and heat transport. In particular, one of the most widely used is the commercial software HYDRUS-2D, which models moisture and heat transport in a two-dimensional approximation [Simunek J. et al, 2008]. Simulation is performed by numerically solving initial-boundary value problems for models based on the Richards equation using non-linear finite element schemes of Galerkin type. For the applications of HYDRUS-2D to model moisture movement, root water uptake, and wetted zones in soil see, e.g., the paper [Provenzano G., 2007] focused on sandy-loam soil and the paper [Morianou et al., 2023] that review the applications for tree species under drip irrigation.

The closeness and commercial nature of such products as HYDRUS-2D means that, primarily in research, scientists may need to use codes developed by themselves. Such situations include the need to use different models of soils' hydro-physical properties; to solve specific inverse problems (e.g., when automating the selection of SDI system parameters [Romashchenko M. et al, 2023; abd el Baki H.M. et al, 2017; Kandelous M.M. et al, 2012; Seidel, S. J. et al, 2015] or to use non-classical moisture transport models. The latter are used in cases when soil structure or the other factors that influence the modeled processes have peculiarities. Particularly, in the case of significant soil fissures, the processes are adequately described by double porosity models, and for modeling processes in soils, the structure of which can be described as fractal, it is effective to use fractional-order differential equations [Pachepsky Y. et al, 2000].

Thus, modeling can be considered as an effective tool for studying the regularities of wetted zones formation subject to the properties of soils, the characteristics of crops development, the parameters of SDI systems, and other factors. Here mathematical modeling tools are used for the determination of characteristics of wetted zones formed under subsurface drip irrigation in soils of Ukraine of different texture and further determination of the dependencies between the parameters of wetted zones, structural parameters of SDI systems (depth of pipeline installation, emitter discharge rate), and the level of pre-irrigation threshold.

MATERIALS AND METHODS

Mathematical Modeling Technique

To simulate moisture transport under drip irrigation (surface and subsurface), we use a mathematical model based on the Richards equation [Richards L.A., 1931] stated in terms of water head in a two-dimensional formulation that has the following form [Romashchenko M. et al, 2021a]:

$$C\left(h\right)\frac{\partial}{\partial t}H = \frac{\partial}{\partial x}\left(k\left(H\right)\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial z}\left(k\left(H\right)\frac{\partial H}{\partial z}\right) - S, 0 \leq x \leq L_x, 0 \leq z \leq L_z, t \geq 0 \quad (1)$$

where $h\left(x,z,t\right) = \frac{P(x,z,t)}{\rho g}$ is the water head, *m*, $H\left(x,z,t\right) = \frac{P(x,z,t)}{\rho g} + z$ is the full moisture potential, *m*, $P(x,z,t)$ is the suction pressure, *Pa*, ρ is the water density, kg/m^3, g is the acceleration of gravity, m/s^2, $C\left(h\right) = \frac{\partial\theta}{\partial h}$ is the differential soil moisture content, $\theta(x,z,t)$ is the volumetric soil moisture content, %, $k(H)$ is the hydraulic conductivity, *m/s*, $S(x,z,t)$ is the source function, *1/s*, that models the extraction of moisture by plant roots and its supply by subsurface drip irrigation.

The two-dimensional model based on Equation (1) with solution domain orthogonal to the irrigation pipeline assumes that the distance between the emitters is sufficient for the formation of uniform wetting along the pipeline.

Boundary and initial conditions for Equation (1), as well as the form of the source function, are given in detail in [Romashchenko M. et al, 2021a]. At the lower boundary (here, the depth of 1 m) only gravitational flow is modeled. This simulates the assumption of no significant influence of irrigation on the movement of moisture at this depth. On the lateral boundaries of the simulation domain, which are at the equal distance from the neighboring pipelines, the no-flow condition is set simulating the symmetry of the processes around the domain.

On the upper boundary $z = 0$ the following Neumann condition is set:

$$k\frac{\partial H}{\partial z} = Q_e(t) - Q_p(t) - Q_I(t) \tag{2}$$

where $Q_e(t)$, $Q_p(t)$, $Q_I(t)$ are the fluxes, *m/s*, caused by evaporation, precipitation, and surface irrigation.

We assume that a fixed number of plants and a fixed number of subsurface drip irrigation pipelines are placed at a given depth in the simulation domain. The parameters of SDI system in the model are the installation depth and the number of pipelines for a given distance (the case of 10 m is considered). The number, rather than the distance, between pipelines was chosen as a parameter in order to use the same domain size in all simulation scenarios.

The water retention curves of the soil are described for each soil layer by the van Genuchten equation [van Genuchten M. T., 1980] in the form

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (10\alpha|h|)^n]^{1-1/n}} \tag{3}$$

where θ_s is the saturated soil moisture content, θ_r is the residual moisture content, $\alpha > 0$, $n > 1$ are the parameters obtained fitting them by minimizing the least-squares objective function (the sum of squares of differences between the experimental data and the approximation by the model).

The dependency between hydraulic conductivity and full moisture potential is represented according to the Averyanov model [Averyanov S. F., 1982] in the form

$$k(H) = k_f\left(\frac{\theta(H - z) - \theta_r}{\theta_s - \theta_r}\right)^\beta \tag{4}$$

where k_f is the hydraulic conductivity of water-saturated soil (filtration coefficient), β is a fixed exponent, the value of which is obtained from experimental dependencies $k(H)$.

The discretization of the above-described problem is performed using to the implicit finite-difference Crank-Nicolson scheme [Samarskii A.A., 2001] on a uniform grid. Systems of linear algebraic equations are further solved by the TFQMR algorithm [Freund R.W., 1993]. The basic value of the time step was taken to be equal to *1 s.* It changes in the process of calculations according to the heuristic approach described in detail in [Bohaienko V., 2023].

The step with respect to the spatial variables was determined the way to ensure the convergence of the numerical scheme (see [Romashchenko M. et al, 2021a] for details).

During the simulation, the initial distribution of moisture was assumed to be at the level of field capacity, after which the drying of soil was simulated until the time when the average moisture content of the root layer did not become less than the pre-irrigation threshold. The irrigation rate was determined according to Kostyakov's formula and the supply of the corresponding volume of water was further simulated.

After automatic selection of the step with respect to the spatial variables, the finite-difference grid in the computational experiments had a size of 75x150. The maximum length of the time step was 50 s.

Simulated wetted zone was defined as the zone in which pressures at the end of irrigation event increase more than on 0.5 kPa compared with the moment when irrigation starts.

Determination of Soils' Hydro-Physical Parameters

The parameter that determines the movement of moisture in the soil and characterizes the energy of the connection of water with the solid phase of soil is the capillary pressure P, which depends on the soil moisture content θ and has a negative value in a non-saturated soil.

Thus, performing simulations, at the first stage we created a database of the hydro-physical parameters of soils. It consisted of data about sandy loam and light loam soils obtained experimentally [Romashchenko M. et al, 2021b] for two sites, as well as the data obtained using the Rosetta software for soils of different texture typical for the territory of Ukraine. For a review of Ukrainian soils and their current state see [Baliuk et al., 2021].

Moisture content corresponding to the level of field capacity was determined for each type of soil according to the water retention curve using the approach described in [Romashchenko M. et al, 2021b].

During irrigation, zones of water-saturated soil can be formed. The rate of water head dissipation in them significantly depends on the filtration coefficient. Therefore, its value should be present in the set of initial data and is essential for the accuracy of wetted zones simulation.

Some of the obtained water retention curves are shown in Figure 1 that also contains the values of field capacity (FC) for soils of different texture. The data shown in Figure 1 was obtained experimentally for tilled soils that were considered as two-layered. The average differential moisture content of soils, or the free capacity of moisture available for plants, was in the upper layer equal to 28.30% for sands, 22.34% for sandy loams, 18.11% for light loams, 8.9% for medium loams, 18.60% for heavy loams, 12.51% for clays. In the lower layer the values were 29.01% for *sands, 27.90% for sandy loams, 27.38% for light loams, 8.9% for medium loams, 16.44% for heavy loams, 13.08% for clays.*

Hydraulic conductivity is calculated for a set of values of capillary pressure (P_i) and generally represents a continuous dependency of hydraulic conductivity on the pressure $K_P = f(P)$ [Romashchenko M. et al, 2019]. For different types of soil it is shown in Figures 2, 3. From the figures it can be seen that for certain values of capillary pressure, the curves are intertwined, which influences the formation and sizes of wetted zones.

Figure 1. Water retention curves for soils of different texture (0.00-0.30 m layer)

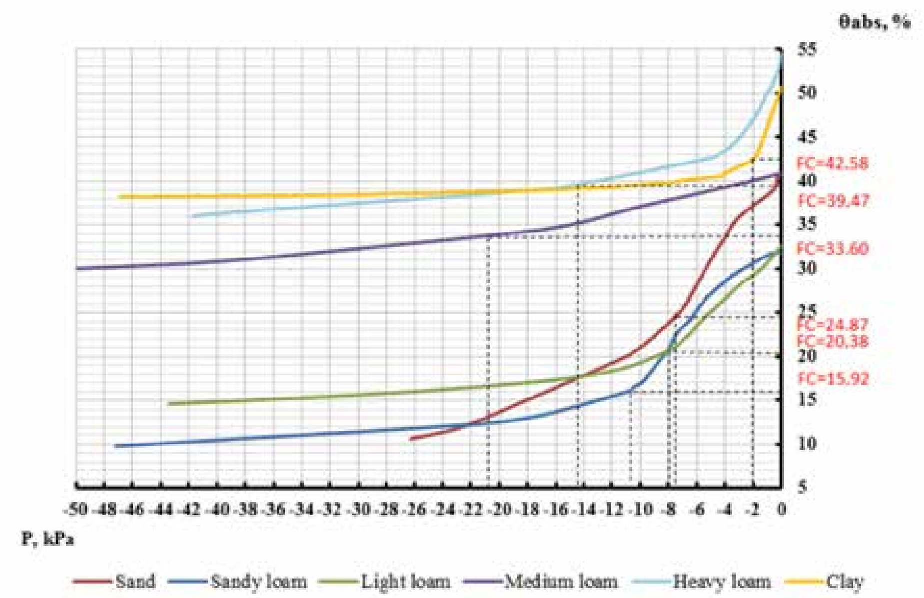
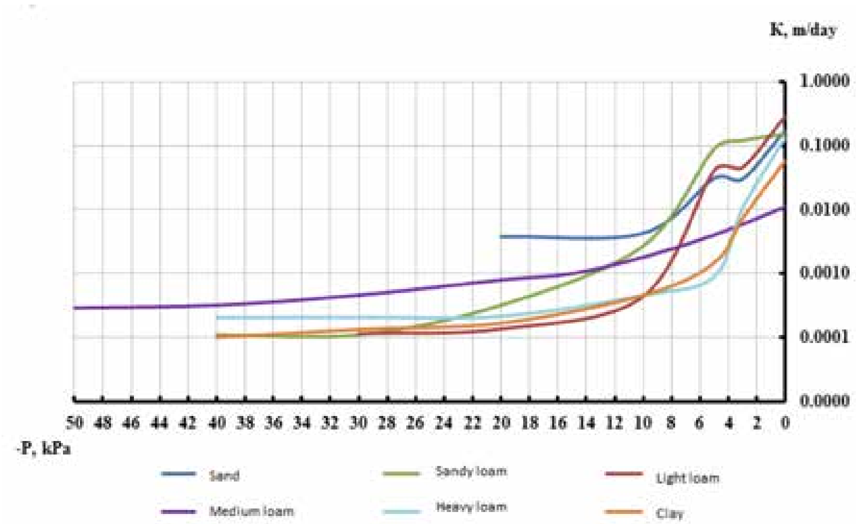


Figure 2. Dependencies of hydraulic conductivity on capillary pressure for soils of different texture (0.00-0.30 m layer)



The traditional irrigation management approach in Ukraine, which is based on the use of 70-80-90% of field capacity as the lower limit of optimal moisture content range, is unsuitable for many soil types because it does not take into account significant nonlinearity of water retention curves. Particularly, when determining the range of optimal moisture content for medium loams, heavy loams, and clays with the use of water retention curves, it could be completely included in the range of 100%-85% of field capacity. Therefore, we have adopted capillary pressure values of 20 kPa for sands and sandy loams and 45 kPa for light, medium, heavy loams, and clays as the lower limit of optimal moisture content range (the pre-irrigation threshold). Based on this, the calculated irrigation rates for moistening a 0.5 m layer are shown in Table 1.

Figure 3. Dependencies of hydraulic conductivity on capillary pressure for soils of different texture (0.30-0.70 m layer)

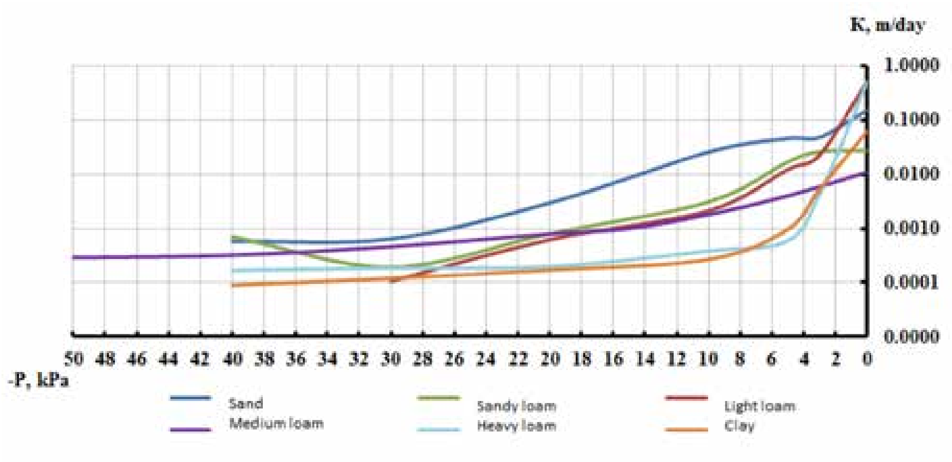


Table 1. Parameters for managing water regime of soils according to their hydro-physical parameters

Soil layer, m	Field capacity, %	Moisture content for the pre-irrigation threshold of P=-45 kPa, %	The range of free capacity from 100% of field capacity to the pre-irrigation threshold, $\Delta\theta$, %	Soil layer used for calculations	Maximum irrigation rate, m^3/ha	% of field capacity
Sand						
0.05-0.20	24.87	13.50*	11.37	0.00-0.25	284.25	54.3
0.30-0.45	14.05	12.00*	2.05	0.25-0.50	51.25	85.4
Total				**0.00-0.50**	**335.50**	
Sandy loam						
0.05-0.20	15.92	12.00*	3.92	0.00-0.25	98.00	75.4
0.35-0.50	16.61	13.00*	3.61	0.25-0.50	90.25	78.3
Total				**0.00-0.50**	**188.25**	
Light loam						
0.05-0.20	20,38	14.50	5.88	0.00-0.25	147.00	71.1

continued on following page

Table 1. Continued

Soil layer, m	Field capacity, %	Moisture content for the pre-irrigation threshold of P=-45 kPa, %	The range of free capacity from 100% of field capacity to the pre-irrigation threshold, $\Delta\theta$, %	Soil layer used for calculations	Maximum irrigation rate, m^3/ha	% of field capacity
0.35-0.50	16.72	13.00	3.72	0.25-0.50	93.00	77.8
Total				**0.00-0.50**	**240.00**	
Medium loam						
0.00-0.50	33.60	30.00	3.60	0.00-0.50	180.00	89.3
Total				**0.00-0.50**	180.00	
Heavy loam						
0.00-0.20	39,47	35.50	3.97	0.00-0.25	99.25	89.9
0.20-0.40	37.55	32.00	5.55	0.25-0.50	138.75	85.2
Total				**0.00-0.50**	**238.00**	
Clay						
0.10-0.25	42.58	38.00	4.58	0.00-0.25	114.50	89.2
0.30-0.45	41.69	37.30	4.29	0.25-0.50	107.25	89.5
Total				**0.00-0.50**	**221.75**	

* P=-20 kPa

Under the pre-irrigation thresholds given in Table 1, the water regime is formed within the wetted zones, which meets the requirements of providing plants with readily available moisture on the one hand. On the other hand, in case of impossibility of performing watering within a specified period, the volume of moisture available to plants that can cover the daily water consumption is stored in the wetted zones.

RESULTS AND DISCUSSION

The Formation of Wetted Zones Depending on Irrigation Rate and Emitter Discharge

Simulation of wetted zones (their shapes and sizes) depending on the irrigation rate and emitter discharge was performed for soils of different texture (sands, sandy loams, light, medium, heavy loams, and clays). Some of the simulation results are given in Table 2.

Here irrigation pipeline was simulated to have the distance between emitters equal to 0.50 m with emitters discharge rate equal to 0.6, 1.0, and 2.0 *dm^3/h.* The depth of pipeline installation was equal to 0.30 m.

Table 2. Geometric parameters of wetted zones for soils of different texture depending on the irrigation rate and emitters discharge (w_s – width on the surface, w – maximum width, h_a – height above the pipeline, h_b – depth below the pipeline)

Soil texture	Pre-irrigation threshold, % of field capacity	Pre-irrigation threshold, kPa	Irrigation rate, m^3/ha	Emitters discharge - 0.6 dm^3/h				Emitters discharge - 1.0 dm^3/h				Emitters discharge - 2.0 dm^3/h			
				w_s, m	w, m	h_a, m	h_b, m	w_s, m	w, m	h_a, m	h_b, m	w_s, m	w, m	h_a, m	h_b, m
Sand	70	-10.8	290.6	0.84	1.40	0.30	0.69	0.73	1.40	0.30	0.69	0.55	1.16	0.30	0.54
	75	-9.8	242.1	0.73	1.40	0.30	0.69	0.63	1.27	0.30	0.62	0.44	1.05	0.30	0.50
	80	-8.9	193.7	0.60	1.27	0.30	0.69	0.49	1.11	0.30	0.55	0.31	0.95	0.30	0.45
	85	-8.1	145.3	0.44	1.08	0.30	0.57	0.33	0.97	0.30	0.49	0.09	0.81	0.30	0.39
	90	-7.4	96.9	0.20	0.89	0.30	0.46	0.00	0.81	0.27	0.39	0.00	0.65	0.23	0.31
	95	-6.8	48.4	0.00	0.65	0.22	0.31	0.00	0.55	0.21	0.27	0.00	0.47	0.17	0.22
Sandy loam	70	-11.8	315.4	0.73	1.40	0.30	0.69	0.63	1.21	0.30	0.57	0.44	1.00	0.30	0.46
	75	-10.8	262.8	0.63	1.21	0.30	0.62	0.52	1.11	0.30	0.53	0.33	0.92	0.30	0.42
	80	-10.0	210.2	0.52	1.11	0.30	0.55	0.41	0.97	0.30	0.47	0.17	0.81	0.30	0.38
	85	-9.3	157.7	0.36	0.95	0.30	0.49	0.23	0.84	0.30	0.41	0.00	0.71	0.26	0.34
	90	-8.7	105.1	0.00	0.79	0.29	0.39	0.00	0.68	0.25	0.33	0.00	0.57	0.22	0.27
	95	-8.1	52.6	0.00	0.55	0.21	0.26	0.00	0.49	0.19	0.23	0.00	0.39	0.15	0.18
Light loam	70	-19.7	295.7	1.05	1.16	0.30	0.47	1.03	1.11	0.30	0.39	0.89	0.97	0.30	0.31
	75	-16.8	246.4	0.97	1.11	0.30	0.43	0.92	1.03	0.30	0.37	0.81	0.92	0.30	0.30
	80	-14.4	197.1	0.87	1.03	0.30	0.41	0.81	0.95	0.30	0.34	0.68	0.84	0.30	0.26
	85	-12.5	147.9	0.71	0.92	0.30	0.34	0.63	0.84	0.30	0.29	0.52	0.73	0.30	0.25
	90	-10.8	98.6	0.49	0.76	0.30	0.27	0.41	0.71	0.30	0.23	0.25	0.60	0.30	0.19
	95	-9.4	49.3	0.00	0.55	0.27	0.19	0.00	0.49	0.25	0.17	0.00	0.44	0.23	0.14

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Table 2. Continued

Soil texture	Pre-irrigation threshold, % of field capacity	Pre-irrigation threshold, kPa	Irrigation rate, m^3/ha	Emitters discharge - 0.6 dm^3/h				Emitters discharge - 1.0 dm^3/h				Emitters discharge - 2.0 dm^3/h			
				w_s, m	w, m	h_a, m	h_b, m	w_s, m	w, m	h_a, m	h_b, m	w_s, m	w, m	h_a, m	h_b, m
Medium loam	70	-723.3	402.9	0.00	0.49	0.25	0.26	0.00	0.49	0.25	0.25	0.00	0.44	0.22	0.22
	75	-258.3	335.7	0.28	0.65	0.30	0.33	0.17	0.60	0.30	0.30	0.00	0.55	0.27	0.27
	80	-127.8	268.6	0.41	0.73	0.30	0.37	0.28	0.65	0.30	0.33	0.00	0.57	0.27	0.29
	85	-74.2	201.4	0.41	0.73	0.30	0.37	0.25	0.65	0.30	0.33	0.00	0.55	0.27	0.27
	90	-47.2	134.3	0.31	0.68	0.30	0.34	0.07	0.60	0.30	0.30	0.00	0.49	0.25	0.25
	95	-31.6	67.1	0.00	0.52	0.26	0.26	0.00	0.44	0.22	0.23	0.00	0.36	0.18	0.18
Heavy loam	80	-99.2	338.2	0.00	0.47	0.22	0.31	0.00	0.41	0.19	0.27	0.00	0.33	0.17	0.22
	85	-14.3	253.7	0.00	0.71	0.27	0.45	0.00	0.55	0.23	0.37	0.00	0.39	0.18	0.27
	90	-7.3	169.1	0.00	0.60	0.25	0.39	0.00	0.47	0.21	0.33	0.00	0.33	0.17	0.23
	95	-4.7	84.6	0.00	0.36	0.18	0.27	0.00	0.31	0.15	0.21	0.00	0.23	0.11	0.13
Clay	85	-21.8	271.5	0.00	0.52	0.26	0.21	0.00	0.49	0.25	0.18	0.00	0.44	0.23	0.17
	90	-4.7	181.0	0.33	0.71	0.30	0.26	0.23	0.63	0.30	0.23	0.00	0.55	0.27	0.19
	95	-1.7	90.5	0.00	0.63	0.29	0.22	0.00	0.55	0.26	0.19	0.00	0.44	0.22	0.15

Based on the simulation results, it was determined that with an increase in the pre-irrigation threshold from 70% to 95% of field capacity (thus reducing the irrigation rate), the width of wetted zones decreases for sands, sandy loams, and light loams. For these cases the dependency of wetted zone width on the value of irrigation rate can be described by a linear function. For medium loams, heavy loams, and clays, this dependency is polynomial. The maximum width of wetted zones for medium loams is formed at the pre-irrigation threshold equal to 80-85% of field capacity, for heavy loams – to 85% of field capacity, for clays – to 90% of field capacity. That is, when soil texture becomes heavier, the maximum width of wetted zones is achieved with the narrower range of soil moisture regulation.

Considering sands, sandy loams, and light loams, the maximum influence of emitters discharge rate on the width of wetted zones is observed for sands, and the minimum one - for light loams. For medium loams, heavy loams, and clays, the maximum influence is observed for heavy loams, a little less one - for clays, and the minimum one - for medium loams.

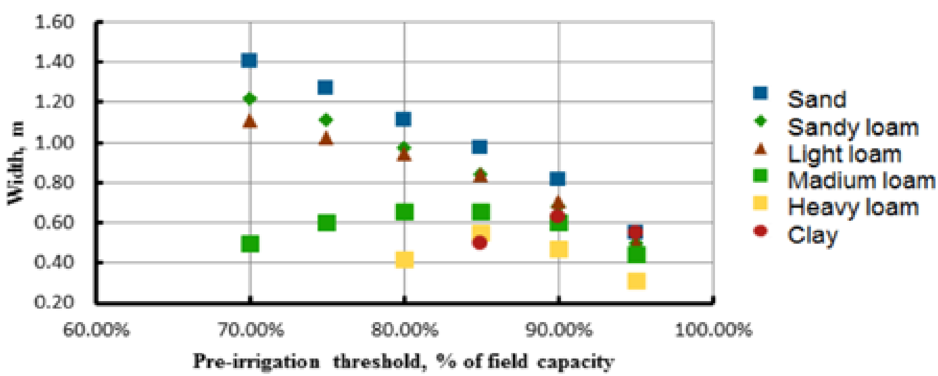
The regression equations of the width of wetted zones depending on the irrigation rate and emitter discharge are given in Table 3.

Table 3. Regression equations of the width of wetted zones depending on the pre-irrigation threshold and emitters discharge

Soil texture	**Emitters discharge - 0.6 dm³/h**	**Emitters discharge - 1.0 dm³/h**	**Emitters discharge - 2.0 dm³/h**
Sand	$y = -3.11x + 3.68$, $R^2 = 0.94$	$y = -3.29x + 3.73$, $R^2 = 0.98$	$y = -2.74x + 3.11$, $R^2 = 0.99$
Sandy loam	$y = -3.26x + 3.69$, $R^2 = 0.99$	$y = -2.86x + 3.25$, $R^2 = 0.99$	$y = -2.41x + 2.71$, $R^2 = 0.98$
Light loam	$y = -2.41x + 2.91$, $R^2 = 0.94$	$y = -2.36x + 2.80$, $R^2 = 0.96$	$y = -2.13x + 2.51$, $R^2 = 0.99$
Medium loam	$y = -15.23x^2 + 25.26x - 9.73$, $R^2 = 0.99$	$y = -12.57x^2 + 20.59x - 7.77$, $R^2 = 0.99$	$y = -10.86x^2 + 17.88x - 6.54$, $R^2 = 0.99$
Heavy loam	$y = -48x^2 + 83.15x - 35.32$, $R^2 = 0.97$	$y = -29.33x^2 + 50.53x - 21.23$, $R^2 = 0.97$	$y = -16x^2 + 27.25x - 11.23$, $R^2 = 0.99$
Clay	$y = -53.33x^2 + 97.07x - 43.45$, $R^2 = 1$	$y = -42.67x^2 + 77.33x - 34.41$, $R^2 = 1$	$y = -42.67x^2 + 76.8x - 34.01$, $R^2 = 1$

Here with heavier soil texture the maximum width of wetted zones decreases (Figure 4). Maximal simulated width was observed for sands and the minimal one - for heavy loams. With a change in emitter discharge rate, this trend remains. Only absolute values of the width decrease with an increase in the discharge rate.

Figure 4. The maximal width of wetted zones for soils of different texture depending on the pre-irrigation rate (emitter discharge - 1.0 dm³/h)



If we consider the depth of wetting below the pipeline (h_b), then the linear trend of its decrease with an increase in the pre-irrigation threshold (decrease in irrigation rate) is preserved for sands, sandy loams, and light loams, and a polynomial trend - for medium loams, heavy loams, and clays. The absolute values of h_b for sands and sandy loams are similar, but for light loams they are much smaller. The maximum depth is observed for medium loams at the pre-irrigation threshold equal to 80, 85% of field capacity, for heavy loams – at 85% of field capacity, for clays – at

90% of field capacity, as in the case of the width of wetted zones. With a change in emitters discharge, the tendency of changes in h_b is identical to the case of the width of wetted zones.

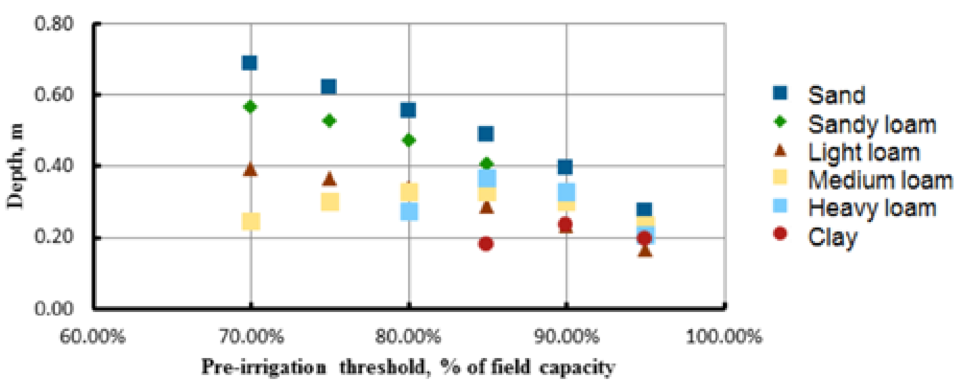
The regression equations for the depth of wetting below the pipeline depending on the irrigation rate and emitter discharge are given in Table 4.

The graphs of h_b for soils of different texture are shown in Figure 5. The value of h_b is maximal for sands and minimal for clays. With a change in emitters discharge rate, this trend remains, only the absolute values of the depth decrease with an increase in the discharge rate.

Table 4. Regression equations of the wetted zones depth below the pipeline depending on the pre-irrigation threshold and emitter discharge

Soil texture	Emitters discharge - 0.6 dm^3/h	Emitters discharge - 1.0 dm^3/h	Emitters discharge - 2.0 dm^3/h
Sand	$y = -1.52x + 1.82$, $R^2 = 0.86$	$y = -1.61x + 1.83$, $R^2 = 0.98$	$y = -1.27x + 1.45$, $R^2 = 0.98$
Sandy loam	$y = -1.65x + 1.86$, $R^2 = 0.98$	$y = -1.33x + 1.52$, $R^2 = 0.98$	$y = -1.07x + 1.23$, $R^2 = 0.96$
Light loam	$y = -1.11x + 1.27$, $R^2 = 0.97$	$y = -0.91x + 1.05$, $R^2 = 0.97$	$y = -0.69x + 0.81$, $R^2 = 0.95$
Medium loam	$y = -7.14x^2 + 11.81x – 4.51$, $R^2 = 0.99$	$y = -5.81x^2 + 9.55x – 3.59$, $R^2 = 0.99$	$y = -5.43x^2 + 8.79x – 3.27$, $R^2 = 0.99$
Heavy loam	$y = -25.33x^2 + 43.99x – 18.66$, $R^2 = 0.96$	$y = -21.33x^2 + 36.85x – 15.55$, $R^2 = 0.99$	$y = -16x^2 + 27.36x – 11.43$, $R^2 = 0.99$
Clay	$y = -18.67x^2 + 33.73x – 14.98$, $R^2 = 1$	$y = -18.67x^2 + 33.73x – 15.01$, $R^2 = 1$	$y = -13.33x^2 + 23.87x – 10.49$, $R^2 = 1$

Figure 5. The depth of wetted zones below the pipeline for soils of different texture depending on the pre-irrigation rate (emitters discharge - 1.0 dm^3/h)



It was not possible to detect a single dependency for the height of wetted zones above the pipeline (h_a) for soils of different texture; each type of soil is individual first of all regarding the reaching of moisture to soil surface. Some of the regression equations of the height h_a depending on the pre-irrigation threshold and emitters discharge are given in Table 5.

For sands, with the pre-irrigation threshold in the range from 70 to 85% of field capacity, moisture reaches soil surface regardless of the value of emitters discharge with only the width of wetting zones on soil surface that depends on the discharge. But at 90 and 95% of field capacity the soil on the surface remains dry. What is more, the layer that does not get wet depends on the emitters discharge: the higher the discharge rate, the larger is the layer that does not get wet.

In sandy loam soils, moisture reaches the surface when the pre-irrigation threshold is in the range from 70 to 80% of field capacity. At 85-95% of field capacity, the soil on the surface remains dry and the thickness of the dry layer has similar trend to the one for the sands.

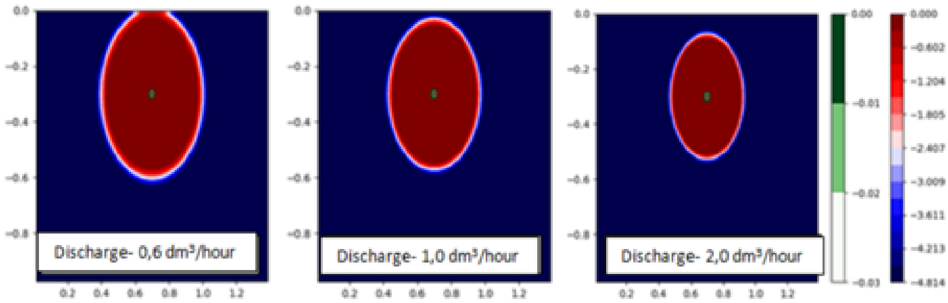
In light loams, moisture does not reach soil surface only in the case of the pre-irrigation threshold equal to 95% of field capacity. In the range from 70 to 90% of field capacity, moisture reaches soil surface regardless of the emitters discharge.

For other types of soil, there are peak values of the wetted zone width on the surface: for medium loams it is reached with the pre-irrigation threshold in the range from 75 to 90% of field capacity, for heavy loams – for 85% of field capacity, for clays – for 90% of field capacity, regardless of the emitters discharge (the case of medium loam is shown in Figure 6).

Table 5. Regression equations of the wetted zones height above the pipeline depending on the pre-irrigation threshold and emitter discharge

Soil texture	Emitters discharge - 0.6 dm^3/h	Emitters discharge - 1.0 dm^3/h	Emitters discharge - 2.0 dm^3/h
Medium loam	$y = -3.33x^2 + 5.54x - 1.99$, $R^2 = 0.89$	$y = -4.76x^2 + 7.78x - 2.87$, $R^2 = 0.88$	$y = -5.05x^2 + 8.17x - 3.02$, $R^2 = 0.97$
Heavy loam	$y = -12x^2 + 20.71x - 8.66$, $R^2 = 0.98$	$y = -9.33x^2 + 16.04x - 6.66$, $R^2 = 0.98$	$y = -6.67x^2 + 11.32x - 4.62$, $R^2 = 0.99$
Clay	$y = -10.67x^2 + 19.47x - 8.58$, $R^2 = 1$	$y = -18.67x^2 + 33.73x - 14.94$, $R^2 = 1$	$y = -18.67x^2 + 33.47x - 14.73$, $R^2 = 1$

Figure 6. Simulated wetted zones in medium loams (pre-irrigation threshold - 90% of field capacity)



Therefore, the maximum wetted zones are formed at different pre-irrigation thresholds: for medium loams - at 80-85% of field capacity, for heavy loams - at 85% of field capacity, for clays - at 90% of field capacity.

In the case when moisture reaches soil surface, the width of wetted zones on the surface (w_s) was determined. For sands, sandy loams, and light loams this indicator has a linear relationship with respect to the change in the pre-irrigation threshold. For medium loams and clays it has a polynomial form.

Regression equations of w_s depending on the pre-irrigation threshold and emitters discharge are given in Table 6.

In order to determine and exclude the influence of physical evaporation from the soil surface on the width of wetted zones on soil surface during simulation, different physical evaporation from the soil surface was set ranging from 5 mm/day to 12 mm/day. The width of wetted zones on soil surface in these scenarios varied slightly within the range of 3 cm.

With an increase in the emitters discharge, the width of wetted zones on soil surface decreases for all considered soil textures. Also, with an increase in the pre-irrigation threshold, this indicator decreases for light soils (sands, sandy loams, light loams). For medium loams, there is a peak value that corresponds to the pre-irrigation threshold equal to 85% of field capacity.

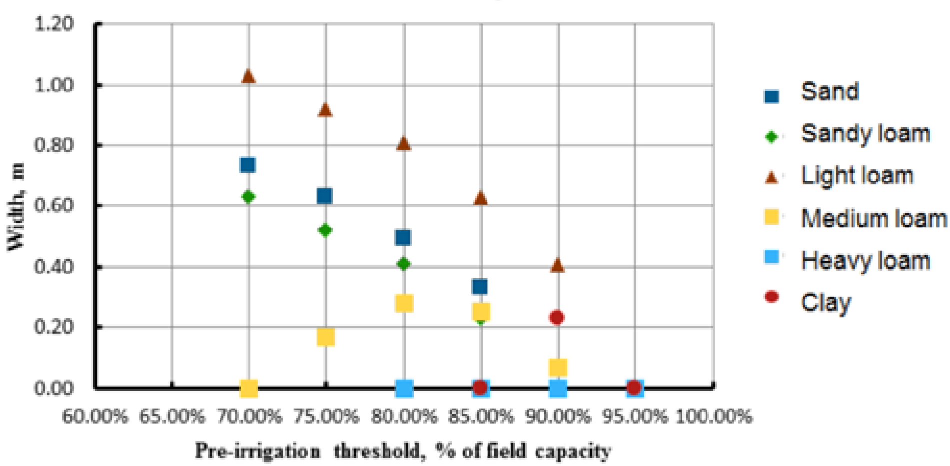
The graphs of the width of wetted zones on soil surface for soils of different texture depending on the pre-irrigation threshold (emitters discharge - 1.0 dm^3/h) are shown in Figure 7.

The fact that there is no single dependence between the parameters of wetted zones and the texture of soils can be explained by the value of hydraulic conductivity in them. With high values of capillary potential (which are created during irrigation) in the upper layer of the soil (0.00-0.30 m), light loams has the highest values of hydraulic conductivity, which leads to the formation of the largest wetted zones on soil surface.

Table 6. Regression equations of the width of wetted zones on soil surface depending on the pre-irrigation threshold and emitters discharge

Soil texture	Emitters discharge - 0.6 dm^3/h	Emitters discharge - 1.0 dm^3/h	Emitters discharge - 2.0 dm^3/h
Sand	$y = -3.14x + 3.07$, $R^2 = 0.97$	$y = -2.68x + 2.62$, $R^2 = 0.99$	$y = -3.02x + 2.69$, $R^2 = 0.97$
Sandy loam	$y = -2.44x + 2.45$, $R^2 = 0.98$	$y = -2.62x + 2.48$, $R^2 = 0.98$	$y = -2.7x + 2.314$, $R^2 = 0.99$
Light loam	$y = -18.07x^2 + 25.90x - 8.26$, $R^2 = 0.99$	$y = -13.86x^2 + 18.94x - 5.46$, $R^2 = 0.99$	$y = -10.07x^2 + 13.02x - 3.29$, $R^2 = 0.99$
Medium loam	$y = -27.64x^2 + 45.66x - 18.42$, $R^2 = 0.99$	$y = -16.86x^2 + 27.63x - 11.07$, $R^2 = 0.89$	-

Figure 7. The width of wetted zones on soil surface depending on the pre-irrigation rate (emitters discharge - 1.0 dm^3/h)



The maximum sizes of simulated wetted zones when pipeline is installed at the depth of 30 cm are formed for medium loams at the pre-irrigation threshold equal to 90% of field capacity and emitters discharge equal to 0.6 dm^3/h ($w_s = 0.31$ m; $w = 0.68$ m; $h_a = 0.30$ m; $h_b = 0.34$ m); for heavy loams - at the pre-irrigation threshold equal to 85% of field capacity and emitters discharge equal to 0.6 dm^3/h ($w_s = 0.00$ m; $w = 0.71$ m; $h_a = 0.27$ m; $h_b = 0.45$ m); for clays - at the pre-irrigation threshold equal to 90% of field capacity and emitters discharge equal to 0.6 dm^3/h ($w_s = 0.33$ m; $w = 0.71$ m; $h_a = 0.30$ m; $h_b = 0.26$ m).

The Formation of Wetted Zones Depending on the Depth of Irrigation Pipelines Installation

To simulate the shape and sizes of wetted zones for various depth of irrigation pipelines installation we considered the scenarios with the distance between emitters equal to 0.50 m, their discharge rate equal to 1.0 dm^3/h, and three depths of pipelines installation - 0.20, 0.30, 0.40 m. For comparison, modeling was additionally carried out for the case of a surface placement of irrigation pipelines.

The obtained regression equations of wetted zones' width depending on the pre-irrigaiton threshold and the depth of pipelines installation are given in Table 7. The graphs of wetted zones' width for soils of different texture are shown in Figure 8.

Table 7. Regression equations of the width of wetted zones depending on the pre-irrigation threshold and the depth of pipelines installation

Soil texture	SDI (depth - 0.20 m)	SDI (depth - 0.30 m)	SDI (depth - 0.40 m)
Sand	$y = -3.37x + 3.76$, $R^2 = 0.99$	$y = -3.29x + 3.73$, $R^2 = 0.98$	$y = -3.37x + 3.76$, $R^2 = 0.99$
Sandy loam	$y = -2.94x + 3.28$, $R^2 = 0.99$	$y = -2.87x + 3.25$, $R^2 = 0.99$	$y = -2.86x + 3.19$, $R^2 = 0.99$
Light loam	$y = -2.61x + 3.03$, $R^2 = 0.97$	$y = -2.36x + 2.80$, $R^2 = 0.96$	$y = -1.87x + 2.21$, $R^2 = 0.97$
Medium loam	$y = -12.76x^2 + 20.86x – 7.85$, $R^2 = 0.98$	$y = -12.57x^2 + 20.59x – 7.77$, $R^2 = 0.99$	$y = -12.57x^2 + 20.59x – 7.77$, $R^2 = 0.99$
Heavy loam	$y = -24x^2 + 41.41x – 17.38$, $R^2 = 0.98$	$y = -29.33x^2 + 50.53x – 21.23$, $R^2 = 0.97$	$y = -40x^2 + 69.52x – 29.35$, $R^2 = 0.96$
Clay	$y = -48x^2 + 87.2x – 38.97$, $R^2 = 1$	$y = -42.67x^2 + 77.33x – 34.41$, $R^2 = 1$	$y = -37.33x^2 + 66.93x – 29.51$, $R^2 = 1$

For sands and sandy loams, the width of wetted zones almost does not change subject to the depth of pipelines installation. For light loams, the width is the largest in the case of surface placement of pipelines, for their installation at the depths of 0.20 and 0.30 m it is slightly smaller, while for the installation at the depth of 0.40 m it significantly decreases. For medium loams, the maximum width was simulated in the scenario when the pipeline was placed on soil surface. It was smaller for SDI, but the depth of installation did not influence the absolute values of this indicator.

An interesting dependence was obtained for heavy loams: with an increase in the depth of pipelines installation, the width of wetted zones also increases. Moreover, the absolute values of this indicator were almost identical for the surface placement of pipelines and for their placement at the depths of 0.20 and 0.30 m. In the case of the depth of 0.40 m, a sharp increase in the width of wetted zones was simulated. The opposite situation was observed for clays – with an increase in the depth of pipelines installation, the width of wetted zones decreases and yet sharply for the depth equal to 0.40 m.

In the range of the pre-irrigation threshold from 70% to 80% of field capacity, there is a tendency of width decrease with the transition from lighter to heavier-textured soils. But when moisture availability is maintained in the high range with the pre-irrigation threshold valued from 85% to 95% of field capacity, this trend is broken.

The depth of infiltration into the horizons lower relative to the depth of pipelines installation was almost independent of it. Only in the range of the pre-irrigation threshold from 70 to 80% of field capacity there was a slight decrease in absolute values at the pipelines installation depth of 0.40 m. For sandy loams, the depth of wetting decreases with an increase in the depth of pipelines installation. For light loams, the maximum values of the wetting depth were simulated at the depth of pipelines installation equal to 0.40 m, a little lesser values - at the depth of 0.20 m, and the smallest ones - at a depth of 0.30 m.

For medium loams, no influence of pipelines installation depth on the formed depth of wetting was observed. For heavy loams, as in the case of wetting width, the depth of wetted zones increases with the increase of the depth of pipelines installation. For clays, the maximum depth of wetting was recorded for the depth of pipelines installation equal to 0.3 m, a little lesser values - for the depths of 0.20 m and 0.40 m.

The obtained regression equations of the depth of wetted zones depending on the pre-irrigation threshold and the depth of pipelines installation are given in Table 8.

However, it was not possible to detect the same common dependencies for the height of wetting above the pipeline (h_a) for different textures of soil, again regarding the fact that in some case moisture reaches soil surface.

At the depth of pipelines installation equal to 0.20 m, simulated moisture reaches the surface on all types of soils regardless of the pre-irrigation threshold.

For sands, at the depth of installation equal to 0.30 m, moisture does not reach soil surface only at high levels of the pre-irrigation threshold (90% and 95% of field capacity). At the depth of 0.40 m, this range expands to 85% - 95% of field capacity and, because of this, soil layer from 0.05 to 0.16 m is not sufficiently moistened (Figure 9).

For sandy loams at the depth of installation equal to 0.30 m, moisture does not reach the surface at the pre-irrigation threshold equal to 90 and 95% of field capacity and the layer from 0.05 m and 0.16 m becomes not sufficiently moistened. At the depth of pipelines installation equal to 0.40 m, starting from the pre-irrigation threshold equal to 75% of field capacity, soil layer from 0.04 to 0.19 m is not sufficiently moistened.

Figure 8. The width of wetted zones for soils of different texture depending on the depth of irrigation pipelines installation and pre-irrigation threshold

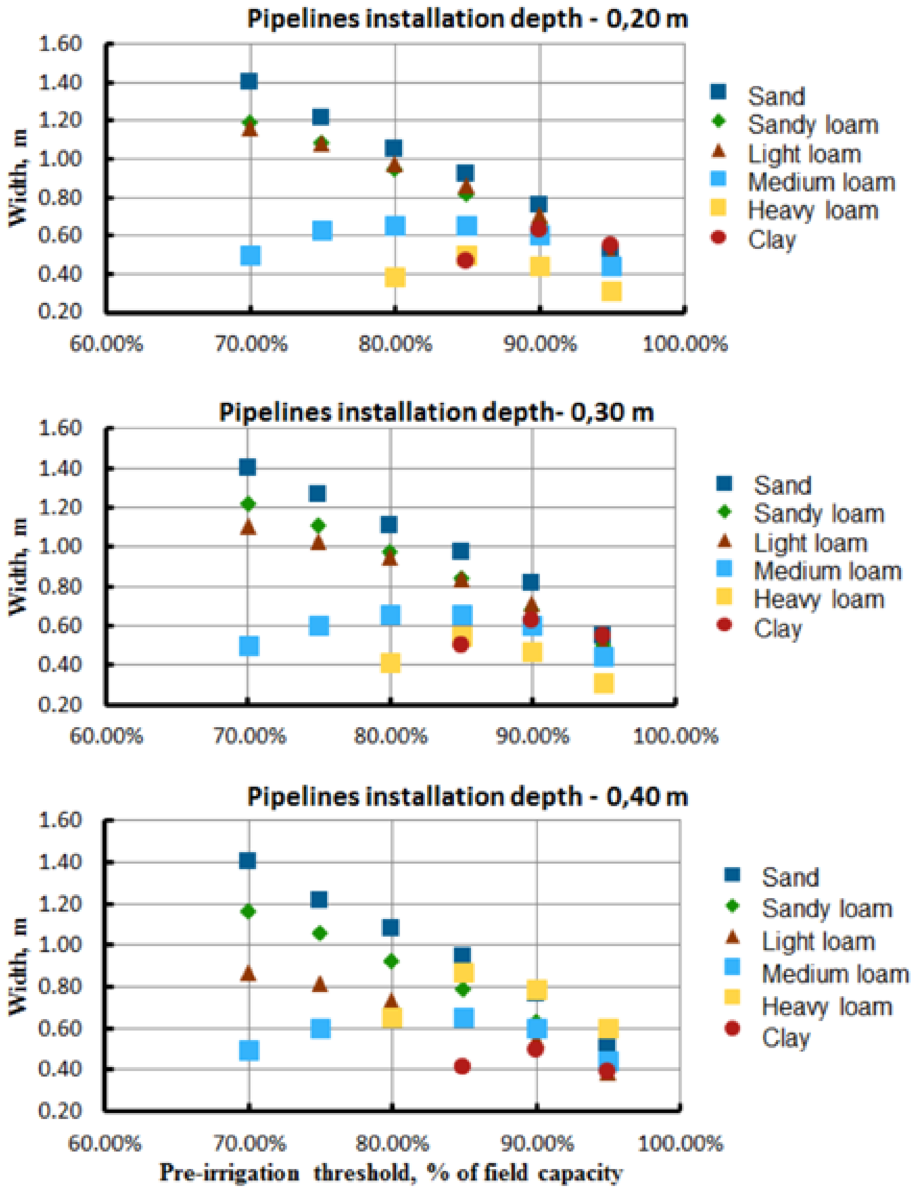
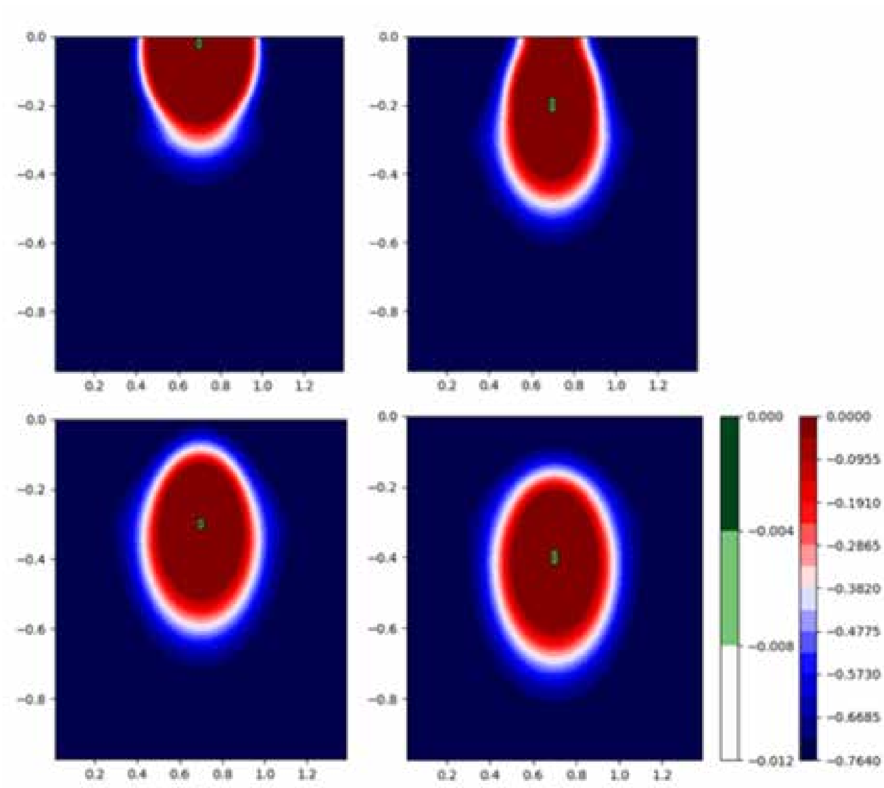


Table 8. Regression equations of the depth of wetted zones depending on the pre-irrigation threshold and the depth of pipelines installation

Soil texture	SDI (depth - 0.20 m)	SDI (depth - 0.30 m)	SDI (depth - 0.40 m)
Sand	$y = -1.569x + 1.79, R^2 = 0.98$	$y = -1.61x + 1.83, R^2 = 0.98$	$y = -7.05x^2 + 10.35x - 3.20, R^2 = 0.99$
Sandy loam	$y = -1.36x + 1.56, R^2 = 0.98$	$y = -1.33x + 1.52, R^2 = 0.98$	$y = -1.33x + 1.52, R^2 = 0.98$
Light loam	$y = -0.81x + 0.99, R^2 = 0.97$	$y = -0.91x + 1.05, R^2 = 0.97$	$y = -1.14x + 1.31, R^2 = 0.93$
Medium loam	$y = -6.67x^2 + 10.97x - 4.15, R^2 = 0.99$	$y = -5.81x^2 + 9.55x - 3.59, R^2 = 0.99$	$y = -6.67x^2 + 10.94x - 4.15, R^2 = 0.99$
Heavy loam	$y = -13.33x^2 + 23.01x - 9.69, R^2 = 0.94$	$y = -21.33x^2 + 36.85x - 15.55, R^2 = 0.99$	$y = -21.33x^2 + 37.01x - 15.59, R^2 = 0.98$
Clay	$y = -13.33x^2 + 24.13x - 10.67, R^2 = 1$	$y = -18.67x^2 + 33.73x - 15.01, R^2 = 1$	$y = -29.33x^2 + 52.67x - 23.36, R^2 = 1$

Figure 9. Wetted zones in sand depending on the depth of pipelines placement (the pre-irrigation threshold - 90% of field capacity, emitters discharge - 1.0 dm³/h)



For light loams at the depth of pipelines installation equal to 0.30 m, moisture does not reach the surface at the pre-irrigation threshold equal to 95% of field capacity and at the depth of 0.40 m – when the pre-irrigation threshold is in the range from 85% to 95% of field capacity. Soil layer from 0.03 to 0.19 m is not sufficiently moistened in this case.

For medium loams, heavy loams, and clays at the depths of pipelines installation equal to 0.30 m and 0.40 m, there are peak values of the pre-irrigation threshold (80% for medium loams, 85% for heavy loams, and 90% for clays), at which moisture is maximally close to soil surface.

In the case when moisture reaches soil surface, the simulated width of wetted zones on soil surface was determined. The regression equations of this width depending on the pre-irrigation threshold and the depth of pipelines installation are given in Table 9.

Table 9. Regression equations of the width of wetted zones on soil surface depending on the pre-irrigation threshold and the depth of pipelines installation

Soil texture	**SDI (depth - 0.20 m)**	**SDI (depth - 0.30 m)**	**SDI (depth - 0.40 m)**
Sand	$y = -2.86x + 2.93$, $R^2 = 0.94$	$y = -3.26x + 3.05$, $R^2 = 0.95$	$y = -4x + 3.36$, $R^2 = 0.99$
Sandy loam	$y = -2.75x + 2.79$, $R^2 = 0.93$	$y = -2.79x + 2.60$, $R^2 = 0.96$	-
Light loam	$y = -3.32x + 3.52$, $R^2 = 0.93$	$y = -3.92x + 3.87$, $R^2 = 0.93$	$y = -3.38x + 2.94$, $R^2 = 0.91$
Medium loam	$y = -19.57x^2 + 31.92x – 12.43$, $R^2 = 0.99$	$y = -16.86x^2 + 27.63x – 11.07$, $R^2 = 0.89$	-
Heavy loam	$y = -42x^2 + 72.74x – 31.21$, $R^2 = 0.95$	-	-
Clay	$y = -84x^2 + 152.2x – 68.45$, $R^2 = 1$	$y = -92x^2 + 165.6x – 74.29$, $R^2 = 1$	-

For sands, sandy loams, and light loams, this indicator has a linear dependency on the pre-irrigation threshold. For medium loams, heavy loams, and clays it has a polynomial form. With an increase in the depth of pipelines installation, the width of wetted zones on soil surface decreases. With an increase in the pre-irrigation threshold, this indicator also decreases for light soils (sands, sandy loams, light loams). For medium loams, heavy loams, and clays there are peak values that correspond to the pre-irrigation thresholds equal to 80, 85, 90% of field capacity, correspondingly.

The maximum wetted zone is formed for medium loams at the pre-irrigation threshold equal to 90% of field capacity ($w_s = 0.07$ m; $w = 0.60$ m; $h_a = 0.30$ m; $h_b = 0.30$ m); for heavy loams - at the pre-irrigation threshold equal to 85% of field capacity ($w_s = 0.00$ m; $w = 0.55$ m; $h_a = 0.23$ m; $h_b = 0.37$ m); for clays - at the pre-irrigation threshold equal to 90% of field capacity (w_s = 0.23 m; w = 0.63 m; h_a = 0.30 m; h_b = 0.23 m).

Comparison of Experimental and Simulated Wetted Zones

Experimental determination of the parameters of wetted zones depending on the duration of irrigation was carried out on light loam and sandy loam soils. The parameters of wetted zones in light loam, simulated and determined experimentally, are given in Table 10, the corresponding values for sandy loam are given in Table 11.

General tendencies in the dynamics of wetted zones according to the experiment and simulation coincide with the presence of certain differences in absolute values. The significant difference in the width of wetted zones can be explained by the fact that the used method for the determination of hydraulic conductivity measures it only in horizontal direction. However loess soils (as in our case) exhibit anisotropy regarding hydraulic conductivity [Clay and loess soils, 2018] with its values in the horizontal and vertical directions differ by almost two times. This gives a significant difference in the sizes of wetted zones according to the data of experimental determination and simulation.

Table 10. Geometric parameters of wetted zones in light loam

Duration of irrigation, hours	Geometric parameters of wetted zones, m					
	experimental			simulated		
	h_a	h_b	w	h_a	h_b	w
1	0.10	0.08	0.26	0.26	0.17	0.52
2	0.11	0.14	0.51	0.30	0.25	0.73
3	0.11	0.31	0.69	0.30	0.31	0.95
4	0.12	0.47	0.96	0.30	0.38	1.11
5	0.13	0.54	1.10	0.30	0.43	1.29
6	0.14	0.57	1.27	0.30	0.49	1.40
7	0.15	0.59	1.32	0.30	0.54	1.40

Table 11. Geometric parameters of wetted zones of sandy soil

Duration of irrigation, hours	Geometric parameters of wetted zones, m					
	experimental			simulated		
	h_a	h_b	w	h_a	h_b	w
1	0.13	0.14	0.30	0.20	0.23	0.44

continued on following page

Table 11. Continued

Duration of irrigation, hours	Geometric parameters of wetted zones, m					
	experimental			simulated		
	h_a	h_b	w	h_a	h_b	w
2	0.17	0.16	0.36	0.20	0.35	0.65
3	0.18	0.20	0.44	0.20	0.43	0.84
4	0.20	0.29	0.52	0.20	0.51	0.95
5	0.20	0.39	0.60	0.20	0.56	1.08
6	0.20	0.47	0.70	0.20	0.63	1.19
7	0.20	0.71	0.79	0.20	0.68	1.27

CONCLUSIONS

In our study we grounded on the approach that consists of the use of the desorption part of water retention curve to determine the optimal range of moisture supply to crops. As its upper limit, we use the value of capillary potential that corresponds to the point on the normalized desorption kinetics curve $\overline{\theta} = f(\bar{t})$, where the derivative $\frac{\partial \overline{\theta}}{\partial \bar{t}} = 1$ (which, according to the physical definition, corresponds to the level of field capacity). As the lower limit we use the value of the capillary potential corresponding to the point, in which the volume of moisture available to plants, sufficient to cover daily water consumption, is stored in the wetted zone.

Using such an approach for water regime formation under subsurface drip irrigation, we applied a mathematical modeling technique to determine the geometric parameters of wetted zones in Ukrainian soils of different texture. According to the simulation results, similarly to the experimental data, it was observed that with a decrease in the pre-irrigation threshold, all parameters of wetted zones increased, and the process of their formation for sands, sandy loams, and light loams is described by a linear relationship, while for medium loams, heavy loams, and clays, it has a polynomial character. With an increase in emitters discharge rate, the absolute values of the parameters of wetted zones decrease.

The maximum width of wetted zones for medium loams, heavy loams, and clays virtually does not depend on the depth of pipelines installation, and the maximum depth of wetted zones increases with the increase of pipelines installation depth. At the depth of 0.40 m, the top layer of soil is not sufficiently moistened, therefore, when using SDI for irrigating field crops on these soils, it is recommended to limit the depth of pipelines installation to 0.30 m.

Simulated widths of wetted zones indicate that the distances between pipelines at which uniform irrigation can be ensured depend on soil type. This distance for the depth of pipelines installation equal to 0.30 m and emitters discharge rate equal to 0.6 dm^3/h is for sands equal to 0.60 m at the pre-irrigation threshold of 95% of field capacity; for sandy loams – to 0.80 m at 90% of field capacity; for light loams – to 0.90-0.95 m at 85% of field capacity, for medium loams – to 0.70 m at 90% of field capacity; for heavy loams – to 0.60 m at 90% of field capacity, for clays – to 0.70 m at 90% of field capacity.

Generally, the obtained regression equations could give preliminary assessments of wetted zones' sizes for SDI systems design while the used techniques for soil analysis and moisture transport simulation can be applied for more accurate determination of system parameters in each specific case. These assessments of wetted zones allow preventing unnecessary water loses due to evaporation and deep percolation while planning irrigation regimes. Combined with generalized crop yield models such as water-yield dependencies [Shatkovskyi et al., 2022] and the approaches for determining the cost of water supply [Romashchenko et al., 2021c] they form the base for setting and solving quantitative optimization problems in water-energy-food dimensions.

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Chapter 14
Strategic Ways of Post-War Restoration of Irrigated Agriculture in the Southern Steppe of Ukraine

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ABSTRACT

The chapter outlines strategic approaches to the post-war restoration of irrigated agriculture in the Southern Steppe of Ukraine, with a focus on the Kherson region, which has been severely impacted by military operations. The region has faced significant anthropogenic damage, including military degradation of soil cover, destruction of the Kakhovka Dam and Reservoir, looting of reclamation systems, and

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loss of fertile soil layers. The chapter proposes a comprehensive set of ecological and remedial measures, including agronomic, remedial, and technical interventions, to restore the irrigated agriculture system. One of the keys is the restoration of hydro-technical structures such as the Kakhovka Hydro Power Plant in a revised framework. This entails an evaluation of the infrastructure and the implementation of necessary upgrades or modifications to ensure reliable functioning in the post-war context. The chapter emphasizes the importance of integrating ecological considerations into restoration efforts, such as soil conservation practices and the protection of natural habitats.

BACKGROUND

The Kherson region lies within the temperate geographical belt of Eurasia, characterized by a steppe zone covering an area of 28.5 thousand km^2. Geologically, the region is part of the platform, specifically the southern portion of the Precambrian East European platform, with a marginal depression toward Crimea. This depression forms the Black Sea Lowland, sloping from north to south. The climate is moderate-continental, featuring relatively mild winters (with average temperatures ranging from -10°C to -30°C) and hot, lengthy summers (with average temperatures around +22°C to +23°C). The average annual temperature ranges from 9.3°C to 9.8°C, showing a consistent upward trend. The region typically receives around 400 mm of precipitation annually, with recent years seeing an increase of 50-80 mm on average. However, rising temperatures lead to increased evaporation from water surfaces and soils (About Kherson region, 2021).

These climatic conditions underscore the necessity of implementing irrigation for crops, as the region falls within the zone of risky agriculture. Concurrently, existing agricultural challenges demand attention alongside the restoration of irrigation systems.

The intensive development of the Lower Dnieper and Black Sea regions began in the late 19th century. Development initiatives favored selective rather than extensive irrigation, fearing excessive water usage could transform the steppe into marshland, as cautioned by D.I. Mendeleev (Chugaev L.A., 2009)..

At the onset of the 20th century, a survey of the Dnieper revealed that constructing a dam with locks near Zaporizhzhia would suffice to create a waterway “from sea to sea” on the river. However, these warnings, lacking ecological and economic justifications, were disregarded in the post-war years. The construction of the Kakhovka Hydro Power Plant (HPP) and its accompanying reservoir, along with irrigation canals, has contributed to an ongoing environmental and resource crisis described as a “permanently progressive creeping environmental and resource catastrophe” (term proposed by G.M. Romanenko and D.O. Ladychuk, 2010). Unfortunately, despite the destruction during military conflict (Figure 1) the ecological and reclamation situation in irrigated areas has not seen rapid improvement.

Figure 1. The current state of the Kakhovka Dam after the explosion

According to modern assessments of experts to the Black Sea, given the infiltration processes that flood a third of Ukraine, the Dnipro River does not deliver roughly 30 billion m^3 of water from the 65-68 billion m^3 of water catchment of its basin today, taking into account climate changes. As a result, the water areas of the Dnipro River throughout the entire territory of the Kherson region are practically swamped and self-poisoned, where the natural biological productivity has decreased by 42-45 times over the past 30 years, and out of the 10,000 fish hatcheries released by fish farms, only a few fish of various species, most of which do not breed in the Dnipro River, only 1-2 survive. According to official figures, the average annual production of one- and two-year-old juveniles in the Lower Dnipro River and the Kakhovka reservoir was estimated at 700 tons, and the catch from this water area was only 95-100 tons.

The main problem is the regulation of drainage and infiltration losses, which have turned the Dnipro River into a sedimentation system with progressive waterlogging processes and an increase in the toxicological impact of bottom accumulations from discharges and silt deposits (Timchenko V. et al, 2011).

In addition to losses of water resources, losses of land resources of the region are currently observed in the territory of the Kherson region. Humus losses occur in soils practically in the presence of most degradation processes: water and wind erosion, secondary salinization and salinization, etc. (Zhuikov O. et al, 2022; Lavrenko S.O. et al, 2021; Ladychuk D. et al, 2021; Ladychuk D., et al., 2021).

Long-term extensive use of land in agriculture leads to a decrease in their productivity and increases the dependence of agriculture on weather conditions. According to the results of long-term soil monitoring, during the last 15-20 years there has been a progressive decline in their fertility indicators, which is expressed in a dynamic decrease in the content of humus, the main macro- and microelements, a decrease in evaluation criteria (agrochemical and ecological-agrochemical evaluations, fertility resource), etc. Today, the scheme of land use with the participation of organic fertilizers has been replaced by the artificial introduction of mineral fertilizers and toxic chemicals, which are exhausting for the soil. At the same time, plants absorb about 40% of the chemical nutrients contained in mineral fertilizers, the remaining 60% is washed out of the soil and enters reservoirs and groundwater, polluting them. The shortage of organic fertilizers in Ukraine as a result of the decline of the livestock industry leads to a decrease in the content of humus in the soil.

Today, in the agriculture of the Kherson region, there are not enough about 15 million tons of organic fertilizers for annual application to maintain a balance of humus without a deficit. The actual dose of mineral fertilizers is only 8th of the required amount. And that is why there is a need to return to the principles of growing ecologically clean products - and the basis of these principles should be the principles of "organic farming" (Lykhovyd P.V. et al, 2022; Lavrenko S. et al, 2022; Vozhehova R.A. et al, 2023; Chaban V. et al., 2023).

Global climate changes in recent decades have added to this, which significantly affected the amount of precipitation in the southern region - in the last decade, their average annual amount is already 420-480 mm, even though the temperature regime of the territory is gradually increasing.

But the most significant factor in the loss of humus with the destruction of the soil profile in large areas is combat operations. According to the studies of many scientists, there are several main factors of soil damage: the passage of heavy military equipment, the explosion of rockets and other types of weapons, and the construction of fortifications, and it must be taken into account that 100% of the chemical part of the projectile enters the environment. Therefore, there is an increased content of aluminum, copper, and other heavy metals in the soil. In addition, as a result of the oxidation of explosives, sulfur and nitrogen enter the air and soil. As a result, there is a destruction of the soil profile as a whole, and to date, a single mechanism for the reproduction of the soil cover in the territories of military operations has not yet been developed.

The most significant losses in irrigated agriculture of the region are observed with the destruction of the Kakhovka HPP Dam and the destruction of the Kakhovka reservoir, which it formed. The entire irrigation system of several regions of southern Ukraine (Kherson, Zaporizhzhya, Dnipropetrovsk, Mykolaiv, etc.) was regulated under the created Kakhovka reservoir. This factor significantly limits the use of already known methods of irrigated agriculture in modern realities and requires the development of more progressive agronomic and technical methods of restoring agriculture in the region (Kuzmych L et al, 2023a,b; L.Kuzmych, 2023).

The above-mentioned problems of irrigated agriculture are characteristic not only of southern Ukraine and require a detailed analysis of each of them.

METHODS AND TECHNIQUES

The development is based on the classic principle that soil is one of the important objects that affect the production of the final product - plant and agricultural products. Based on previous studies and the generalization of already existing approaches to determining the essence and structure of agricultural production in the south of Ukraine as a whole, there was a need to develop ecological and remedial measures to restore the system of irrigated agriculture. During the research, a long-term agricultural experiment was used. Fieldwork was carried out to monitor exogenous processes in the territory of the Kherson region. The agricultural and ecological reclamation research conducted by the authors during the years 2011-2021 in field and laboratory conditions allows them to formulate the peculiarities of restoration of irrigated agriculture on the degraded, in one way or another, agricultural lands of the south of Ukraine and to improve their current condition to obtain guaranteed harvests of agricultural products.

RESULTS AND DISCUSSION

With the beginning of irrigation, the nature of soil-forming processes changes, and a change in the parameters of most soil properties is observed. These changes take place with different intensities and in different directions. But at the same time, the state of the landscape changes, when it goes from a state of natural ecological stability (saturated with biodiversity) to a state of critical stability or loss of previous equilibrium, and the greater the deviations of the soil-forming process due to economic activity from the natural one, the faster the decrease in soil fertility occurs. After the start of operation of irrigated agricultural landscapes, it is necessary to monitor them (soil condition, infrastructure of hydrotechnical structures and equipment, forest protection plantations, structure of runoff, etc.). At the same time, it is mandatory to operate a scientifically based ecologically safe system of irrigated agriculture, especially based on an adaptive landscape approach (L.Kuzmych et al, 2022a,b,c) .

The total area of agricultural land in the region is 1970 thousand hectares. Of them, the area of deflation-dangerous lands is 1,689.3 thousand hectares. Water erosion is widespread on the slopes of the valleys of the Ingulets River, the former Kakhovka Reservoir (Figure 2), and the Dnieper River estuary. The total of 264.3 thousand hectares of agricultural land are affected by water erosion in the region.

Figure 2. Sediments in the area of action of the Kakhovka NPP Dam

The degradation of agricultural lands in the Kherson region has reached a critical level, with approximately 65% of the total area affected. Among the degradation processes, secondary salinization and soil salinization are particularly severe. Analysis reveals that between 1991 and 2021, the area of saline lands in the region increased to 300,000 hectares (or 61.4%) during the period 1991-2021while the volume of irrigated lands constituted 58.1%. Notably, the area of saline lands was 25,000 hectares during the period 1996-2000, indicating a significant increase in salinity. Despite this, the actual area of irrigated land in the region is gradually decreasing.

The productivity of salted lands is notably lower (by 20-26%) compared to non-salted soils. Consequently, farmers in the Kherson region are estimated to lose 550-600 tons of fodder units of grain and fodder crops from irrigated fields. A contributing factor to these negative phenomena is the poor quality of irrigation water, with 40-50% of the irrigated area receiving water classified as “limitedly suitable” (2nd class) or unsuitable (3rd class) without prior treatment. Unfortunately, the quality of irrigation water continues to deteriorate annually.

Anthropogenic factors, including activities within Kherson and upstream regions of Ukraine, have contributed to the deterioration of natural water quality. Changes in water quality include increased concentrations of chlorides, sulfates, sodium, potassium, and magnesium. Moreover, the regulation of watercourses has led to increased siltation and elevated saprobity coefficients in surface water sources.

To address these challenges, the Kherson branch of the Institute of Soil Protection of Ukraine primarily employs chemical reclamation methods, notably plastering. However, significant investments are required for the improvement of salted lands, with estimates ranging from 1,500 to 2,200 million UAH for plastering alone. Alternatively, more cost-effective chemical meliorants, such as limestone flour, offer promising solutions. Nonetheless, there is a need for increased application of organic fertilizers and mineral substances to address deficits in soil humus and essential nutrients. Perennial herbs in crop rotations play a vital role in improving humus content, but their presence is currently minimal.

The cost of plastering for improving salted lands in the Kherson region is approximately 450 UAH per hectare, amounting to an estimated total investment of 1,500-2,200 million UAH. However, more cost-effective alternatives, such as limestone flour, offer promising solutions. Applying 10 t/ha of limestone flour can recover costs within a year while providing a longer-lasting ameliorative effect compared to gypsum. Gypsum, when applied at the same rate, gets washed out beyond the half-meter layer of soil within the second year after application, making limestone flour a more sustainable option.

Official data on the content of humus in the soils of the Kherson region show the following: in most districts of the region, the content of humus is steadily increasing (on average in the Kherson region in the period from 1993-1997 to 2014-2018, the content of humus increased from 2.29 to 2. 36%, in some regions the difference is 0.10-0.58%), and this contradicts the conclusions of the Kherson branch of the state institution "Institute of Soil Protection of Ukraine", whose experts claim that today, in the agriculture of the region, for a deficit-free the humus balance lacks about 15 million tons of organic fertilizers for annual application. The volumes of actual application of organic matter are very small and are not able to cover the cost of humus from the soil.

The deficit of mineral substances in the soil, as a whole in the region, is currently 111.4 kg/ha, including 43.2 kg/ha of nitrogen, 32.7 kg/ha of phosphorus, and 35.5 kg/ha of potassium. Even though the actual dose of mineral fertilizers is only 8th of the required amount. For reference: according to the results of scientific research by prominent soil scientists of Ukraine, it was established for our zone that an increase in humus is possible by 0.2-0.3% over a 35-40 year period if certain conditions are met, one of which is the saturation of crop rotations on almost 30% of the area perennial herbs.

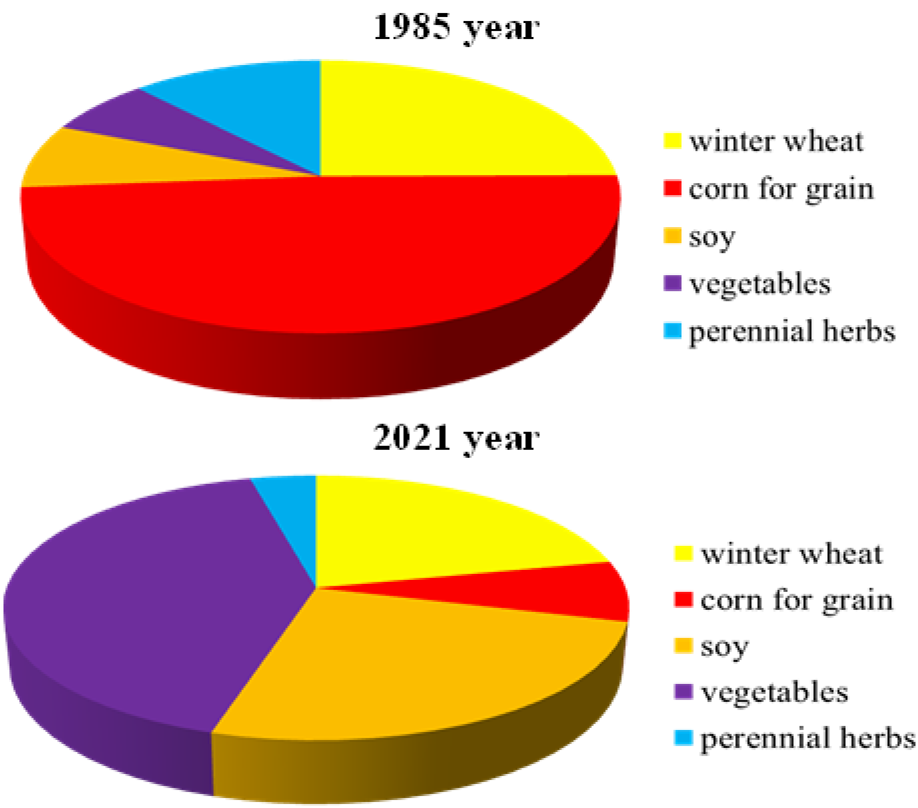
But as can be seen from the diagram (Fig. 3), perennial grasses are almost absent in crop rotations. In addition, it should be taken into account that the uncontrolled use of fertilizers can lead to negative changes in the humus state of soils, significant depletion of the arable layer of the soil with humus, and disruption of the agroecological system.

However, perennial grasses are almost absent in current crop rotations, and uncontrolled fertilizer use can lead to negative changes in soil humus status and significant depletion of the arable layer, disrupting the agroecological system. Additionally, while the area of irrigated land has decreased by 43%, the supply of irrigation water has only decreased by 36.2%, indicating irrational water resource use.

The main methods of irrigation in the Kherson region remain sprinkling, drip irrigation, and surface irrigation. But each method of watering has its advantages and disadvantages, which are often not taken into account when using them.

The analysis of water supply to irrigation systems shows that the reserve for increasing the economic efficiency of crop production is the introduction of scientifically based irrigation norms. It is appropriate to remember that holding 1 m^3 of water and using it for crop formation is 10 times cheaper than providing it for irrigation from any source. At the same time, the potential danger of droughts on crop formation is significantly reduced.

Figure 3. Structure of agricultural land (irrigated land)



Therefore, the optimization of the water balance of territories under irrigation conditions, in such conditions of modern management, consists of limiting the total water inflow during the irrigation season to 300 mm. For this, it is necessary, first of all, to take into account the water-holding capacity of the soil, evaporation from the soil surface, and transpiration of moisture by plants, the calculations of which must be carried out for each period of the growing season to prevent the replenishment of groundwater. Against this background, changes in price indicators for the same irrigation water and the use of drainage are quite inexorable.

So, in 2014, 1m^3 of water for growing rice cost 0.028 UAH, then in 2021 the price rose to 0.138-0.151 UAH/m^3. The cost of water for use by irrigation machines has increased from 0.60 UAH/m^3 (2014) to 2.20 UAH/m^3 (2021). Prices have risen especially sharply in the last 2 years: the cost of water has doubled (What Threatens the Confrontation, 2021).

Similarly, the volume of costs for drainage water removal also increased, but during this period the volume of pumped water decreased from 102 million m^3 to 42 million m^3.

It should be noted that an open distribution system creates corresponding threats. There is a rise in the average annual level of groundwater over a multi-year period at an average rate of 0.1-0.3 m/year.

In some areas located directly near the main canals, a significant increase in groundwater levels in soil massifs due to additional inflow (filtration) of surface water has been established. Thus, on each hectare of irrigated land, 960-990 m^3 of irrigation water is lost annually to replenish groundwater. Seasonal losses of water from the North Crimea main canal, which in recent years amounted to about 80-110 million m^3, as well as average annual losses from the Kakhovka Main Canal of 60-80 million m^3 should be added to this.

Of course, it is necessary to preserve and optimize certain areas of irrigation, but where it can be maximally effective and predictably safe under the conditions of protection of the territories with appropriate measures, and not to reproduce total irrigation.

First of all, this is primarily the reconstruction of irrigation and drainage systems in the areas specifically determined by the inventory (audit); construction of drainage and flushing mode of irrigation on saline soils; chemical melioration of irrigation water and irrigated land; selection of crops resistant to saline soils; water- and soil-saving irrigation regimes; monitoring of irrigated lands, primarily in degradation zones.

It should be remembered that the conversion of arable land into natural fodder land is a measure that ensures the interests of both crop and livestock farming and contributes to the protection of soils and their preservation for future generations.

It is quite clear that the entire set of proposals aims to change approaches to the activities of the entire water management complex of the region, to study its effects on the ecological and resource potential and socio-economic “indicators of the region's depression” as comprehensively as possible over time - and, realizing and understanding the main causes of the relevant effects, to find ways to overcome negatives and optimize water consumption and land conservation.

To prevent serious violations of the hydrogeological and reclamation state, it is extremely important to comprehensively solve the problems of irrigation, linking into a single complex the constructions that bear the technological and environmental load. This allows you to create controlled natural and technical systems that significantly reduce, and in many cases, eliminate the unwanted impact of irrigation.

This approach requires the implementation of the following measures, which can be conditionally divided into agricultural, technical, ecological, and remedial measures. A single complex combination of such measures will allow us to create an effective way not only to restore irrigated agriculture in the studied territory but also to improve the condition of the studied agro-landscapes.

Agricultural activities:

- ✓ use of only closed irrigation networks on agricultural lands, both distribution networks and intra-farm and area networks;
- ✓ the use of only low-pressure sprinklers as irrigation equipment, which will allow to significantly reduce amelioration costs for irrigation;
- ✓ actively use drip and in-soil irrigation methods;
- ✓ actively use “green” energy (especially wind) as energy resources.

Mode of irrigation of crops:

- ✓ development and use of irrigation regimes for regionalized crops, taking into account global and regional climate changes, as well as the absence of the Kakhovka Reservoir;
- ✓ to establish the maximum irrigation rate at the level of the maximum water-holding capacity of the soils of each of the irrigated agricultural landscapes;
- ✓ ban on the use of underground fresh water (which can be used for drinking water supply) for irrigation of crops, both within the irrigation system and in residential areas.

Technical measures:

- ✓ complete inventory and certification of hydro-technical structures and their inspection with drawing up of an inspection report;
- ✓ based on inventory and certification, establishment of the possibility of resumption of work, reconstruction, or new construction of the studied hydraulic structures using modern achievements in the field of hydraulic construction.

Ecological and remedial measures:

- ✓ establish strict control over the use of water resources following the Water Code of Ukraine;
- ✓ development of modern measures to prevent water and wind erosion processes;
- ✓ development of methods to prevent processes of secondary salinization and salinization, soil salinization for modern farming conditions;
- ✓ development of modern methods of restoration of damaged, or destroyed as a result of military operations or degraded soil cover for each separate territory;

- ✓ use only planar horizontal drainage to prevent flooding of irrigated areas. Along with this, develop methods of cleaning drainage water for its reuse;
- ✓ develop measures and actively use new methods and devices for improving the quality of water sources used as sources of irrigation water;
- ✓ restore or build an automated monitoring network for the state of groundwater in all irrigated areas.

ILLUSTRATIVE EXAMPLE

For the effective management of irrigated agriculture, important factors must be available and have optimal values, both individually and in combination in a single landscape-ameliorative system, without which the existence of this system is simply impossible. According to Ivashchenko O.O., Ivashchenko O.O. (2008), these include the following factors: a sufficient area of arable land that has a flat or close to flat topography; availability of fertile soils, with clearly defined natural or artificial effective fertility; a fairly long-growing season, which is characteristic of the studied area; the arrival of a powerful flow of solar radiation; the presence of reserves of moisture available for plants in the soil or its artificial reproduction with the help of hydro-technical agricultural land reclamation; regular precipitation during the growing season, which is currently quite problematic for the research area due to global and regional climate changes in the south of Ukraine.

Climate changes significantly affect the natural environment of the studied landscapes. There are changes in natural and plant zones (for example, the Steppe zone is actively shifting to the north, and these changes occur within a short time), the level regime of groundwater is changing (one of the significant factors of such changes, in addition to climate changes, is the rise in the levels of the World Ocean) and significantly river flow is redistributed. Agriculture is most affected in such conditions (Barabash M.B. et al, 2004).

Climate change is an objective reality, and not only for the studied area. The vast majority of famous scientists, based on their many years of scientific research and observations, claim the natural cyclical nature of climate change, which will help in the future to develop a mechanism to prevent such negative phenomena.

It is a fact, based on long-term statistical data, that over the past 100 years, the average temperature in Ukraine has risen by almost 1°C, and only over the past 10 years - by 0.3°C (Barabash M.B. et al, 2004).

To analyze possible climate changes in the research area (Kherson region, which is typical for southern Ukraine) and establish representative patterns of their further development, the following meteorological data were analyzed: air temperature (°C) and amount of precipitation (mm), as well as derivatives of their indicators.

The analysis of meteorological data was performed for long-term and short-term periods: from 1945 to 2021 and from 2010 to 2021 inclusive. For each of the given years, the average annual air temperature was calculated and the annual amount of precipitation was determined. Based on these data, a distribution of climatic indicators was constructed, which was processed using statistical methods.

The analysis of multi-year data for long and short periods in the research territory (according to the data of the Kherson Hydrometeorological Center) showed the following. In the Kherson region only for a short time (the last 12 years), the average annual air temperature has increased by 1.4-1.8°C and has been fixed permanently, which confirms temperature changes at the regional level. At the level of the average annual air temperature, it can be stated that until the beginning of the 90s of the twentieth century, it was at the level of 9.8°C in the territory of the city of Kherson and its adjacent territories, now its values are at the level of 10.1°C. With the loss of the Kakhovka Reservoir, the average annual air temperature may increase. Along with the process of temperature change, there is also a decrease in the total amount of atmospheric precipitation for the observation period from 1998 to 2021, by 55.5 mm per year. With the loss of the Kakhovka Reservoir and the disruption of the regional water cycle established during its existence, a further decrease in the amount of precipitation for the studied area is possible, which requires additional scientific research on this process.

The results of the analysis of dynamic changes in climatic indicators on the example of the Kherson region in 2 periods 1947-2021 and 2010-2021 are shown in tables (tables 1-3) and graphic form in figures 4-13.

During the studied time in the territory of research (Kherson region), there is a relatively constant increase in the amount of precipitation and the humidity coefficient during the growing season with an increase in air temperature. This happened due to the intensive short circulation of water in this area with the participation of the Kakhovka Reservoir and a large number of open irrigation canals. With their short-term loss, since the destruction of the Kakhovka Dam, these indicators of the water balance of the territory have significantly decreased. This can now and in the future have extraordinary consequences for natural and economic objects of agricultural and hydro-technical purposes in the territory of the Kherson region and requires significant clarification of crop irrigation regimes.

For a more complete picture of the development of climatic changes and to display the exact climatic characteristics of the studied region based on the already obtained initial data, their derivative characteristics, such as evaporation and the humidity coefficient, were calculated.

The humidity coefficient (K_{hyd}) is the ratio of annual precipitation to evaporation during the same period. This indicator is one of the main climatic indicators and indicates the aridity, or vice versa, of the humidity of the climate. The higher the index, the wetter the climate, and the lower it is, the drier. If the amount of precipitation and evaporation coincide, then the coefficient is equal to one. It should be taken into account that the calculations take into account potential evaporation, not real, since part of the precipitation usually does not evaporate, but seeps into the soil, flows down rivers, etc. (Pestushko V.Yu. et al, 2003; Ladychuk D.O. et al, 2021).

Table 1. Indicators of atmospheric precipitation in the territory of the Kherson region

Average monthly rainfall, mm												
Years	**Months**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2010-2021	42.9	39.1	32.9	16.3	48	45.9	49.9	61.5	22	33.3	46.3	37.1
1947-2021	32.6	30.4	28.4	34.3	43.1	48.9	40.9	36	35	29	35.9	38.5

Figure 4. Dynamics of changes in atmospheric precipitation indicators in the Kherson region (for the period 2010-2021)

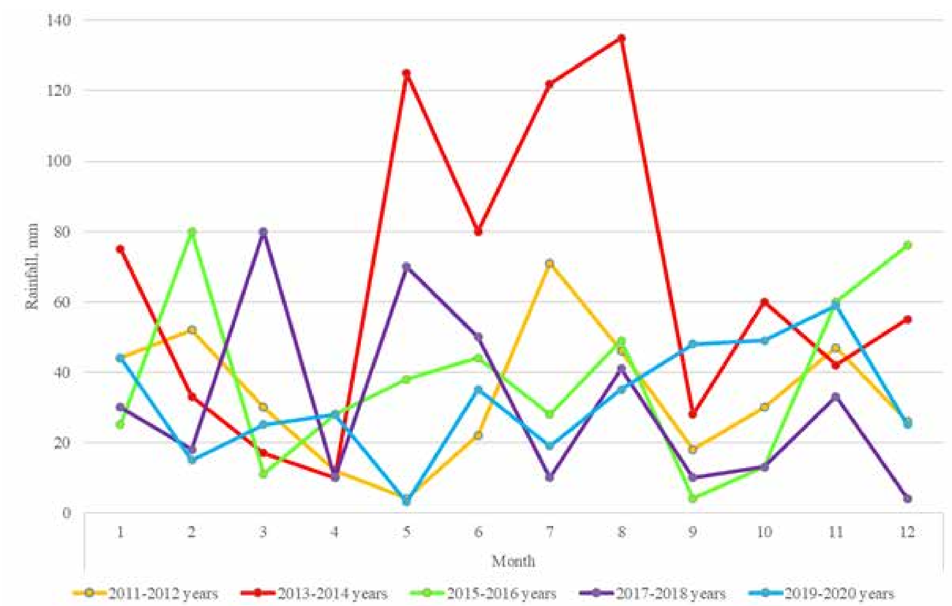


Figure 5. Graph of the annual amount of atmospheric precipitation in the Kherson region (for the period 2010-2021)

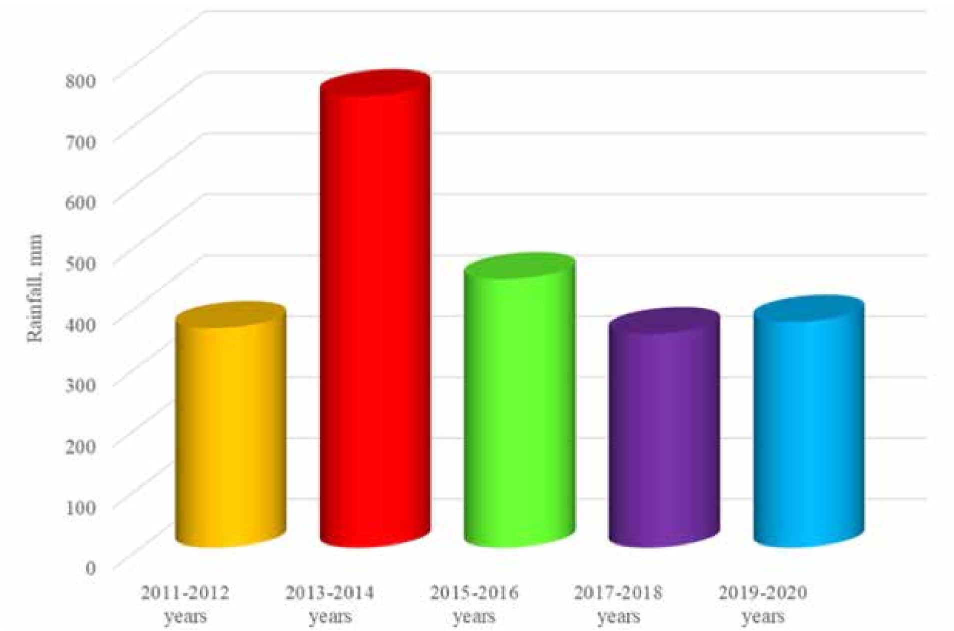


Figure 6. Dynamics of changes in precipitation indicators in the Kherson region (for two time intervals: 2011-2021 and 1956-2021)

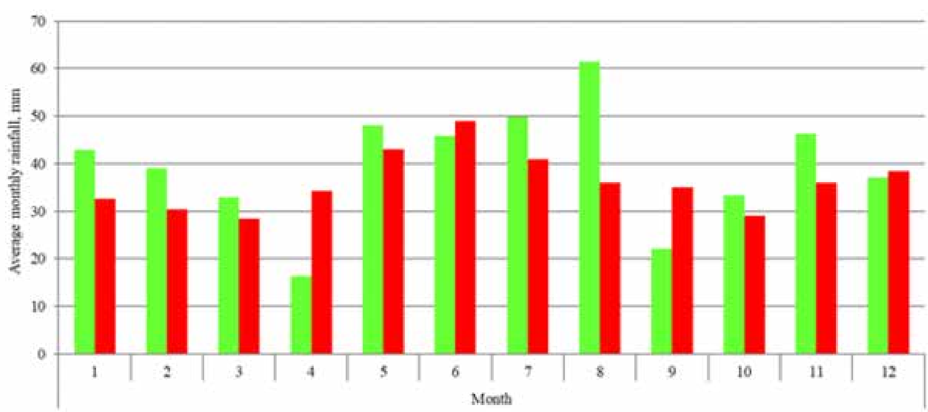


Table 2. Indicators of average annual air temperature in the Kherson region

Air temperature, °C												
Years	**Months**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2010-2021	-0.5	-2.3	3.3	10	17.7	20.9	23	23.8	18.1	11.8	5.2	2
1947-2021	-2.6	-1.9	2.5	10	16.4	20.5	22.9	22.2	16.9	10.5	4.5	0.3

According to the classification of N.M. Ivanova,, K_{hyd} indicates natural zones (Kolpakov V.V. et al, 1988):

– semi-desert - 0.5;
– dry steppe - 0.5-0.8;
– step - 0.8-1;
– forest-steppe - 1-1.2;
– forest zone - more than 1.3.

K_{hyd} is an abstract indicator and it must be taken into account that the real humidity of the climate is influenced by many factors. However the conducted studies prove that such indicators as the amount of precipitation, average temperatures, and air humidity are the main ones for determining natural zones in terms of their moisture, and in general, the location of natural zones corresponds to the values of these indicators. Long-term research was carried out on the territory of the Biosphere Reserve "Askania-Nova" named after F.E. Falz-Fein showed that according to these indicators, in the period 1990-1993, the territory belonged to the Dry Steppe zone, and in the period 2012-2018, it already belonged to the semi-desert zone.

Figure 7. Dynamics of changes in atmospheric air temperature indicators in the Kherson region (for the period 2010-2021)

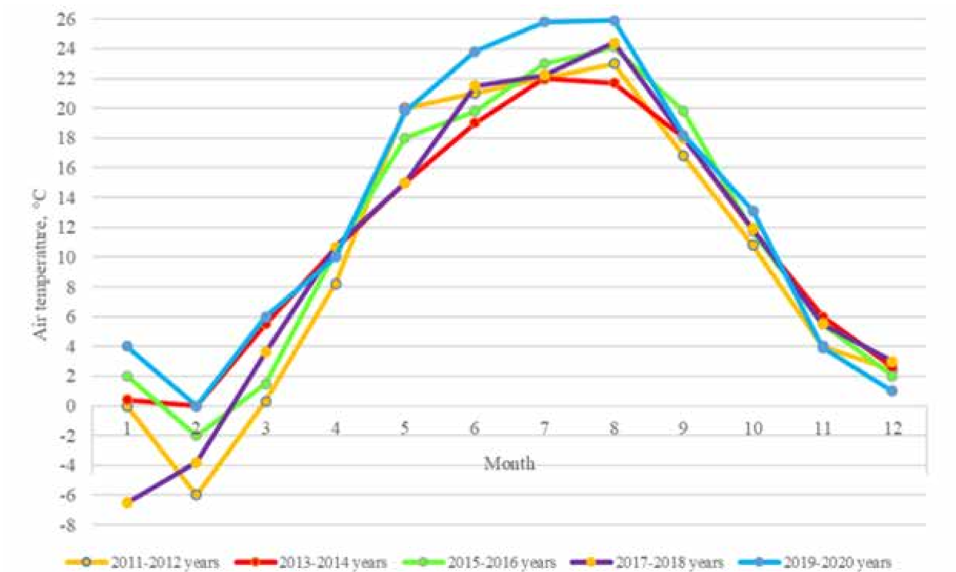


Figure 8. Average indicators of atmospheric air temperature in the Kherson region (for the period 2010-2021)

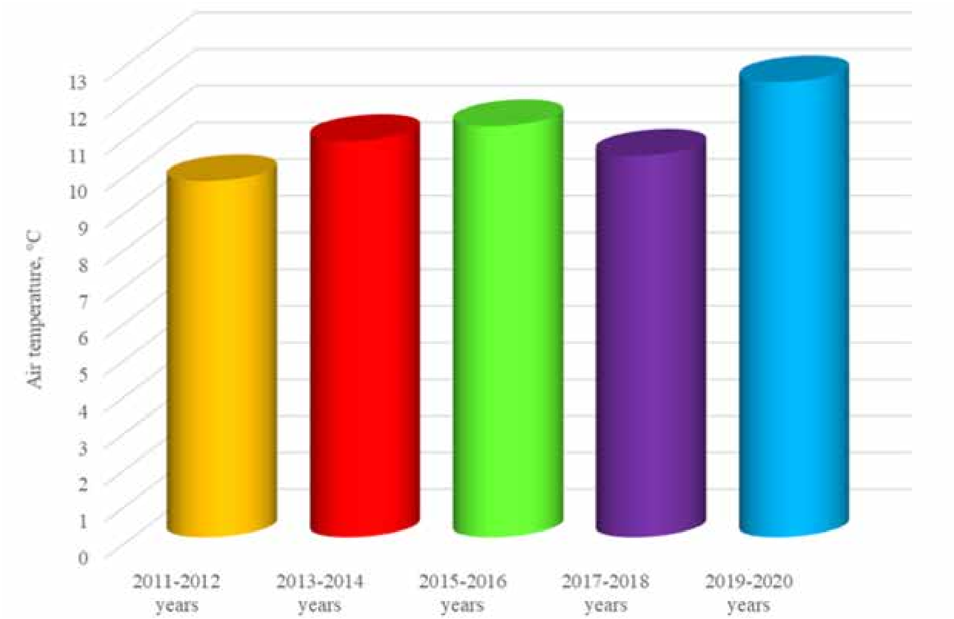


Figure 9. Dynamics of air temperature changes in the Kherson region for two time periods, 2011-2021 and 1947-2021

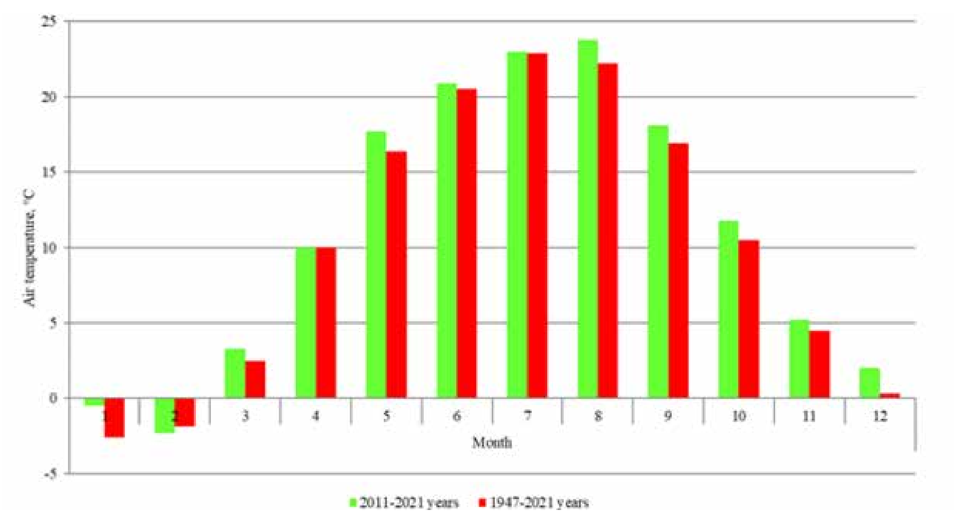
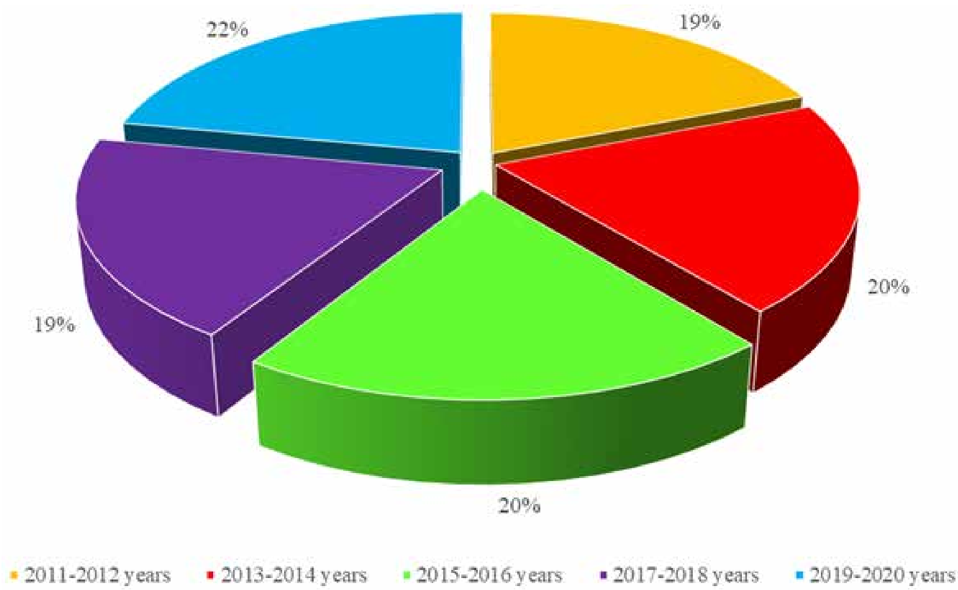


Figure 10. The percentage composition of the evaporation indicator in the Kherson region (for 2010-2021)



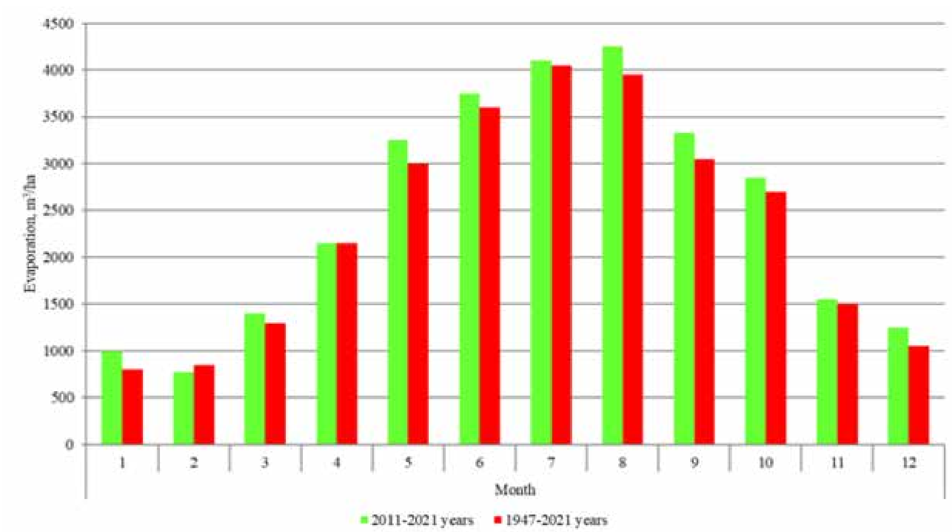
Under the action of natural and anthropogenic factors, including regional climate change, the water balance of the territory is being transformed. During the existence of the Kakhovka Reservoir, an increase in precipitation during the growing season (precipitation falls as downpours and is practically retained in the soil at the level of 15-20% of the total amount) with constant evaporation leads to an increase in surface and underground runoff. As a result of this, there will be an increase in such negative processes as water erosion of soils, processes of ravine formation, and processes of flooding of landscapes of varying degrees of technophile. For example, the low-lying left-bank part of the Kherson region is already suffering from an intensive rise in groundwater, especially in the coastal areas and in the depressions of the relief (subsoils). The result is flooding of agricultural landscapes, and residential areas, and intensification of secondary soil salinization processes, which is associated with a high degree of mineralization of groundwater, at the level of 16.0-21.0 g/dm^3. According to all indicators, the processes of flooding in the future were only to intensify. However, the loss of the Kakhovka Reservoir significantly changed the development of climatic indicators, which requires additional research in the long-term perspective.

Adjusting the regime of irrigation of crops using the bioclimatic method of Professor S.M. Alpatyeva showed that irrigation was carried out at inflated rates given the net irrigation rate, which leads to excessive costs of labor, funds and, of course, water, and therefore to an increase in groundwater levels, soil degradation in irrigation areas.

To reduce the dynamics of rising groundwater levels, it is necessary to envisage environmental improvement measures and reduce the incoming items of the water balance (adjustment of irrigation norms, timely repair work on canals and structures on the network, etc.).

The main and limiting factor in determining the maximum rate of irrigation is the water-holding capacity of the soil, the quantitative characteristic of which is the lowest soil moisture capacity (LMC) for the research area (Ladychuk D.O. et al, 2021).

Figure 11. Dynamics of changes in average evaporation rates in the Kherson region for two time periods: 2011-2021 and 1947-2021



The main types of soils in the research area are black soils in the south and dark chestnut soils in the loess. The values of their lowest moisture content are within the limits, respectively: 22.30-32.05 and 21.70-32.20% of the soil weight. Taking into account the negative process of soil lithification, LMC values decrease to: 20.60-31.90 and 21.30-29.50, depending on the genetic horizon of the soil (Demyokhin V.A. et al, 2007).

It was established with the help of appropriate calculations that with the above soil characteristics, the net irrigation rate Q_{nt} should not exceed 400-420 m^3/ha.

For this case, the greatest interest is caused by the gross irrigation rate Q_{br} (with a relatively known net irrigation rate Q_{nt}), which will constantly increase due to the increase in the amount of total evaporation (Q_{br} - Q_{nt} = total evaporation + transpiration of moisture by plants or total water consumption) (Figures 10, 11). Then, due to the increase in total evaporation and taking into account the relative constancy of the LMC, the number of irrigations increases when compared with the calculated mode of irrigation of crops. In the conditions of the studied area, the increase in watering occurs, at least by 1 watering (for grain and technical crops), and for moisture-loving crops (such as, for example, vegetables), the number of waterings can increase to 2. This makes it necessary to adjust the estimated modes of irrigation of crops throughout the growing season (Ladychuk D.O. et al, 2021).

The established significant impact of climate change will, first of all, affect the properties of the soil cover, and therefore the fields of agriculture and crop production, and subsequently, the entire agrolandscape as a whole, since soils are the basis of any agrolandscape.

Table 3. Coefficient of humidification (K_{hyd}) for a certain time in the Kherson region

Coefficient of humidification K_{hyd}												
Years	**Months**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2010-2021	0.040	0.040	0.020	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.030	0.030
1947-2021	0.040	0.030	0.020	0.020	0.010	0.010	0.010	0.010	0.010	0.010	0.020	0.030

Climate changes will cause changes in the physical, water-physical, physico-chemical, and agrochemical properties of soils, especially light, low-buffer zones, which are spread over the research territory, especially on the Left Bank of the Kherson region.

Significant changes in the temperature regime will affect the change in physical and chemical properties and, above all, the structure of the absorption complex, which depends not only on the level of fertility but also on the soil itself, as the carrier of this main property (Ladychuk D.O. et al, 2021).

Figure 12. Dynamics of the humidity coefficient in the Kherson region for two time periods: 2010-2021 and 1947-2021

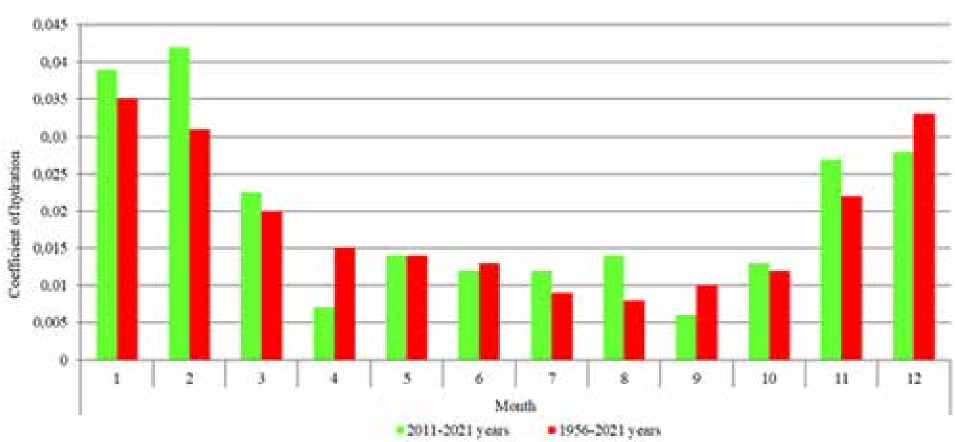
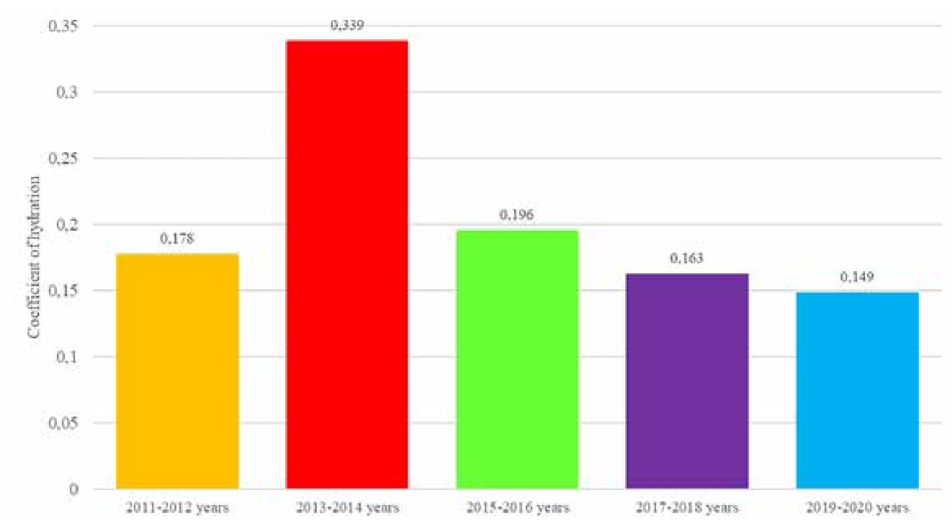


Figure 13. Dynamics of changes in the humidity coefficient in the Kherson region according to average annual indicators for 2010-2021



Calcium and magnesium, which make up the largest part of the cation exchange capacity of the soil, serve as regulators of the reaction of the environment. Calcium is a coagulator of soil colloids, protects them from destruction and removal to the lower horizons of the profile; contributes to the formation and preservation of humus and its stable compounds; calcium creates appropriate physical conditions, plays a decisive role in structure formation; Together with magnesium, mobile forms of compounds of aluminum, iron, and manganese bind, which harm cultivated vegetation. Calcium and magnesium are nutrients for plants and soil microorganisms and, finally, they play an exclusive mobilizing role in the soil, increasing the content of the main nutrients available to plants, primarily nitrogen and phosphorus, significantly increasing the effectiveness of fertilizers (Mazur G..A., 2008).

At critically low negative temperatures, the quantitative displacement of absorbed magnesium by the neutral salt cation increases sharply. At critically high temperatures, displacement of absorbed calcium into the soil solution increases significantly. In this regard, it is predicted that under conditions of a sharp cooling, an increase in the composition of chemical meliorants of magnesium compounds by 20-25%, and under conditions of a sharp increase in the temperature factor, a decrease of calcium carbonate doses by 20-25% to balance the ratio between calcium and magnesium in soil solution. This should be taken into account when calculating the application of mineral fertilizers and soil conditioners.

An increase in irrigation of crops grown on farms by 1 irrigation will not significantly affect farm expenses, if the mandatory net irrigation rate is observed, which will not exceed 400-420 m^3/ha, and it is even possible to save 86191.5 m^3 of irrigation water. This will amount to UAH 255.75/ha, in average prices for the 2021 irrigation season.

In summary, both global and regional climate changes are altering irrigation regimes, leading to increased anthropogenic pressure on soil and irrigated agriculture in the studied region. Future research directions should focus on understanding the evolving factors affecting agricultural landscapes in southern Ukraine, particularly in areas affected by military actions. The transformation of previously established landscape-ameliorative systems under modern influences necessitates new approaches to restoration and effective functioning.

FUTURE RESEARCH DIRECTIONS

The evolving factors affecting agricultural landscapes in southern Ukraine signal the need for a reevaluation of irrigated agriculture development in the region. Previously established landscape-ameliorative systems, tailored to regional temporal and spatial characteristics, are now subject to new influences. Consequently, these systems are operating under different dynamics, altering their properties and states from their previously stable condition. While individual indicators of the agricultural landscape state can be restored to previous stages, reinstating the systemic interaction structure presents significant challenges.

Research conducted thus far suggests that while each specific indicator of the agricultural landscape state can be brought back to previous levels of development, reconstructing the intricate systemic interactions is exceedingly difficult. This underscores the need for further research to focus on the restoration and effective functioning of agricultural landscapes in southern Ukraine.

In essence, the transformation of landscape-ameliorative systems due to changing factors necessitates a nuanced understanding of their new dynamics. Future research efforts should aim to unravel these complexities and devise strategies for restoring and enhancing agricultural landscapes in the region.

CONCLUSION

In conclusion, the preservation and optimization of specific irrigated territories, especially those affected by military actions, must prioritize maximum effectiveness and predictable safety. This entails implementing environmental and remedial measures across various dimensions. Attempting to replicate total irrigation is deemed inappropriate; instead, ecological and remedial efforts should focus on targeted interventions. These include reconstructing irrigation and drainage systems based on thorough inventory assessments, constructing drainage systems, adopting flushing irrigation methods for saline soils, and implementing chemical melioration of irrigation water and soils. Additionally, adopting water- and soil-saving irrigation practices and instituting comprehensive monitoring, especially in areas facing degradation, are crucial.

Currently, the primary focus in irrigation restoration should be on minimizing the meliorative burden on soil through rational and standardized water usage. Moreover, transitioning irrigated agriculture to adaptive landscape systems that prioritize ecological safety is paramount. The scarcity of water resources and the ecological landscape should serve as guiding principles in irrigation project development, incorporating modern scientific and technical advancements in irrigated agriculture and hydro-technical reclamation.

It is imperative to acknowledge that global climate changes will exacerbate water resource scarcity and degrade water quality in the coming 5 to 7 years. Therefore, proactive measures must be taken to mitigate these effects and ensure the sustainable management of water resources in irrigated agricultural regions.

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Chapter 15
Restoration of Drainage Systems as the Foundation for Agricultural Production Stability and Ecological Balance of Ukrainian Polissia

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ABSTRACT

The changing conditions of crop cultivation and the shift in the use of drained lands necessitate the restoration of drainage systems, expanding their functional tasks, and ensuring water regulation on drained lands. The research focuses on agricultural lands in the farms of LLC "Vasiuty and LLC Bilinsket" in the Kovel district of the Volyn region of Ukraine. Studies conducted on reclaimed lands of the drainage systems "Melnitska" and "Bobrovka" have shown that the implementation of a complex of works to restore open and collector-drainage canals to design specifications, the operation of hydraulic structures, allowed for timely drainage of excess water in the spring period and regulation of soil water regime in the early vegetation period. Maintaining moisture in the active soil layer within close to optimal limits at the end of the vegetation period is possible through the accumulation of additional water reserves in the open channel network. Yield indicators of the studied crops (winter wheat, maize, sunflower) on drained lands have been determined

BACKGROUND

Climate change manifests differently in regions around the globe, and its impact on the environment and socio-economic development of regions is becoming increasingly apparent, emerging as one of the key issues in the global economy and politics. Today, it poses a potentially serious threat to the global economy and international security due to increased risks at various levels related to food security, access to clean water, and the stable existence of ecosystems (Balabukh, 2017; Degodyuk et al, 2008; Guidance on meteorological forecasting, 2019; Ivanyuta et al, 2020; Ivashchenko, 2008; Kuzmych et al, 2021, 2022a, 2022b, 2022c,2023a, 2023b,2023c; Parry et al, 1990; Prykhodko et al, 2023; Rokochinskiy et al, 2019, 2020, 2023a; Romaschenko, 2019; Saiko, 2008; Yakymchuk et al, 2022).

Among the main consequences of climate change, such as rising air temperatures and changes in annual patterns of atmospheric precipitation, is the alteration of water resources and their availability to various sectors of the economy. Climate change significantly impacts agricultural production, one of the most climate-dependent sectors of the economy, leading to water scarcity, which is a major limiting factor for sustainable agriculture (Degodyuk et al, 2008; Gladiy, 2020; Korobiichuk et al, 2017,2020; Kuzmych et al, 2022d, 2022e, 2023d, 2023e, 2023f, 2023g; Parry Romashchenko, 2019; Ivashchenko, 2008; Land Reclamation, 2015; Saiko, 2008; Slyusar, 2008, Turcheniuk et al, 2022a).

Modern climate changes influence technological maps and crop rotation structures of agricultural enterprises and drainage reclamation zones. The agricultural sector now prioritizes economically attractive crops such as corn, sunflower, soybeans, and rapeseed, aligning cultivation with market demand for agricultural products (Koval et al, 2014; Kvasnikov et al, 2023; Kuzmych et al, 2022h, 2022i, 2023j, 2023k; Land Reclamation, 2015; Mirzaei et al, 2021; Pimentel et al, 2006).

Significant land areas are engaged in agricultural production, and crops grown at all stages of development are directly influenced by weather and climate conditions. The impact of weather conditions on crop yields accounts for approximately 52% (Malézieux et al, 2009; Nechyporenko O., 2008). Therefore, in the face of climate change, modern agriculture requires the development and implementation of adaptation measures (Rokochinskiy et al, 2023b; Shevchenko et al, 2021; S. Kuzmych et al, 2023; Onanko, A. et al, 2022, 2023; Slyusar et al,, 2015; Zuzuk et al, 2012).

Considering that climate change hinders sustainable agricultural practices, utilizing the potential of drainage systems becomes essential for enhancing agricultural efficiency through the adoption of modern cultivation technologies for economically viable crops and achieving stable yields. Simultaneously, the changing conditions for crop cultivation and the shift in land use directions necessitate expanding the functional tasks of drainage systems and restoring water regulation on drained lands.

Due to the change in agricultural production specialization, there is an oversaturation of crop structures with intensive crops and a disregard for crop rotation as a crucial measure for preserving soil quality and agricultural culture (Gladiy et al, 2020; Onanko, Yu. et al, 2022; Prasuhn et al, 2013; Vashchuk et al, 2021; Turcheniuk et al, 2022b).

Given the current state of drainage systems in the drainage zone, there is a need for their restoration through two approaches outlined in the “Irrigation and drainage strategy in Ukraine for the period up to 2030”: modernizing operational reclamation systems and modernizing non-operational reclamation systems.

Today, due to military aggression and occupation, a significant portion of drainage systems have been damaged or repurposed for fortifications along Ukraine's borders. The cultivation of more attractive crops necessitates the restoration of collector-drainage infrastructure and its improvement towards utilizing two-way drainage systems to incorporate irrigation and regulate soil water regimes in cultivation areas.

Simultaneously, the development of agricultural production in the Polissia zone requires addressing the issue of land protection from waterlogging and flooding. This problem affects agricultural lands in the farms of “Vasyuti” and “Bilinske” in the Kovel district of the Volyn region, specializing in crops such as sunflower, winter rapeseed, winter wheat, corn, and others.

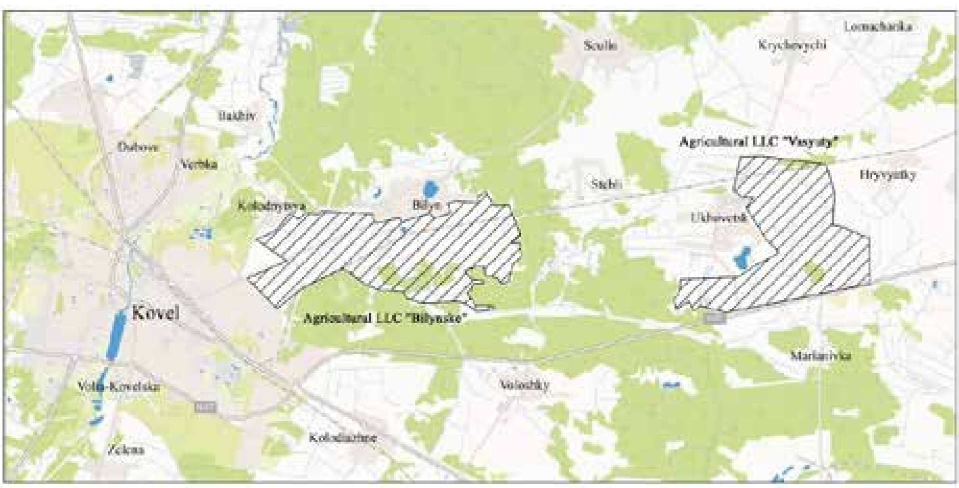
The research aims to assess the state of drainage systems, develop recommendations for their restoration to reduce the risks of flooding and improve the water-ecological situation in the research areas.

CHARACTERISTICS OF THE RESEARCH OBJECT

Kovel district is located in the northwestern part of Volyn Oblast (Vashchuk K.M. et al, 2021). The area of the district is 7708.7 km^2, which accounts for 38% of the total area of Volyn Oblast. The geographical position of the district is characterized by its proximity to Belarus in the north, Poland in the west, Kamin-Kashyrskyi district in the east, Lutsk district in the southeast, and Volodymyr-Volynskyi district in the south. The total land area is 773.1 thousand hectares. The land resources of Kovel district are structured as follows: agricultural land - 403.4 thousand hectares (52.2%), built-up land - 20.4 thousand hectares (2.6%), forested areas - 279.6 thousand hectares (36.2%), marshy lands - 33.0 thousand hectares (4.3%), and other lands - 36.7 thousand hectares (4.7%).

The farms “Vasiuty” and “Bilinske” are in the Kovel district of Volyn region on a total area of 2000 hectares (Figure 1).

Figure 1. Scheme of the location of farms “Vasiuty” and “Bilinske” in Kovel district of Volyn region



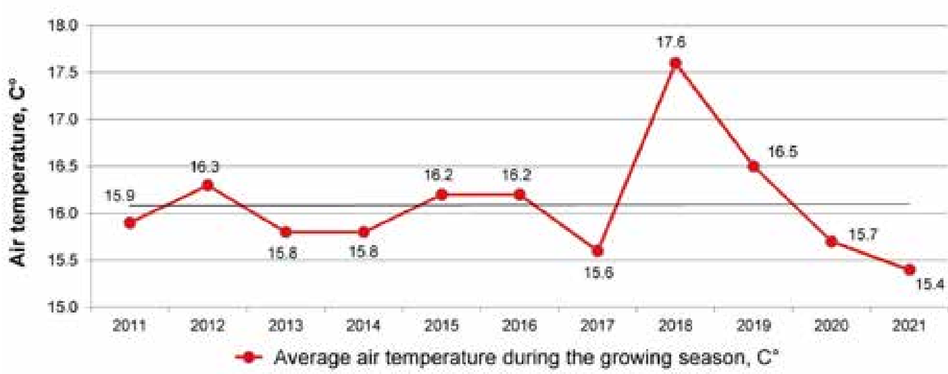
The land plots of the "Vasiuty" farm are located near the village of Ukhovets, which is almost in the center of Kovel district, 21 km east of the city of Kovel, and 3 km from the Kyiv-Warsaw highway. The village is situated on an elevated plain. The absolute height above sea level is 195 m. The land plots of the "Bilinske" farm are located near the village of Bilin, which is 9 km from the city of Kovel. The average height above sea level is 170 m.

AGROCLIMATIC CONDITIONS

A study was conducted on the influence of modern climatic factors on the formation of soil water regimes, using archives of meteorological data from the Kovel weather station (Volyn Oblast) for the period 2011-2022. The main meteorological factors analyzed were air temperature and precipitation, which are the main factors influencing modern climate changes in the soil water regime formation.

The dynamics of average air temperature indicators during the vegetation period over the years of research are presented in Figure 2.

Figure 2. Dynamics of air temperature during the vegetation period 2011-2021, °C; Kovel weather station, Volyn region

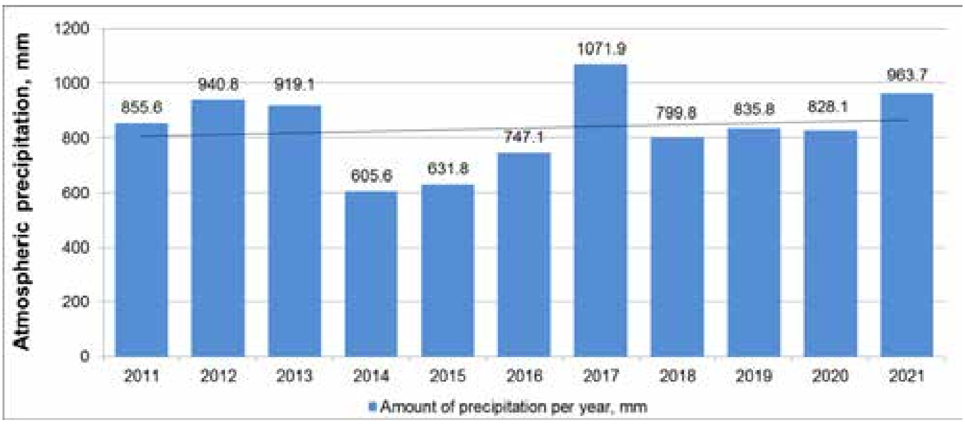


From the presented materials, the average air temperature during the vegetation period over the past 11 years varied from 15.4 to 17.6 °C. There is no overall trend of increasing or decreasing average air temperature during the vegetation period. The highest monthly air temperatures occur in July and August, while the lowest is in April. However, it is noted that the increase in average annual and monthly air temperatures in Ukraine is determined by the increase in minimum and maximum air temperatures throughout the year. In the cold period, there is a significant increase in minimum temperature, and in the warm period, in maximum temperature. Therefore, such trends can be observed in the analyzed period and the dynamics of temperature indicators recorded in 2018.

Considering that atmospheric precipitation is one of the main factors determining the characteristics of the regional climate, the amount and distribution of precipitation are crucial indicators for the formation of the territory's moisture regime.

Information on the annual amount of atmospheric precipitation for the study period is presented in Figure 3.

Figure 3. Dynamics of total atmospheric precipitation per year, 2011-2021, mm; Kovel weather station, Volyn region



According to the classification of precipitation by amount (Guidance on meteorological forecasting, 2019), it is established that during 2011-2021, the share of weak precipitation (up to 3 mm) averaged 14%, moderate (4-14 mm) - 43%, significant (15-49 mm) - 37%, heavy (50-79 mm) - 5%, and extreme (≥ 80 mm) - 1% of the total amount. It is determined that the water regime of the active soil layer is formed by the influence of moderate and significant precipitation (Kuzmych et al, 2023a, c, d, k).

SOIL CONDITIONS

The soil cover of the Kovel district, especially in its northern part, is characterized by significant marshiness. Excessive soil moisture is unfavorable for planting crops, so these areas are used as pastures or hayfields. The predominant types of soils are sod-podzolic, medium-podzolic, sandy, loamy, peaty, and peat soils (Figure 4, Table 1).

Figure 4. Soil map of Volyn region (Zuzuk et al, 2012)

Table 1. Characteristics of soils and key natural factors in the Kovel district of the Volyn region

Natural parameter	Features of natural parameters of agrosoil district
Soils	Significant areas are covered by sod-podzolic gleic sandy and loamy soils (code 6), sod-podzolic gleic sandy and loamy soils (code 9), sod-podzolic weakly and medium-podzolic sandy and loamy soils (code 2), sod-podzolic gleic sandy and loamy soils (code 7), peat soils (code 138), carbonated sod-podzolic soils (code 165), etc. The district is characterized by its significant heterogeneity.
Parental substrates	Commonly found are medium-Quaternary water-glacial heterogeneous sands, loams, and loess, as well as glacial moraine deposits of boulder sands, sandy-gravel mixtures; Upper Quaternary alluvial deposits of sands and loams of the first floodplain terrace of the Turiya, Stokhid rivers, loams and clays of the second floodplain terrace of the Western Bug river; Holocene bog and alluvial deposits of the floodplains of Turiya, Stokhid, Vyzhivka rivers and their tributaries; Holocene aeolian sandy formations. Eluvial formations of Upper Cretaceous rocks cover small areas.
Undergroundwater	Groundwater of modern bog formations lies at a depth of 0-0.5 m, sometimes 1 m. The depth of groundwater in the Upper Quaternary deposits of the first and second floodplain terraces is 1-3 m. In the middle Quaternary fluvioglacial deposits, the depth of the groundwater table reaches 1-3 m and in moraine deposits - 3-5 m. The artesian chalky aquifer is located at a depth of 3-5 m.
Relief	The district is located within the boundaries of the Povorsk-Manevych and Lyuboml-Kovel end-moraine geomorphological regions and the Turiy-Ovadny denudation region. The relief is dominated by gently undulating and end-moraine hilly-ridge surfaces of the Dnieper glaciation. Denudation surfaces of Upper Cretaceous age cover a significant portion of this region. River floodplains are wide with gentle slopes separating them from interfluves. The first terrace on the Turiya and Stokhid rivers is barely noticeable. Only the second terrace on the Western Bug River is clearly distinguished. There are ridges and eskers in the end-moraine zone, and dunes on the coast of the Western Bug River. Numerous karst forms of relief are present. The main European watershed passes through this area.
Groundwater	Rivers Western Bug, Vyzhivka, Turiya, Stokhid and their tributaries. The number of lakes, mostly of glacial and karst origin, decreases from north to south of the district.
Land use	Arable land is 30-40.5%, in some places up to 47%, forests - 15-34%. The lands of this district are well developed. Forests cover up to 35% of the area. Lowlands are covered with shrubs and unproductive forests that are not used in agriculture.

Kovel district lies within the Volyn-Podillya artesian basin, so significant reserves of groundwater are present.

Samples of soil were collected, and their physical properties were determined to obtain basic water-physical constants and soil properties in the agricultural lands of the farms “Vasiuty” and “Bilinske” (Table 2).

Laboratory determinations of the basic water-physical constants and properties of soils were carried out on six soil monoliths. The maximum hygroscopicity of the soil (MH), which characterizes the soil dispersion, was determined on samples of disturbed structure collected during the equipment of monoliths for hydrophysical tests. From this value, derived parameters were calculated: the specific surface area of the soil S, m^2/g, where S=4MH, and wilting moisture content (WM), where WM=1.34 MH. The specific surface area (S) most accurately characterizes the soil dispersion. Based on the WM values, the granulometric class of the soil was determined according to the recommendations without conducting an expensive and time-consuming granulometric analysis of soils.

Table 2. Results of determination of water-physical properties of soil profile samples

Sample number	Interval, m	End bulk density ρ, g/cm³	Specific surface area S, m²/g	MG, % by mass	WM, % by mass	FM, % by volume	SM, % by volume	SM, % by mass	RAM=FM_{Θ}-SM_{Θ}	Granulometric class of soil by WM (according to S.A. Verigo)
Yarinche										
40	0.00-0.15	1.43	6.89	1.72	2.31	44.75	21.32	14.92	41.46	Sandy loam
27	0.30-0.45	1.66	7.93	1.98	2.66	33.71	17.66	10.66	29.30	Sandy loam
Naftoprovid										
25	0.05-0.20	1.55	19.49	4.87	6.53	43.20	32.55	20.95	33.05	Light-medium loam
23	0.30-0.45	1.73	10.61	2.65	3.55	34.54	20.08	11.62	28.40	Sandy loam - Light loam
Rakove										
36	0.05-0.20	1.42	4.34	1.08	1.45	40.86	24.87	17.58	38.80	Sand
20	0.30-0.45	1.69	2.59	0.65	0.87	36.97	14.05	8.30	35.50	Sand

It is noteworthy that light soils predominate in these research areas - from sand in the Rakove area to medium loam in the Naftoprovid area. By characterizing the degree of differentiation of the soil profile based on the determined indicators, it is quantitatively described that the granulometric class of the soil lightens with depth, which is most vividly reflected in the specific surface area (S). With depth, the bulk density (ρ) of the soils increases, while the values of NV, PV, and the range of active moisture (RAM) decrease systematically.

CHARACTERISTICS AND CONDITION OF DRAINAGE AND DRAINAGE NETWORK

The areas of the farms LLC "Vasyuti" and LLC "Bilinske" are located within the drainage systems "Melnitska" and "Bobrovka" on the lands of the Kovel district of the Volyn region (Zuzuk et al, 2012). The characteristics of the drainage systems "Melnitska" and "Bobrovka" are presented in Table 3.

Table 3. Characteristics of the drainage systems "Melnitska" and "Bobrovka"

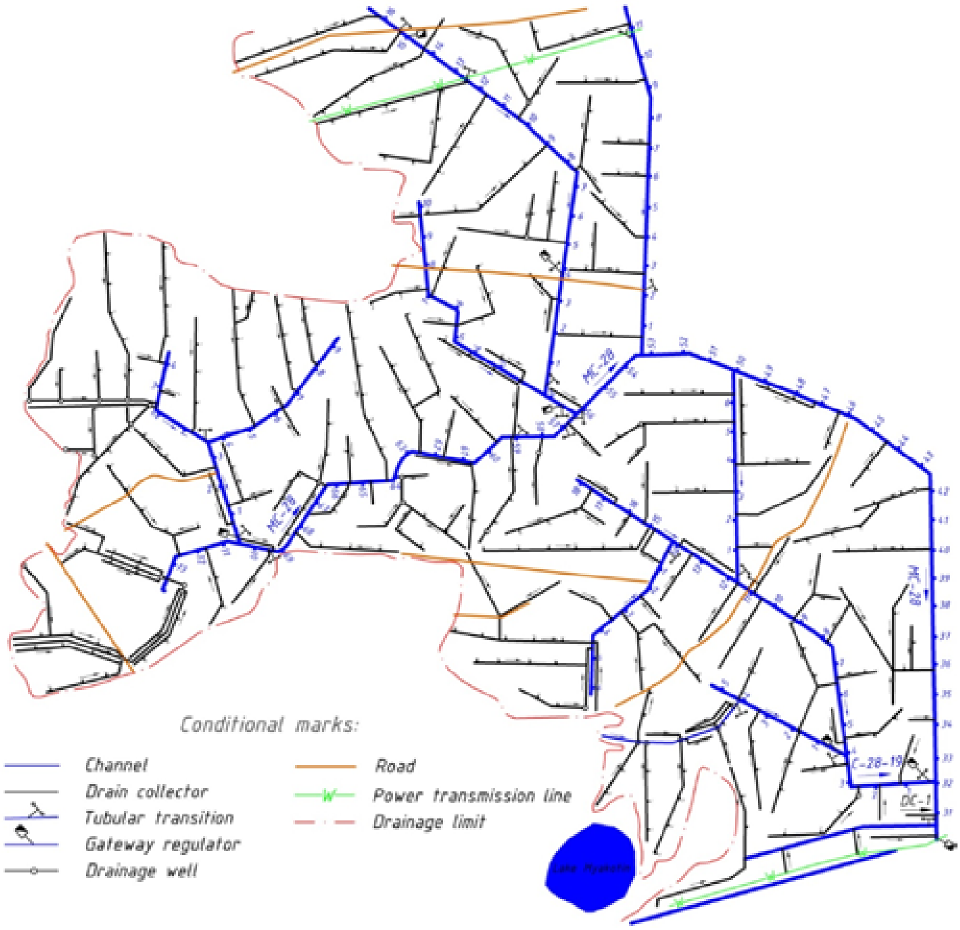
System Name		"Melnytska"	"Bobrovka"
The total area of drained lands, thousand ha		13.928	3.684
Drained by closed drainage, thousand ha		8.592	2.841
Area of systems with two-way regulation, thousand ha		4.570	1.677
Length of regulated water receivers, km		24.0	15.4
Area of drainage with mechanical water lifting, thousand ha		-	-
Length of open channel networks, km		489.8	116.6
Length of closed drainage networks, km		5671.4	1440.7
Structures on water receivers and open drainage networks, units	regulators	104	25
	bridges	4	3
	culverts	309	69
	others	17	11
Structures on closed drainage networks, units		2201	574
Hydrometric devices, units	weirs	1	0
	wells	6	0
Balance value, thousand UAH		39471.9	7399.7

The drainage system "Melnytska" was built in 1969-1971 and covers an area of 18,840 ha, with 13,928 ha in the Kovel district. 8,592 ha are drained by closed ceramic drainage. The area of the system with two-way regulation is 4,570 ha. The length of open channel networks is 489.8 km, and the length of closed drainage networks is 5671.4 km. There are 104 regulators, 4 bridges, 309 culverts, and 17 other structures on water receivers and open drainage networks. There are 2201 structures on the closed drainage network. The system includes 1 hydrometric weir and 6 wells. The balance value of the system is 39471.9 thousand UAH.

The drainage system "Bobrovka" covers an area of 3,684 ha. 2,841 ha are drained by closed ceramic drainage. The area of the system with two-way regulation is 1,677 ha. The length of open channel networks is 116.6 km, and the length of closed drainage networks is 1440.7 km. There are 25 regulators, 3 bridges, 69 culverts, and 11 other structures on water receivers and open drainage networks. There are 574 structures on the closed drainage network. The balance value of the system is 7399.7 thousand UAH.

To drain waterlogged soils, a network of drainage channels and horizontal drainage systems has been built (Figures 5, 6).

Figure 5. Location of the drainage channel network and horizontal drainage system in the LLC "Vasyuti" within the Melnitska drainage system on the MC-28 plot

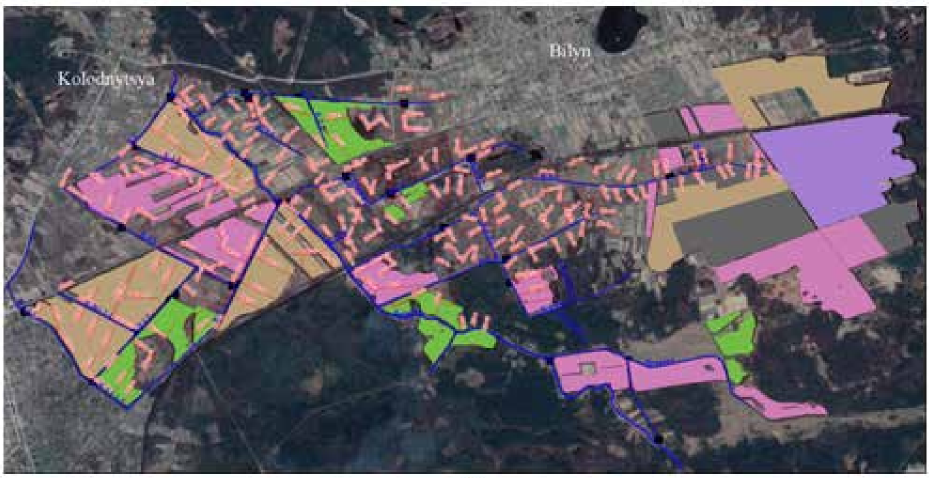


To assess the technical condition of drainage systems and restore them to design parameters, a series of tasks are carried out, including assessing the condition of drainage systems and developing recommendations for their restoration for sustainable agricultural activities. Field and desk work has been conducted to gather information on the current flooding and waterlogging conditions and justify protective measures, including:

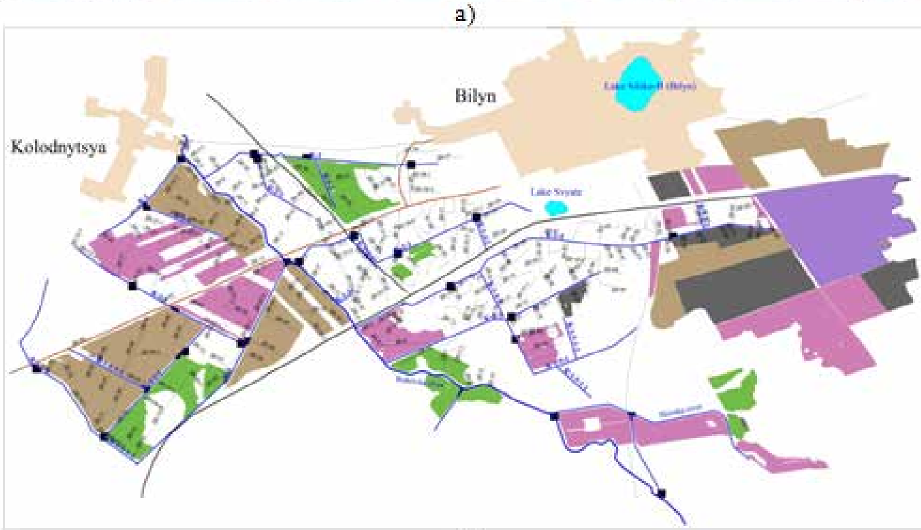
- inspection of flooded areas, drainage and drainage networks, and structures (drainage outlets, culverts, regulators);
- excavation of closed drainage;

- collection of cartographic materials and project documentation;
- mapping of flooded areas of farms;
- analysis of meteorological conditions at the research site.

Figure 6. Location of the drainage channel network and horizontal drainage system in the LLC “Bilinske” within the operation of the Bobrovka drainage system: a) - satellite image; b) – scheme



a)



б)

The location of drainage outlets and closed drains was determined through visual inspection and excavation of trenches using an excavator. Based on the excavation results, the characteristics of siltation and drainage operation, and the condition of drainage pipes and filters after prolonged use were established.

Horizontal drainage is represented by tile drains and collectors. The internal diameters of drains range from 40 to 75 mm, while collectors range from 75 to 150 mm. Smaller drains discharge into collectors, which in turn divert the drainage flow to drainage channels. Tile drains are made of clay with special additives. The pipes have a cylindrical hexagonal or octagonal shape. Their length is 333 mm with allowable deviations from 5 to 10 mm. The drainage line consists of tightly laid short pipes. Their walls are practically impermeable to water, so water enters the pipes only through the joint gaps. The average width of the gaps is from 1 to 3 mm. The main advantage of tile drainage is its durability. Properly designed and well-built tile drainage can function for 100 years or more.

The condition of the existing drainage system is of crucial importance for protecting areas from flooding. According to the inspection results of the drainage systems on the farm plots, it was found that the drainage systems are in unsatisfactory technical condition. The internal farm network of channels is silted and overgrown with shrubs. The outlets of drains and collectors that discharge into the internal farm channels are not visible (Figure 7).

Figure 7. Condition of open channels in the "Bobrovka" drainage system

The open inter-farm channel MC-28 (under the jurisdiction of the State Water Agency of Ukraine) was cleared, and the water levels in it were lower than the outlet of the closed tile drainage by 0.5 m (Figure 8).

Figure 8. Condition of the open channel MC-28 and the outlet of the closed horizontal drainage DC-1 in the Melnytska drainage system

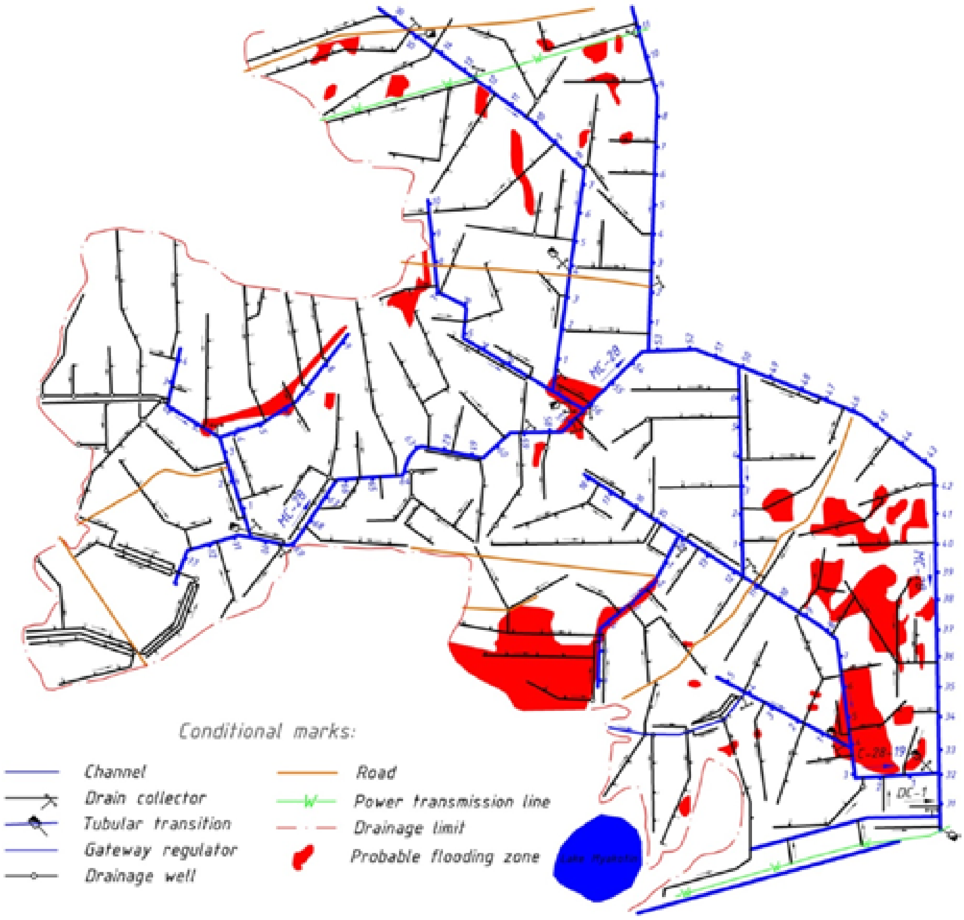
The tile drainage on the territory of the farm "Vasiuti" was in satisfactory condition, with intact tile drains. However, there was observed siltation of drainage outlets about 2 m from the source, which prevented the drainage system from operating in the designed mode and performing water drainage functions (Figure 9). Additionally, the sluice regulators on the internal farm and inter-farm network are in a closed state and do not allow the passage of floodwaters.

Figure 9. Excavations of closed horizontal tile drainage with ceramic pipes on collector DC-1

There are areas on the farm plots that are prone to flooding and waterlogging. These areas are located within the canal zones and flat depressions. The actual flooding zones of the farm "Vasiuti" as of 2021 are shown in Figure 10. The area of flooding in these territories is approximately 10% of the total area of the farm. Flooding was mainly observed in flat depressions and the area between channels C-28-19 and MC-28.

Based on the research of the structural and technological parameters of the "Melnytska" and "Bobrovka" drainage systems, the need to restore the engineering infrastructure within the agricultural lands of the farms "Vasiuti" and "Bilinske" was established, and the cleaning of drainage channels (up to design levels) and outlets of drains and collectors from siltation was carried out, restoring the operation of hydraulic structures.

Figure 10. Flooding zones of agricultural lands in the farm "Vasiuti" as of March-April 2021



RESTORATION OF DRAINAGE SYSTEMS

With decreasing attention to reclamation systems due to insufficient funds for their maintenance, which has been observed in recent decades, there is a threat of deterioration of the technical condition of systems, restoration of waterlogging, and secondary peat formation on drained areas.

The operational efficiency of the existing drainage system is affected by its long service life (as of 2023, it is 54 years old), overgrowth of drainage channels, and silting of drainage outlets on collectors. Therefore, during the spring period, the existing system will not be able to meet the requirements for maintaining groundwater levels at necessary depths.

The significant vulnerability of the areas in terms of flooding and waterlogging during wet periods necessitates the continuous maintenance of drainage systems in working conditions and the implementation of regulated operational measures in full.

The restoration of existing drainage systems includes the following set of measures:

- Cleaning drainage channels from overgrowth and silting.
- Cleaning and restoring drainage outlets on collectors.
- Relocating drainage sections that cannot be repaired.

One of the most important measures to ensure the normal operation of the drainage system and timely and unimpeded drainage of surface and drainage waters is to maintain the collector-drainage network at the proper level. Therefore, it is necessary to clear drainage channels on agricultural plots to ensure design elevations. In the areas where drainage outlets are located, it is advisable to reinforce the channel bed slope, which will significantly improve drainage efficiency, stabilize silting, maintain the channel bottom at design elevations, increase reliability, and improve the conditions for operating drainage outlets.

During the operation of the channel, it is necessary to ensure unimpeded water drainage and continuous drainage action to guarantee the maintenance of groundwater levels at the required depth. The creation of water barriers in the channel will hinder its functions, and reduce the efficiency of drainage collectors that discharge into it.

To ensure the operation of the existing drainage system in the design mode, it is necessary to clean drainage outlets and collectors from silting. According to surveys, all drainage outlets in the research areas have been silted.

The restoration of engineering infrastructure on agricultural plots has improved the water-ecological state of the areas, reduced the risks of flooding, and allowed for their use in agricultural production. In 2022, sunflowers, corn for grain, and winter wheat were sown on the agricultural plots.

Observations were conducted during the vegetation period on the amount of precipitation and temperature regime (Figure 11, Figure 12).

Figure 11. Monthly precipitation sum in the vegetation period of 2022, LLC "Vasiuty"

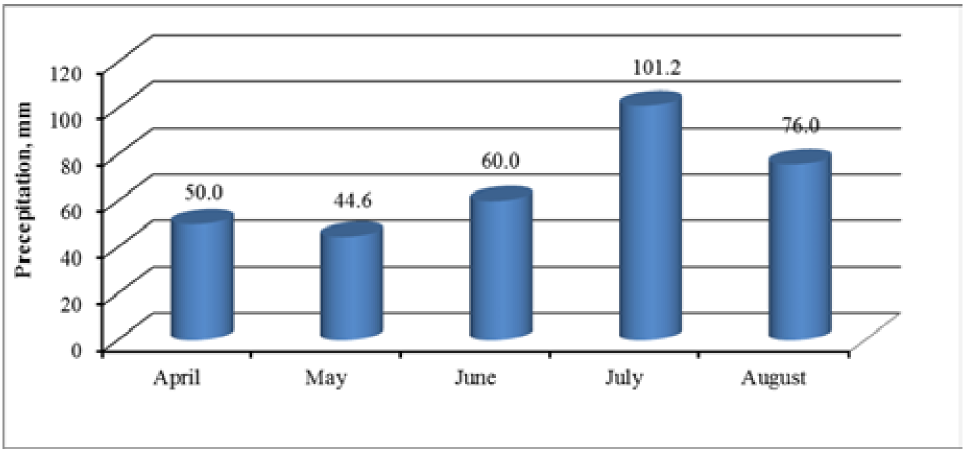
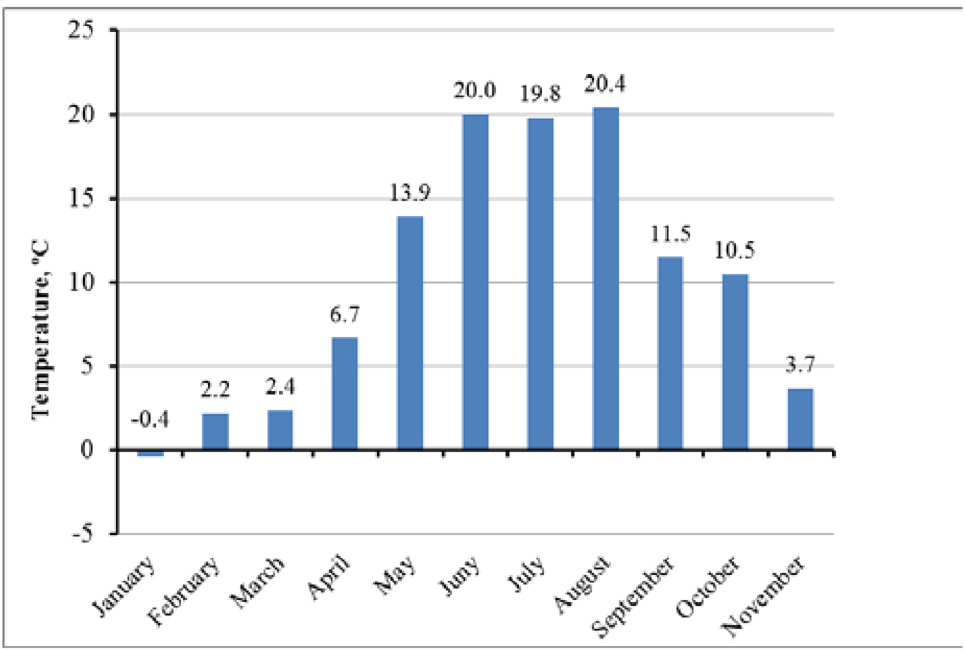


Figure 12. Average monthly air temperature in 2022, LLC "Vasiuty"



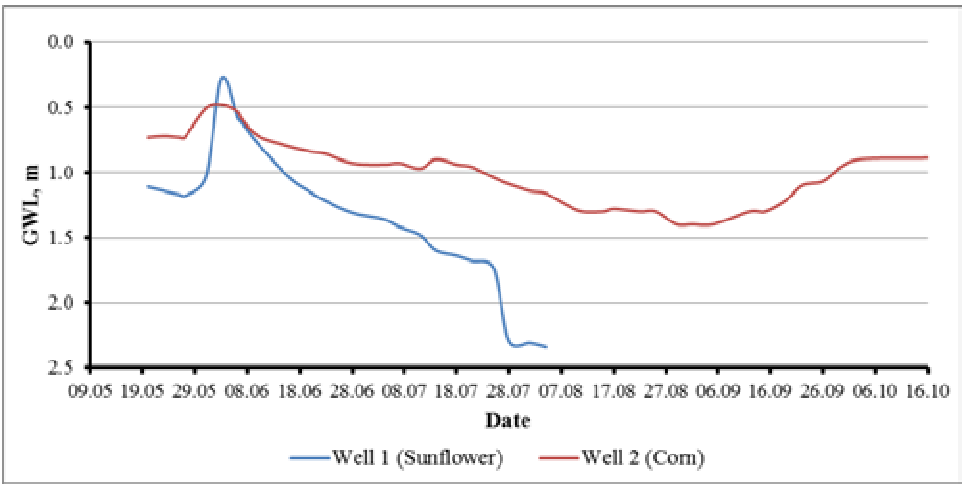
During the vegetation period, 331.8 mm of precipitation fell. The distribution of precipitation throughout the vegetation period is uneven, with the least precipitation in May (44.6 mm) and the most in July (101.2 mm).

One of the peculiarities of this year was the cold spring. The deviation of the average monthly air temperature from the long-term norm during the vegetation period is insignificant.

To monitor groundwater levels in the research areas within the LLC "Vasiuty" and "Bilinske" farms, 5 observation wells were installed. The results of observations on groundwater levels are shown in Figures 13,14.

The cultivated crops on the research plots were sunflowers and corn for grain at LLC "Vasiuty" and corn for grain and winter wheat at LLC "Bilinske."

Figure 13. Dynamics of groundwater levels in the vegetation period of 2022, LLC "Vasiuty"

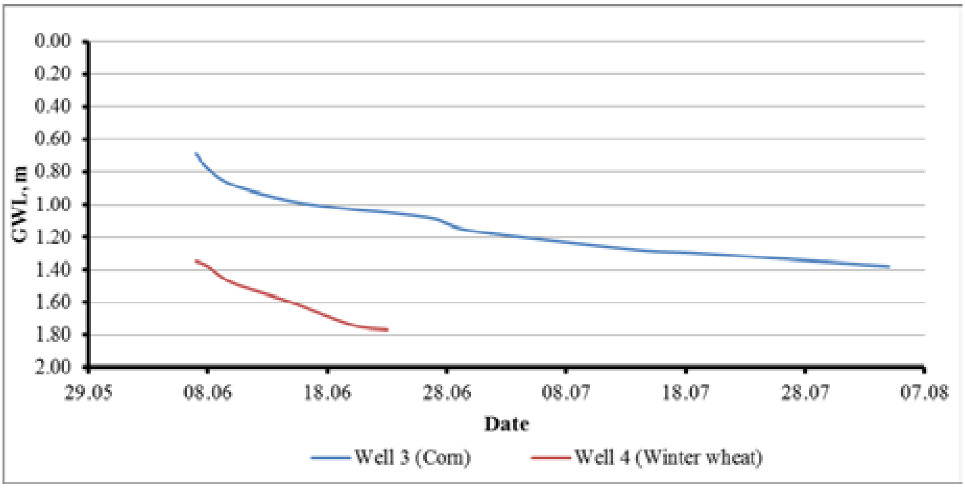


On the reclaimed lands of LLC "Vasiuty," according to the research results (well No. 1, cultivated crop - sunflower), groundwater levels during the vegetation period ranged from 0.28 to 1.1 m from the end of May to mid-June. From mid-June to early August, groundwater gradually dropped to 2.3 m without regulating the soil water regime. There was no water in the well from early August.

On the reclaimed lands of LLC "Vasiuty," according to the research results (well No. 2, cultivated crop - corn for grain), groundwater levels during the vegetation period ranged from 0.5 to

1.4 m. From late July to the end of the vegetation period, groundwater was below 1.0 m from the ground surface.

Figure 14. Dynamics of groundwater levels in the vegetation period of 2022, LLC "Bilinske"



On the reclaimed lands of LLC "Bilinske" (well No. 3, cultivated crop - corn for grain), groundwater levels were at 0.78 m at the beginning of June. Subsequently, there was a gradual decrease in groundwater levels to 1.38 m by August 4, 2022.

On the plot where winter wheat was grown (well No. 4), groundwater levels were at 1.38 m at the beginning of June, reaching 1.77 m by the end of June (June 23, 2022), with no water in the well thereafter. Therefore, no regulation of the soil water regime was carried out on the site. Maintaining moisture in the active soil layer close to optimal levels by the end of the vegetation period is possible through the accumulation of additional water reserves in the network of open channels.

During the monitoring period of groundwater dynamics, observations were made on the development stages of the cultivated crops (Table 4).

Table 4. Development stages of cultivated crops during the vegetation period of 2022

Plot	Crop	Date	Stage
Well No.1	Sunflower	07.06.2022	7-9 leaves
		14.07.2022	flowering
		11.08.2022	fruit ripening
Well No.2	Corn	07.06.2022	6-9 leaves
		14.07.2022	tasseling
		11.08.2022	milk ripeness

continued on following page

Table 4. Continued

Plot	Crop	Date	Stage
Well No.3	Corn	08.06.2022	7-9 leaves
		14.07.2022	tasseling
Well No.4	Winter wheat	08.06.2022	heading
		14.07.2022	seed ripening

The yield indicators of the researched agricultural crops on the drained lands of the "Melnytska" and "Bobrovka" systems are presented in Table 5.

Table 5. Crop yields on drained lands of the "Melnytska" and "Bobrovka" systems, 2022

Crop	Sunflower	Corn for grain	Winter wheat
Yield, t/ha	2.86	6.60	5.31

Thus, the restoration of the drainage systems "Melnytska" and "Bobrovka" to design specifications allowed for timely drainage of excess water in the spring period and regulation of the soil water regime in the early vegetation period. This improved the water-ecological situation in the research areas, minimized the risks of flooding and waterlogging of drained areas, increased the efficiency of using drained lands, ensured sustainable agriculture, and yielded stable harvests of crops.

THE DIRECTION OF FUTURE RESEARCH

Given the formation of new conditions for growing crops and changes in the use of drained lands, modern agricultural production needs to improve the design and technological solutions of drainage systems and optimal water regulation parameters on drained lands, study the possibilities of expanding their functional capacity to ensure effective water regulation on drained lands. At the same time, it is relevant to determine and implement improved maintenance and reconstruction technologies for the engineering infrastructure of drainage systems to ensure their effective operation and long-term service, as well as to introduce new water regulation technologies that take into account modern requirements for environmental safety and optimization of water resource utilization in the current climate change conditions.

Future research in these areas will not only improve existing drainage systems but also ensure sustainable and effective agricultural activities on drained lands, considering modern challenges and the preservation of natural resources.

CONCLUSIONS

Based on the research results of the design and technological parameters of the drainage systems "Melnitska" and "Bobrovka," the need for restoring the engineering infrastructure of these systems within the agricultural lands of the farms "Vasiuti" and "Bilinske" was established. The restoration works on the existing drainage systems consist of the following set of measures: cleaning drainage channels from overgrowth and siltation, cleaning and restoring drainage outlets on collectors, and relocating drainage sections that cannot be repaired. Restoring the drainage systems "Melnitska" and "Bobrovka" to design indicators allowed timely removal of excess water in the spring period and regulation of soil water regime in the initial period of vegetation, creating conditions for increasing the efficiency of agricultural production on drained lands. Based on the research on the "Melnitska" and "Bobrovka" drained lands, meteorological factors (precipitation and air temperature) and water-physical properties of soils were determined. Measurements were taken and the dynamics of groundwater levels were determined at the observation wells. For the cultivated crops, namely sunflower and maize for grain (Vasiuti farm); maize for grain, and winter wheat (Bilinske farm), research was conducted on their biometric indicators, and yield was determined. Yield indicators of the studied crops (winter wheat, maize for grain, sunflower) on drained lands were established. The yield indicators of the cultivated crops were 10-20% higher than the regional average. Maintaining moisture in the active soil layer close to optimal levels at the end of the vegetation period is possible by accumulating additional water reserves in the network of open channels. For modern agricultural production, it is important to improve the design and technological solutions of drainage systems and optimal water regulation parameters on drained lands, which enable the implementation of modern agricultural production technologies considering environmental safety requirements and efficient use of water resources in changing climate conditions.

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Chapter 16
Ensuring Food Security Through Biocontrol in Medicinal Plant Cultivation

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ABSTRACT

The chapter demonstrated the ecologically friendly way to obtain safe and high quality of medicinal herbal supplements under environmental changes. Global warming has a significant impact on medicinal plant productivity, including changes in the strategies of disease agents that compromise health and food security. Plant pathogens increase their ability to survive and reproduce intensively, resulting in strengthened plant disease severity, contamination of raw materials with toxic fungal metabolites, and yield losses. The repeated application of biologicals has proven to be effective in addressing this issue. The positive impact of microbial preparations on Calendula officinalis L. was observed in various aspects such as field seed germination, plant vegetative mass, and root system development. Treated calendula plants showed

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reduced stress during drought periods compared to the control group. Additionally, there was a significant decrease in leaf disease incidence and severity. This led to an improvement in the quality of calendula inflorescence weight and seed mass.

BACKGROUND

For centuries, medicinal plants and their bioactive compounds have been essential parts of nature, providing crucial support for the health, food security, and well-being of human societies. (Petrovska, 2012; Theodoridis et al., 2023).The demand for herbal medications, natural health products, and secondary metabolites derived from medicinal plants continues to rise that stimulate the necessity in herbal raw materials (Chen et al., 2016). The commercialization of specific medicinal plants and their medicinal properties is steering and guiding research in medicinal plant cultivation that presents opportunities to enhance the purity, quality, consistency, and bioactivity of raw materials, as well as increase biomass production (R. Cruz et al., 2022; Mofokeng et al., 2022; Rizvi et al., 2022; Sharrif Moghaddasi Mohammad, 2012; Silori & Badola, 2000; R. Zhang et al., 2021).

In Ukraine, over 45% of drugs manufactured by the chemical and pharmaceutical industry are derived from herbal raw materials. These medications are employed for the prevention and treatment of various conditions, including cardiovascular diseases, liver disorders, and gastrointestinal tract ailments (Mirzoieva et al., 2021; Sen & Samanta, 2015). Out of 2,219 species of medicinal plants utilized in human, veterinary, and traditional herbal medicine, 244 (10%) are cultivated, while the majority are wild plants. Specifically, 150 medicinal plant species are intentionally cultivated for the purpose of obtaining raw materials used for medicine and food (Basanetc, 2023).

Calendula officinalis is among those growing medicinal plants. It is known worldwide for its medicinal properties, boast inflorescences rich in various beneficial substances (Preethi et al., 2006). These include carbohydrates, amino acids, lipids, fatty acids, carotenoids, terpenoids, flavonoids, quinones, coumarins, and other components. These compounds confer a range of therapeutic effects, including wound-healing, immunostimulating, spasmogenic, antispasmodic, hepatoprotective, genotoxic, antiamylase, anti-inflammatory, anti-edematous, antibacterial, antifungal, antioxidant, antidiabetic, antiteratogenic, hypoglycemic, and gastroprotective properties (John & Jan, 2017; Köberl et al., 2013; Shahane et al., 2023). Calendula is grown in continuous cropping or monocropping systems, which have negative impacts on soil fertility, nutrient balance, and consequently slow plant growth, increase disease incidence, and reduce overall crop yield and quality (Liu et al., 2020; Tkachova, 2018; Y. Zhang et al., 2021). Additionally, the growth and quality of medicinal plants are closely linked to environmental factors and climate conditions. The global climate changes have a significant impact on plant pathogens compromising the quality, safety and properties of medicinal herbal material (Anderson et al., 2016; Kuzmych et al., 2023; R. Zhang et al., 2021). The increase in temperature and the occurrence of prolonged dry periods during plant growth phases make *C. officinalis* more vulnerable to pathogens. Conversely, calendula pathogens, under the influence of climate changes, adjust their life strategy by increasing the number of generations and intensifying their aggressiveness. Warm winters enable most pathogens stored on plant residues and in the soil to successfully survive the winter, resulting in disease outbreaks during the subsequent growing season and significant harvest losses (Evans et al., 2008; Shen et al., 2021).

Powdery mildew and *Alternaria* leaf spot are the most common diseases that occur on *C. officinalis* plants during the growing season in Ukraine (Marchenko, 2014b, 2015; Sirik, 2013). One of the agents of powdery mildew identified on calendula is *Podosphaera fusca* (Fr.) U. Braun & Shishkoff. This fungus causes early wilting and death of plant leaves and flowers by covering them with a cobweb-like layer of mycelium that later transforms into white cushions. *Alternaria calendula* Ondřej is one of the causative agents of *Alternaria* leaf spot in calendula plants. This pathogen leads to seed mold and the formation of round brown spots measuring 0.5 cm or larger on the leaves and inflorescence petals, which eventually merge together. As the infection progresses, the spots grow larger, turn brown, and develop an uneven appearance. Infected leaves eventually yellow and dry out prematurely (Marchenko, 2014a; Myronova, 2023). The primary impact of these diseases is the reduction in leaf assimilation surface due to tissue death caused by the growth of mycelium and spot development, leading to decreased plant productivity. Sirik et al. (2013) reported that disease-related losses of medicinal plants can vary from 13-40%, and during years of widespread outbreaks, it can surpass 80% (Sirik et al., 2018).

The primary method employed in agriculture to protect plants against fungal pathogens is the application of chemical pesticides. However, medicinal herbs have a distinct purpose as they are directly utilized for pharmaceutical, health-related and food purposes, leading to prohibition on the use of chemicals during their cultivation. In that case, the use of microbial biologicals emerges as an environmentally friendly approach to produce high-quality medicinal plant products without chemical residues (Ayaz et al., 2023; Sood et al., 2020; Tyśkiewicz et al., 2022).

Biologicals mainly include bacteria and fungi that, upon application, are able to induce systemic resistance in plants, promote better plant growth by improving nutrient availability, and control plant disease agents due to the production of compounds with antimicrobial and antifungal properties (Ayaz et al., 2023). A number of studies have shown that the application of microbial preparations on medical plants helps to overcome challenges related to environmental stresses such as drought, enhance soil properties and biomass yield, and disease control in continuous cropping systems (Makukha, 2020; Rizvi et al., 2022; Sood et al., 2020; G. Wang et al., 2022). The positive results in plant growth promotion and disease protection were obtained with biologicals that include bacterial species *Agrobacterium*, *Alcaligenes*, *Arthrobacter*, *Azotobacter*, *Bacillus*, *Enterobacter, Erwinia, Paenibacillus, Pseudomonas*, *Rhizobium, Serratia, Stenotrophomonas*, *Streptomyces*, and *Xanthomonas*, as well as fungi such as *Trichoderma* species (Ayaz et al., 2023; Bonaterra et al., 2022; Jeong et al., 2019). The latter are widely used biological control agents known for their multifunctionality and high effectiveness against plant pathogens (Dojima & Craker, 2016; Dutta et al., 2022; Guzmán-Guzmán et al., 2023).

The aim of this study was to assess the effects of soil and foliar treatments with biological preparations on plant growth and development, as well as their effectiveness in controlling powdery mildew (caused by *P. fusca*) and *Alternaria* leaf spot (caused by *A. calendula*) on *C. officinalis* plants grown continuously.

METHODS AND TECHNIQUES

The field experiments were conducted during the 2021, 2022 and 2023 growing seasons at the Demonstration collection field of agricultural crops of the Department of Crop Production at the National University of Life and Environmental Sciences of Ukraine, Kyiv (50.37°N, 30.50°E). The experimental design was a randomized complete block with a split-plot consisted of 16 variants. There were three replicate blocks, giving a total of 48 experimental units (plots) in each year. Plots (experimental units) had size 4 m^2 consisting of 4 rows spaced 25 cm apart. A total 50 plants were sowed on each plot. Calendula had been cultivated on the research plot using standard agronomic practices for the two years preceding. In the present study the variety of calendula utilized was Radio.

The present study employed biological Graundfix®, Phytocid®, Fitohelp®, Ecostern®Classic and Mycohelp® produced by BTU-CENTER (Ladyzhyn, Vinnytsia region, Ukraine). The formulation of Graundfix®, Phytocid®, Fitohelp® based on different combinations of bacterial strains from genera *Bacillus, Paenibacillus, Azotobacter, Enterobacter, Enterococcus* and *Agrobacterium*. While Ecostern®Classic and Mycohelp® include as bacterial as well *Trichoderma* strains.

The treatment program included the separate application of Ecostern®Classic at a rate of 1.5 l/ha, Mycohelp® at 1.5 l/ha, and Groundfix® at 3.0 l/ha in October of each year. During the growing season, the calendula plants were sprayed twice: first at the seedling stage and then at the blooming stage with Phytocid® at 1.5 l/ha, Fitohelp® at 1.5 l/ha, or Mycohelp® at 1.5 l/ha.

Calendula plants were collected in September each year to assess plants development, disease incidence, and severity, 1000 inflorescence weight and 1000 seed mass. The plant parameters such as height and root length were measured using a ruler, and the data were recorded in centimeters. Before measurement, the roots were delicately washed to remove soil using a gentle stream of water and then dried using filter paper. The calendula inflorescences and seeds were air-dried for 14 days, and their weight was recorded in grams.

The increase of plant organ parameters compared to control was estimating using a formula (Hilty et al., 2021):

$$\%\ increase = 100 \times \left(\frac{T - C}{C}\right) \tag{1}$$

where T– trial meaning, C – control meaning.

Disease incidence was visually assessed at plant maturity by determining the presence or absence of disease. The percentage of plant disease incidence (I) was calculated using a formula (Madden & Hughes, 1999):

$$I = \frac{n \times 100}{N} \tag{2}$$

where n – the number of plant units that are (visibly) diseased, N – the total number assessed plant units.

At plant maturity, disease severity was assessed by visually scoring symptoms. Using intensity symptoms of powdery mildew on individual plants was rated on a scale developed by O.M. Sirik for evaluation of medicinal plant resistance to diseases (Markov et al., 2023). The scale is from 9 to 1, i.e. 9 – disease symptoms are absent, 0%, 8 – a weak cobweb-like layer on the leaves, up to 5%, 7 – on the leaves, there are small individual cushions and a cobweb-like layer, up to 10%, 6 – the lower third of the plant is affected to a mild degree, up to 15%, 5 – the plant is affected from the base to the middle, the lowest leaves are severely affected, higher are moderately and weakly, 4 – the plant is affected up to flowering: the leaves of the lower third are significantly affected, up to 75-90%, with the lower leaves dying off, 3 – the plant is affected before flowering: the leaves of the lower third are dying off up to 100%, the leaves of the middle tier are noticeably or heavily affected – 60-70%, 2 – the entire plant is affected, with leaves severely affected, resulting in the death of plants in the lower and middle tiers - 100%, infection on the inflorescence, 1 – the entire plant is affected, the leaves are very wilted, their death is observed (Markov et al., 2023).

Using disease scale levels from 9 to 1 classes according to infected plants by leaf spot, i.e. 9 – disease symptoms are absent (0%), 8 – lower leaves turn yellow, have small spots covering up to 5% of the leaf surface, 7 – lower leaves turn yellow, have small spots covering up to 10% of the leaf surface, 6 – lower leaves turn yellow, have small spots covering up to 15% of the leaf surface, 5 – the plant is affected from the base to the middle, with the lower leaves showing damage ranging from 50-80%, while the upper leaves are affected by 25%, 4 – the plant is affected before flowering. The leaves of the lower third are significantly affected, up to 90%, with the lower leaves dying off. The upper leaves are affected up to 50%, 3 – the plant is affected before flowering. The lower leaves are completely affected, up to 100%, while the middle tier leaves are noticeably or heavily affected, around 60-70%, 2 – the entire plant is affected, with leaves showing up to 100% damage. Plant death is observed in the lower and middle canopy. Infection is also present on the inflorescence, 1 – the entire plant is affected, the leaves are very wilted, their death is observed (Markov et al., 2023).

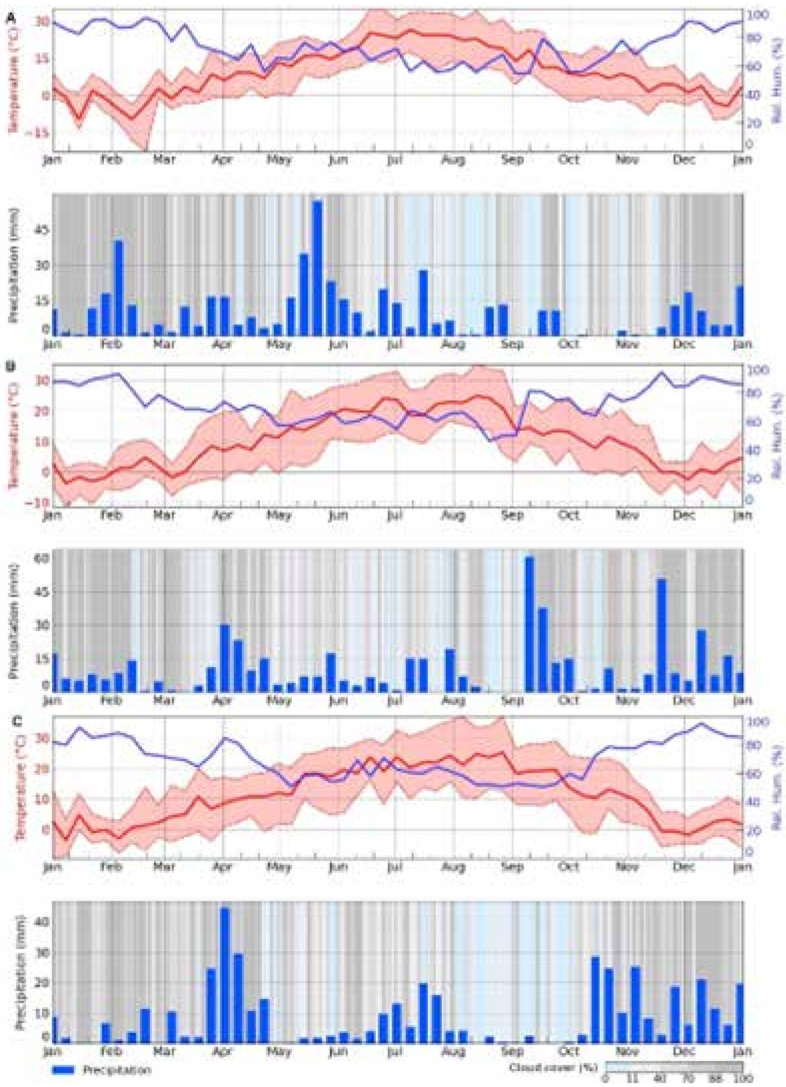
The percentage of plant disease severity (S) was estimated using the formula (Chiang et al., 2017):

$$S = \frac{\sum(a \times b) \times 100}{H \times k} \quad (3)$$

where a – the number of plant units that are (visibly) diseased, b – the rating score of disease intensity; H – the total number assessed plant units; k – the maximal rating score of disease intensity.

The graphical models of temperature and precipitation data for Kyiv (Ukraine) from 2021 to 2023 were obtained from Meteoblue® (Meteoblue AG, Basel, Switzerland) (Figure 1).

Figure 1. The graphical models of weather data in the area of trials with biological preparations for the years 2021 (A), 2022 (B), and 2023 (C)



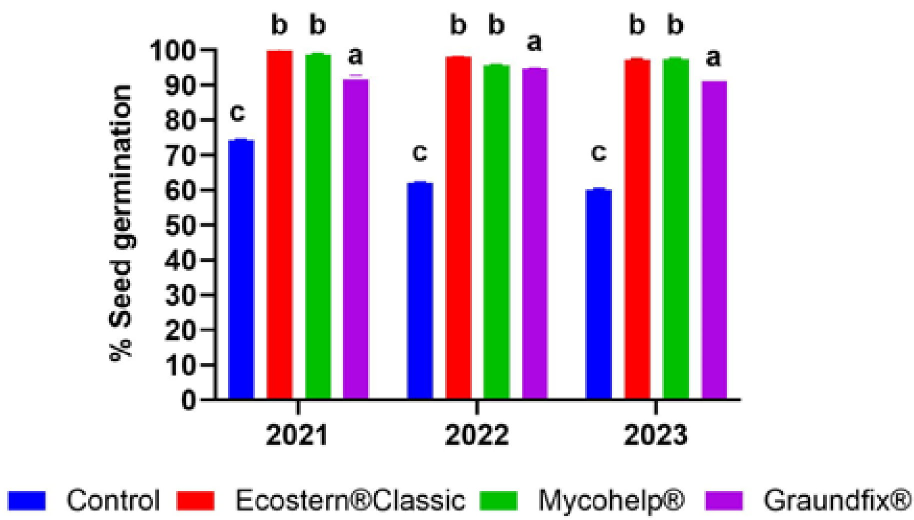
The graphs display temperature (red line) and relative humidity (blue line) for the first 15 days, as well as the minimum, maximum, and mean temperature for longer time intervals. Additionally, precipitation amount is represented by blue bars, clouds by a grey background, and sunshine by a light blue background. The darker the grey background, the denser the cloud cover.

The statistical analyses were performed using Microsoft Office Excel 2010 (Microsoft Co., Redmond, WA, USA) and GraphPad Prism version 10.3.0.(507) (GraphPad Software, Boston, MA, USA). Means of the three replicates for % seed germination, plant height, % height increase, root length and % root length increase, % incidence, % severity, 1000 inflorescence weight, % 1000 inflorescence weight increase, 1000 seed mass, and % 1000 seed mass increase were calculated for each entry year, and figures are based on these means ± the standard error of the mean (SEM). One-way analysis of variation (ANOVA) was performed using GraphPad Prism version 10.1.0. Significant differences between the control group and each other group were determined using Tukey's multiple comparisons test ($p \leq 0.05$).

RESULTS AND DISCUSSION

The influence of autumn soil application of biologicals at the seedling stage was assessed by analyzing the percentage of field seed germination. All microbial preparations demonstrated a higher *C. officinalis* seed germination rate, ranging from 92.9% to 98.4%, compared to the control plots, which had an average germination rate of 65.5% (Figure 2).

Figure 2 The impact of autumn soil application of biological preparations the growth of C. officinalis seedlings over studying years

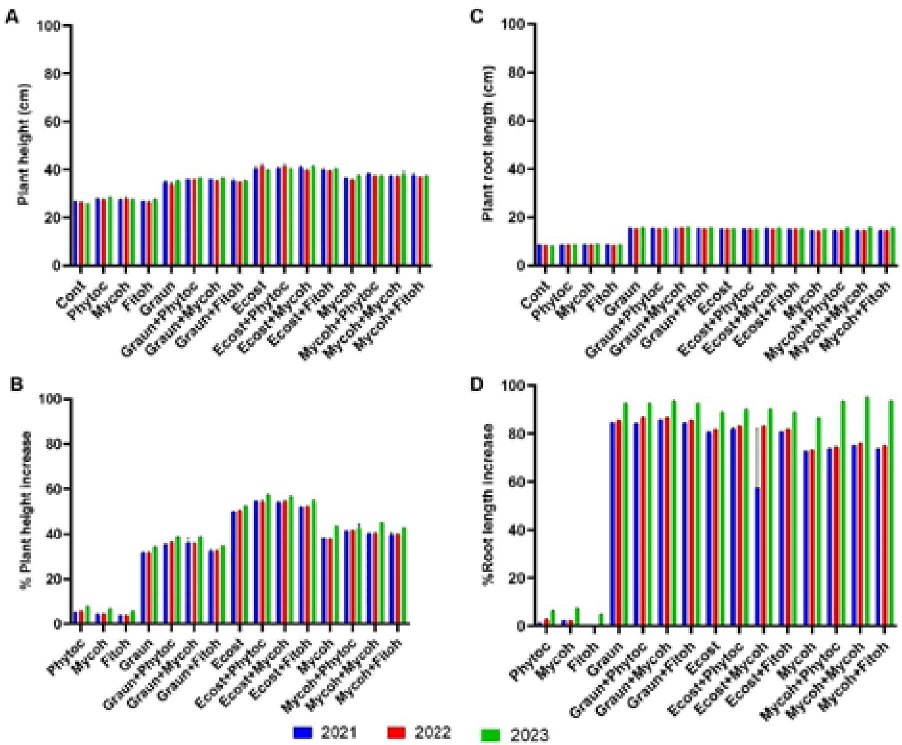


Bar graphs represent mean % seed germination ± SEM (n=3). Different letters indicate significant differences between the control and from each other based on Tukey's multiple comparisons test ($p < 0.05$).

It is worth noting that the seed germination rate of the control plants has decreased over the years. It started at 74.3% in the first year and dropped to 60.2% by the third year due to the ongoing cultivation of calendula plants in monoculture. The application of biologicals Ecostern® Classic and Mycohelp®, which includes *Trichoderma* strains, resulted in a high percentage of calendula seedlings, with an average of 98.4% and 97.3%, respectively, under the same field conditions. Groundfix® supported seed germination at a slightly lower rate of 92.9% during the observation years. The present data show that autumn soil application of microbial preparations can promote initial plant growth as effectively as seed pretreatment described in other studies (Cardarelli et al., 2022; F. Cruz et al., 2024; Kthiri et al., 2020; Kuzmenko, 2003; Miri et al., 2013).

To better understand the effects and variations among plants in soils with and without biologicals, and the influence of additional foliar treatments, we measured plant height and root length. The application of biological preparations has had a positive effect on plant growth and development (Figure 3A, 3C). Overall, microbial preparations enhanced the vegetative mass development of *C. officinalis*, resulting in an average increase of 3.8% to 57.5% in plant height and 1.2% to 95.1% in root length compared to plants grown on control plots (Figure 3B, 3D). The soil treatment with Ecostern®Classic and its combined applications with foliar fungicides Phytocid®, Mycohelp®, and Fitocid® resulted in the highest increase in plant height, averaging 50.8%, 55.7%, 55.0%, and 53.1%, respectively. In contrast, when biologicals Phytocid®, Mycohelp®, and Fitocid® were used alone during the vegetation period, the increase in calendula plants was the lowest on average at 6.2%, 5.3%, and 4.4%, respectively. It is worth noting that the alone soil application of Graundfix®, Ecostern®Classic, and Mycohelp® and their combination with foliar treatment of plants with Phytocid®, Mycohelp®, and Fitocid® stimulated the growth and branching of the root system (Figure 3C, 3D). When used alone, the application of Graundfix® and its combinations with plant treatments such as Phytocid®, Mycohelp®, and Fitocid® led to the highest average increase in the root length of calendula by 87.9% (Figure 3D). These results support the findings of other studies that soil inoculation with biologicals contributes to better above-ground phytomass and root development (F. Cruz et al., 2024; K. et al., 2021; Kuzmenko, 2003) as well as drought tolerance observed during the years of the experiment (Azizi et al., 2022; G. Wang et al., 2022). In contrast, a minimal increase in root length averaging at a rate of 1.6% to 4.1% was observed when using foliar fungicide alone.

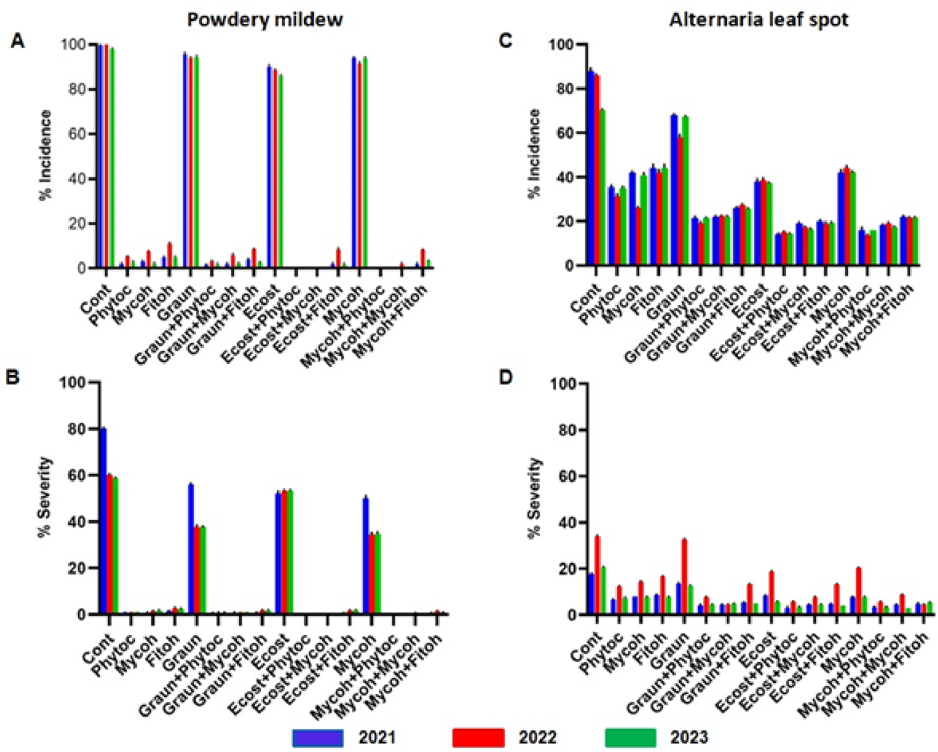
Figure 3. The effect of application of microbial preparations on the development of C. officinalis as measured by plant height (A), % height increase (B), root length (C) and %) andength increase (D)



The Graundfix®, Ecostern®Classic, and Mycohelp® were applied in autumn for soil treatment, while the fungicides Phytocid®, Mycohelp®, and Fitohelp® were used for foliar treatment either alone or in combination. No preparations were applied on control plots. Bar graphs represent mean plant height, % height increase, root length or % root length increase ± SEM (*n*=3).

The efficacy of microbial preparations was evaluated for controlling powdery mildew (caused by *P. fusca*) and *Alternaria* leaf spot (caused by *A. calendula*) in monocropping cultivation of *C. officinalis*. The incidence and severity of powdery mildew and *Alternaria* leaf spot were determined by evaluating the presence and type of lesions (Figure 4). The plants most affected by powdery mildew were observed in the control plot, with an incidence rate of 100.0% and severity ranging from 58.6% to 80.0% on average, depending on the observation year (Figure 4A, 4B). Control plants infected with *Alternaria* leaf spot showed a similar situation, with an incidence rate ranging from 71.1% to 88.4% and severity averaging between 17.7% and 34.4% (Figure 4C, 4D). The use of microbial preparations had different impacts on diseases development. The most effective approach was a combination of treating the soil in autumn and applying the preparation to the foliage twice during the growth of calendula plants. This approach showed the strongest inhibition against both disease agents, resulting in lower incidence and severity of the diseases (Figure 4).

Figure 4. The effect of the application of microbial preparations on the development of powdery mildew (left panel) and Alternaria leaf spot (right panel) on plants of C. officinalis was measured by % incidence (A, C) and % severity (B, D)



The products Graundfix®, Ecostern®Classic, and Mycohelp® were applied in autumn for soil treatment, while the fungicides Phytocid®, Mycohelp®, and Fitohelp® were used for foliar treatment either alone or in combination. No preparations were applied on control plots. Bar graphs represent mean % incidence or % severity ± SEM (*n*=3).

Notably, powdery mildew of calendula started to appear during the flowering phase. However, it was effectively controlled and not detected on the plants when Ecostern®Classic was applied in autumn, followed by Phytocid® or Mycohelp® during the growing season. Similarly, a combination of Mycohelp® in the fall and Phytocid® at foliar treatment also suppressed the powdery mildew (Figure 4A, 4B). Other combinations involving autumn application along with treatment on vegetative plants significantly reduced the incidence of powdery mildew to a range of 2.0% to 8.3% and severity to 0.3-1.7%, depending on the observation year.

The effectiveness of combinations of biologicals against *A. calendula* was also significant, although less compared to *P. fusca*. The combination of soil preparations Ecostern® Classic or Mycohelp® with Phytocid® resulted in the lowest incidence and severity of *Alternaria* leaf spot on calendula plants (Figure 4C, 4D). The average disease incidence was 14.0% and 15.3%, respectively, while the severity was 3.7% and 4.0% during the observation period. In general, the incidence of the disease detected in other combined applications ranged from an average of 16.6% to 27.7%, with a severity level of 2.5% to 13.3% depending on the observation year.

The foliar treatment of plants with Phytocid®, Mycohelp®, or Fitohelp® resulted in a noticeable reduction in the incidence and severity of both diseases. It is worth noting that the agent causing powdery mildew was more susceptible to biologicals than *Alternaria* leaf spot. The average incidence of powdery mildew was 3.5% with Phytocid®, 4.5% with Mycohelp®, and 6.8% with Fitohelp®, with severity rates of 0.9%, 1.3%, and 1.8% respectively. In contrast, *Alternaria* leaf spot had an incidence of 33.4% with Phytocid®, 35.9% with Mycohelp®, and 43.3% with Fitohelp®, with disease development values of 8.8%, 10.1%, and 11.0% respectively (Figure 4A, 4B).

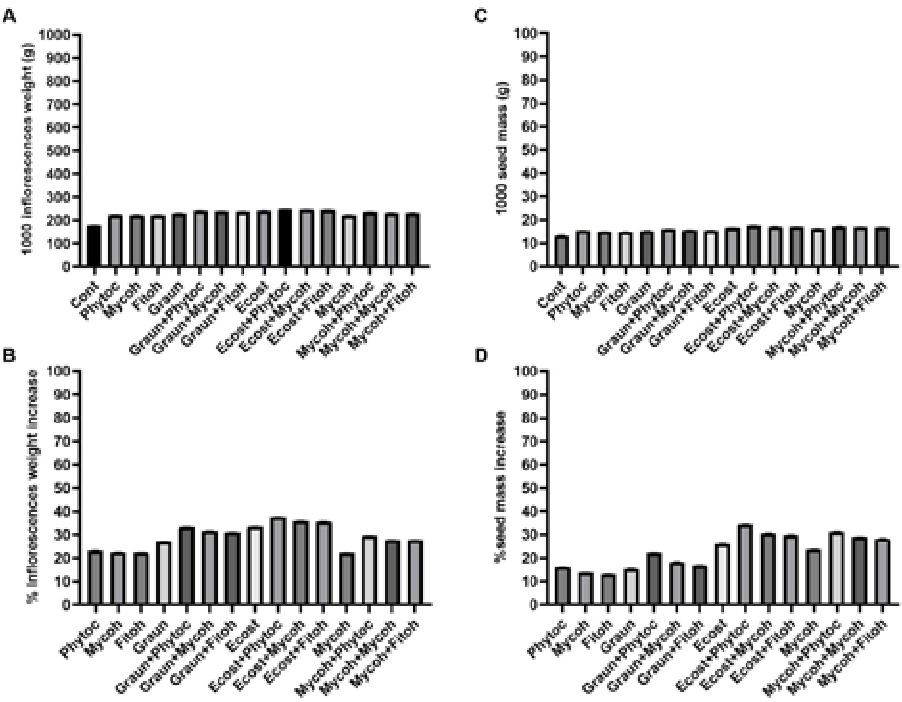
Plants from plots treated with soil preparations Graundfix®, Ecostern®Classic, or Mycohelp® alone did not show a significant reduction in the incidence of powdery mildew, with average rates of 94.5%, 88.0%, and 93.0% respectively. However, disease severity decreased compared to control plants, with average values of 43.7% with Graundfix®, 52.9% with Ecostern®Classic, and 39.6% with Mycohelp®. In contrast, Graundfix®, Ecostern®Classic, and Mycohelp® alone applied to the soil were more effective against *Alternaria* leaf spot. The incidence of the disease was reduced to an average of 64.4%, 38.2%, and 42.6%, respectively. These treatments significantly decreased the severity of the disease by an average of 19.8% with Graundfix®, 10.9% with Ecostern®Classic, and 12.2% with Mycohelp® (Figure 4C, 4D). It is important to mention that *Alternaria* leaf spot appeared at different times on calendula plants in the control and experimental areas. In the control plot, plants showed signs of *Alternaria* infection during the seedling phase. While in areas where microbiological preparations were applied to the soil, the damage occurred much later. This could be attributed to the enhancement of the plant's defense, which activates induced systemic resistance, including against pathogens. This phenomenon has been observed in various studies involving the use of microbial preparations in the plant cultivation (Mehmood et al., 2023; G. Wang et al., 2022).

In our study, preparations containing *Bacillus* spp. and *Trichoderma* spp. have shown effectiveness against powdery mildew and *Alternaria* leaf spot. These results are consistent with previous studies that have also demonstrated their strong antagonistic activity against these plant diseases (Ahmed et al., 2024; Kim et al., 2013; Marchande et al., 2020; Rakesh Roshan & Kartik Chandra, 2022).

Weather conditions are crucial for plant growth and disease spread. Microbial preparations studied had a positive effect on plant height and root development in trial years. However, weather conditions were found to be important for the effectiveness of biological controls against diseases during observation periods. During the drought periods from June to August 2021, characterized by high temperatures and sudden weather changes, the calendula plants in the control plots wilted, making them more vulnerable to powdery mildew and *Alternaria* leaf spot compared to plants in plots treated with microbial preparations (Figure 1A, Figure 4). The combination of soil treatment with leaf treatment, as well as foliar treatment alone, significantly reduced the severity of both diseases. It is worth noting that applying biologicals only to the soil was less effective overall compared to other treatment options. However, soil treatment had a greater impact on the appearance and severity of leaf spot than on powdery mildew. This difference may be due to the better effectiveness of soil microbial preparations during the initial plant growth, such as the seedling stage when leaf spot disease appeared, while powdery mildew developed much later during the flowering stage. In 2022, the growing season was the driest, impacting the performance of biologicals compared to years with milder drought conditions (Figure 1B). Notably, better control of diseases was observed with two foliar treatments and their combination with autumn soil treatments, rather than soil treatment alone. The drought conditions greatly affected the efficacy of soil microbe preparations against *Alternaria* leaf spot severity, which was the highest compared to other years (Figure 4D). In 2023, the growing season experienced less dryness and more humidity compared to the two preceding years (Figure 1C). This weather conditions enhanced the effectiveness of microbial preparations in controlling powdery mildew and leaf spot on calendula. The combination of soil treatment and foliar application demonstrated the most significant decrease in the occurrence and intensity of both diseases. Wang et al. (2021) also discovered that repeated treatment is a promising option for maintaining the beneficial effects of microbial preparations (Z. Wang et al., 2021).

The impact of biological preparations on calendula was assessed using quality yield parameters such as the mass of 1000 inflorescences and mass of 1000 seeds. The use of biologicals, either alone or in combinations, led to positive outcomes in terms of achieving a harvest of high-quality raw materials and seeds compared to the control (Figure 5).

Figure 5. The impact of the application of microbial preparations on the quality yield parameters of C. officinalis plants was measured by 1000 inflorescence weight (A), % inflorescence weight increase (B), 1000 seed mass (C), and % seed mass increase (D)



Graundfix®, Ecostern®classic, and Mycohelp® were applied in autumn for soil treatment, while the fungicides Phytocid®, Mycohelp®, and Fitohelp® were used for foliar treatment either alone or in combination. No preparations were applied on control plots. Bar graphs represent mean1000 inflorescence weight, % inflorescence weight increase, 1000 seed mass or % seed mass increase ± SEM (*n*=9).

The greatest increase in inflorescence weight was seen when using Ecostern®-Classic alone or in combination with Phytocid®, Mycohelp®, or Fitohelp®. After three years of observation, the average weights were 239.3 g, 247.1 g, 243.9 g, and 243.4 g, respectively, compared to 179.6 g in the control plants (Figure 5A). This represents an increase in inflorescence weight of 33.3%, 37.6%, 35.8%, and

35.5% in the same order (Figure 5B). The mass of 1000 inflorescences increased significantly when Graundfix® was used in combination with foliar preparations Phytocid®, Mycohelp®, or Fitohelp®. The average weight increases were 33.2%, 31.5%, and 31.0%, respectively. The smallest increase in florescence mass was seen with the soil application of Mycohelp® alone and with the foliar treatments of Phytocid®, Mycohelp®, or Fitohelp® alone. The average increase ranged from 22.1% to 23.1% (Figure 5B). These results support the findings of other studies that the application of biofertilizer based on beneficial microorganisms had a positive impact on flower formation by *C. officinalis* (Nada et al., 2024; Sharma et al., 2017; Zaferanchi et al., 2019).

The increase in mass of 1000 calendula flowers was reflected in the mass of 1000 seeds in plants treated with Ecostern®Classic alone and in combination with Phytocid®, Mycohelp®, or Fitohelp® (Figure 5C). After three years, the average weights of 1000 seeds were 16.5 g, 17.6 g, 17.1 g, and 17.0 g, respectively, compared to 13.1 g in the control plants. This represents an increase in seed weight of 25.9%, 34.3%, 30.1%, and 29.7% in the same order (Figure 5D). Unlike the weight of the flowers, the use of Graundfix® resulted in a small increase in the weight of 1000 seeds, averaging from 15.2% to 22.1%. In contrast, the application of Mycohelp® alone or in combination with Phytocid®, Mycohelp®, or Fitohelp® led to greater increases in the weight of seeds, with improvements of 23.6%, 31.2%, 28.9%, and 28.2%, respectively. The smallest increase in seed weight was observed when using foliar fungicides Phytocid®, Mycohelp®, or Fitohelp® alone, with an average increase ranging from 13.0% to 16.0% (Figure 5D). Healthy plants typically yield heavier seeds because they contain a higher concentration of essential nutrients crucial for plant growth. Calendula seeds are a valuable source of fatty acids, such as calendic acid, making them a valuable raw material (Dulf et al., 2013).

Taken together, the field application of microbial preparations had a positive impact on calendula plant growth and development. In this study, we observed a plant growth-promotion effect and an increase in germination and phytomass, as well as better root development, which were likely supported by improving soil health and fertility due to the activity of beneficial microbes applied to the soil. It is worth noting the positive trend of a decrease in the incidence and severity of diseases in treated calendula plants, regardless of the level of drought stress. This can be explained by the stimulation of induced systemic resistance, which is another possible positive microbial mode of action. Finally, plant treatment with microbial preparations enhanced the quality of raw materials of *C. officinalis* by increasing flower weight and seed mass. Future research comparing the fertility of control soils to those treated with biologicals, as well as evaluating the changes in native microbial and pathogenic populations, could provide insights into the differences in calendula plant yield and raw material quality during continuous cultivation.

CONCLUSION

Consistent with previous studies, microbial inoculations play an important role in reducing the environmental footprint of agricultural systems by supporting sustainable practices and addressing climate change. In this study, a combination of soil and foliar treatments with biologicals proved to be highly effective in enhancing the productivity of *C. officinalis* and controlling the growth of pathogens. The resulting high-quality inflorescence and seeds contain valuable compounds that can be used in pharmaceutical applications to support human health and food security through the prevention of foodborne illnesses, and extend the shelf life of food products without the need for chemical preservatives. We believe that conducting field trials to systematically test the effectiveness of microbial inoculants and gaining knowledge on microbe invasion are crucial steps in the development of biocontrol methods to cultivate medicinal plants and improve current disease management strategies in agricultural ecosystems. This will help tackle climate change challenges and ensure food security.

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Chapter 17
Plant Extracts as Antimicrobial Agents Against Fungal Food Contamination

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ABSTRACT

Plants are known as a source of secondary metabolites and have been used as antimicrobials in human health, animal health and crop protection. With the development of organic agriculture, new methods have been developed to innovate with plant extracts as herbicides, insecticides and fungicides in agriculture. The aim of this chapter is to review the literature on potential plants that could be used to develop new natural fungicides to combat foodborne fungal contamination. It will describe of the most cited plants as antifungal in agriculture, methods extraction and antifungal tests. Then, it will present newly discovered compounds from plants as effective antimicrobial agents in food manufacturing.

1. INTRODUCTION

Pathogenic fungi are involved in the contamination of humans, crops and livestock (FAO, n.d.; Moumni et al., 2021). Microorganisms are present in food and are the major cause of food spoilage and degradation, including changes in organoleptic properties, spoilage, and loss of flavor and odor emission (Abdel-Khalek et al., 2022). Fungi in sporulation are highly resistant to food processing and other treatments using heat application or pasteurization (Zhou et al., 2023). Certain fungal

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contaminants including those of the genera Aspergillus, Fusarium and Penicillium are capable of producing mycotoxins, which are toxic compounds to consumers (humans and animals). These mycotogenic fungi can be found in crops during pre and post-harvest. According to Food and Agriculture Organization (FAO), mycotoxins are responsible for 25% of crop contamination and can occur at all stages of food manufacturing: transportation, processing, and storage (FAO, n.d.). Contaminated food can cause economic losses due to agricultural contaminants. Consumption of food contaminated by fungi may be responsible for liver and kidney tumors, autoimmune diseases, free radical production, carcinogenic and mutagenic effects (Phuong et al., 2023; Zhou et al., 2021).

To reduce fungal contamination in modern agriculture, synthetic chemicals are commonly used. However, misuse and overuse of these compounds can have adverse effects on both human and environmental health (Basaglia et al., 2021; Xiong et al., 2020).

In addition, the development of the food industry has led to the availability of many ready-to-eat food products in the market. These foods often contain new chemical additives, including antimicrobials, to preserve their sensory properties such as color, flavor, texture and freshness during storage. However, these additives can also alter the consumer's microbiome and lead to adverse health effects such as colorectal cancer, hyperglycemia and high blood pressure (Mohamed, Allagui, & Gianfranco, 2024; Wani et al., 2021). The modern consumer is increasingly aware of the potential risks associated with synthetic chemicals in food production and preservation. As a result, there is a growing demand of natural additives and extended shelf life in ready-to-eat foods. As a result, the food industry has developed new approaches to crop protection and food preservation against fungal contamination based on indigenous ancestral strategies. Traditionally, preservatives such as salt, vinegar or sugar have been used to limit food contamination by fungi and to improve food shelf life. These products are capable of inhibiting bacterial and fungal growth on foods and their derivatives. Plants and mushrooms are potential sources of secondary metabolites that protect against insect or microbial contamination (Ingle et al., 2017; Mohamed, Allagui, & Gianfranco, 2024). These compounds could be natural alternatives to improve food shelf life and crop protection (Azwanida, 2015).

This chapter reviews the literature on potential plants that could be used to develop new natural fungicides to control foodborne fungal contamination. It describes some most cited plants as antifungal in agriculture, methods of extraction and antifungal tests.

2. TRADITIONAL PRACTICES FOR FOOD PROTECTION

Traditional agriculture has been sustained for centuries, largely via the adoption of eco-friendly practices. Indigenous expertise systems have ensured the manufacturing of plant and animal foods even as promoting environmental safety for human beings and other organisms. Local communities have developed various practices for crop protection (Pandey & Tripathi, 2014). They adapted farming practices to the local environment and contributed to make sure biodiversity protection (Doughari, 2012). They have developed several crop protection techniques that improved production and transmitted from generation to generation. Ancestral knowledge was used to protect seeds and other planting materials from pests in storage and in the field. They adopted traditional methods of seed selection, storage, and protection of food grains using traditional containers. To control pest damage, traditional farmers have widely used *Azadirachta indica* (Neem) and *Nicotiana tabacum* (tobacco) as pesticidal plants (Naghdi et al., 2008; Sasidharan et al., 2011; Zhao et al., 2013). Many wild plants possess crop and food protection properties, and some are part of the rich indigenous knowledge in certain parts of Africa and other regions of the world. However, some of these plants are less well known than others. Table I below provides an overview of the properties of the most documented species used for crop protection. The material plant materials used by indigenous people are safe, biodegradable, less persistent, non-toxic and readily available in their environment. This has led to the adoption of crop production that suits their preferences and abilities allowing them to produce crops during specific seasons necessary for their livelihoods. Below are some of the traditional practices followed by local farmers from generation to generation (Mello et al., 2003; Siani et al., 2000).

3. EXTRACTION METHODS AND ANTIFUNGAL TESTING SUSCEPTIBILITY

3.1. Plant Extraction Methods

3.1.1. Extraction Solvents

Extraction involves the separation of the active ingredients of plant tissues from the inert components using selective solvents in standard extraction procedures. Consequently, products obtained from plants are relatively impure liquids, semi-solids or powders after evaporation or lyophilization. These include classes of preparations known as decoctions, infusions, liquid extracts, tinctures, and dry powdered extracts. The resulting extract may be ready for use as an active ingredient or for incorporation into any dosage form such as tablets or capsules (Azwanida, 2015; Azwanida, 2015; Ingle et al., 2017). Classically, three categories of solvents have been used for plant extractions based on solvents polarity:

- Unpolar solvents (polarity less than 0.2): *n*-Hexane, cyclohexane, diethyl ether;
- Semipolar solvents (Polarity between 0.2 and 0.4): Ethyl acetate, chloroform, dichloromethane, acetone,
- Polar solvents (Polarity superior to 0.4): n-butanol, Ethanol, methanol and water.

3.1.2. Extraction Methods

- **Maceration:** Plant material such as organs or powder is placed in a closed container with the solvent and allowed to stand at room temperature for a period of at least 3 days with frequent stirring until the soluble matter has dissolved. The mixture is then strained, the residue is pressed, and the combined liquids are clarified by filtration or decantation after standing (Azwanida, 2015; Doughari, 2012; Pandey & Tripathi, 2014).
- **Infusion:** Fresh infusions are prepared by briefly macerating the raw drug in hot or cold water. The preparation was soaked, and stored for a short time. This method is suitable for extracting easily soluble bioactive components. It is also a good way to prepare fresh extracts before use. The solvent to sample ratio is typically 4:1 or 16:1 depending on the application (Azwanida, 2015; Naghdi et al., 2008; Sasidharan et al., 2011).
- **Decoction:** The raw material is boiled in a certain amount of water for a certain amount of time, then cooled and filtered. This process is suitable for extracting water-soluble and heat-stable constituents. The process is lasted for a short period time, usually about 15 min. The ratio of solvent to crude drug is usually 4:1 or 16:1 (Azwanida, 2015; Ingle et al., 2017).

Table 1. List of plants traditionally used as crop protection (Isaac & Merlin, 2017; Kumar et al., 2011)

Scientific names	Families	Pests managed	Plant part used
Azadirachta indica A Juss.	Meliaceae	Sucking pest, defoliators and stored grain, pests	Leaf, bark, seed, kernel
Nicotiana tabacum L.	Solanaceae	Defoliators	Leaf, stem

continued on following page

Table 1. Continued

Scientific names	Families	Pests managed	Plant part used
Millettia pinnata L.	Fabceae	Sucking pest and defoliators	Leaf, seeds
Calotropis gigantea (L.) Dryand	Apocynaceae	Stored grain, pests	Leaf
Acorus calamus L.	Araceae	Stored grain, pests	Rhizome
Annona squamosa L.	Annonaceae	Stored grain, pests	Leaf, seeds
Vitex negundo L.	Lamiaceae	Stored grain, pests	Leaf, seeds
Allium sativum L.	Liliaceae	Defoliators and, sucking pests	Pods
Justica adhatoda L.	Acanthacea	Leaf scrappers	Leaf
Nerium oleander L.	Apocynaceae	Defoliators	Leaf and stem
Tanacetum vulgare L.	Asteraceae	Defoliators	Flowers
Tagetes minuta L.	Asteraceae	Defoliators	Flowers
Piper nigrum L.	Piperaceae	Defoliators	Leaf
Capsicum annum L.	Solanaceae	Pulsebeetle	Fruit
Acacia nilotica (L.) Wild. ex Delile	Fabaceae	Stem borer and leaf feeders	Leaves, seed, bark
Paspalum scrobiculatum L.	Poaceae	Leaf hoppers in rice	Plant
Bersama abyssinica Fres.	Melianthaceae	Defoliators	Leaf, bark
Ricinus communis L.	Euphorbiaceae	Stored grain, pests	seeds
Cymbopogon citratus	Poaceae	Sucking pests and stored grain	leaves
Lippia alba Britton & P. wilson	Verbenaceae	Stored grains	leaves
Eucalyptus piperita Sm.	Myrtaceae	Grains stored	Seeds
Ocimum basilicum	Lamiaceae	Grains stored, pests	Leaves

- **Percolation** is the most commonly used method for extracting active constituents in the preparation of tinctures and liquid extracts. A percolator (a narrow conical vessel open at both ends) is the apparatus used for this type of extraction. The solid ingredients are moistened in an appropriate amount according to the prescribed menstruation and left for about 4 hours in a tightly closed container, after which the mass is packed and the top of the filter is closed. Additional ruler is added to form a flat layer on top of the mass and the mixture is left to soak in a sealed filter for 24 hours. The filter outlet is then opened and the liquid inside allowed to drip slowly. Additional quantities are added as needed until the permeation is approximately 3/4 of the required volume of the finished product. The pulp is then pressed, and the pressed liquid is added to permeate. A sufficient amount of menstruum is added to create the required volume and the mixed liquid is clarified by filtration or by allowing to stand and then decanting (Doughari, 2012; Pandey & Tripathi, 2014).

- **Hot continuous extraction (Soxhlet)** is a method in which the finely ground crude drug is placed in a porous bag or "tube" made of durable filter paper which is placed in the chamber of the Soxhlet apparatus. The extraction solvent is heated and its vapor condenses in a condenser. The concentrated extract flows into a tube containing the crude drug and contact extract. The advantage of this method over previously described methods is that large amounts of drug can be extracted with much smaller amounts of solvent. This results huge savings in time, energy and therefore financial contributions. On a small scale, it is only used as a batch process, but it becomes much more economical and viable when converted to a medium or large scale continuous extraction process (Azwanida, 2015; Naghdi et al., 2008; Sasidharan et al., 2011).
- **Ultrasound Extraction (Sonication)** involves the use of ultrasound with frequencies ranging from 20 kHz to 2000 kHz; which increases the permeability of the cell wall and creates air bubbles. A disadvantage of this procedure is the infrequent but known harmful effect of ultrasound energy (more than 20 kHz) on the active constituents of the plants through the formation of free radicals and their aftereffects, resulting in unwanted changes in the active molecules (Azwanida, 2015; Doughari, 2012).
- **Microwave assisted extraction** is one of the advanced extraction processes to prepare medicinal plants. This technique uses dipole rotation and ion transfer by displacing charged ions present in the solvent and drug. This method is suitable for flavonoids extraction. It involves the application of electromagnetic radiation at frequencies from 300 MHz to 300 GHz and at wavelengths from 1 cm to 1 m. Microwaves applied at a frequency of 2450 Hz generate power of 600 to 700 W. The heat generated then facilitates the movement of the solvent within the drug matrix. When polar solvents are used, dipole rotation and ion migration occur, increases solvent penetration and facilitates the extraction process. This method is not suitable for non-polar solvent. Microwave-assisted extraction has special advantages such as minimizing solvent and extraction time as well as increasing results. This method is only suitable for phenolic and flavonoid compounds. Compounds such as tannins and anthocyanins can be decomposed by high temperatures (Azwanida, 2015).
- **Supercritical Fluid Extraction** (**SFE**) is an alternative sample preparation method with the general goal of reducing organic solvent consumption and increasing sample yield. Factors to consider include temperature, pressure, sample volume, analyte collection, flow and pressure control, and restrictors.

Cylindrical extraction tanks are used for SFE and their performance is certainly good. Collecting the extracted analyte after SFE is another important step: There can be significant loss of analyte during this step, leading the analyst to believe that the actual performance is poor. Using CO2 as an extract has many advantages. In addition to its favorable physical properties, carbon dioxide is inexpensive, safe, and abundant. But although carbon dioxide is the preferred liquid for SFE, it still has some limitations in terms of polarity. Solvent polarity is important when extracting polar solutes and when there are strong interactions between the analyte and the matrix. Organic solvents are often added to the carbon dioxide extraction solution to alleviate polarity limitations. Recently, argon has been used to replace carbon dioxide because it is cheaper and more inert. The composition recovery rate generally increases as pressure or temperature increases: the highest recovery rate in the case of argon is achieved at 500 atm and 150°C (Azwanida, 2015; Ingle et al., 2017; Naghdi et al., 2008; Sasidharan et al., 2011).

- **Distillation of water and steam to extract essential oils:** In this method, steam can be generated in a satellite boiler or in a still, although separated from the plant. Like water distillation, water and steam distillation is widely used in rural areas. Additionally, it requires no more investment than water distillation. Additionally, the equipment used is generally similar to that used to distill water, but the plant material is supported above the boiling water on a perforated rack. In fact, it is common for people who perform water distillation to turn to water distillation and steam distillation. Accordingly, when rural distillers produced a few batches of oil using water distillation, they realized that the quality of the oil was not very good due to its mild odor (off aroma). As a result, a number of changes were made. Using the same method, a perforated shelf or plate is shaped so that the plant material is raised above the water. This reduces the capacity of the cylinder but allows for better oil quality. If the amount of water is insufficient to complete the distillation, a cohobation tube will be attached and the condensate will be manually added back to the still, ensuring that the water used as the steam source will not now exhausted.

During water distillation, the material is completely immersed in water, boiled by heat transfer through direct fire, steam jacket, closed steam jacket, closed steam coil or open steam coil. The main feature of this process is that there is direct contact between boiling water and plant material (Ingle et al., 2017; Naghdi et al., 2008; Sasidharan et al., 2011).

3.2. Antifungal Susceptibility Testing (AFST) Approaches

Several methods have been used to test the antifungal activity of natural products of plant origin, depending on the properties of the extract and the compound tested. Specific growth media are used to monitor fungal growth. In these evaluations, DMSO can be used to solubilize water-insoluble compounds or extracts and serve as a negative control, while commercial fungicides are used as positive controls (Mohamed, Allagui, & Gianfranco, 2024; Tian et al., 2019).

- **The agar diffusion method** is suitable for testing the antifungal activity of hydrophilic compounds that spread in an agar medium. The compounds of interest (water-insoluble compounds) were mixed and dissolved in melted molten agar medium. The fungi were cultured for 2 to 7 days, then inoculated into the center of a Petri dish and incubated at 25°C for a specified period of time (Hu et al., 2017; Prakash et al., 2012). The minimum inhibitory concentration (MIC) of the compounds was determined when it reached a level that completely stopped fungal mycelial growth.
- **The microdilution method** is suitable for simultaneous testing of small amounts of extracts, fractions, or components at many different concentrations (Elizabeth et al., 2020; Feng et al., 2014; Moghadam et al., 2016). Fungal spores were prepared at a concentration of approximately 1.0 x 105 in a final volume of 100 μl per well. Determination of the minimum inhibitory concentration (MIC) was performed by using a serial dilution technique using 96-well microtiter plates. Microplates were incubated on a rotary shaker (160 rpm) for a period of time at 28°C. The lowest concentration at which no growth was observed (by binocular microscopy) was determined as the MIC. The fungicidal concentration (MFC) was determined by serially inoculating 2 μl of the test compound, dissolved in the medium and inoculated over a period of time, into microtiter plates containing 100 μl of broth per well and incubating for a period of time at 28°C. . The lowest concentration without visible growth was determined as MFC, indicating 99.5% destruction of the original inoculum (Elizabeth et al., 2020).
- **Bioautobiography** is widely used to test the activity of extracts. When the solvent evaporates, the broth and microorganisms are placed on paper or chromatography plates, and after incubation, growth is checked. No growth was observed on topically active ingredients. At the same time, the components of the extract are eluted and identified. Different volumes of mycelial extracts and purified compounds were dissolved in appropriate solutions. Ten microliters of each sample was applied to TLC plates and sprayed with a freshly prepared fungal suspension in nutrient broth (TSB). The plates were

incubated for 18 h at 37°C, then sprayed with 3% purple aqueous piodonitro-tetrazolium solution and stored for an additional 3 h. After this period, the plates were sprayed with 70% EtOH to prevent fungal growth and incubated for 36 h at 28°C. The white inhibition zone on a pink background indicates the antifungal activity of the extract or compound tested. The width of these zones (mm) is a measure of effectiveness and is expressed as the minimum inhibitory concentration (MIC) (Adimasu & Hassen, 2022; Elizabeth et al., 2020).

- **Broth microdilution for molds** is described in the document of Clinical Laboratory Standard Institute (CLSI). In this protocol, the inoculum used for filamentous fungi is 0.4 10^4 to 5 10^4 conidia per mL for non-dermatophytes and 1 10^3 to 3 10^3 conidia for dermatophytes. Filamentous fungi are incubated for duration time depending on the species. The result is a change in the pattern of growth, and this is measured as the minimal effective concentration (MEC), defined as the lowest concentration that leads to the growth of small, round, compact hyphal forms compared to the hyphal growth seen in the control well. This visible change in growth is due to the fact that the compounds are fungistatic against molds rather than fungicidal (Adimasu & Hassen, 2022; Elizabeth et al., 2020).
- **The disc diffusion test i**s one of the oldest susceptibility testing methods and is still widely used in many antifungal assays (37). This testing method involves the use of commercially prepared paper discs containing a fixed concentration of an antifungal drug are used. The diameter of the clearing produced around the disc, called the zone of inhibition, is related to the rate of diffusion of the drug through the agar and the sensitivity of the isolate to that drug. When zone diameters correlate with MICs for a given fungal-antifungal combination, they can be converted into interpretive categories. The pH of the agar should be between 7.2 and 7.4 at room temperature. CLSI recommends the same procedure for preparing inoculum for disc diffusion as for broth microdilution, with a final stock suspension of 1×10^6 to 5×10^6 cells per ml. After the disc containing the medium has been dried for at least 3 minutes but not more than 15 minutes, the disc(s) may be placed on the inoculated medium and gently pressed to ensure complete contact with the surface. If multiple discs are used, they must not be more than 24 mm from their centers. After 20 to 24 h of incubation at 35°C $\pm$ 2°C, the zone diameter of each disc is measured to the nearest millimeter at the point where there is a significant decrease in growth rate. The limitation of this method is that it does not provide MIC values. Criteria for interpretation of zone diameter were developed by comparing zone diameter with to MIC values of multiple isolates. These values were then converted into interpretation criteria based

on overall correlation with MIC. Some initial studies have been performed to test the usefulness of disk diffusion for filamentous fungi (Elizabeth et al., 2020; Fei et al., 1727; Mohamed, Marwa, & Gianfranco, 2024).

4. ANTIFUNGAL NATURAL PRODUCTS

4.1. Plants Extracts

To be a viable alternative to synthetic fungicides, biofungicides must be affordable (based on readily available and inexpensive plant materials) and simple to prepare (no requirements required). In addition, the resulting biofungicide must have low cytotoxicity, have no negative impact on crop productivity, be also harmless to the natural enemies of the target fungus and avoid new fungi and regeneration (Berdy, 2005; Evans, 2009). In recent years, various studies have been conducted to test whether certain plant extracts have the fungicidal potential to be reliable options compared to synthetic fungicides., some of them show very interesting results. The literature search performed revealed several works aimed at investigating the possibility of using natural plant extracts instead of chemical compounds in the management of plant diseases and pests. Pathogenic fungi often cause productive infections through lesions obtained during various stages of processing. Research on plant extracts against fungi has shown moderate effectiveness against *Alternaria tenuissima*, the species that produces mycotoxins. It has been noted that aqueous extracts of plants of the *Cistus* species have antifungal properties. In the search for environmentally friendly remedies against the citrus sour rot pathogen, *Geotrichum citriaurantii*, extracts of the Cistus species inhibited mycelial growth by 80-100% in vitro and significantly reduce (22 to 55%) the incidence of sour rot disease on fruit under laboratory conditions. No cytotoxicity was detected in the tested fruits (Demain & Sanchez, 2008; Phongpaichit et al., 2006). In the search for antifungal properties of crude extract, consisting of different parts of *Agapanthus africanus* (L.), the extracts were tested on peas *in vitro*, in the greenhouse and in the field. The results were promising as the extract had a significant effect in inhibiting the growth of *Botrytis cinerea*, *Sclerotium rolfsii*, *Rhizoctonia solani*, *Botryosphaeria dothidea* and *Mycosphaerella* (97-100%) on detached bean leaves. Under field conditions, the extraction of aerial parts of *Agapanthus africanus* was found to be effective in reducing the occurrence of covered and fragmented smut and had similar results to chemical Pathogens are used for control (Kumar et al., 2011). The mixture of caraway and basil extracts showed a synergistic effect in inhibiting *A. goneii, E. herariorum and F. verticillioides* and reduced primary contamination of *C. cladosporiosis* and *P. aurantiogriseum* on shredded cabbage. A mixture of oregano and basil leaf extracts has been shown to affect the growth of *P. aurantiogriseum* and *F. verticillioides* (Prakash et al., 2015). The results showed that higher antifungal efficacy can be achieved by using multiple extracts at lower concentrations and this is why the combined use of extracts is also widely studied (Marina et al., 2023).

Medicinal plant extracts of *Thymus kotschyanus*, *Bupleurum falcatum*, *Thymus daenensis* and *Stachys pubescens* have demonstrated antifungal effects against saprophytic fungi, pathogenic fungi and phytopathogenic fungi (Tian et al., 2019). In the study on xerophytic plants rich in phenolic compounds, *Prunus incisa* extract had the most pronounced antifungal effect against *F. oxysporum*. This extract was determined to have the effect of preventing the growth of fungal mycelium, destroying the basic structure and hindering the activity of plant pathogenic enzymes, thus *P. incisa* extract may be useful in stimulating host plant resistance to *F. oxysporum* (Hu et al., 2017). In a study conducted by the authors (Prakash et al., 2012), 15 extracts at four different concentrations (10%, 20%, 40% and 60%) were evaluated for their ability to inhibit mycelial growth of *Fusarium oxysporum f. sp. lycopersici*. Among these plant extracts, three extracts were found to significantly inhibit the growth of the pathogen *F. oxysporum, Solanum indicum* (78.33%), *Oxalis latifolia* (70.33%), *Azadirachta indica* (75.00%). The remainder of the plant extracts showed lower inhibition rates at the tested concentrations.

In Ethiopia, Authors (Akinmusire et al., 2014; Feng et al., 2014; Zhou et al., 2021) described the activity of five plant extracts *Allium sativum*, *Eucalyptus globulus*, *Melia azedarach*, *Solanum incanum* and *Solanum nigrum* against *in vitro* growth inhibition of *Aspergillus niger*, *Aspergillus flavus*, *Aspergillus* species *ochraceus* and *Fusarium* and *Penicillium.* The methanol extracts of these plants showed good antifungal activity against the tested fungal species with different inhibition rates at different concentrations. At concentrations of 0.1 g/mL, 0.25 g/mL and 0.5 g/mL, mycelial growth of *A. niger* was strongly inhibited by *S. incanum and S. nigrum* had no significant differences while *A. sativum*, *E. globulus* and *M. azedarach* slightly inhibited the mycelial growth of *A. Niger*. *S. nigrum* crude extract showed strong inhibition of mycelial growth on *A. flavus* at three concentrations (0.1 g/mL, 0.25 g/mL and 0.5 g/mL). Extracts from *E. globulus* and *M. azedarach* showed the ability to inhibit mycelial growth of *A. flavus*. Extracts of *A. sativum*, *E. globulus* and *S. incanum* inhibited *A. ochraceus* to a large extent without significant differences, while *S. nigrum* and *M. Azedarach*. Strong inhibitory activity against *Fusarium* spp. was demonstrated by extracts of *E. globulus* at three concentrations; however, the crude extract of *M. azedarach* showed the least inhibition of *Fusarium* spp. Extracts of *M. azedarach* and *S. incanum* showed inhibition of *Penicillium spp* (Adimasu & Hassen, 2022).

In South Africa, fresh leaves collected from eight medicinal plants were dried and selectively extracted with water, ethyl acetate or acetone. The dry extracts were evaluated for antifungal activity against *Fusarium* pathogens (*F. proliferatum, F. oxysporum, F. subglutinans, F. verticilloides, F. semitectum, F. chlamydosporum, F. solani, F. equisite and F. graminearum*). The acetone extract of *Melia azedarach* showed potent antifungal activity (97% inhibition) against *F. proliferatum*, while the combined acetone extract of *Combretum erythrophyllum* and *Quercus acutissima* showed 96%, 67% and 56% for *F. verticilloides*, *F. proliferatum and F. solani* respectively. *C. erythrophyllum* ethyl acetate and *Q. acutissima* ethyl acetate showed more than 50% inhibitory antifungal activity against *F. proliferatum*. The combined application of *C. erythrophyllum* and Q. *acutissima* Acetone extract showed somewhat synergistic antifungal activity (66.9% inhibition) against *F. proliferatum* (Moghadam et al., 2016).

An ethanolic extract of *Phlomis fruticosa* (Jerusalem sage) (Labiatae) tested by diffusion method inhibited *Aspergillus niger*, *Penicillium ochrochloron*, *Trichoderma viride*, *Fusarium tricinctum* and *Phomopsis helianthi*. Furthermore, this extract has fungicidal activity against *Cladosporium cladosporioides* and *Aspergillus ochraceus* at very low concentrations (10-20 g/mL) (Adimasu & Hassen, 2022). The potent antifungal activity of dealcoholized *Cassia tora* leaf extract is effective against *A. niger* (Adimasu & Hassen, 2022; Fei et al., 1727). Analyzed 29 plant extracts against *Arthrinium sacchari* and *Chaetonium funicola*, ethanol extracts of 15 plants showed antifungal activity, but *Acer nikoense* (Nikko Maple), *Glycyrrhiza glabra* and *Thea sinensis* (Tsa) were the most effective plants in very small quantities.

Antifungal tests of extracts from the branched knapweed plant *Centaurium pulchellum* (Gentianaceae) were investigated as potent biologically active compounds against five fungal species. Methanol extracts of aerial parts and roots showed excellent antifungal activity (0.1 to 2 mg/mL). Antifungal activity of methanol extracts of three different Labiatae (Catmint) species, *Nepeta rtanjensis*, *N. sibirica* and *N. nervosa* (*in vitro* culture) against eight fungal species were evaluated. All tested extracts showed significant antifungal activity, with *N. rtanjensis* being the most potent (Elizabeth et al., 2020). *Rhodobryum ontariense* was evaluated by the microdilution method against *Aspergillus versicolor*, *A. fumigatus, Penicillium funiculosum, P. ochrochloron and Trichoderma viride*. This extract was active against all tested fungi but to varying degrees. This finding implies that *R. ontariense* could be considered a promising raw material for natural antifungal products.

The antifungal activity of extracts of three moss species, two moss species (*Atrichum undulatum, Physcomitrella patens*) and one liverwort species (*Marchantia polymorpha ssp. Ruderalis*), grown under natural conditions and axenic culture, was evaluated by the method microdilution method for five fungal species. Each bryophyte extract was active against all tested fungi. In general, extracts from materials grown *in vitro* exhibit stronger antifungal activity than extracts from materials derived from natural conditions. Some tested mushrooms responded similarly to both extracts (Mohamed, Marwa, & Gianfranco, 2024).

In India, *Fusarium oxysporum* f. sp *lycopersici* is an important disease that causes wilt disease in tomato crop world over. Plant metabolites and plant based pesticides appear to be one of the better alternatives as they are known to have minimal environmental impact and danger to consumers in contrast to synthetic pesticides. In an approach towards the development of eco-friendly management, *in vitro* antifungal assay was conducted against *Fusarium oxysporum* f. sp. *lycopersici* (FOL), using plant extracts of fifteen plants. Out of fifteen plants, three plants proved to be potential in inhibiting the growth of the FOL viz., *Solanum indicum* (78.33%), *Azadirachta indica* (75.00%) and *Oxalis latifolia* (70.33%). Antifungal potency was compared with three chemical fungicides namely via (Mancozeb 82.66%, Copper oxychloride 79.33% and Copper sulphate 82.33%) in different concentrations. This study indicates that the botanical extracts could be a good alternative in developing a potent plant based fungicides which can be used in organic farming for the management of *Fusarium oxysporum* f. sp. *Lycopersici* (Anil et al., 2015).

In Côte d'Ivoire, the author (Kporou et al., 2014) studied activities of *Mitracarpus scaber* Zucc. (Rubiaceae) and *Ocimum gratissimum* Lin. (Lamiaceae), two species of Ivorian medicinal plants known for their antifungal and insecticidal activity. This study showed efficacy of these plants on *F. oxysporum sp. Radicis-lycopersici* in a dose-response relationship. The lowest antifungal parameters were obtained from the aqueous phases of the solvent mixtures. The activities obtained with *M. scaber* were better than those of *O. gratissimum*.

4.2 Essential Oils

Essential oils from aromatic and medicinal plants have been known since ancient times to be biologically active and constitute one of the most studied groups of secondary metabolites. With growing interest in their use in the pharmaceutical and agrochemical industries, systematic testing of the properties of oils is becoming increasingly important. Over the past hundred years, the antibacterial properties of common spice oils have been demonstrated and many studies have been performed on the antifungal activity of essential oils (Moumni et al., 2021). Thus, Abdel-Khalek et al. (2022) found that, out of 119 spice oils tested, 100 essential oils had an antagonistic effect against at least one of 12 plant-pathogenic fungi and 50 compounds of these substances had broad-spectrum activity against all tested fungi. *Origanum Majorana* essential oil has a significant inhibitory effect on *Aspergillus flavus*, *A. niger*, *A. ochraceus*, *A. parasitcus* and *Trichoderma viride* (Mohamed, Allagui, & Gianfranco, 2024). A comparative study on the antifungal activity of essential oils extracted from thyme, rosemary, eucalyptus and wormwood was conducted by a group of researchers on 39 mold strains. Thyme essential oil is believed to be the most effective (Mohamed, Marwa, & Gianfranco, 2024). Essential oils of all spices and cloves completely inhibited *Trichoderma viride, Alternaria alternata, Fusarium oxysporum, Mucor circinelloides, Rhizopus stolonifer, Cladosporium cladosporioides, Aspergillus versicolor and Penicillium citrinum* at a concentration of 2% (Anil et al., 2015).

Origanum syriacum essential oil shows very strong antifungal activity against *Penicillium*, *Aspergillus* and *Fusarium* species (Mohamed, Marwa, & Gianfranco, 2024). The essential oil of *Piper angustifolium* has been shown to be very effective against *Aspergillus niger* and *A. flavus* (Mohamed, Marwa, & Gianfranco, 2024). The antifungal activity of *Monarda citriodora* (lemon mint) and melaleuca (tea tree) essential oils was evaluated in vitro on 15 common postharvest pathogens from different crops. Both essential oils exhibited high levels of antifungal activity, both by direct contact and in the vapor phase. Lemon balm oil is generally more potent than tea tree oil, especially against fast-growing fungi (Dianez et al., 2018). Mohamed, Marwa, and Gianfranco (2024) tested the essential oils of eight commercial plants (*Cinnamomum zeylanicum* (cinnamon), *Cananga odorata* (ylang ylang), *Ocimum basilicum* (sweet basil), *Citrus limon* (lemon), *Cymbopogon citratus* (lemongrass), *Baswellia. thurifera* (Boswellia), *Majorana hortensis* (Marjoram) and *Rosmarinus officinalis* (Rosemary) and showed that all tested oils were able to inhibit the growth of the common spoilage fungus, *A. niger*, even at a concentration of 1 μg/mL broth, except lemon and rosemary oils which have an inhibitory effect at higher concentrations (Dianez et al., 2018; Prakash et al., 2015).

The antifungal activity of four spice essential oils (sage, thyme, oregano, and savory) was analyzed against *Fusarium oxysporum*, *Macrophomina phaseoli*, *Botrytis cinerea*, *Rhizoctonia solani*, *Alternaria solani*, and *Aspergillus parasiticus*. Previous results showed low activity of sage, while thyme, oregano and savory were active against all molds tested (Dianez et al., 2018). Different essential oils have antifungal activity against a variety of fungi. Because of the importance of these oils, 75 different essential oils were tested against *A. niger*. All of the oils have antifungal activity (Kumar et al., 2011). Reserachers tested a variety of essential oils from several plant families (Compositae, Labiatae, Lauraceae, Apiaceae, Cupressaceae, Poaceae, Illiaceae, Myrtaceae, Verbenaceae). Essential oils of *Origanum onites* (wild marjoram), *Satureja thymbra* (salty thyme), Salvia fruticosa (Greek sage) and *S. pomifera* subsp. calycina, which grows wild in Greece, were tested for antifungal activity against 13 fungal species. The oils inhibited all of the fungal species tested.

The antifungal activity of carrot *Daucus carota* L. (Apiaceae) oils was tested on 8 fungal strains (*F. sporotricchoides, Fulvia Fulvum, T. viride, P. ochrochloron, P. funiculosum, A. ochraceus, A. flavus and A. fumigatus*) using microdilution technique.

Essential oils from unripe fruits showed the strongest antifungal activity. These oils are more effective than the commercial drug bifonazole and much more active than ketoconazole (Dianez et al., 2018). The chemical composition and efficacy of the essential oil obtained from Echinophora spinosa (Apiaceae) were tested on different types of fungi. The most resistant fungal species are *P. ochrochloron* and *P. funiculosum* while *Trichoderma viride* is the most sensitive. This tested essential oil showed higher antifungal activity against *T. viride* than the commercial drugs bifonazole and ketoconazole (Dianez et al., 2018). *Lippia alba* (Bushy lippie) (Verbenaceae) essential oil is reported to be an antifungal agent against human pathogenic microorganisms but very few articles are concerned with its use against green mold. Determination of anti-green mold activity of *Bushy lippia* essential oil (*Aspergillus ochraceus*, *A. niger, A. versicolor. A. fumigatus*, *Penicillium ochrochloron, P. funiculosum and Trichoderma viride*) as an alternative to synthetic fungicides. Microdilution testing evaluated the MIC and MFC of the essential oil. Bushy Lippia essential oil has MIC from 0.3 to 1.25 mg/mL and MFC from 0.6 to 1.25 mg/mL (Dianez et al., 2018). The chemical composition and antibacterial activity of essential oils isolated from pink thyme *Satureja thymbra* and *Thymbra spicata* black thyme (Labiatae) were compared. Black thyme oil is more antifungal than pink *S. thymbra* oil. *A. versicolor and A. fumigatus* are the most sensitive species, while *P. ochrochloron* is most resistant to these oils. Essential oil of *Seseli montanum* subsp. *tommasinii* was tested for antifungal activity against four fungal species (*Aspergillus ochraceus, A. fumigatus, Penicillium ochrochloron and Trichoderma viride*). It showed moderate activity against all fungi tested, but the activity against *A. fumigatus* and *T. viride* is stronger than bifonazole. Essential oils obtained from the aerial parts of *S. anuum*, fruits of *S. globiferum*, aerial parts of *S. globiferum* and flowers of *S. rigidum* showed an interesting antifungal activity. Table II listed some essentials oils from plants known with antifungal properties

Table 2. Some essentials oils from plants known with antifungal properties (Dianez et al., 2018; Kumar et al., 2011; Mohamed, Marwa, & Gianfranco, 2024)

Scientific names	Families	Major chemical components	Vegetal part of oil extraction
Cymbopogon martinii	Poaceae	Geraniol, geranyl acetate	Leaf, bark, seed, kernel
Foeniculum vulgare	Apiaceae	Trans-anethol, limonene	Leaves
Laurus nobilis	Lauraceae	1,8-cineole, terpenyl acetat	Leaves
Melaleuca alternifolia	Myrtaceae	Terpineol, alpha-terpinen	Leaves
Salvia sclarea.	Lamiaceae	Linalyl acetate, linalol	Flowers

continued on following page

Table 2. Continued

Scientific names	Families	Major chemical components	Vegetal part of oil extraction
Cananga odorata.	Annonaceae	Germacrene D, benzyle acetate and banzaoate, farnesene	Flowers
Pogostemon cablin.	Lamiaceae	Patchoulol, alpha-patchoulene, alpha-bulnesene	Flowering
Melaleuca quinquenervia.	Myrtaceae	1,8 cineole, α-pinene, viridiflorol	Leaves
Boswellia carterii	Buseraceae	α-Pinene; β-Myrcene;β-Caryophyllen	Oleoresin
Lavandula angustifolia	Lamiaceae	Linalyle acetate, linalol, camphor	Flowering
Citrus sinensis.	Rutaceae	Limonene	Zest
Citrus paradisii	Rutaceae	Limonene	zest
Syzygium aromaticum	Myrtaceae	Eugenol, eugenyl acetate	floral buds
Mentha piperita.	Piperaceae	Menthol, menthone	Leaves
Gautheria fragrantissima	Ericaceae	Methyl aalicylate	Flower, Leaves
Artemisia dracunculus.	Herbaceae	Estragole, chavicol	Flowering
Citrus limon.	Rutaceae	Limonene, limonum citrus	Zest
Daucus carota	Apiaceae	Carotol, alphapinene	Seeds
Zingiber officinale	Zingiberaceae	zingeberene, gingerol, bisabolene	Rhizome
Ocimum basilicum	Lamiaceae	Estragol (Methylchavicol	Flowering
Piper nigrum	Piperaceae	Caryophyllene, limonene	Fruit
Cinnamomum verrum	Lauraceae	E-cinnamaldehyde, cinnamyl acetate	Cinnamon bark

Table 2. continued (Dianez et al., 2018; Mohamed, Marwa, & Gianfranco, 2024)

Scientific names	Families	Major chemical components	Vegetal part of oil extraction
Citrus reticulata	Rutaceae	Limonene, γ-Terpinene	Zest
Citrus aurantium	Rutaceae	Limonene, linalyl acetate, linalol	Leaves, Flowers
Cymbopogon nardus	Poaceae	Citronellal, geraniol, citronellol, limonene, elemol	Aerial part
Pelargonium asperum	Geraniaceae	Citronellol, geraniol	Leaves
Juniperus communis	Cupressaceae	α-Pinene, Sabinene	Branch
Chamaemelum nobile.	Asteraceae	Isobutyl angelate, Isoamyl angelate, methylallyl angelate	Flowers

continued on following page

Table 2. Continued

Scientific names	Families	Major chemical components	Vegetal part of oil extraction
Cedrus atlantica	Pinaceae	Himachalene	Wood
Cupressus sempervirens.	Cupressaceae	Alpha pinene, Delta 3 carene	Branch
Ocimum basilicum	Lamiaceae	Estragol (Methylchavicol)	Flowering

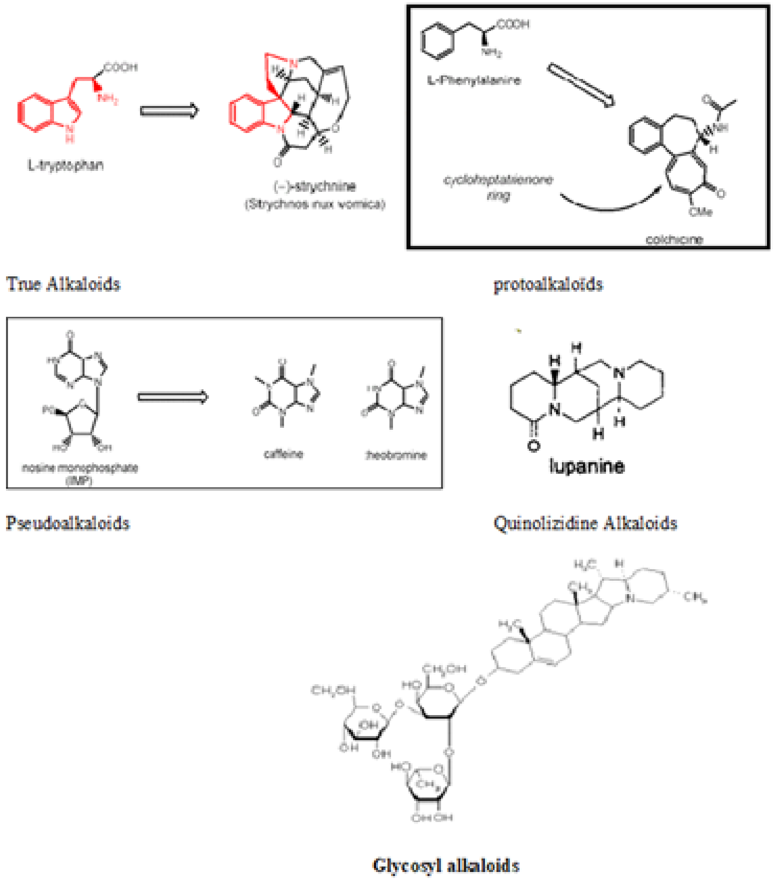
5. PHYTOCHEMICALS KNOWN AS ANTIFUNGAL COMPOUNDS

Phytochemicals (such as polyphenols and thiols) and plant essential oils (terpenoids) possess antimicrobial activities that are able to prevent food spoilage due to fungi (e.g., Aspergillus, Penicillium) and intoxications (due to mycotoxins), both of which are important economic and health problems worldwide. Major interesting antifungal bioactive compounds used as food preservation are terpenoids (as thymol), polyphenols (as resveratrol) and thiols (as allicin). These phytocompounds are widely distributed in different organs of plants and act to inhibit growth of important spoilage and pathogenic fungi, affecting especially mycelial growth and germination. Terpenoids and essential oils are the most abundant group of secondary metabolites found in plant extracts, especially in common aromatic plants, but polyphenols are a more notable group of bioactive compounds as they exhibit a wide range of bioactivities (Berdy, 2005; Demain & Sanchez, 2008; Saúl et al., 2020). Other secondary metabolites cited below are also involved in food preservation and control of agricultural fungal contaminants.

5.1. Alkaloïds

Plant alkaloids form a diverse group and exhibit a broad spectrum of activity. Basic nitrogen is the only unifying structural feature of many of these compounds (Figure. 1). Alkaloids typically originate from plant sources, contain one or more nitrogen atoms (usually in the form of heterocyclic rings) and often exhibit significant pharmacological activity (Berdy, 2005; Saúl et al., 2020). Alkaloids constitute a major tool for plant defense against pathogens and predators due to their toxicity. Plants in their natural habitat are exposed to a variety of competitors, including bacteria, fungi, viruses, nematodes, insects, and other herbivores, which ultimately lead to reduced growth and plant growth. It has more than 20 different groups, including pyrrolidines, pyrrolizidine, quinolizidine, tropanes, piperidine, pyridines and others. Most alkaloids function as nitrogen sinks, defense elements against predators, especially animals, vertebrates, insects, as well as arthropods due to their block and their general toxicity, and regulate growth, as the structure of some alkaloids is similar to known plant growth.

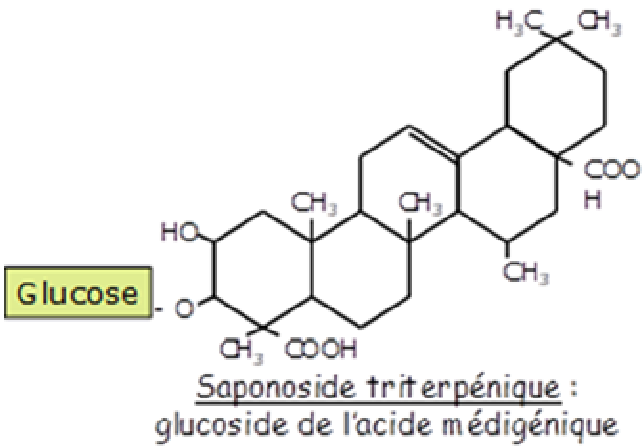
Figure 1. Structure of some alkaloids



5.2. Saponosids

The name "saponin" is derived from sapo, the Latin word for soap, because these compounds have surface-active properties and form stable, soap-like foam when shaken in an aqueous solution. These molecules are amphipathic glycosides with a triterpene or steroid skeleton. It is a large and structurally diverse group of biologically active natural products found mainly in plants, most commonly in dicotyledons (Figure 2) (Sparg et al., 2004). Many plants used in traditional medicine contain saponins, which often have medicinal effects and protect against potential pathogens through their antibacterial activity (Marina et al., 2023). For instance, Extract of *Chenopodium quinoa* containing olearane saponin showed antifungal activity (Dini, Schettino, Simioli et al, 2001; Dini, Tenore, Schettino et al, 2001) Saponins are extremely toxic to cold-blooded animals, but their oral toxicity in mammals is low (Marina et al., 2023). Due to their toxicity to various organisms, saponins can be used for their insecticidal, antibiotic, fungicidal, and pharmacological properties. The high chemical diversity of triterpenoid and steroid saponins has led to renewed interest and research in these compounds in recent years, especially as potential chemotherapeutic agents (Osbourn, 2003; Yendo et al., 2010).

Figure 2. Structure of saponosids



5.3. Phenolic Compounds

Phenolic compounds are found in a wide variety of plants and can be simple or complex structures containing at least one aromatic ring in which one or more hydrogens are replaced by hydroxyl groups (Fig. 3 and Fig. 4). Because phenolic compounds are plant secondary metabolites, they have different structures, such as phenolic acids and coumarin derivatives, and can be water-soluble pigments of flowers, fruits and leaves. In addition, this class of compounds includes lignin and tannin, polymers that have important functions in plants (Marina et al., 2023). In 2020, authors (Kporou et al., 2020) tests showed that in extract of *Ocimum gratissimum* inhibiting *Fusarium oxysporum* subsp *tulipae*, *Fusarium graminearum* and *Fusarium oxysporum* sub sp, there were some phenolic compounds such as phenolic acids (gallic acid, protocatechuic acid, gentisic acid, chlorogenic acid, caffeic acid, p-coumaric acid and ferulic) acidand flavonoids (rutin, quercetin, kaempferol) which were analyzed by HPLC approach.

Figure 3. Synthesis of cinnamic acid at the origin of phenolic compounds

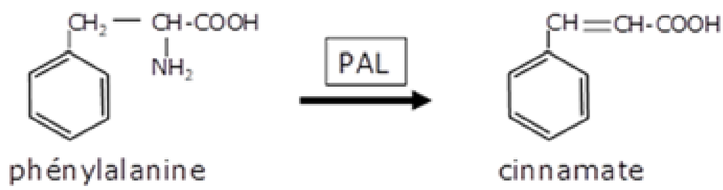
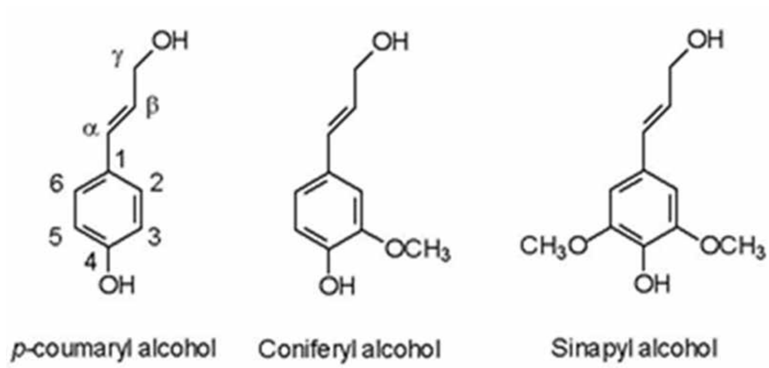


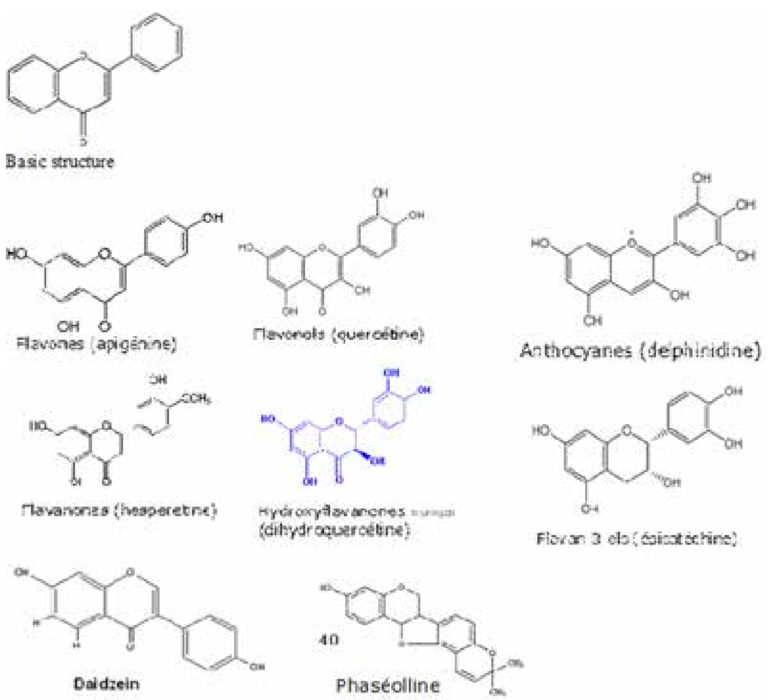
Figure 4. Structures of some monolignol compounds



5.4. Flavonoids

Flavonoids are bioactive compounds with antioxidant and anti-inflammatory properties that are found in large quantities in certain plants as a result of their prevalence among secondary metabolites (Figure 5). These compounds represent one of the most important phenolic groups (polyphenols) and have a role in various functions, including the protection of plants against ultraviolet and visible light; protection against insects, fungi, viruses, and bacteria; the attraction of animals for pollination; and the action of plant hormones. In addition, they function as antioxidants, allelopathic agents and enzyme inhibitors (Doughari, 2012; Ingle et al., 2017; Saúl et al., 2020). Flavonoids have also been shown to have anti-microbial effects could provide an alternative to conventional fungicides in the fight against plant diseases caused by fungi. Twenty-five flavonoids were examined to determine their effects on mycelial growth of the plant pathogen, Verticilim *alboatrum*. Minimum inhibitory concentrations (MICs) for the two most active compounds, flavones and flavanones. Other flavonoids inhibited mycelial growth and some compounds were ineffective at the highest concentrations used. The active compounds do not share a common substitution pattern. Unsubstituted flavonoids are more potent growth inhibitors and in most cases, increasing the number of substitutions (hydroxylation, methoxylation and glycosylation) results in a loss of antifungal activity. The fungicidal activity of two isoflavones, one isoflavanone and seven isoflavanes, was tested against *Aspergillus repens, A. amstelodami, A. knighti, A. flavus and A. petrakii*. While isoflavones have low activity, both isoflavans have strong inhibitory effects (Saúl et al., 2020). Two natural isoflavones, genistein and biochanin A, and their dihydroderivatives (isoflavanones) as well as nine perhydrogenated isoflavones (isoflavanes) were tested for their effects against Rhizoctonia solani and *Sclerotium rolfsii* (Berdy, 2005; Demain & Sanchez, 2008). Although previous results have demonstrated that Isoflavans are generally more active than the corresponding isoflavans. isoflavones and isoflavones (Marina et al., 2023).

Figure 5. Structures of different categories of flavonoids

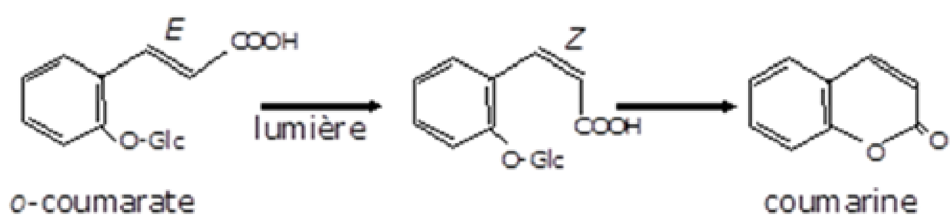


5.5. Coumarins and Xanthones

Coumarins are widely distributed in plants but can also be found in fungi and bacteria. Structurally, acid lactones are *O*-hydroxycinnamic acids, and the simplest representative is coumarin (Figure 6). Studies of three preparations from the essential oil of *Citrus bergamia* (bergamot natural essence, furocoumarin-free extract and the distilled extract) showed antifungal activity against dermatophytes and yeast pathogens. Bergamot oil is directly obtained from the fruit and consists of a volatile fraction (93%–96%), whose main components are, with approximate percentages, limonene (40%), linalool (8%) and linalyl acetate (28%), and a non-volatile fraction (4%–7%) consisting primarily of coumarins and psoralens (*i.e.*, bergamottin, citroptene, bergaptene, *etc*.). The furocoumarin-free extract (bergaptene-free) and distilled extract (absolutely devoid of non-volatile residues) were more active than the natural essence against all of the species tested (Doughari, 2012; Ingle et al., 2017; Saúl et al., 2020).

Xanthones are simple three-membered ring compounds that are mainly found as secondary metabolites in higher plants and microorganisms. Xanthones have very diverse biological profiles, including antihypertensive, antioxidative, antithrombotic, anticancer and antimicrobial activities, depending on their exact structures, which are diverse as a result of differences in the substituents on the ring system. The notable structural scaffold and pharmacological importance of xanthone derivatives have attracted many scientists to isolate or synthesise xanthone compounds for study as novel drug candidates (Doughari, 2012; Ingle et al., 2017; Saúl et al., 2020).

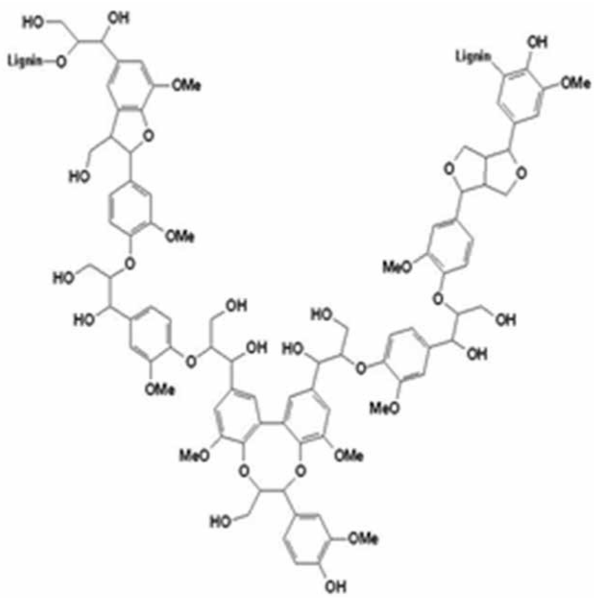
Figure 6. Synthesis basic structure of coumarins



5.6. Lignans

Lignans are phenolic plant compounds found in high concentrations in flax and sesame seeds and in lower concentrations in grains, other seeds, fruits and vegetables. Lignans are stereospecific dimers of cinnamic alcohols (monolignols) bonded at carbon 8 (C8-C8) that are derived in the phenylpropanoid pathway and formed through phenolic oxidative coupling processes (Figure 7). In the plant, lignans (monolignol dimers) usually occur in the free state or bound to sugars, and diglucosides of pinoresinol, secoisolariciresinol, and syringaresinol are common. Lignans, neolignans and their analogues are involved in plant defence (as antioxidants, biocides, phytoalexins, *etc*.), provide protection against diseases and pests and possibly participate in plant growth control (Doughari, 2012; Ingle et al., 2017; Saúl et al., 2020).

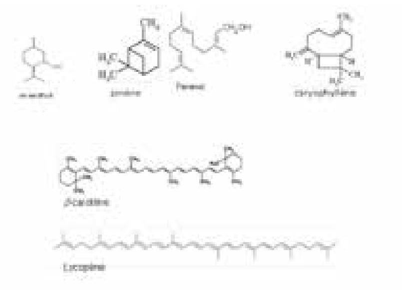
Figure 7. Structure of lignin



5.7. Tannins

Tannins are particularly important gustatory components that are responsible for the astringency of many fruits and vegetables (Figure 8). Tannin-protein binding is the basis for the ability of tannins to control insects, fungi as well as their biological activities (Saúl et al., 2020). Phytochemical investigation of *Terminalia mollis* and *Terminalia brachystemma* resulted in the isolation of many compounds, including the tannin ellagitannin punicalagin, which showed activity against some fungi.

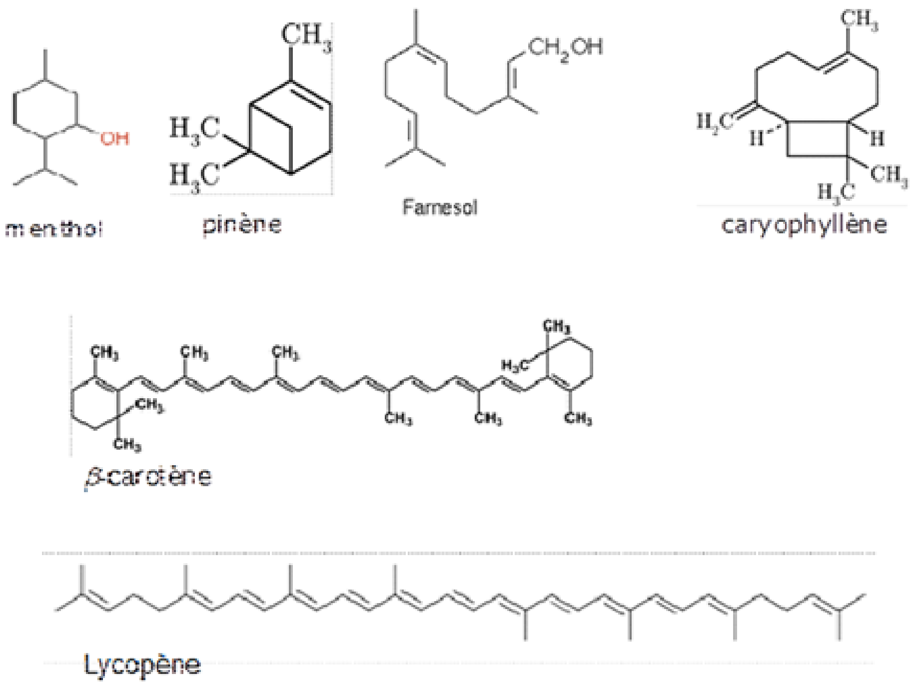
Figure 8. Structures of tannins



5.8. Terpenoids or Terpenes

Terpenes are the widest group of chemical compounds found in plant extracts, showing important antimicrobial activity that can be enhanced by the presence of other phytochemicals (from the plant extract) in a synergistic way (Figure 9). Depending on the plant species and the plant tissue that is extracted, the chemical profile of these essential oils will differ (Connolly & Hill, 2005). Terpenoids are some of the substances in essential oils and terpene compounds from natural vegetable oils are frequently monoterpenes (approximately 90% of the volatile oil) and sesquiterpenes. Other terpenoids, such as diterpenes, are found only in volatile oils and can be extracted using solvents (Connolly & Hill, 2005). Studies have indicated that terpenoids may show antioxidant and antimicrobial properties against pathogenic fungi. Grifolin, a sesquiterpene compound isolated from fruiting bodies of the fungus *Albatrellus dispansus*, inhibits the mycelial growth of plant pathogenic fungi such as *Sclerotinina sclerotiorum* and also produces an almost total inhibition of spore germination on *Fusarium graminearum*, *Gloeosporium fructigenum*, and *Pyricularia oryzae*. Sesquiterpene lactones are natural products present in many families of plants, but mostly distributed in the family Compositae. They display a wide spectrum of biological activity, one of the most important of which is antifungal activity. This group of compounds was analyzed for potential antifungal activity, in vitro against *Aspergillus niger*, *A. ochraceus*, *Penicillium ochrochloron*, *Trichoderma viride*, *Fusarium tricinctum*, *Phomopsis helianthi* and *Cladosporium cladosporioides*. Guaianolides from *Centaurea nicolai* were found to be highly active (0.8-25 µg/ml) (Connolly & Hill, 2005). Sesquiterpene lactones isolated from *Centaurea achaia*, *C. thessala* and *C. attica* also exhibited excellent antifungal activity against *Aspergillus niger*, *A. ochraceus*, *A. versicolor*, *A. flavus*, *Penicillium ochrochloron*, *P. funiculosum*, *Trichoderma viride*, *Fusarium tricinctum*, *Phomopsis helianthi*, *Alternaria alternata* and *Cladosporium cladosporioides* with germacranolides providing the greatest antifungal activity (Connolly & Hill, 2005; Yendo et al., 2010).

Figure 9. Structures of terpenes



6. FUTURE RESEARCH DIRECTION

Recent advances research demonstrated that also plants proteins could be used as antifungal agents for agricultural and industrial applications. Plants have evolved various mechanisms in their innate immune system to defend against fungal pathogens, including soluble proteins secreted from plants with antifungal activities. These proteins can inhibit fungal growth and infection through a variety of mechanisms while exhibiting diverse functionality in addition to antifungal activity.

One of the best known and most studied plant antifungal proteins is chitinase, which belongs to PR-3. Chitinases are strongly induced when the host plants are under attack from pathogens and function as defense molecules against fungal infection. These proteins inhibit fungal growth by lysing hyphal tips in fungi and break down chitin into its oligomers. Chitinases display strong antifungal activity against a wide range of phytopathogenic fungi. This includes *Botrytis cinerea*, a necrotrophic fungi that is considered one of the top fungal pathogens based on scientific and economic importance and infects over 200 species worldwide, as well as *Rhizoctonia solani* (Karasuda et al., 2003; Phuong et al., 2023), which causes sheath blight in rice, one of the most widespread diseases of rice. In addition to chitinases, other proteins such as Defensins, Osmotin and,Osmotin-Like Proteins, Protide-G, Potato Protease Inhibitor I and II, Bowman-Birk Protease Inhibitor, Prosystemin, StSN1, Puroindoline A and B, Ginkbilobin2, AFP1/AFP2, VdCRR1, TaCRR, PvPGIP2, 2S Albumin and 2S Albumin Orthologshave have been tested against food and crop spoilage pathogens. The potential of using natural plant proteins exogenously to control agricultural fungal diseases remains largely untapped and needs to be considered when developing future eco- and environmentally-friendly antifungal agents (Karasuda et al., 2003; Phuong et al., 2023; Tiffany et al., 2022).

CONCLUSION

Indigenous methods are great alternatives to chemical fungicides combined with botanical ingredients. Based on this knowledge, numerous scientists initiate some research on antifungal potential of some plants. Plant-based factors need to be more focused to effectively control fungal contamination to overcome the side effects of chemical compounds. More than a hundred plants have been studied for activity against several types of agricultural fungi contaminants, and the results show good performance. These plant extracts can be used as biofungicides to protect crops and foods. In summary, there are many on-going efforts in the discovery of new compounds from plant extracts with potential antifungal activity. Some of these compounds may become future prototypes of new antifungal drugs for foods preservation. However, more research is needed to ensure the safe use of these natural compounds. Obtaining plant extracts requires the selective use of various solvents, including non-polar, semi-polar and polar solvents. Extraction methods using these solvents include decoction, maceration, infusion, hydrodistillation, percolation, soxhlet extraction, sonication, microwave extraction and supercritical fluid extraction. Ultimately, the extracts obtained will be tested on target microorganisms regularly implicated in food contamination, i.e. *Aspergillus*, *Fusarium*, *Penicillium*, *Trichoderma*, *Alternaria*, *Acremonium, Stachybotrys* species and so on. In addition, depending on the laboratory, different methods can be used to assess the antifungal activity of the extracts. These include the agar diffusion method, the microdilution method, method, bioautobiography, microdilution in broth, and the disk method. The variability of the antifungal tests from one laboratory to another makes it difficult to compare the results for a given plant and tested on different conditions. However, it is clearly apparent from the literature that the antifungal tests carried out using plant extracts have shown a real potential for inhibiting fungal growth. The efficacy of the extracts shows that it is a complex of compounds which would be responsible for this antifungal activity. Under these conditions, trying to separate the compounds in order to test them individually could lead to an inefficiency because the compounds could act synergistically. In this regard, several families of secondary metabolites have been cited as having antifungal properties. These include alkaloids, saponosides, phenolic compounds, flavonoids, coumarins, lignans, tannins, terpenes and sterols. Essential oils have been widely documented for their antifungal effect. However, the production of these oils is not only time-consuming, consumes a large amount of biomass and the yield is very low. The valorization of these oils into real antimicrobials for the preservation of food would be a very good opportunity but they would be very expensive for the manufacturers, this could have an impact on the cost of the food that contains them. Finally, all of the plants cited have great potential for the development of new food preservatives, and the most studies have been performed with complex mixture, extracts, and essentials oils. It will be safety for consumers, if these compounds could be also evaluated for their toxicity. This process is a challenge to researchers and food industry. However, for the sustainable industrial exploitation of the plant species that are candidates for this valorization process, it would be desirable to initiate their cultivation to ensure biodiversity conservation.

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Chapter 18
The Role of Biologicals Azotohelp®, Liposam®, and Organic-Balance® as Mitigators of Abiotic Stress in Maize Plants

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ABSTRACT

In this study the expression of drought-resistance marker genes ZmNHL1, ZmVPP1, ZmNAC111: the antiradical activity, relative water content and biochemical chromatographic profiling of the phenolic compound complex in the leaves of maize plants treated by biopreparations under drought stress, was investigated. Drought stress significantly affected the expression of stress-responsive genes in plants under the action of biopreparations (in 4-7 folds). The maize leaves in the variant with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha were characterized by the high content of total content of phenolic compounds, highest antiradical activity (88.2%), the most active glycosylation processes of flavonoids (up to 13%), the highest relative water content (97.3%) compared to the control. PCA and PLS-DA showed that the alterations of secondary metabolites, induced by biopreparations, serve as an initial mechanism for activation of the plant's antioxidant system, leading to a more robust defence system post-stress signals.

BACKGROUND

Drought stress is one of the most devastating abiotic stresses, whose intensity has increased over the past decades, affecting yield and global food security. It is projected that by 2050, drought will cause significant problems in plant growth and development in more than 50% of the world's arable lands (Kasim et al., 2013; Kuzmych et al, 2022; Yakymchuk et al, 2022). Due to the global climate change, mainly driven by the rising of the average global temperature, the weather is becoming more unpredictable, with abnormal precipitation and extreme temperatures becoming widespread phenomena. According to recent studies, by 2050 the global average temperature will rise and probably exceed by 2∘C under the current high emission scenario. This escalation will significantly amplify the consequences of climate change, affecting billions of people worldwide.

Abiotic stresses represent pivotal challenges for agriculture, since crop production is the most vulnerable sector to global climate change. Among different kinds of abiotic stress, drought stress is the most detrimental one to plants, as it causes transpiration rates to surpass the water uptake, resulting into the disruption of water potential gradients, changes of cell volume, denaturation of protein, reactive oxygen species (ROS) production and disruption of membrane integrity. These processes collectively lead to severe plant organisms damage and yield reductions or even losses.

Corn is a cornerstone of Ukraine's agricultural economy. According to the Food and Agriculture Organization (FAO), Ukraine is one of the world's largest producers and exporters of corn, contributing significantly to the global supply. This crop supports food production, animal feed, and biofuel industries, directly impacting economic stability and growth. Corn production in Ukraine generates substantial income for farmers and creates numerous jobs in rural areas, helping to sustain local economies. The Ukrainian Agribusiness Club reports that the corn industry contributes billions of dollars annually to the national economy, highlighting its critical economic role.

In most of the countries, maize is cultivated under rainfed areas with 300–500 mm of precipitation, which is lower than the critical level to obtain decent yield. Depending on the intensity or duration of drought stress and crop stage, the maize yield losses vary from 30 to 90%, severely affecting the flowering and grain filling stages. To combat the adverse effects of water stress, plants have developed a wide range of responses including physiological and biochemical mechanisms. Most of them are the result of the regulation of the expression of associated genes, leading to shifts in the phytohormone balance, stomatal closure, osmolytes and antioxidants production, cuticle thickness augmentation and root growth stimulation, making plants more resilient to harsh environmental conditions. Drought stress-related genes pose a huge interest for genomics studies, since they represent a key to crop resistance improvement, assuring sustainable crop production under unpredictable conditions.

According to the results of the whole-genome scale analysis, 83 genetic variants, resolved to a total of 42 candidate genes, were significantly associated with drought tolerance in maize seedlings. The most significant variation occurs within a gene *ZmVPP1*, encoding a vacuolar H^+ pyrophosphatase, which has synergistic role with the vacuolar H^+-ATPase, maintaining a proton gradient across tonoplasts. Transgenic maize with enhanced *ZmVPP1* expression exhibits improved drought tolerance that is most likely due to enhanced photosynthetic efficiency and root development (X. Wang et al., 2016).

Extensive studies of the role of the late embryogenesis abundant (LEA) proteins, which are a family of mainly low molecular weight (10-30 kDa) proteins, showed they are involved in protecting higher plants from damage caused by environmental stresses, especially osmotic stress. Bioinformatics analysis of *ZmNHL1* revealed that the protein encoded by *ZmNHL1* belongs to the LEA-2 protein family. Tissue specific expression analysis showed that *ZmNHL1* is relatively abundant in stems and leaves, highly expressed in tassels and only slightly expressed in roots, pollens and ears. Under favorable conditions, no significant differences in relative water content (RWC) and antioxidant enzymes activity were found between transgenic and wild-type (WT) plants, but under the drought stress, the RWC, the activity of superoxide dismutase and peroxidase of plants from the three 35S::*ZmNHL1* transgenic lines were significantly higher than that of the WT plant. It is thought that *ZmNHL1* promotes maize tolerance to drought stress in transgenic plants by improving ROS scavenging and maintaining the cell membrane permeability (G. Wang et al., 2023).

ZmNAC111 is a maize marker gene for drought resistance. It is a regulatory gene that influences other genes expression and encodes a transcription factor of the NAM, ATAF, and CUC (NAC) family. *ZmNAC111* expression is induced by drought, high temperatures, and salinity and it regulates the expression of genes involved in the response to abiotic stresses.

Apart from the developmental aspects, plants have developed antioxidant systems, including antioxidant enzymes and non-enzyme components, provide an effective ROS-scavenging mechanism for protecting plants against oxidative damage induced by water stress. Plants mitigate stress-induced oxidative damage by changing antioxidant enzymes activity and accumulation of non-enzyme antioxidants, such as ascorbic acid, flavonoids, etc. Flavonoids are secondary metabolites in the phenylpropane pathway and reportedly, they play important roles in plant responses to biological and non-biological stresses. As non-enzymatic antioxidants, hydroxyl groups in the 3′ and 4′ positions of flavonoids participate in the scavenging of oxygen free radicals, and the role of flavonoids in alleviating stress-induced oxidative damage has been widely reported. A group of flavonoids, flavonols, were shown to be involved in guard cells H_2O_2 accumulation and stomatal movement, preventing stomatal closure by lowering H_2O_2 level (Li et al., 2021).

The application of biopreparations effectively enhances plant resistance to abiotic stress. The mechanisms of plant drought resistance mediated by PGPR include phytohormonal activity, volatile compounds formation, alteration of root morphology, increased ACC-deaminase activity, accumulation of osmolytes, production of exopolysaccharides (EPS), and antioxidant defense activation.

Efthimiadou et al. (2020) investigated the influence of microbial plant biostimulants (MPB), such as *Azotobacter chroococcum*, *Bacillus subtilis*, *Bacillus megatherium*, and their combinations on maize under Mediterranean climatic conditions (hot, dry summers and cool, wet winters) through soil and foliar application. Treatment with *A. chroococcum* increased the rate of photosynthesis, chlorophyll content and transpiration rate. The best maize yields were noted in plants treated with *B. megatherium* and a mixture of *A. chroococcum* and *B. subtilis* (1:1) when applied zonally. Abd El-Daim, I.A., Bejai, S. & Meijer, J. (2019) identified significant metabolic and molecular changes associated with the ability of *Bacillus velezensis* to enhance resistance to abiotic stress in wheat. *B. velezensis* improved the chlorophyll content and survival rate of wheat under abiotic stress. Metabolite analysis using NMR and ESI-MS demonstrated evidence of metabolic reprogramming in seedlings treated with *B. velezensis*, as well as the accumulation of several typical stress-related metabolites in wheat seedlings that had endured stress.

Maize plants subjected to drought stress and inoculated with five strains of PGP *Pseudomonas* spp., namely *P. entomophila*, *P. stutzeri*, *P. putida*, *P. syringae*, and *P. montelli*, demonstrated significantly lower activity of antioxidant enzymes compared to non-inoculated ones (Sandhya et al., 2010). Similarly, maize plants inoculated with *Bacillus* species developed drought stress protection by reducing the activity of antioxidant enzymes APX and glutathione peroxidase (GPX) (Vardharajula et al., 2011). Microbial consortia consisting of strains of EPS-producing bacteria, *P. penneri* (Pp1), *P. aeruginosa* (Pa2), and *A. faecalis* (AF3), exhibited greater drought resistance potential in maize compared to individual PGPR strains. A decrease in the activity of APX, CAT, and GPX enzymes was observed in maize plants inoculated with EPS-producing bacteria, conferring increased stress resistance. During drought stress, inoculated plants exhibited an increase in relative water content, proteins, sugars, and proline, as well as a decrease in the activity of antioxidant enzymes (Naseem and Bano, 2014).

Coinoculation of wheat plants with *Azotobacter chrocoocum* (E1) and *Pseudomonas* sp. (E2) ameliorated drought stress through anatomical changes such as increased thickness of epidermis, mesophyll and phloem tissues, xylem vessel diameter, and vascular bundles size in the root system (El-Afry et al., 2012).

There is an importance of addressing potential environmental and ecological ramifications of using biopreparations. These include the risk of non-target effects on beneficial organisms, such as pollinators and soil microbes, which can be inadvertently affected by the introduction of new microbial agents. There is also the possibility of microbial resistance developing, which could reduce the efficacy of biopreparations over time. Additionally, the long-term impact on soil health and biodiversity is a concern, as the introduction of foreign microorganisms might disrupt existing soil ecosystems and lead to unintended ecological consequences. Addressing these issues will provide a more holistic view of the use of these biopreparations.

Our study aimed to evaluate the effects of microbiological preparations, based on plant growth-promoting bacteria (PGPB) and their metabolites, particularly exopolysaccharides known for their water stress mitigation capabilities, on drought resistance and metabolite profiles in maize. The purpose of the research is to investigate the expression of drought resistance marker genes *ZmNHL1*, *ZmVPP1*, *ZmNAC111*, antioxidant potential indicators, relative water content (RWC), and biochemical chromatographic profiling of the complex of phenolic compounds in the leaves of maize plants grown under drought stress conditions.

METHODS AND TECHNIQUES

The experiment was conducted during the 2023 growing season at the trial station of the Institute of Agriculture of the Northeast of the National Academy of Agrarian Sciences of Ukraine.

The connection between soil type and the efficiency of biological applications, such as biofertilizers and biopesticides, is critical for optimizing their benefits in agricultural practices. Different soil types, characterized by their texture, structure, pH, organic matter content, and nutrient availability, can significantly influence the effectiveness of biologicals. The research area is located in the black soil zone of the northern Steppe of the Right Bank of Ukraine in the subzone of ordinary black soil transitional to deep.

The soil of the experimental plot is ordinary black soil, transitional to deep, heavily loamy on loess. The topsoil contains 4.69% humus, 13.7% easily hydrolysable nitrogen, 10.0 mobile phosphorus and 15.1 mg of exchangeable potassium per 100 g of soil. The reaction of the soil solution has a salt pH of 5.8.

«Tristan» FAO 270 maize was cultivated under field conditions. The experimental plot was exposed to water stress due to limited precipitation during critical growth stages in May and June. Maize plants were treated with commercially available biopreparations obtained from LLC "TH BTU-CENTER," including «Azotohelp®», «Liposam®», and «Organic-Balance®». Treatment was applied at the 3-5 leaf stage (BBCH 13-15).

Experimental variants were:_1. Control; 2. «Organic-Balance®» 0.5 l/ha; 3. «Azotohelp®» 0.3 l/ha; 4. «Liposam®» 0.5 l/ha; 5. Stop-Stress complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha).

«Azotohelp®» contains living *Agrobacterium pusense* cells, growth-promoting biologically active metabolites; it enhances stress resistance and boosts crop yields. «Liposam®» has oligo/polysaccharides of microbial origin, it is effective sticking agent, enhances plants' drought tolerance. «Organic-Balance®» contains nitrogen-fixing, phosphorus- and potassium-mobilizing plant growth-promoting bacteria, biologically active microbial compounds, has fungicidal properties.

Drought resistance of maize was assessed via the analysis of expression of key water stress marker genes (*ZmNHL1*, *ZmVPP1*, *ZmNAC111*) using qPCR.

Antioxidant properties were evaluated via the DPPH radical scavenging assay. The assay was conducted according to Dzięcioł M, Wróblewska A, Janda-Milczarek K. (2023).

The hydroxyl radical (·OH) scavenging activity was conducted according to Rana SM, Islam M, Saeed H et al. (2023).

To investigate the antioxidant potential, a 722G spectrophotometer model was used.

Additionally, the flavonoid profile was examined using high-performance thin-layer chromatography (HPTLC) to compare phenolic profiles. Biochemical chromatographic profiling of the phenolic compounds complex in maize leaves was carried out using HPTLC on silica gel G60 plates (Merck, Germany) in a specific solvent system (Reich E., Schibli A., 2006). This methodological approach allows for a detailed comparison of phenolic compounds, crucial in understanding the varying antioxidant capacities and interactions in maize leaf tissues.

To determine the chemical nature of the substances, the chromatograms were treated with chromogenic reagents (Reich E., Schibli A., 2006). The Rf values of individual compounds were determined photodensitometrically using the Sorbfil TLC Videodensitometer computer program. Phenolic compounds capable of fluorescence were detected under UV light ($\lambda max = 365$ nm). To detect individual substances with high antioxidant potential on the chromatogram, after thorough drying, the plate was treated with special solutions, incubated for 10 minutes in the dark, and then heated for 30 seconds at 60°C. The chromatogram was scanned on a flatbed scanner and analyzed with the Sorbfil TLC Videodensitometer software module.

The reliability of the differences between the average values of the peak intensities of secondary metabolites on the chromatograms was determined by one-way ANOVA. The assessment of statistically significant differences between the medians of the respective indices of the studied plant groups was performed using the Kruskal - Wallis test ($p < 0.05$). Principal component analysis (PCA), Partial least squares discriminant analysis (PLS-DA), multiple correlation analysis (Pearson), and construction of heat maps to visualize the levels of association between phenolic synthesis products and maize treatment methods were performed using the software module on the MetaboAnalyst 5.0 platform, which contains functions and R program libraries prepared for metabolomics data analysis, visualization, and functional interpretation of the results.

The Relative Water Content (RWC) of leaves was measured to evaluate overall plant fitness and the severity of water stress using a gravimetric method (Barrs, HD. and Weatherley, PE. 1962; Noun, G. et al., 2022). This measure provides a direct indication of the plant's ability to maintain water content under stress conditions, reflecting its adaptability and resilience.

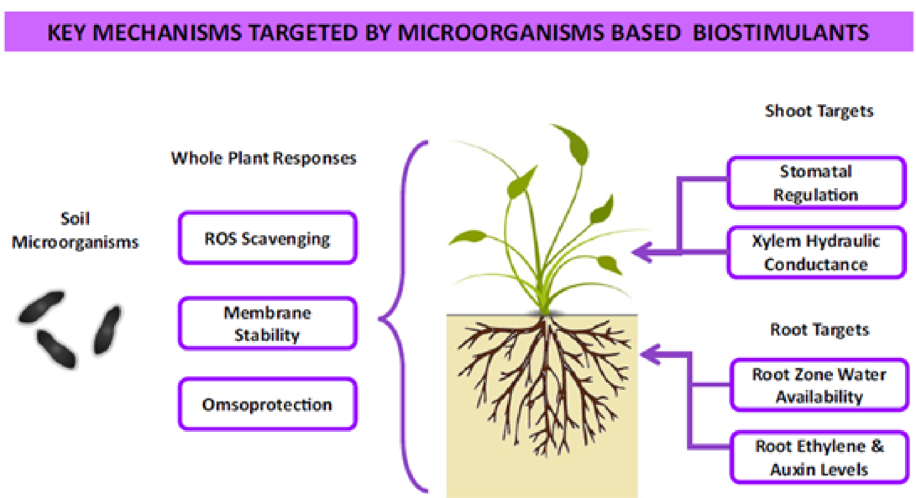
RESULTS AND DISCUSSION

The term “induced systemic tolerance” (IST) describes the physical and chemical changes in plants induced by microorganisms, leading to increased resistance to abiotic stresses (Yang et al., 2009).

The concept of “induced systemic tolerance” (IST), where microorganisms induce physical and chemical changes in plants to enhance resistance to abiotic stresses, is indeed intriguing. However, many IST studies are observational or conducted under uncontrolled conditions, making definitive conclusions difficult (Borzykh O. I. et al., 2022; Bilous S. et al., 2023; Lishchuk, A et al., 2023). The responses of plants and microorganisms to environmental stresses are highly variable, complicating the generalization of findings. Furthermore, the precise biochemical and molecular mechanisms underlying IST are not fully understood, but experimental plants demonstrate higher resistance to pathogenic microorganisms and even pest insects.

According to Batool et al. (2020) and Begum et al. (2022), the application of microbial plant biostimulants (MPB) is a sustainable approach to promote crop growth and tolerance under water deficit conditions. MPBs enhance drought stress resistance by releasing various phytohormones, volatile organic compounds, diverse exopolysaccharides, and ACC-deaminase, thereby modulating osmolytes, stress-responsive genes expression, and enhancing modifications in root structure (Barnawal et al. 2017, Niu et al. 2018, Moon and Ali 2022a) (Figure 1).

Figure 1. The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants (Van Oosten, M.J., Pepe, O., De Pascale, S. et al., 2017)



Our experimental data revealed that the relative expression levels of marker genes in all variants treated with microbiological biopreparations were significantly lower than in the control group. The most substantial reduction was observed in plants treated with «Liposam®», «Organic-Balance®», and the «Stop-Stress» complex. These results suggest that PGPB enhances drought tolerance in maize, likely by increasing their water retention and antioxidant capacity through phytohormone and biologically active compound synthesis.

The accumulation of secondary metabolites and changes induced by PGPB represent an initial mechanism for priming the antioxidant system in plants, leading to a more robust defense system following stress signals. This phenomenon, known as priming, stimulates plant growth and underlies PGPB-induced metabolic reprogramming and oxidative stress mitigation during drought through non-enzymatic mechanisms. Overall, the balance in the content of individual flavonoids in maize leaves was well-maintained. Given the critical role of these compounds in regulating plant physiological processes, their synthesis appears to be finely tuned and relatively independent of external factors.

The ability of crops to maintain adequate water status and efficiently utilize available resources is vital for their growth and survival in water-deficient environments. The water content of plant organs reflects their metabolic activity. The distribution of water among roots, stems, leaves, and fruits is a crucial aspect of resource allocation in crops, directly reflecting their pattern of water acquisition and utilization. During drought stress, the relative water content of leaf tissues is adversely affected, dropping from nearly 98% in fully turgid leaves to about 30-40% in severely desiccated and dying leaves.

Investigantion of the Expression of Drought Resistance Marker Genes *ZmNHL1*, *ZmVPP1*, *ZmNAC111*

Drought stress significantly affected the expression of stress-responsive genes, which were positively altered in plants due to the action of biopreparations. Investigating gene expression is a powerful tool for understanding and comparing the comprehensive responses of plants to both abiotic and biotic stresses. To analyze differences in gene expression levels between control and treated maize plants, a qPCR analysis was conducted.

RNA was extracted from the leaves of maize (taken from the middle part of the stem) and amplified with primers to drought resistance marker genes *ZmNHL1*, *ZmVPP1*, *ZmNAC111*. The products of these genes participate in the plant's response to drought, mediating various biochemical and physiological pathways to enhance resilience and adaptability.

Drought Resistance Markers in Leaves

ZmNHL1 is a marker gene for analyzing plant response to drought resistance. It encodes one of the late embryogenesis abundant (LEA) proteins: a group of plant proteins that protect other cellular proteins from aggregation during dehydration.

ZmNHL1 is a maize (*Zea mays*) gene that encodes a protein from the NHL family. It is suggested that *ZmNHL1* participates in the adaptive responses of maize to environmental stresses. It may regulate seed germination and leaf development processes.

ZmVPP1 – a marker of plant drought resistance; gene for H+ pyrophosphatase of the vacuolar type, which provides nutrient ion transport in cell vacuoles. *ZmVPP1* is a maize gene that encodes vacuolar pyrophosphatase. These genes represent crucial components in understanding the molecular mechanisms underlying maize's response to environmental stressors, particularly drought, and provide targets for genetic and biotechnological interventions to enhance crop resilience.

ZmNAC111 – a drought resistance marker in plants; a regulatory gene controlling activity, influencing other genes expression, coding for a transcription factor of the NAM, ATAF, and CUC (NAC) type. *ZmNAC111* is a maize gene that encodes a transcription factor from the NAC family with the following characteristics: regulates the expression of genes involved in the response to abiotic stress, *ZmNAC111* is involved in regulating stress tolerance and adaptation in maize.

NAM, ATAF, and CUC (NAC) transcription factors are a large family of plant transcription factors regulating the expression of genes involved in various biological processes, particularly stress response. NAC factors provide finely tuned regulation of gene expression necessary for growth, development, and stress adaptation of plants.

qPCR analysis revealed increased regulation of some stress-related genes in control plant variants that experienced drought stress. The molecular-genetic analysis results showed that the most substantial differences between control maize plants and those treated with biopreparations were observed following treatment with «Azotohelp®» individually, «Liposam®» individually, and the complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha). In the case of *ZmNHL1*, the differences reached 5 and 4 times, respectively, and for *ZmVPP1* - 7 times. The expression level of the transcription factor (*ZmNAC111*) decreased by 5.5 times in plants treated with «Azotohelp®» (Figure 2).

Decreased transcript levels in plants treated with «Azotohelp®» individually, «Liposam®» individually, and the complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha) indicate an increase in drought resistance due to the action of biopreparations. The similarity in gene expression between the «Liposam®» individually and the Stop-Stress complex indicates that «Liposam®» plays the most significant role in the Stop-Stress complex.

Figure 2. Comparative analysis of the relative expression levels of three genes in maize leaves (the expression level in the control sample is taken as 1)

It should be noted that treating plants with «Organic-Balance®» individually did not lead to significant changes in the expression of the three genes.

Similar results were obtained by Gontia-Mishra, I., et al. (2016). Drought stress significantly affected various growth parameters, water status, membrane integrity, osmolyte accumulation, and the expression of stress-responsive genes, which were positively altered during inoculation with PGPR in wheat.

qPCR analysis revealed an increase in the regulation of some stress-related genes (*DREB2A* and *CAT1*) in non-inoculated wheat plants experiencing drought stress. Plants inoculated with *Klebsiella* sp., IG 10 (*Enterobacter ludwigii*), and IG 15 (*Flavobacterium* sp.) showed decreased transcript levels, indicating improved drought resistance due to the interaction with PGPR (Gontia-Mishra, I., Sapre, S., Sharma, A., and Tiwari, S., 2016).

Maize plants represent a great interest as an agricultural crop, that raises a question of genetic control of their growth and development under influence of various stresses, in particular drought. Different molecular genetic techniques were applied to examine maize genotypes and genes associated with drought tolerance, among them Quantitative trait loci (QTL) mapping and genome-wide association study (GWAS) analysis, transcriptomics, and proteomics. As a result, several marker genes encoding proteins and transcription factors were identified and can be used as a promising material for breeding approaches. Transgenic maize cultivars that are resistant to drought stress were developed using genetic engineering approaches including gene editing technology (Sheoran et al., 2022; Rasheed et al., 2023).

The mechanism of action of «Liposam®» in this experiment is supported by thorough scientific research. Bacterial EPS play an essential role in enhancing plant resistance to drought stress (Grover et al., 2011). Wheat treated with PGPR + salicylic acid (SA) has significantly increased protein and sugar content and maintained a considerable amount of chlorophyll, chlorophyll fluorescence, and productivity index under rainfed wheat cultivation. Integrated use of PGPR and SA is an ecological approach to reduce water stress in plants (Khan & Asghari, 2019).

Aggregates formed by EPS-producing bacteria significantly reduce the impact of drought stress and regulate the flow of water and nutrients in plant roots (Grover et al., 2011). EPS can bond with Na+ cations to remove them from direct access to plant roots, forming a soil zone around the root that reduces the rate of Na+ ion entry towards the apoplast (Dimpka et al., 2009). Using strains of EPS-producing bacteria in crop production is an environmentally friendly strategy that mitigates the impact of drought stress on plants. These strains use various mechanisms, such as the production of osmolytes, phytohormones, and synthesis of antioxidants, which enhance plant resistance to drought (Ilyas et al., 2020).

Drought stress can render the physicochemical and biological properties of the soil unsuitable for the activity of soil microbes and crop yield. The presence of water controls the production and consumption of protein and polysaccharides by bacteria (Roberson and Firestone, 1992) and thus indirectly affects the structure of the soil.

The production of exopolysaccharides (EPS) protects bacteria from adverse conditions and allows them to survive. The capsular material of *A. brasilense* Sp245 contains high molecular weight carbohydrate complexes (lipopolysaccharide-protein (LP) complex and polysaccharide-lipid (PL) complex), responsible for protection in extreme conditions such as desiccation. The addition of these complexes to a suspension of decapsulated cells of *A. brasilense* Sp245 significantly increased survival under drought stress conditions (Konnova et al., 2001).

EPS released into the soil as capsular and mucilaginous materials by soil microbes can be adsorbed onto clay surfaces due to cation bridges, hydrogen bonds, Van der Waals forces, and anion adsorption mechanisms, thus forming a protective capsule around soil aggregates (Tisdall and Oades, 1982; Sandhya et al., 2009).

EPS provide a microenvironment that retains water and dries out more slowly than the surrounding environment, thus protecting bacteria and plant roots from desiccation. It has been shown that bacterial EPS production improves permeability by increasing soil aggregation and maintaining a higher water potential around the roots, thereby increasing nutrient uptake by the plant with increased plant growth and protection from drought stress (Miller and Wood, 1996; Alami et al., 2000; Selvakumar et al., 2012).

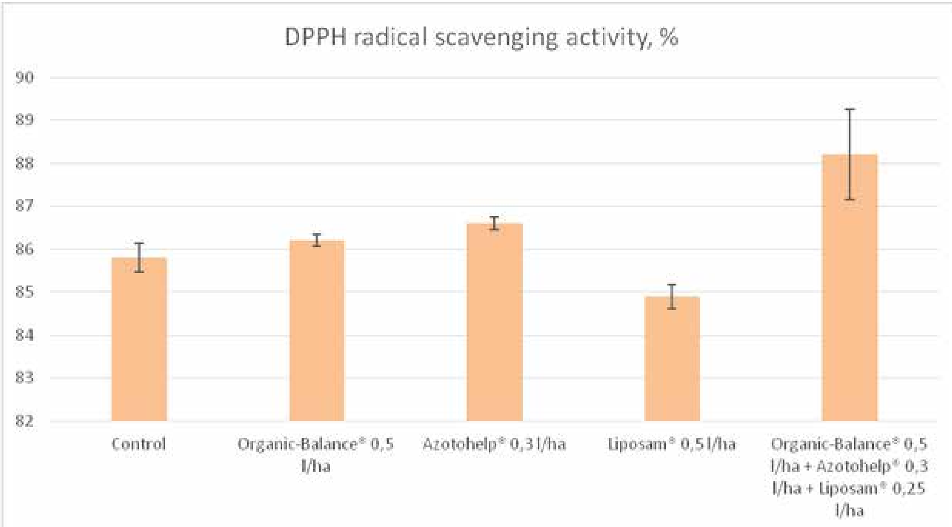
Plants treated with EPS-producing bacteria demonstrate increased resistance to water stress (Bensalim et al., 1998). In the rhizosphere of sunflowers inoculated with the EPS-producing rhizobial strain YAS34 under drought conditions, there was a significant increase in the soil-root adhesion ratio (RAS/RT) (Alami et al., 2000). Inoculation with the *Pseudomonas* sp. strain GAP-P45 increased the survival, plant biomass, and RAS/RT of sunflower seedlings experiencing drought stress.

Inoculated rhizobacteria can effectively colonize the soil adhering to the roots and rhizoplane and increase the percentage of stable soil aggregates. Improved aggregation of RAS leads to increased water and nutrient uptake from the rhizospheric soil, thereby supporting plant growth and survival during drought stress (Sandhya et al., 2009). Seed bacterization of maize with bacterial strains *Proteus penneri* (Pp1), *Pseudomonas aeruginosa* (Pa2), and *Alcaligenes faecalis* (AF3) producing EPS, improved soil moisture content, plant biomass, root and shoot length, and leaf area.

Investigation of Antioxidant Potential Indicators in Maize Leaves Under Various Treatments

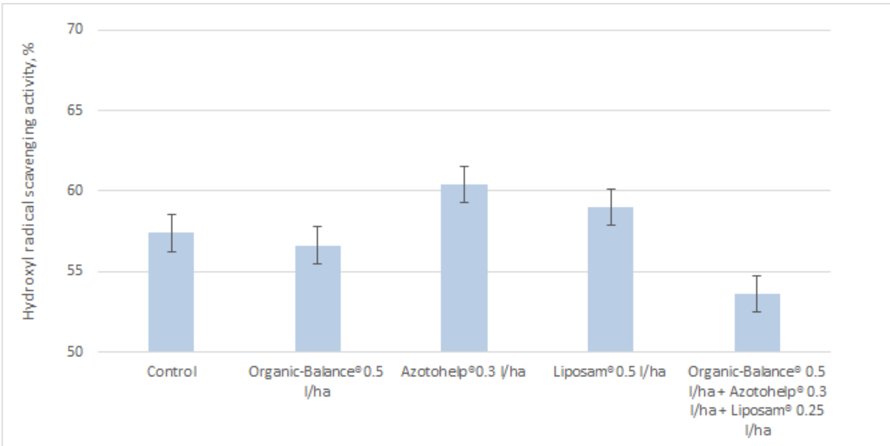
The study of individual indicators of antioxidant potential in maize leaves under various treatments revealed significant differences. Specifically, the ethanol extract from plants treated with Stop-Stress complex was characterized by the highest antiradical activity against the stable 2,2-diphenyl-1-picrylhydrazyl radical (DPPH•) – 88.2%, compared to other extracts (Figure 3).

Figure 3. The effect of microbiologicals treatment on free radical scavenging activity in ethanol extracts of maize leaves



While the capacity to inactivate the highly reactive hydroxyl radical (•OH) was most pronounced for samples, treated with ««Azotohelp®» and «Liposam®» individually, respectively, amounting to 60.4% and 59.0% (Figure 4).

Figure 4. Antiradical activity against the hydroxyl radical of ethanol extracts from leaves of different maize samples (1- Control, 2 - «Organic-Balance®» 0.5 l/ha at the 3-5 leaf stage, 4 -«Azotohelp®» 0.3 l/ha at the 3-5 leaf stage, 5 - «Liposam®» 0.5 l/ha at the 3-5 leaf stage, 8 - Stop-Stress complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha) at the 3-5 leaf stage)



It can be assumed that such differences in antiradical activity against DPPH• and •OH among the studied ethanol extracts from maize leaf samples under various treatments are due to the influence of applied preparations on the synthesis of biologically active compounds capable of inactivating aggressive free radicals.

The total content of phenolic compounds in maize leaf samples under different treatments prevailed in samples with «Azotohelp®», «Liposam®» and Stop-Stress complex («Organic-Balance®» + «Azotohelp®» + «Liposam®») (Table 1).

Table 1. Content of different groups of phenolic compounds in maize leaves under different treatments

Option	*The groups of phenolic compounds*		
	TPC, mg GAE/g extract	**TFC, mg RE/g extract**	**orto-di-Ph-OH, mg Caf/g extract**
Control	22.28 ± 0.48	30.74 ± 0.35	10.57 ±0.45
«Organic-Balance®» 0.5 l/ha at the 3-5 leaf stage	30.79 ± 0.68	26.71 ± 0.47	6.83 ± 0.37
«Azotohelp®» 0.3 l/ha at the 3-5 leaf stage	**57.20 ± 1.76**	32.26 ± 0.86	8.49 ± 1.78
«Liposam®» 0.3 l/ha at the 3-5 leaf stage	**117.25 ± 2.12**	**48.32 ± 1.46**	**14.43 ± 0.69**

continued on following page

Table 1. Continued

Option	*The groups of phenolic compounds*		
	TPC, mg GAE/g extract	**TFC, mg RE/g extract**	**orto-di-Ph-OH, mg Caf/g extract**
Stop-Stress complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha) at the 3-5 leaf stage	**108.42 ± 1.89**	34.62 ± 1.25	**18.61 ± 1.97**

It was found that determining the content of different groups of phenolic compounds is consistent with the data obtained in the study of individual indicators of antioxidant potential. These samples, especially «Azotohelp®» and Stop-Stress complex, were characterized by high antiradical activity against the stable 2,2-diphenyl-1-picrylhydrazyl radical (DPPH•). The increase in the level of phenolic compounds in plants, namely phenolic carboxylic acids, largely determines their high radical-inhibitory activity.

The content of flavonoids was the highest in sample with «Liposam®» and amounted to 48.32 ± 1.46 mg RE/g extract. According to the literature, flavonoids, due to their complex chemical structure, are able to effectively inactivate the highly reactive hydroxyl radical, which causes complex damage to important biopolymers.

High levels of ortho-dihydroxyphenols were also found in samples «Liposam®» and Stop-Stress complex: 14.43 ± 0.69 mg Caf/g extract and 18.61 ± 1.97 mg Caf/g extract. The concentration of o-dihydroxyphenols indicates the degree of plant resistance, as they become highly reactive upon oxidation and can form substances toxic to pathogens or inactivate enzymes, including hydrolytic enzymes produced by plant pathogenic fungi.

Biochemical Chromatographic Profiling of the Phenolic Compounds Complex in Maize Leaves

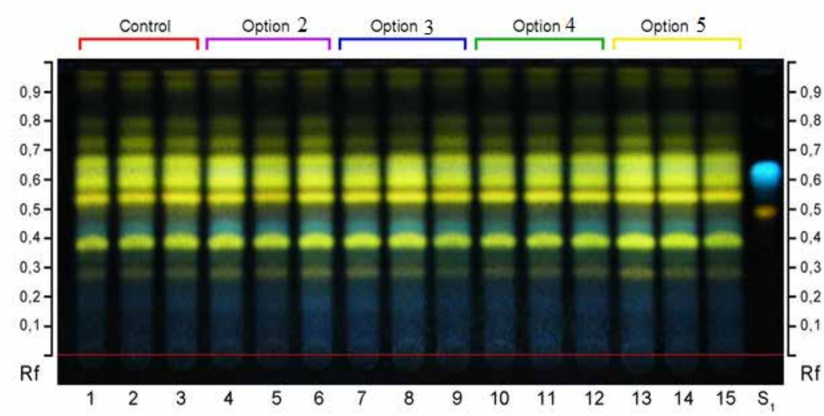
Flavonoids in plant cells and tissues represent a class of phenolic substances, highly important for adaptation reactions. The exceptional selectivity of these compounds is so significant that they can be considered as molecular regulators of complex physiological processes: from transmembrane transport of molecules, acting as ionophores, controlling the activity of enzymes, and regulating the function of transport proteins (especially those responsible for auxin transport), to interactions between organisms, serving as specific signaling molecules for many symbiotic microorganisms in the soil.

Among the primary substances of the phenol class, flavonoids occupy an intermediate position in terms of content in plant tissues. On average, their amount varies from 0.5 to 20.0 mg/g dry mass depending on plant species, age, and growth conditions.

In maize, the main flavonoids are represented by flavone C-glycosides: isovitexin and iso-orientin. From the first compound, further derivatives such as ramnosylisovitexin and apimaysin are formed, and from the second, ramnosyliso-orientin and maysin are derived. These substances possess high biological activity, particularly helping plants defend against pests.

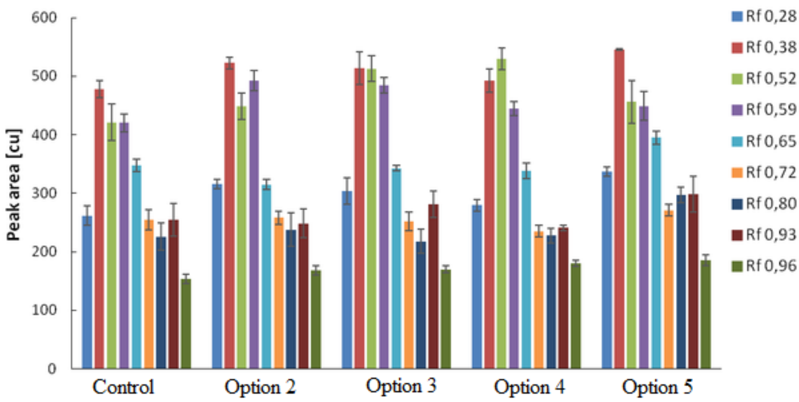
Flavanones naringenin and eriodictyol serve as precursor molecules for the synthesis of all the aforementioned C-glycosides (Peniche-Pavía et al., 2022). Our chromatographic profiling of five samples in maize leaves revealed 9 major flavonoids (Figure 5).

Figure 5. Chromatogram of methanol extracts of maize leaves: control (1-3), option 2 - treatment with «Organic-Balance®» 0.5 l/ha (4-6), option 3 - treatment with «Azotohelp®» 0.3 l/ha (7-9), option 4- treatment with «Liposam®» 0.5 l/ha (10-12), option 5 - treatment with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha (13-15). S1 – standards: rutin, chlorogenic acid



The order of their placement on the histogram corresponds to the retention index on the chromatogram (Rf). The first five compounds (F1-F5) are the most polar in their position on the chromatogram and correspond to the characteristics of C-glycosides (isovitexin, iso-orientin, from which ramnosylisovitexin and apimaysin, ramnosyliso-orientin and maysin are formed) (Figure 6).

Figure 6. The impact of different biological treatments on the content of individual flavonoids in maize leaves (based on the areas of chromatographic peaks) (option 2 - «Organic-Balance®» 0.5 l/ha at the 3-5 leaf stage, option 3 -«Azotohelp®» 0.3 l/ha at the 3-5 leaf stage, option 4 - «Liposam®» 0.5 l/ha at the 3-5 leaf stage, option 5 - Stop-Stress complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha) at the 3-5 leaf stage)

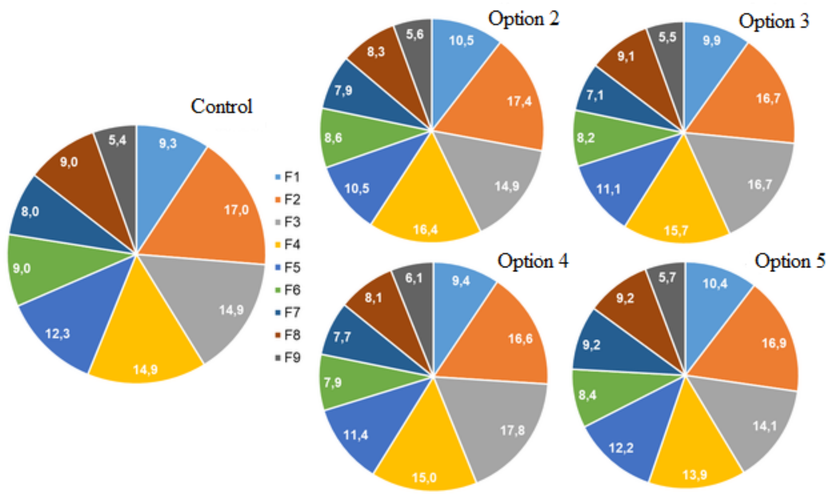


Flavonoids (F6-F7) with retention indices Rf ~ 0.72 and 0.80, respectively, are medium-polar (likely corresponding to isovitexin and iso-orientin). To confirm this assumption, further analysis of these compounds by LC-MS is necessary. It should also be noted that isovitexin, formed from apigenin, would be expected among the less polar compounds. However, among these flavonoids, only two (Rf ~ 0.93 and 0.96) candidates were detected, likely represented by precursor substances – naringenin (4',5,7-trihydroxyflavanone) and eriodictyol (3',4',5,7-tetrahydroxyflavanone). It is possible that the separation capacity of the chromatography conditions did not allow detecting other flavonoids present in minor quantities in the leaves.

Depending on the method of treatment, the proportion of the main polyphenols of this class in the leaves somewhat varied (Figure 7). Compared to the control, the total sum of flavonoids increased in all samples. However, according to the results of the analysis of variance (ANOVA), this increase was statistically significant ($p < 0.05$) only in plants treated with Stop-Stress complex. It should be noted that the proportion of flavonoid F5 in the total varied by 1.8% depending on the treatment conditions, F4 by 2.5%, while the variability of flavonoid F9 content under different conditions was only 0.7%.

Overall, the ratio of individual flavonoids in maize leaves was balanced. Considering the extremely important role of these compounds in regulating physiological processes of the plant organism, each step in their synthesis is coordinated and does not significantly depend on external factors. Nevertheless, under plant treatment conditions, the content of three main glycosides (Rf ~ 0.38, 0.52, 0.59) increased quantitatively against the overall increase in the sum of flavonoids.

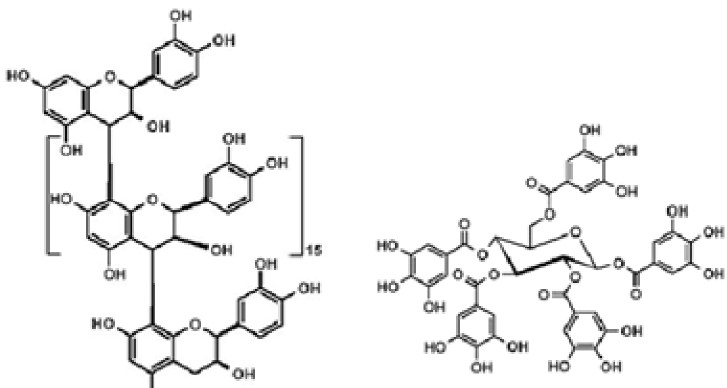
Figure 7. Proportion of individual flavonoids in their total sum (%) contained in maize leaves under various treatment methods (Option 1- Control, Option 2 - «Organic-Balance®» 0.5 l/ha at the 3-5 leaf stage, Option 3 -«Azotohelp®» 0.3 l/ha at the 3-5 leaf stage, Option 4 - «Liposam®» 0.5 l/ha at the 3-5 leaf stage, Option 5 - Stop-Stress complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha) at the 3-5 leaf stage)



Since flavonoids in maize leaves are products of sequential metabolic transformations, with glycosylated forms as the end compounds in the synthesis pathways, it is evident that the majority of them are represented by compounds F1-F5. Under the action of biopreparations, their proportion in the leaves increased by 8-13% depending on the treatment variant. The most active glycosylation processes of flavonoids (up to 13%) occurred under plant treatment with «Stop-Stress» complex.

Conducting multiple correlations between the content of flavonoids allowed for the identification of systematic links between the products of flavonoid synthesis (Figure 8).

Figure 8. Correlation matrices for the dynamics of flavonoid content in maize leaves under the influence of biopreparations: considering all plant treatment methods (a), considering treatment with «Liposam®» 0.5 l/ha, and with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha (b)

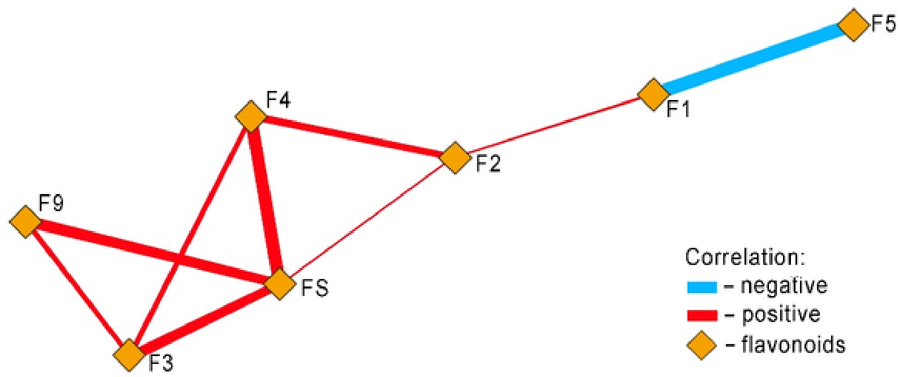


Pentagalloylglucose

It was determined that the most significant positive correlation with glycosides has flavonoid (F9) with the highest retention index (Rf ~ 0.96). The total sum of flavonoids also has a close positive relationship with this compound. Therefore, the increase in its synthesis under all variants of plant treatment led to an increase in the total sum of flavonoids. As a result, the adaptive status of the plants grew, especially under treatment options «Liposam®» 0.5 l/ha and «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha (Figure 8, b).

From the results of the analysis of the interrelationship of individual flavonoid contents, it was found that only four of them are closely and positively related (F2-F4 and F9) (Figure 9). Flavonoid F5 (Rf ~ 0.65) has an inverse relationship with F1, likely the most polar product of this class of compounds with the lowest chromatographic mobility (Rf ~ 0.28) in the distribution system.

Figure 9. Metabolic interactions network among individual flavonoids in maize leaves under the influence of biotic and abiotic factors



Correlation networks can provide information about the most probable biochemical synthesis pathways for key products. A high degree of conformity in modeled biochemical networks lays the foundation for identifying new connections between metabolites, potentially uncovering yet undiscovered metabolic regulatory interactions. Discovering such new interactions could expand the understanding of the nature of cellular metabolism.

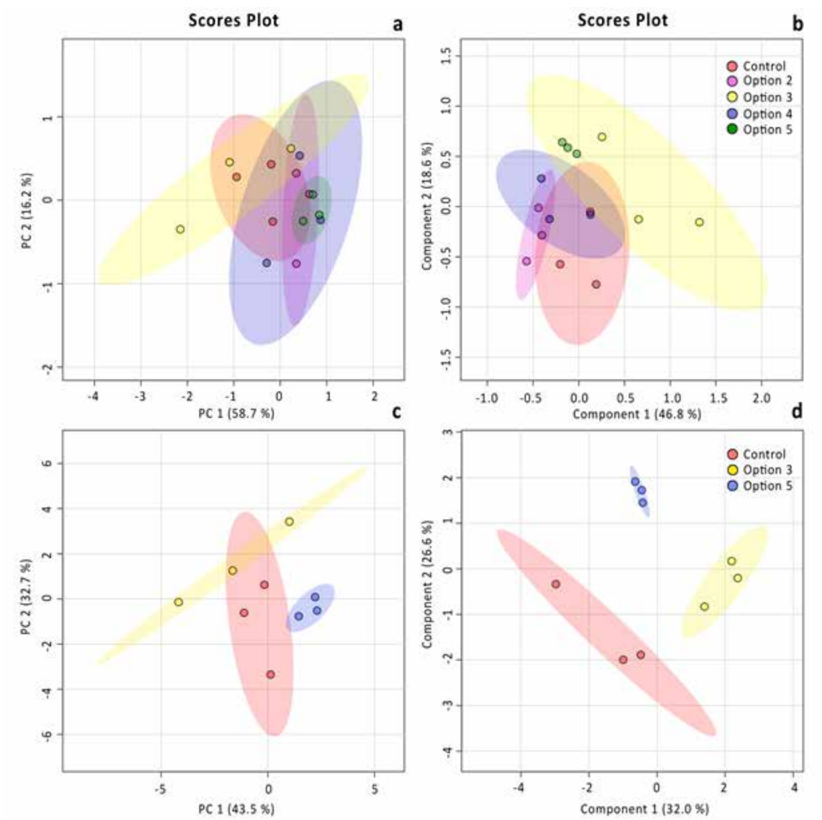
To understand the sensitivity of individual steps in flavonoid synthesis to specific maize plant treatments, principal component analysis (PCA) and partial least squares discriminant analysis (PLS-DA) were employed. These analytical techniques facilitate classification and the identification of potential biomarkers of plant responses to influencing agents. During the double cross-validation procedure, it was determined that the discriminant model describing plant responses considering all treatment options of the crop was not sufficiently reliable for accurately assessing the statistical significance of its performance (Figure 10, b).

This may indicate that the difference in plant metabolomics, including data from all treatment options, does not allow distinguishing the obtained samples as separate groups. However, the model based on data from samples treated with «Liposam®» 0.5 l/ha and «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha proved to be quite acceptable for interpretation (Figure 10, b, c). Consequently, it was elucidated that plants under the influence of these treatment methods indeed change their metabolic status, which is associated with increased productivity of flavonoid synthesis.

For the treatment with «Liposam®» 0.5 l/ha, specific molecular markers of plant response may be flavonoids: F3, F4, and F9, while for the treatment with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha, F1 and F7 may also be specific. To more fully and deeply understand the mechanisms of action of these active compounds, additional research is required, which involves:

- Identification of the specified flavonoids;
- Determining the antioxidant potential of flavonoids;
- Conducting specialized studies on their role in plant adaptation and in the defense system against pathogens and pests;
- Determining the effects of these flavonoids on endophytic microorganisms and the rhizosphere;
- Clarifying their role in the communication system between the plant and soil microorganisms;
- Investigating the expression of genes responsible for the sequential synthesis of flavonoids in metabolic pathways.

Figure 10. The results of Principal component analysis (PCA) (figures a and c) and Partial least squares discriminant analysis (PLS-DA) (figures b and d) were utilized to evaluate the variations in the composition of the flavonoid complex in maize leaf samples treated with various biopreparations (Option 1- Control, Option 2 - «Organic-Balance®» 0.5 l/ha at the 3-5 leaf stage, Option 3 -«Azotohelp®» 0.3 l/ha at the 3-5 leaf stage, Option 4 - «Liposam®» 0.5 l/ha at the 3-5 leaf stage, Option 5- Stop-Stress complex («Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha) at the 3-5 leaf stage)



Flavonoids and other phenolic compounds have antioxidant capacity, and their accumulation can prevent the formation of ROS. The accumulation of secondary metabolites and their changes, induced by PGPR, serve as an initial mechanism for the preliminary activation of the plant's antioxidant system, leading to a more reliable defense system after stress signals, through the phenomenon of priming, which leads to the stimulation of plant growth and is based on PGPR-induced metabolic reprogramming and the mitigation of oxidative stress caused by drought through non-enzymatic mechanisms.

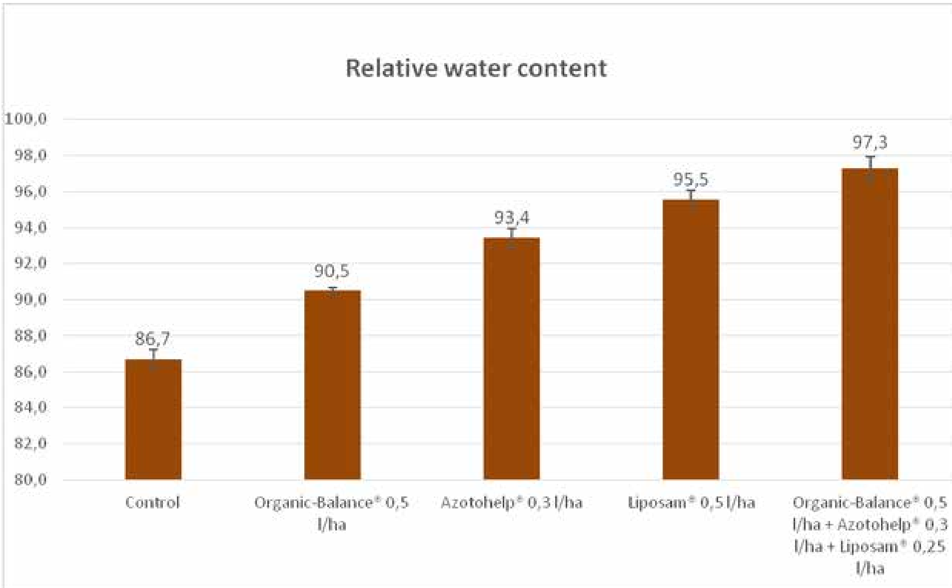
Determination of Relative Water Content, Relative Turgidity (RWC)

Water deficit adversely affects the growth and development of plants, causing a series of changes at molecular and cellular levels that lead to alterations in plant physiology and morphology. During drought stress, plants perceive stress signals through receptors and sensors, initiating a general signal transduction pathway that leads to the production of secondary messengers and the activation of a phosphorylation cascade targeting proteins involved in regulating stress protection genes. Stress-regulated genes and their products play a key role in stress responses and drought tolerance, regulating cellular and physiological changes such as osmolyte accumulation, membrane protection, ROS scavenging, and stomatal closure. However, the natural plant response to drought stress is not always sufficient to ensure plant survival under drought conditions. To overcome this, the recent focus has been on the use of biostimulants as a sustainable strategy.

Research findings indicate that in the absence of rainfall in May at the experimental station of the Institute of Agriculture of the Northeast, maize plants treated with «Organic-Balance®» 0.5 l/ha + «Azotohelp®» 0.3 l/ha + «Liposam®» 0.25 l/ha had the highest relative water content (97.3%) compared to the control (86.7%).

In our experiment, the RWC of control plants was 86.7%, while plants treated with microbiological preparations ranged from 91% to 97% (Fig.11). This indicates significantly higher water stress resistance and the ability of plant organisms to maintain normal metabolism under harsh environmental conditions.

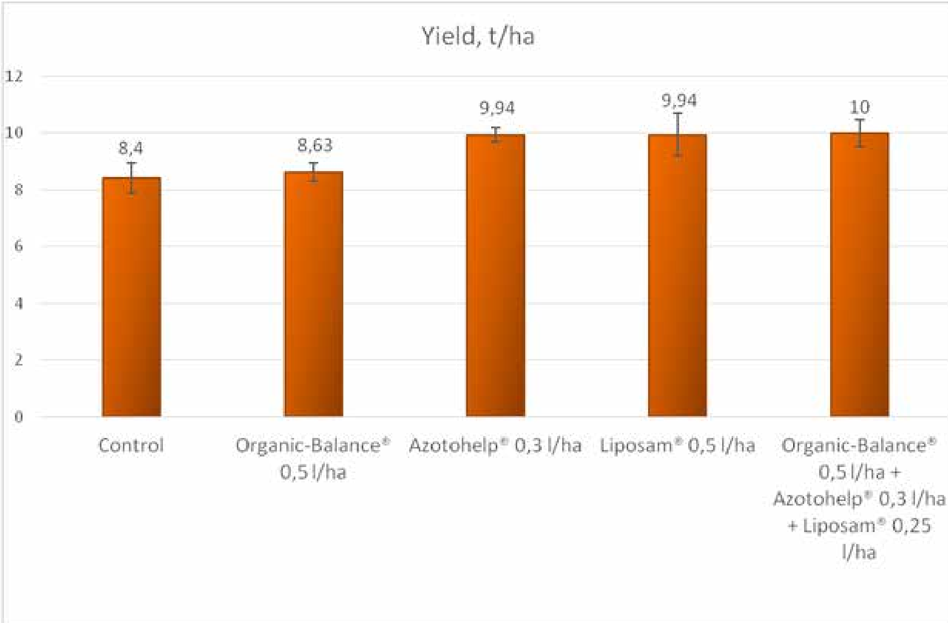
Figure 11. The impact of treating maize plants with biopreparations on the relative water content of the leaves



Similarly, inoculation with PGPR *Pseudomonas putida* GAP-P45 improved plant biomass, relative water content, and leaf water potential by accumulating proline in maize plants experiencing drought stress (Sandhya et al., 2010). Plant inoculation with PGPR increases the available concentrations of proline; a significant amount of proline increased when maize plants were inoculated with *P. fluorescens* during drought stress (Ansary et al., 2012).

The increased ability to sustain essential physiological processes under stressful conditions translates into higher yields. Control plants yielded an average of 8.4 t/ha, whereas plants treated with «Organic-Balance®», «Azotohelp®», «Liposam®» and a mixture of all three yielded 8.63 t/ha, 9.22 t/ha, 9.94 t/ha, and 10.0 t/ha, respectively.

Figure 12. The effect of biopreparation treatments on maize yield



In conclusion, our comprehensive investigation into the effects of microbiological preparations, incorporating PGPB and water stress-mitigating exopolysaccharides, on maize's drought resistance has yielded promising results. This study provides strong evidence of the significant benefits of these preparations. Treated maize plants exhibited enhanced drought resistance, as indicated by decreased expression of key water stress marker genes and an elevated flavonoid profile. Notably, the RWC measurements demonstrated the capacity of treated plants to maintain vital metabolic functions even in adverse environmental conditions.

THE DIRECTION OF FUTURE RESEARCH

While we have highlighted the positive outcomes of microbial biopreparations, it is equally important to address the limitations and challenges of implementing these solutions at a larger scale.

These challenges include the variability in effectiveness across different soil types and climatic conditions, the high cost and complexity of large-scale production and application, and the need for specialized knowledge and training for farmers. Additionally, regulatory hurdles and the time required for rigorous testing and approval processes can delay the adoption of these products.

We are going to investigate the effectiveness of "BTU-center" biologicals of are of great significance in the context of sustainable agriculture, offering a potential solution to the challenges posed by water stress in crop production. By utilizing microbiological approaches and harnessing the beneficial properties of PGPB and their metabolites, we can enhance maize's ability to withstand drought. This not only leads to increased yields but also holds promise for more resilient and sustainable agricultural practices. As global concerns over water stress and climate change continue to grow, these insights pave the way for innovative and eco-friendly strategies that can contribute to food security and crop productivity in a changing world.

CONCLUSIONS

1. Our experimental data revealed that the relative expression levels of marker genes in all variants treated with microbiological biopreparations were significantly lower than in the control group. The most substantial reduction was observed in plants treated with «Liposam®», «Organic-Balance®» and a «Stop-Stress» complex. These results suggest that PGPB enhances drought tolerance in maize, likely by increasing their water retention and antioxidant capacity through phytohormone and biologically active compound synthesis.
2. The accumulation of secondary metabolites and changes induced by PGPB represent an initial mechanism for priming the antioxidant system in plants, leading to a more robust defense system following stress signals. This phenomenon, known as priming, stimulates plant growth and underlies PGPB-induced metabolic reprogramming and oxidative stress mitigation during drought through non-enzymatic mechanisms. Overall, the balance in the content of individual flavonoids in maize leaves was well-maintained. Given the critical role of these compounds in regulating plant physiological processes, their synthesis appears to be finely tuned and relatively independent of external factors.
3. The ability of crops to maintain adequate water status and efficiently utilize available resources is vital for their growth and survival in water-deficient environments. The water content of plant organs reflects their metabolic activity. The distribution of water among roots, stems, leaves, and fruits is a crucial aspect of resource allocation in crops, directly reflecting their pattern of water acquisition and utilization. During drought stress, the relative water content of leaf tissues is adversely affected, dropping from nearly 98% in fully turgid leaves to about 30-40% in severely desiccated and dying leaves.

4. The RWC of control plants was 86.7%, while plants treated with microbiological preparations ranged from 91% to 97%. This indicates significantly higher water stress resistance and the ability of plant organisms to maintain normal metabolism under harsh environmental conditions.
5. The increased ability to sustain essential physiological processes under stressful conditions translates into higher yields. Control plants yielded an average of 8.4 t/ha, whereas plants treated with «Organic-Balance®», «Azotohelp®», «Liposam®» and the «Stop-Stress» complex yielded 8.63 t/ha, 9.22 t/ha, 9.94 t/ha, and 10.0 t/ha, respectively.
6. In conclusion, our comprehensive investigation into the effects of microbiological preparations, incorporating PGPB and water stress-mitigating exopolysaccharides, on maize's drought resistance has yielded promising results. This study provides strong evidence of the significant benefits of these preparations. Treated maize plants exhibited enhanced drought resistance, as indicated by decreased expression of key water stress marker genes and an elevated flavonoid profile. Notably, the RWC measurements demonstrated the capacity of treated plants to maintain vital metabolic functions even in adverse environmental conditions.

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