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RATIONAL USE OF LAND RESOURCES: ECOLOGICAL AND ECONOMIC ASPECTS OF LAND MANAGEMENT

M. Serbov, *Doctor of Economic Sciences, Professor Dean of the Faculty of Hydrometeorology and Ecology*
E-mail: serbovng@gmail.com
ORCID: 0000-0002-0220-6745
Odesa I.I. Mechnikov National University

A. Chugai, *Doctor of Technical Sciences, Professor Head of the Department of Environmental Science and Environmental Protection*
E-mail: avchugai@ukr.net
ORCID: 0000-0002-8091-8430
Odesa I.I. Mechnikov National University

P. Nikitin, *Senior Lecturer Department of Agrometeorology and Agroecologyor*
E-mail: agroecology87@gmail.com
ORCID: 0009-0004-5755-4116
Odesa I.I. Mechnikov National University

The article examines the problem of ensuring the rational use of land resources under contemporary challenges, including intensive soil degradation, climate change, and the negative consequences of military actions. The purpose of the study is to provide a scientific substantiation of a mechanism for the rational use of land resources through the improvement of land management tools based on the integration of environmental and economic criteria into modeling processes. The theoretical and methodological foundations of rational land use are analyzed. The legislative consolidation of the threefold legal nature of land resources as a territorial basis, a natural object, and a means of production is identified. A territorial spatial planning model is substantiated, in which economic efficiency is subordinated to environmental and economic standards. A system of principles for sustainable land use is considered, combining environmental safety, economic efficiency, and innovation while maintaining a balance between the interests of landowners and society. Criteria for assessing the sustainability of land use aimed at harmonizing environmental requirements and economic interests are defined. An analysis of compliance with the principles of rational land resource use is conducted using the case of Rivne Oblast. The study reveals an expansion of cultivated areas under energy-intensive industrial crops (sunflower and soybean), an intensification of pressure on the region's soils, and a negative humus balance. A multi-objective economic and mathematical model is proposed, based on the principles of balancing the economic efficiency of land use with the environmental safety requirements of territories. The model is substantiated using the scalarization method of objective functions, which provides an effective compromise between maximizing profits from agricultural production and minimizing losses in soil fertility.

***Keywords**: rational land use, land management, ecological and economic aspects, sustainable land use, optimization model, soil degradation, Rivne Region.*

Problem Statement. The current stage of societal development is characterized by an extremely intensive exploitation of land resources, which simultaneously serve as a territorial basis, a natural asset, and a key means of

production. Unsustainable use of land resources is accompanied by excessive ploughing of territories, progressive soil degradation, significant humus losses, and the intensive development of water and wind erosion. In addition to traditional land-use problems, such as violations of crop rotation systems and global climate change, catastrophic consequences of military actions have emerged, causing mechanical destruction, chemical contamination, and mine pollution of vast areas of agricultural land. Consequently, modern land management faces a large-scale challenge: to find an effective compromise between the economic feasibility of agricultural production and the environmental imperative of preserving and restoring soil resources.

Analysis of recent research and publications. Issues related to the rational use of land resources and the environmental and economic aspects of land management have attracted considerable attention from both domestic and international scholars. Fundamental theoretical and methodological principles, as well as practical approaches to the rational use of agricultural land, were established in the works of Moskalenko [1]. Contemporary strategies of sustainable land use, innovative measures for their implementation, and methodologies for assessing the efficiency of land resource utilization by farming enterprises have been comprehensively investigated by a research team including Hutorov, Hutorova, Hroshev, and others [2, 3].

An important direction of modern scientific discourse involves the study of international experience and its adaptation to Ukrainian realities. In particular, the environmental and economic aspects of land use in the United States were examined by Dudych and Dudych [4], while the global experience of state regulation and control of land market transactions was analyzed by Konoplia [5]. A separate body of research focuses on land resource management tools at the local level. Practical aspects of spatial planning for territorial community land use have been investigated by Shevchuk, Chuvpylo, and Domashenko [6]. The significance of land monitoring data as a basis for land management documentation has been substantiated by Hutsuliak and co-authors [7], whereas Sakhno [8] emphasizes the influence of

environmental and economic factors on accounting policies and the audit of land resources.

In the context of current challenges, particular attention is being paid to the functioning of the agricultural sector under crisis conditions. Thus, the environmental and economic aspects of land use under martial law have become the subject of research by Stepanenko [9]. In turn, Pankiv [10] proposes the implementation of nature-based solutions as an effective instrument for mitigating environmental and economic problems.

The purpose of the study is to provide a scientific substantiation of the mechanism for rational land resource use through the improvement of land management tools based on the integration of environmental and economic criteria into modelling processes.

Materials and methods of research. The methodological foundation of the study is a systems approach to the investigation of environmental and economic processes in land use. A combination of general scientific and specialized research methods was employed. The monographic method and systems analysis were applied to investigate the theoretical and methodological foundations of rational land resource use and the principles of sustainable land use. The economic-statistical method was used for the collection, processing, and analysis of primary data on the economic activities of agricultural enterprises (in particular, statistical reports Forms No. 50-ag and No. 24), using the agricultural enterprise Rozvazke (Rivne Oblast) as a case study. The development of the multi-objective environmental and economic optimization model for crop area structure was based on the method of economic and mathematical modelling. In particular, the additive weighted scalarization method was applied to the objective functions to reconcile the competing criteria of profit maximization and the minimization of soil degradation and fertility loss. The computational and constructive method was used to determine the input parameters of the mathematical model, calculate production costs, estimate humus balance, and develop a system of environmental and economic constraints. The abstract-logical

method was employed for the theoretical generalization of modelling results and the formulation of research conclusions.

Results and Discussion. The multifunctional nature of land resources ensures their indispensability across various spheres of social activity, which is manifested through the inseparable combination of spatial and environmental functions. National legislation defines land resources as a complex system integrating environmental, territorial, and economic dimensions. According to Article 14 of the Constitution of Ukraine [11], land is recognized as the principal national wealth under the special protection of the state, thereby establishing its environmental priority as a key component of the biosphere. At the same time, the Land Code of Ukraine specifies this concept through three inseparable dimensions: as a territorial (spatial) basis for the placement of economic sectors and infrastructure; as a natural object subject to protection; and as the primary means of production in agriculture and forestry, reflecting its economic significance [12]. Thus, Ukrainian legislation establishes the threefold legal nature of land resources and formulates a clear regulatory principle: any spatial allocation and intensive economic use of land as a means of production must be strictly subordinated to environmental requirements aimed at preserving soil fertility and maintaining overall ecological balance.

According to contemporary approaches, the rational use of land resources is interpreted as a model of territorial spatial planning in which the achievement of economic efficiency is constrained by environmental and economic standards designed to prevent land degradation. Within the spatial planning system, planning decisions reflect the continuous relationship between the intensive exploitation of land resources and the level of their environmental protection [13].

A practical embodiment of this approach is sustainable land use – a land resource management system that ensures a stable balance between intensive agricultural production and environmental safety [14]. The principles of sustainable land use characterize its logic, structure, and implementation mechanisms, namely: the principle of environmental safety, the principle of economic efficiency, the principle of innovation, and the principle of balancing interests. The comprehensive

implementation of these principles in land management practice facilitates the development of a spatial model that is both economically beneficial for landowners and environmentally safe for society.

In contemporary scientific research, environmental and economic assessment serves as the primary tool for analyzing land use, determining the level of rational territorial utilization and compliance with sustainable development standards [6; 9]. To systematize the multifactor assessment of land-use sustainability, it is advisable to employ a structured analytical framework [16], particularly a system of environmental and economic indicators (Table 1).

Table 1. System of indicators for assessing the sustainability of land use

Land use principle	Indicator group	Specific assessment criteria (indicators)	Data sources
Environmental safety	Natural resource condition	Humus balance, erosion level, soil environmental safety index	Agrochemical field passports, soil survey data
Economic efficiency	Economic performance	Level of differentiated rent, profitability of land protection investments, output per 1 ha	Accounting reports, regulatory monetary valuation
Innovative approach	Technological capacity	Percentage of territory covered by GNSS monitoring, level of GIS data digitization	Geodetic measurements (GNSS/GPS), monitoring materials
Balance of interests	Social and legal condition	Level of compliance of cadastral data, land rent, and budget revenues	State Land Cadastre data (SLC), register of rights

The proposed system of indicators makes it possible to transform the qualitative principles of sustainable land use into quantitative assessment criteria. This is a prerequisite for effective decision-making in land management, ensuring a balance between environmental requirements and economic interests.

Compliance with the principles of rational land resource use was examined using the case of Rivne Oblast, which covers an area of 2,005.1 thousand hectares (3.3% of the territory of Ukraine) and is one of the country's agricultural regions. Within the structure of agricultural land in the study area, arable land accounts for the largest share (over 46.38%) (Table 2). In recent years, the area of agricultural land in Rivne Oblast has shown a tendency to decrease (in 2024, the area declined

by 7.12 thousand hectares, or 0.35%, compared with 2016). This transformation of agricultural land was partly associated with a reduction in arable land areas. The implementation of environmentally oriented land-use practices in the agricultural sector remains relatively slow.

Agricultural lands of Rivne Oblast are characterized by considerable soil cover heterogeneity, which is explained by the region's geographical location within three natural zones: the Forest-Steppe, Polissia, and Small Polissia. Soils with a low humus content (less than 2%) are widespread across all soil-climatic zones and occupy 42.9% of the territory of the region. Degraded lands amounting to 167 ha require reclamation, while 589 ha require conservation measures [17].

Table 2. Structure of the land fund of Rivne Region

Main types of land	2016		2024		Deviation, +/-	
	Thousand ha	Share, %	Thousand ha	Share, %	Thousand ha	Share, %
Total area	2005,1	100	2005,1	100	0	-
Including:						
Agricultural lands	937	46,73	930,0	46,38	-7,0	-0,35
Arable land	648,1	32,32	658,0	32,82	9,9	0,49
Perennial plantations	12,0	0,60	11,0	0,55	-1,0	-0,05
Hayfields	126,8	6,32	124,0	6,18	-2,8	-0,14
Pastures	135,3	6,75	126,0	6,28	-9,3	-0,46
Fallow lands	14,8	0,74	3,0	0,15	-11,8	-0,59
Forest-covered areas	795,3	39,66	803,9	40,09	8,6	0,43
Built-up lands	55,5	2,77	58,0	2,89	2,5	0,12
Degraded lands	106,5	5,31	104,9	5,23	-1,6	-0,08
Other lands without vegetation cover	34	1,70	32,4	1,62	-1,6	-0,08
Water bodies	42,2	2,10	43,3	2,16	1,1	0,05
Other lands	34,6	1,73	32,6	1,63	-2,0	-0,10

One of the key factors determining soil fertility is soil reaction (pH). According to the 2024 soil acidity survey, moderately and strongly acidic soils covering a total area of 8,250 ha of agricultural land require chemical amelioration. Addressing this issue through liming and other chemical reclamation measures is necessary to restore soil fertility and optimize pH levels.

Regarding major land users, the largest share of agricultural land is utilized by agricultural enterprises (422,319 ha) [17]. During the period from 2017 to 2025, the

territory of Rivne Oblast was characterized by unstable conditions and a high level of anthropogenic pressure. An analysis of the production structure by farm category (based on 2025 data) reveals a clear specialization pattern: agricultural enterprises concentrate on the cultivation of resource-intensive industrial crops, including soybean – 123,598 ha (29,3%), maize – 57,667 ha (13,7%), and sunflower – 36,348 ha (8.6%). In contrast, household farms play a crucial role in ensuring food security through the production of potatoes – 65,484 ha (21,7%) and vegetables – 12,004 ha (4.0%) [18].

High crop yields achieved by agricultural enterprises (in particular, wheat yields of 69.4 centners per hectare) indicate an intensive farming model. Such a model requires a well-balanced environmental and economic approach in order to minimize soil degradation processes and ensure the long-term sustainability of agricultural production.

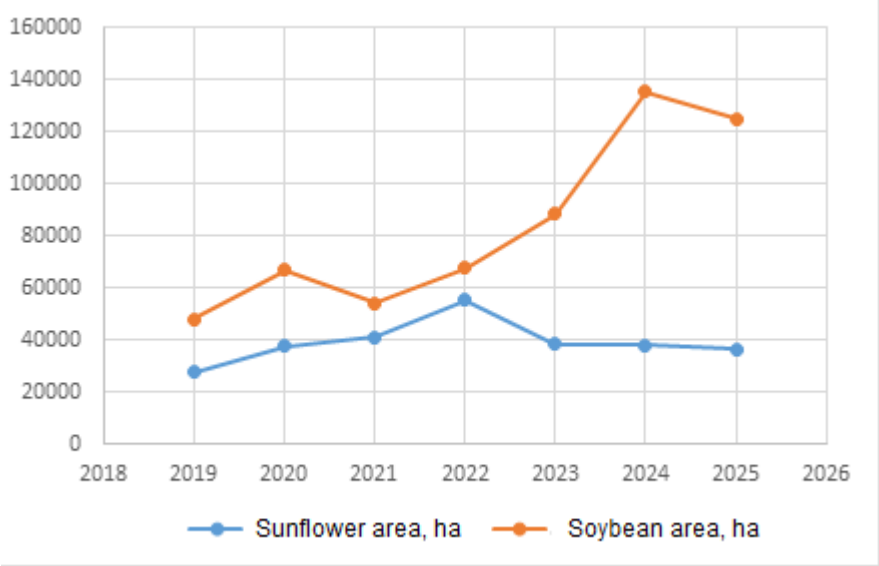

Figure 1. Dynamics of sunflower and soybean sown areas in Rivne Oblast during 2019–2025 [18].

A long-term analysis of statistical data (1995–2024) revealed a pronounced trend toward the extensive expansion of areas cultivated with sunflower and soybean, accompanied by increasing pressure on soil cover (Fig. 1). In particular, the area under sunflower cultivation increased 600-fold compared with 1995. Statistical reports of agricultural enterprises in the region indicate high yields of

wheat (69.4 centners/ha) and soybean (25.5 centners/ha), reflecting the intensive use of land resources. Such production practices contribute to a negative humus balance and lead to disturbances in the environmental and economic equilibrium of land use.

According to data provided by the Rivne Regional Center of the State Institution “Institute for Soil Protection of Ukraine” regarding the biologization of agriculture (incorporation of straw and green manure crops) and humus balance indicators, a direct correlation has been established: soils receiving insufficient organic fertilization demonstrate the most pronounced negative humus balance. At the same time, budget expenditures on environmental protection, soil conservation, and soil rehabilitation account for less than 1% of the total environmental investments of the region. Consequently, land improvement and reclamation measures remain economically inaccessible for the majority of territorial communities within the region [17].

The foundation of rational land use is environmentally adapted planning of agricultural lands. Its key components include the implementation of scientifically grounded crop rotation systems on arable land and the optimization of vegetation cover structure on pastures and hayfields [3]. To substantiate sustainable land use, we propose the application of a multi-objective optimization approach. The objective function is defined as the maximization of agro-landscape profitability under environmental constraints, including the minimization of erosion coefficients and negative humus balance.

The mathematical model is based on a system of linear inequalities that incorporates the spatial characteristics of land parcels obtained through geodetic monitoring. To determine a rational land-use structure, a model is proposed that is founded on balancing the economic efficiency of land use with environmental safety requirements.

The economic component is represented by the maximization of net profit derived from land use, where:

$$Z_1=\sum_{i=1}^{n}(Pi - Ci)\cdot Si \rightarrow max \quad (1)$$

Pi – market price per unit of production of the *i*-th crop;

Ci – production costs associated with cultivating the *i*-th agricultural crop;

Si – area allocated to the *i*-th agricultural crop.

Within the developed model, environmental performance is achieved through minimizing fertility losses and manifestations of land degradation:

$$Z_2=\sum_{i=1}^{n}(Ei - Si)\mathrm{x_i} \rightarrow min \quad (2)$$

where E_i is the indicator of erosion impact or soil degradation associated with the cultivation of the i-th crop; x_i is a variable that determines the area or share of crops of the i-th crop

The model incorporates a system of constraints that influence the formation of an optimal crop area structure and ensure the environmental and economic sustainability of land use.

The resource (land area) constraint stipulates that the total area allocated to agricultural production cannot exceed the available land resources.

$$\sum_{i=1}^{n} Si \leq Stotal \quad (3)$$

The environmental (maximum allowable) constraint determines the permissible level of soil erosion, which must not exceed the established threshold value (E_{max})

$$\sum_{i=1}^{n} Ei \cdot Si \leq Emax \quad (4)$$

The agrotechnical (crop rotation) constraint establishes compliance with the requirements for crop sequencing.

$$\mathrm{S_{min}} \leq \mathrm{S}_i \leq S_{max} \, (5)$$

To obtain the optimal result, the scalar convolution method is applied, in which the objective function takes the following form:

$$\mathrm{F} = \alpha \cdot \mathrm{Z}_1 - \beta \cdot \mathrm{Z}_2 \rightarrow \max \, (6)$$

where α and β are weighting coefficients that determine the priority (economic or environmental) within a specific land management project.

The presented model makes it possible to identify the optimal distribution of land resources by varying the weighting coefficients α and β, providing the ability to simulate different scenarios: from intensive exploitation to conservation and

restoration approaches, depending on the actual agrochemical condition of soils obtained through monitoring.

To verify the effectiveness of the proposed multi-objective optimization model, primary statistical data of the agricultural enterprise SPP "Rozvazke" (Rivne District, Rivne Region) for 2025 were used. According to the report on the main economic performance indicators of agricultural enterprises (Form No. 50-sg), the crop production sector of the enterprise is mainly represented by wheat, grain maize, soybean, and sugar beet. To form the input parameter matrix (Table 3), the production costs of the main crops were calculated. Thus, the total costs of winter wheat cultivation amounted to UAH 5272.7 thousand with a gross yield of 13,340 centners. Soybean cultivation, which is one of the most soil-depleting crops, cost the enterprise UAH 1693.0 thousand with a harvest of 1,960 centners. The most costly crop was grain maize, with production costs of UAH 6670.1 thousand (gross yield of 17,244 centners).

Table 3. Ecological and economic parameters of cultivation of the main agricultural crops of SPP "Rozvazke" (input data for modeling)

Agricultural crop	Gross harvest, c	Production cost, thousand UAH	Calculated cost per 1 c, UAH	Ecological load coefficient (Ei)	Agrotechnical restrictions in crop rotation, %
Wheat	13,340	5,272.7	395.2	Low (0.2)	up to 30%
Corn for grain	17,244	6,670.1	386.8	Medium (0.5)	up to 25%
Soybeans	1,960	1,693.0	863.7	High (0.7)	up to 20%
Sugar beet	41,136	2,919.9	70.9	High (0.8)	up to 10%

A key condition for the correct functioning of the environmental block of the model ($Z_2 \rightarrow \min$) is an objective calculation of the nutrient balance. It should be noted that SPP "Rozvazke" has a well-developed livestock production sector. According to the report on livestock production, the number of farm animals, and their feed supply (Form No. 24), at the end of 2025 the enterprise kept 191 dairy cows and a significant number of young cattle. This factor is crucial for achieving an ecological and economic balance, as the presence of cattle ensures the availability of organic fertilizers (manure) for the enterprise.

During the modeling of the objective function aimed at minimizing fertility losses, the compensatory effect of organic fertilizer application is taken into account. The content of nutrients (nitrogen, phosphorus, and potassium) supplied with manure from the existing livestock population is integrated into the overall nutrient balance, significantly reducing the total degradation index (E_i) for the entire agricultural landscape. By applying the scalar convolution method with weighting coefficients $\alpha = 0.5$ (economic component) and $\beta = 0.5$ (environmental component), a balanced land-use scenario is obtained. The model demonstrates that the combination of moderate areas allocated for commercially attractive but soil-depleting crops (soybean and maize) with the application of organic fertilizers from the farm's own livestock complex makes it possible to maximize total profit (Z_1) without exceeding the permissible environmental limits (Emax).

In the absence of complete agrochemical field passports for SPP "Rozvazke", the ecological and economic impact of cultivating the main crops (E_i) was determined based on standard reference indicators of mineralization and humification of organic matter for the respective soil and climatic zone (Table 4).

Table 4. Calculation of the ecological load coefficient (E_i) based on the standard humus balance for the conditions of the Western region of Ukraine

Agricultural crop	Humus mineralization (losses), t/ha	Humification (formation) from crop residues, t/ha	Humus balance, t/ha	Ecological load coefficient (Ei)
Winter wheat	- 1.2	+ 0.8	- 0.4	0.4
Soybeans	- 1.5	+ 0.6	- 0.9	0.9
Corn for grain	- 1.8	+ 0.7	- 1.1	1.1
Sugar beet	- 2.5	+ 0.5	- 2.0	2.0

According to the data, the greatest threat to soil cover is posed by the cultivation of sugar beet ($E_i = 2.0$) and grain maize ($E_i = 1.1$), which form a negative nutrient balance. However, when modeling the objective function for minimizing degradation ($Z_2 \rightarrow \min$), it is important to consider the overall farm nutrient balance, which must include the content of mineral and organic substances supplied with manure. The use of livestock by-products enables the enterprise to generate

significant amounts of organic fertilizers. The application of manure at the calculated rate neutralizes the environmental risks associated with the cultivation of industrial and row crops. Thus, in the proposed mathematical model, the presence of a developed livestock complex (191 dairy cows) acts as a powerful compensatory factor. This allows the enterprise to expand areas under economically attractive crops (soybean, maize, and sugar beet) without violating the environmental imperative ($E \leq Emax$), ensuring a high level of land-use balance.

Conclusions. Within the framework of the study, the key ecological and economic aspects of land management that form the basis of the optimization model were identified. First, this includes the criterion of soil protection orientation, which involves limiting the cultivation of row crops with a high impact on soil cover. Second, the implementation of the resource aspect of a closed-loop system is achieved through the integration of livestock production into the soil nutrient balance, which allows optimizing the use of land resources and minimizing anthropogenic impact on the ecosystem. Third, maintaining an economic and technological balance, where environmental requirements are considered not as additional costs, but as a tool for long-term preservation of land potential.

The developed mathematical model of multi-objective optimization of land-use structure based on the scalar convolution method allows achieving a balance between economic efficiency (maximum profit) and environmental safety (minimum loss of humus and nutrients). The presence of a developed livestock production sector within the enterprise structure acts as a key environmental compensator, ensuring the achievement of an optimal balance in which the farm maintains high production profitability without exceeding the permissible limits of environmental pressure on land resources.

Further research should focus on improving the methodology of ecological and economic assessment by incorporating specific risks caused by the consequences of military actions, including mechanical destruction and chemical contamination of soil cover.

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М. Г. Сербов, А. В. Чугай, П. С. Нікітін

РАЦІОНАЛЬНЕ ВИКОРИСТАННЯ ЗЕМЕЛЬНИХ РЕСУРСІВ У КОНТЕКСТІ ЕКОЛОГО-ЕКОНОМІЧНИХ АСПЕКТІВ ЗЕМЛЕУСТРОЮ

***Анотація**. У статті розглянуто забезпечення раціонального використання земельних ресурсів в умовах інтенсивної деградації ґрунтового покриву, зміни кліматичних умов та негативних наслідків воєнних дій. Метою роботи є наукове обґрунтування механізму раціонального використання земельних ресурсів шляхом удосконалення землевпорядного інструментарію на основі інтеграції еколого-економічних критеріїв у процеси моделювання. Проаналізовано теоретико-методологічні засади раціонального використання земель. Визначено триєдину правову природу земельних ресурсів як територіального базису, об'єкта природи та засобу виробництва. Обґрунтовано модель просторового планування територій, де економічна ефективність підпорядкована еколого-економічним нормам. Розглянуто систему принципів збалансованого землекористування, що поєднує екологічну безпеку, економічну ефективність та інноваційність із дотриманням балансу інтересів землевласників і суспільства. Визначено критерії оцінки збалансованості землекористування, спрямовані на гармонізацію екологічних вимог та економічних інтересів. Проведено аналіз дотримання принципів раціонального використання земельних ресурсів на прикладі Рівненської області. Виявлено розширення посівних площ в регіоні під енергоємними технічними культурами (соняшник, соя), інтенсифікацію навантаження на ґрунти області та негативний баланс гумусу. Запропоновано багатоцільову економіко-математичну модель, в основу якої закладено принципи збалансування економічної ефективності землекористування та вимог екологічної безпеки територій. Проведено обґрунтування моделі методом скалярної згортки цільових функцій, який забезпечив дієвий компроміс між*

максимізацією прибутку від агровиробництва та мінімізацією втрат родючості ґрунтів.

Ключові слова: *раціональне використання земель, землеустрій, еколого-економічні аспекти, збалансоване землекористування, модель оптимізації, деградація ґрунтів.*