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OPTIMIZATION OF LAND USE SYSTEMS FOR RADIOACTIVELY CONTAMINATED TERRITORIES OF UKRAINIAN POLISSIA: THEORETICAL AND PRACTICAL APPROACHES

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The radioecological situation in territories contaminated due to the Chornobyl Nuclear Power Plant accident remains challenging, particularly in the Zhytomyr, Kyiv, and Rivne regions, where certain products continue to exhibit elevated levels of radionuclide content. Contemporary challenges — such as the full-scale war, which has led to the loss of productive lands in southern and eastern Ukraine, and climate change, manifested through rising temperatures, altered precipitation patterns, and intensified erosion processes — underscore the urgent need to fully reintegrate radioactively contaminated territories into agricultural production to ensure the country's food security. The objective of this study is to develop theoretically grounded and practically feasible recommendations for optimizing land use in radioactively contaminated areas of Ukrainian Polissia, based on an adaptive-landscape farming system and a scenario-based approach to agricultural activities, taking into account current ecological, climatic, and socio-economic challenges. The study employed methods of scenario modeling, multi-criteria analysis, spatial modeling, expert ranking, systems analysis, and geospatial modeling. Five model scenarios for agricultural activities were developed: "Current Practice" (crop-based), "Dairy Farming" (crop-livestock), "Bioenergy" (livestock-crop), "Beef Farming," and "Intensive Beef Farming" (livestock-based), considering the level of ^{137}Cs contamination, soil types, climate change, war-related impacts, and the requirements of the European Green Deal. Comparative analysis based on criteria of economic efficiency, ecological safety, social acceptability, adaptability to climate change, and compliance with international standards demonstrated the highest effectiveness of the adaptive-landscape farming system for Polissia conditions. The proposed classification of lands by the level of radioactive contamination enables a differentiated approach to their use, ranging from cultivation of all regionally adapted crops to afforestation and phytoremediation. The integration of scenarios with the adaptive-landscape system reduces radionuclide accumulation in products by 2–3 times through the selection of crops and crop rotations, restores the fertility of sod-podzolic soils, and enhances economic profitability. The study's findings can be utilized to develop national strategies for reintegrating contaminated lands into agricultural production, establishing incentive mechanisms, and ensuring Ukraine's food security.

Keywords: *radioecological safety, adaptive-landscape system, agricultural production scenarios, climate change, war-related impacts, bioenergy, crop rotations, phytoremediation, soil fertility.*

INTRODUCTION

Despite the reduction in the area of radionuclide-contaminated lands in the decades following the Chornobyl Nuclear Power Plant accident, the radioecological situation remains complex, particularly in the Zhytomyr, Kyiv, and Rivne regions, where certain products (milk, mushrooms, berries) continue to exhibit elevated levels of radionuclide content [1; 2]. Contemporary challenges, such as the full-scale war that has resulted in the loss of productive lands in southern and eastern Ukraine, underscore the urgent need to fully reintegrate radioactively contaminated territories into agricultural production to ensure the country's food security [3; 4]. Concurrently, climate change, manifested through rising temperatures, altered precipitation patterns, and intensified erosion processes, presents both new opportunities and risks for agriculture in Polissia [5].

Global experience in managing degraded lands demonstrates a variety of approaches. In the United States, EPA standards are applied to balance economic, social, and environmental objectives [6; 7], while Japan utilizes GIS technologies to model radionuclide migration [2]. In Europe, emphasis is placed on phytoremediation and adaptive farming practices [8]. In Ukraine, studies substantiate the effectiveness of adaptive-landscape systems and agricultural production scenarios in reducing radioecological risks and enhancing soil productivity [9–13]. However, a comprehensive approach that integrates radioecological, climatic, war-related, and socioeconomic factors remains underdeveloped. The lack of up-to-date monitoring data, outdated methods for assessing contamination, and limited coordination among institutions hinder the rational use of Polissia's lands.

The objective of this study is to develop theoretically grounded and practically feasible recommendations for optimizing the land use system of radioactively contaminated territories in Ukrainian Polissia, based on an adaptive-landscape farming system and a scenario-based approach to agricultural activities, taking into account contemporary ecological, climatic, and socio-economic challenges.

REVIEW OF RECENT RESEARCH AND PUBLICATIONS

The issue of managing radioactively contaminated lands in Ukrainian Polissia is a subject of active investigation within the context of restoring their agricultural production potential. Global research offers various approaches to the rehabilitation of degraded territories. For instance, in the United States, recommendations have been developed that emphasize balancing economic, social, and environmental factors in land use planning [6–7]. Japan employs GIS technologies and radionuclide transfer models to assess risks and adapt agricultural production [2], while in Chile, geospatial systems are used to classify lands based on their suitability for use [14]. In Italy, models such as Dyna-CLUE are applied to forecast land use changes with a focus on phytoremediation [8], whereas strategies in China and Brazil are grounded in risk assessment and socio-economic contexts [15–17].

In Ukraine, significant contributions have been made by researchers from the Institute of Agroecology and Environmental Management, who substantiate the economic and energy efficiency of adaptive-landscape systems and agricultural production scenarios for radioactively contaminated lands in Polissia [9–13; 18–19]. These studies demonstrate that the appropriate selection of crops and crop rotations can reduce radionuclide accumulation in products by 2–3 times. S. O. Galaburda and others highlight the necessity of adapting to climate change, which affects the region's agroclimatic potential, particularly through rising temperatures and altered precipitation patterns [5]. The impact of military actions on soil degradation has been examined by numerous researchers [20; 21], emphasizing the long-term consequences for land productivity.

International standards, particularly the principles of the European Green Deal (EGD) and the UN Food Systems Summit, underscore the importance of resource-efficient technologies, circular economy practices, and bioenergy for sustainable development [22]. However, there is a lack of comprehensive studies that integrate radioecological, climatic, war-related, and socio-economic factors to develop adaptive land use scenarios for Polissia conditions, highlighting the relevance of this research.

MATERIALS AND METHODS

The study was conducted using a comprehensive approach that integrated theoretical and applied analytical methods. To optimize model scenarios for agricultural production, the scenario modeling method was employed, taking into account key modifying factors. Five model scenarios with different specializations were developed based on the adaptive-landscape farming system [23] and studies [9–13; 18].

To compare pathways for optimizing land use, a multi-criteria analysis was conducted based on the following key criteria: economic efficiency, ecological safety, social acceptability, adaptability to climate change, and compliance with international standards. The evaluation was performed using the expert ranking method with a scoring scale.

The optimization of the land use structure was based on spatial analysis with the classification of lands according to the level of ^{137}Cs contamination. The integration of agricultural production scenarios with the adaptive-landscape system was achieved through geospatial modeling, considering the agrochemical properties of soils and the radioecological characteristics of the territories.

Data sources included scientific publications, reports from governmental organizations, radioecological monitoring data, and results from the authors' own research, as well as studies conducted by the Institute of Agriculture of Polissia of the NAAS. Methods of systems analysis, abstract-logical reasoning, and monographic approaches were used to provide theoretical justification for the results.

RESULTS AND DISCUSSION

The studies [9–13; 18–19; 23] facilitated the development of a comprehensive system for optimizing land use in radioactively contaminated territories of Ukrainian Polissia, integrating an adaptive-landscape farming system with a scenario-based approach to agricultural production. The primary focus was on four key aspects: optimization of model agricultural production scenarios, comparison of land use optimization pathways, classification of lands based on contamination levels, and integration of scenarios with the land use structure. Five model scenarios for agricultural production were developed, tailored to key modifying factors: the level of radioactive contamination, soil types, climate change, war-related impacts, and the requirements of the European Green Deal (EGD) (*Table 1*). The scenarios include: No. 1 "Current Practice" (crop-based), No. 2 "Dairy Farming" (crop-livestock), No. 3 "Bioenergy" (livestock-crop), No. 4 "Beef Farming" (livestock-based), and No. 5 "Intensive Beef Farming."

Scenarios No. 1 and No. 2 are the most resource-efficient and suitable for the conditions of limited resources during wartime, while scenarios No. 3–5, particularly the bioenergy scenario, show potential for long-term development with sufficient investment, contributing to energy independence and ecological sustainability [9–13]. The optimization of scenarios accounts for the balance between humification and mineralization of organic matter, which is critical for restoring soil fertility. Traditional scenarios involve the application of 10 t/ha of organic fertilizers and 150–200 kg/ha of mineral fertilizers, whereas alternative scenarios utilize green manures and by-products at a ratio of 1 t of organic matter to 15 kg of active ingredient mineral fertilizers.

Comparison of land use optimization pathways based on key criteria (*Fig. 1*) demonstrated that the adaptive-landscape farming system is the most effective for Polissia. This system accounts for the agrochemical properties of soils, climate change, and the consequences of military actions, enabling a 2–3-fold reduction in radionuclide accumulation in products through the selection of crops (winter cereals instead of spring cereals, alfalfa instead of clover) and crop rotations [9].

Table 1

Optimization of model scenarios for agricultural production in radioactively contaminated territories of Ukrainian Polissia based on key modifying factors

Scenario	Impact of Climate Change	Adaptation of Agricultural Practices	Prospects for Crop Cultivation	Challenges of Erosion and Soil Degradation	Socio-Economic and Innovative Solutions
Scenario No. 1 "Current Practice"	Introduction of climate-resilient crops (soybean, sunflower, buckwheat)	Minimal tillage, no-till practices	Winter wheat, potatoes, soybean, sunflower, buckwheat	Preservation of soil structure, reduction of erosion	Limited use of innovations due to financial constraints
Scenario No. 2 "Dairy Farming"	Introduction of climate-resilient crops (maize, oats, lupine, triticale)	Traditional organo-mineral fertilization system (manure + NPK)	Maize, oats, lupine, triticale	Use of local feed at the initial stages of fattening	Increased productivity of dairy cows, need for investment
Scenario No. 3 "Bioenergy"	Introduction of bioenergy crops (miscanthus, willow)	Minimal tillage, precision agriculture system	Maize for silage, bioenergy crops	Preservation of soil structure, reduction of erosion	Use of biogas plants, the need for investment
Scenario No. 4 "Livestock 1"	Introduction of climate-resilient crops (winter wheat, maize, potatoes, lupine)	Organo-mineral fertilization system, minimal tillage	Winter wheat, maize, potatoes, lupine	Preservation of soil structure, reduction of erosion	Waste processing for bioenergy, need for investment
Scenario No. 5 "Livestock 2"	Introduction of climate-resilient crops (winter wheat, maize, potatoes, sunflower)	Organic fertilization system, minimal tillage	Winter wheat, maize, potatoes, sunflower	Preservation of soil structure, reduction of erosion	Use of biogas plants, need for investment

Source: adapted by the authors based on [9–13].

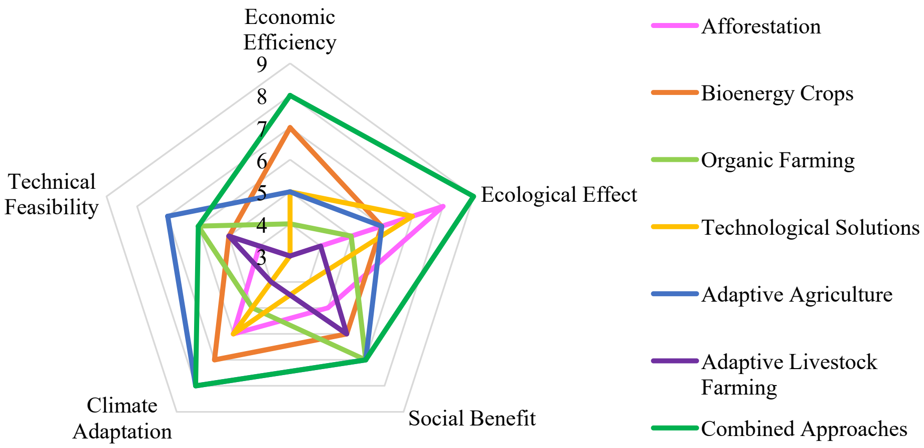

Fig. 1. Comparison of land use optimization pathways in Ukrainian Polissia based on key criteria

Source: constructed by the authors.

Sod-podzolic soils exhibit a higher restorative potential compared to chernozems, facilitating faster reintegration of lands into agricultural use with the application of organic and mineral fertilizers at the specified rates [12–13]. The adoption of water-saving technologies (No-Till, Strip-Till, and drip irrigation) enables adaptation to intensified erosion processes caused by climate change and military activities. The bioenergy scenario (No. 3) proved promising for lands with moderate contamination, as the cultivation of energy crops (maize, rapeseed) reduces radioecological risks and enhances economic profitability [9; 24]. Overall, combined approaches were found to be the most effective across all selected criteria.

The optimization of the land use structure is based on the adaptive-landscape farming system, which classifies lands according to the level of ^{137}Cs contamination (*Fig. 2*): <37 kBq/m^2 — unrestricted use for all regionally adapted crops; 185–370 kBq/m^2 — restrictions on the cultivation of certain crops (e.g., lupine, table potatoes);

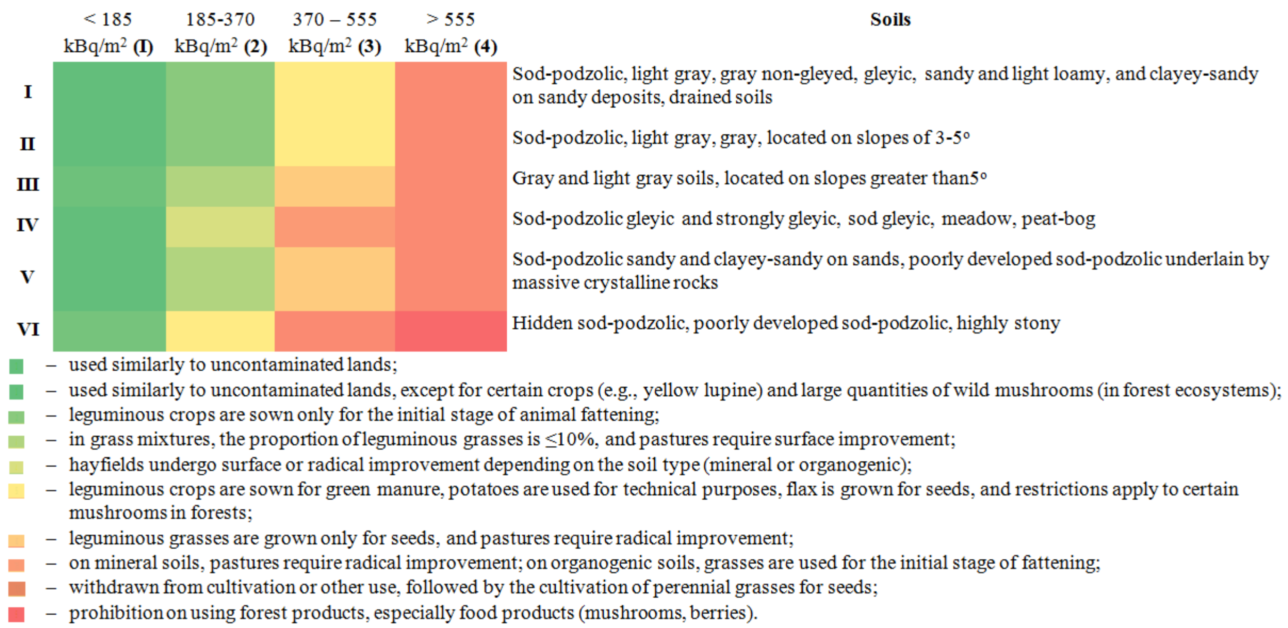

Fig. 2. Optimization of the land use structure for radioactively contaminated territories: I — lands suitable for all regionally adapted crops; II — lands suitable for continuous cropping; III — sloped lands requiring grassing; IV — lands designated for haymaking under livestock specialization; V — lands designated for pastures under livestock specialization; VI — lands designated for forestry purposes

Source: constructed by the authors based on [23].

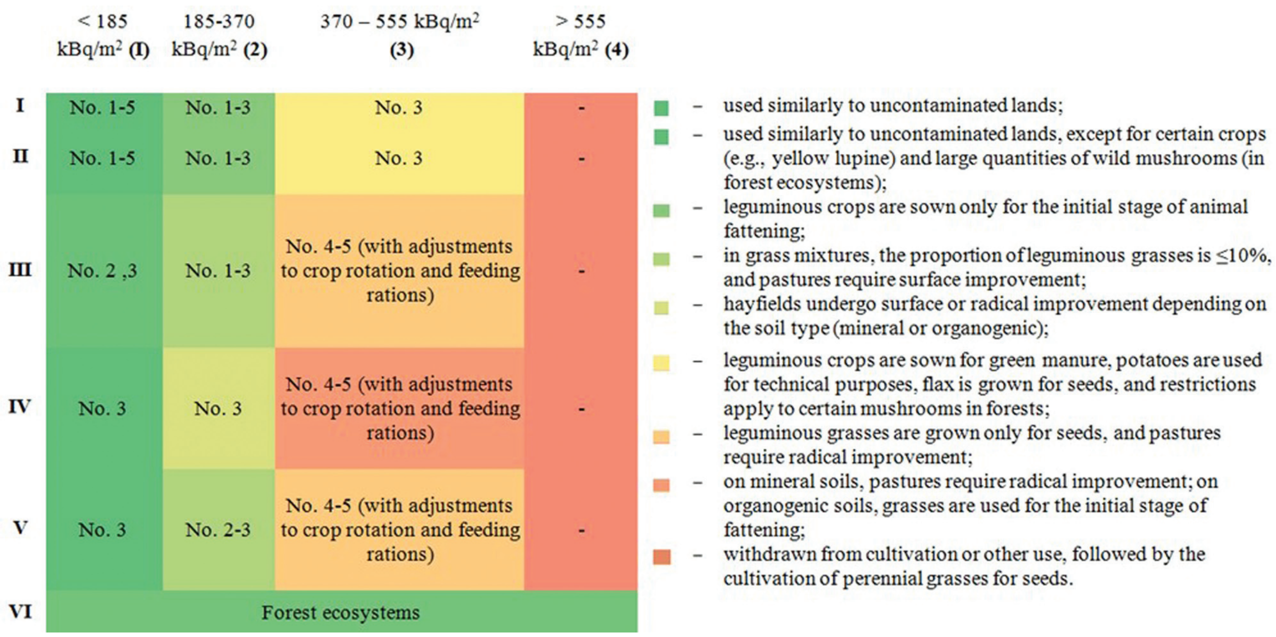

Fig. 3. Optimization of the land use structure for radioactively contaminated territories based on different agricultural production scenarios:
I — lands suitable for all regionally adapted crops; II — lands suitable for continuous cropping; III — sloped lands requiring grassing; IV — lands designated for haymaking under livestock specialization; V — lands designated for pastures under livestock specialization; VI — lands designated for forestry purposes

Source: constructed by the authors based on their own research and [9–13; 23].

370–555 kBq/m² — grain legumes used only as green manures, with an emphasis on technical crops; >555 kBq/m² — withdrawal from cultivation, afforestation, or phytoremediation. This system accounts for the varying capacities of crops to accumulate ^{137}Cs. The integration of agricultural production scenarios with this structure (*Fig. 3*) ensures a differentiated approach to land use: all scenarios are applied to lands with low contamination, crop-based and bioenergy scenarios are used for moderately contaminated lands, and afforestation or pasture use with radical improvement is employed for highly contaminated lands.

The proposed system delivers ecological, economic, and social outcomes. Ecologically, it reduces radionuclide content in products, improves the agrophysical properties of soils, and mitigates erosion. Economically, it enhances crop yields, reduces reclamation costs, and ensures profitability. Socially, it contributes to job creation and improves quality of life [9; 12]. Military actions that have caused soil degradation in Ukrainian Polissia necessitate a focus on bioenergy and afforestation, aligning with international sustainable development standards. Future research should prioritize enhancing monitoring techniques (GIS, drones, AI), developing climate-adapted crop varieties with low radionuclide accumulation, and establishing economic incentive mechanisms.

CONCLUSIONS

The conducted research facilitated the development of five model scenarios for agricultural production ("Current Practice," "Dairy Farming," "Bioenergy," "Beef Farming," and "Intensive Beef Farming"), tailored to key modifying factors: the level of radioactive contamination, soil types, climate change, war-related impacts, and the requirements of the European Green Deal. Scenarios No. 1 and No. 2 are resource-efficient and suitable for conditions with limited resources, while scenarios No. 3–5 hold potential for long-term development, particularly in bioenergy.

The comparison of land use optimization pathways demonstrated that the adaptive-landscape farming system reduces radionuclide accumulation in agricultural products through the selection of crops (winter cereals, alfalfa) and crop rotations, while also promoting the restoration of sod-podzolic soil fertility through the application of organic and mineral fertilizers or the alternative use of green manures.

The optimization of the land use structure, based on the adaptive-landscape system, involves classifying lands according to the level of ^{137}Cs contamination. This approach mitigates radioecological risks and ensures adaptation to local conditions. The integration of agricultural production scenarios with the adaptive-landscape system achieves ecological (reduced radionuclide content in products, decreased erosion, improved agrophysical soil properties), economic (increased crop yields, reduced reclamation costs), and social (job creation, improved product quality) outcomes, aligning with international sustainable development standards.

Climate change expands opportunities for cultivating non-traditional crops (soybean, sunflower, maize) but exacerbates erosion, necessitating the adoption of water-saving technologies (No-Till, Strip-Till, drip irrigation). Military actions, which have caused soil degradation, highlight the need for bioenergy crops and afforestation to restore the land.

Future research should focus on improving radioecological monitoring using modern technologies (GIS, drones, AI), developing crop varieties with low radionuclide accumulation, and establishing economic incentive mechanisms to accelerate the rehabilitation of radioactively contaminated territories.

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ОПТИМІЗАЦІЯ СИСТЕМИ ЗЕМЛЕКОРИСТУВАННЯ РАДІОАКТИВНО ЗАБРУДНЕНОЇ ТЕРИТОРІЇ УКРАЇНСЬКОГО ПОЛІССЯ: ТЕОРЕТИЧНІ ТА ПРАКТИЧНІ ОРІЄНТИРИ

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Радіоекологічна ситуація на територіях, забруднених унаслідок аварії на Чорнобильській АЕС, залишається складною, особливо в Житомирській, Київській і Рівненській областях, де окремі продукти зберігають підвищений рівень вмісту радіонуклідів. Сучасні виклики — повномасштабна війна, що спричинила втрату продуктивних земель півдня та сходу України, та кліматичні зміни, які проявляються в підвищенні температур, зміні режиму опадів і посиленні ерозійних процесів — актуалізують потребу повноцінного повернення радіоактивно забруднених територій до агровиробництва для забезпечення продовольчої безпеки країни. Метою дослідження є розроблення теоретично обґрунтованих і практично реалізованих рекомендацій щодо оптимізації землекористування радіоактивно забруднених територій Українського Полісся на основі адаптивно-ландшафтної системи землеробства та сценарного підходу до агровиробничої діяльності з урахуванням сучасних екологічних, кліматичних і соціально-економічних викликів. Використано методи сценарного моделювання, багатокритеріального аналізу, просторового моделювання, експертного ранжування, системного аналізу та геопросторового моделювання. Розроблено п'ять модельних сценаріїв агровиробничої діяльності: "Сучасна практика" (рослинницький), "Молочне скотарство" (рослинницько-тваринницький), "Біоенергетичний" (тваринницько-рослинницький), "М'ясне скотарство" та "Інтенсивне м'ясне скотарство" (тваринницькі) з урахуванням рівня забруднення ^{137}Cs, типу ґрунтів, кліматичних змін, воєнних наслідків і вимог Європейського зеленого курсу. Порівняльний аналіз за критеріями економічної ефективності, екологічної безпеки, соціальної прийнятності, адаптивності до кліматичних змін і відповідності міжнародним стандартам показав найвищу ефективність адаптивно-ландшафтної системи землеробства для умов Полісся. Запропонована класифікація земель за рівнем радіоактивного забруднення дає змогу диференційовано підходити до їх використання: від вирощування всіх районованих культур до залісення та фітомеліорації. Інтеграція сценаріїв з адаптивно-ландшафтною системою забезпечує зниження накопичення радіонуклідів у продукції у 2–3 рази через підбір культур і сівозмін, відновлення родючості дерново-підзолистих ґрунтів та підвищення економічної рентабельності. Результати дослідження можуть бути використані для розробки національних стратегій повернення забруднених земель до агровиробництва, створення механізмів стимулювання та забезпечення продовольчої безпеки України.

Ключові слова: *радіоекологічна безпека, адаптивно-ландшафтна система, агровиробничі сценарії, кліматичні зміни, воєнні наслідки, біоенергетика, сівозміни, фітомеліорація, ґрунтова родючість.*

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