

This study focuses on the processes and mechanisms of land use management in the context of sustainable development. The task under consideration is associated with the fragmentation of information support to the ecological-economic mechanism behind land use (EEMLU), which complicates the objective assessment of land resources.

The feasibility of a conceptual approach to improving EEMLU information support at various levels of management has been substantiated. A multi-level land information system has been designed, categorized by type and content, and consolidated into a single information space (SIS), taking into account regional characteristics.

An approach to designing an EEMLU information support system has been proposed, taking into account the potential of the latest digital technologies and the principles of open data. The principles of forming and functioning of information support were outlined and categorized; the factors influencing its effectiveness were systematized.

An algorithm has been developed to enhance the significance of land efficiency assessment methods through the use of integrated indicators, which enables comprehensive consideration of the environmental, economic, and social outcomes of land use. A model has been built to substantiate the effectiveness of EEMLU information support, which makes it possible to assess the range of benefits for all participants in land and property relations.

The results are attributed to a comprehensive approach that took into account regional characteristics and modern information and analytical tools. The findings could be practically implemented provided that a SIS for land resources is constructed and the proposed model is applied in state and local government, taking into account regional characteristics, in order to improve the effectiveness of land use assessment

Keywords: *ecological-economic mechanism, land use, single information space, regionality, digital technologies*

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A SYSTEM OF INFORMATION SUPPORT TO THE ECOLOGICAL-ECONOMIC MECHANISM OF LAND USE WITHIN THE PARADIGM OF SUSTAINABLE DEVELOPMENT

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1. Introduction

The intensification of the economic and environmental crises whose consequences are felt both at the global and local levels is one of the key problems of the current stage of development. This necessitates the need to define new priorities for sustainable development. The leading place among them is occupied by the greening of the economy, which involves harmonizing the relationship between economic interests, the value of natural resources, and the preservation of human life and health.

Social expectations regarding sustainable development, accountability, and transparency are formed under the influence of regulatory requirements and the strengthening of environ-

mental challenges caused by the irrational use of resources and the degradation of ecosystems [1]. One of the key tasks of our time is the adoption of a sustainable development paradigm focused on the transformation of the economic system in compliance with the principles of justice. This paradigm is based on three approaches. The economic approach involves the rational use of resources and the introduction of resource-saving technologies. The ecological approach focuses on the preservation of natural systems and biodiversity [2]. The social approach encompasses the protection of human rights, the development of humanitarian values, and the maintenance of socio-cultural stability. The interrelationship of social, economic, and environmental priorities is possible only under the condition of global coordination and balanced regulation of human activity.

The concept of sustainable development, formed under the influence of the consequences of the industrial revolution and the crises of the 20th century, has actualized the need for economical use of land resources. The key goal of state policy in this area is the formation of mechanisms for motivating and holding economic agents accountable in the context of implementing environmentally friendly practices and preserving land as the basis of natural capital and the well-being of future generations [3].

Land use is complicated by financial, economic, administrative, and information barriers. Among the main problems are the low profitability of environmental protection measures, limited state support, contradictory land policy, and a low level of environmental culture and motivation of land users. Overcoming these barriers requires improving land resource management, developing incentive mechanisms, and increasing environmental responsibility.

Effective management requires a holistic land management system. Such a system ensures the accounting and valuation of lands, the organization of their rational use, protection, monitoring, and control [4]. Therefore, land management should integrate economic, legal, and administrative mechanisms to coordinate the interaction of subjects and objects of management. The conditions of digital transformation increase the need to improve EEMLU as the imperfection of information support limits its effectiveness. The growth of the operational load on land deepens environmental risks and exacerbates the conflict of interests between the authorities and business [5]. That is why the topic under study is relevant; its results could contribute to the formation of an effective, transparent, and environmentally responsible model of land use that meets the needs of sustainable development of society.

2. Literature review and problem statement

The transformation of the economies of resource-rich countries from a raw material to an innovative and technological model with an emphasis on the role of state policy, international cooperation, and institutional reforms is considered in [6]. However, there are still unresolved issues regarding the productive use of natural resources as a starting potential for increasing the sustainability of national development. Study [7] focuses on improving the institutional and economic support to international environmental policy in the system of sustainable development of the national economy. In this context, in [8], a legal mechanism for guaranteeing the environmental security of Ukraine is proposed. The issue of increasing the economic potential of land resources is crystallized in [9]. Most attention is on the formation of a holistic state policy on environmental management, while it is also necessary to focus on the implementation of mechanisms for financing ecosystem services.

Study [10] considers the formation of a multifactor methodology for rational land use. It is shown that the development and implementation of a management mechanism integrates economic, environmental, social, production, and legal aspects of management. This is the approach used in [11], which describes a multi-component model of an innovative mechanism for land resource management. At the same time, the ecological aspects of land use are emphasized by scientists in [12]; however, it is necessary to emphasize the importance of restoring soil fertility and minimizing anthropogenic impact.

The authors of [13] emphasize the need to coordinate market processes with land use, strengthen institutional support, and modernize regulatory instruments, taking into account their

development potential and involve business structures in creating a legal framework in this context. Paper [14] substantiates the directions for the development of land use planning tools and devised measures for effective practices in this area. It is emphasized that such tools are evolving in the context of the transition to the 5.0 era, which entails a wider integration of new technologies, in particular blockchain, VR/AR, quantum computing, and digital twins into the land administration system.

The authors of work [15] proved that reliable information on land use serves as the basis for designing an effective monitoring system, objective assessment of the state of lands. But the issues of developing effective protective measures in the context of the functioning of complex socio-economic and ecological systems remained unresolved. At the same time, the practical implementation of the methodology [16] of information support for the inventory of land plots reduced the time for obtaining the necessary data by 33% and increased the measurement accuracy by approximately 1%, confirming its effectiveness for optimizing accounting and management processes.

At the same time, the problem of constructing a holistic and coordinated system of information support to EEMLU, capable of providing a comprehensive ecological, economic, and social assessment of land resources, remains unresolved in scientific research. Thus, there is a scientific and practical need to devise a conceptual approach to improving the information support to the ecological-economic mechanism behind land use, which would enable the formation of a multi-level system of land information within a single information space and increase the validity of management decisions at the state and regional levels.

3. The aim and objectives of the study

The purpose of our study is to improve the information support system of the ecological-economic mechanism of land use in the context of the sustainable development paradigm. This will make it possible to allow for increased efficiency in making management decisions, strengthen the ecological justification and economic efficiency of land resource use, and also form a comprehensive system of tools capable of supporting the balanced development of territories under conditions of digital transformation.

To achieve the goal, the following tasks were set:

- to devise an approach to the formation of an information support system to EEMLU;
- to build an algorithm for increasing the validity and analytical significance of assessing the effectiveness of land use;
- to substantiate the effectiveness of the model for the functioning of EEMLU and land protection based on the introduction of the latest digital technologies.

4. The study materials and methods

The object of our study is the processes and mechanisms of land use management in the context of sustainable development.

The principal hypothesis assumes that the construction of a holistic information space based on digitalization and geographic information systems (GIS) could significantly improve the efficiency of EEMLU.

It is assumed that digitalization and the use of GIS improve the efficiency of EEMLU, the available data are sufficient to form a single information space, and the participants in land relations act rationally. To simplify the analysis,

information flows are structured, types of land users are generalized, indicators are aggregated into integral indices, and regional factors are considered as generalized parameters.

The methodological basis of our study is the provisions from the theory of management, development, modern approaches to the digitalization of information processes and the concept of ecological-economic mechanisms of nature management. To determine the goals, objectives and formulate system requirements for the information support system, an abstract-logical method was used. Scientific abstraction and dialectical cognition were used to substantiate the conceptual approach to building a unified information space taking into account regional characteristics. The comparative analysis method allowed us to identify factors that affect the effectiveness of the information support to EEMLU. System-structural analysis was used to devise a scheme for organizing the regional information space of land information. The induction method was applied to generalize factors and categorize principles, and deduction was employed to build an algorithm and model of the system's functioning. Factor analysis and matrix modeling of impacts were exploited to assess the adequacy of methods for economic and social assessment of land use and the effectiveness of their application. Mathematical methods helped us calculate the effectiveness of EEMLU functioning, in particular, integral assessment and construction of generalized indicators. The results of the study are based on a complex combination of theoretical generalizations, analysis of practical experience in land use management, and the use of modern digital tools for modeling information flows. The validity and reliability of the results are confirmed by the use of resource-targeted and systemic approaches to improving the methodology of land use management and regulation of land and property relations through the development of information support.

5. Results of investigating information support to the ecological-economic mechanism behind land use in the paradigm of sustainable development

5.1. Approach to the formation of a system of information support to the ecological-economic mechanism behind land use

EEMLU is an integrated system of legal, financial, economic, and informational tools and levers that combines the principles of economic efficiency with the requirements of social responsibility and environmental safety, ensuring balanced and long-term use of land. The structure of EEMLU includes functional subsystems of an economic, environmental, and social nature, which enable the coordination of the interests of various economic entities. High efficiency of land use is achieved only under the condition of the development of all elements of the mechanism and its comprehensive improvement. Until economic incentives for the greening of production are formed in economic sectors, the land use mechanism will remain ineffective. Negative environmental consequences are mostly due not to technical imperfection, but to the insufficient maturity of the environmental management mechanism and the inconsistency of public and private interests in ensuring environmental safety.

The specified mechanism conceptualizes the interaction of the environmental and economic components in the land use management system, where each element performs a specific function in order to optimize land use. The environmental component of the mechanism includes a system of principles, norms, and measures aimed at maintaining the ecological bal-

ance of territories, monitoring the condition of lands, rational and environmentally sound use of lands taking into account environmental restrictions. It also includes the preservation of the natural properties of soils, restoration and reclamation of disturbed lands, the designation of protected areas and territories with a special protection regime. The economic component of the mechanism is represented by a set of methods, tools, and management levers that ensure the efficiency of land use. Its content forms a financial and incentive environment for land use, within which the land market, taxation system, lease relations, mechanisms for assessing the effectiveness of land use and instruments of economic encouragement and sanctioning operate. In general, the ecological-economic component is integrated into all domains of social development, covering political and economic, social, scientific and cultural, involving significant labor, financial and intellectual resources in the processes of environmental safety and land use. In this context, the formation of effective EEMLU should be based on the development and implementation of a holistic state economic policy with an environmental focus, which is implemented according to different levels of management through legal, organizational, eco-political, and other institutional instruments.

The interaction among EEMLU participants is based on the exchange of information, which acts as a connecting link between all subsystems. Therefore, special attention is paid to the analysis of the information support system, highlighted as a separate subsystem. This allowed us to specify such key concepts as "information support" and "land information".

The information support to EEMLU is understood as a subsystem that provides participants in land and property relations with reliable and systematized data on the condition and use of land within SIS. It includes methods and means of collecting, processing, systematizing, and representing data, as well as mechanisms for categorizing, coding unified documentation and optimizing document flow. As an integration component of the mechanism, information support contributes to the coordination of information flows between management participants, improving the quality of land assessment and scientific substantiation of management decisions. The effective functioning of this subsystem provides transparency, adaptability, and scientific verification of land policy, contributing to the balanced development of territories and socio-economic stability of regions.

Land information is interpreted as a set of data on land resources that reflect their quantitative, qualitative, legal, environmental, and economic parameters. It appears as a complex socio-ecological-economic object of system management, which forms the subject area of information support to land use and enables the development of innovative and scientifically sound management solutions within the framework of modern information systems.

A large number of participants in land relations and the absence of a single structured resource complicate access to current data. The insufficient level of digitalization limits the possibilities of operational interpretation and visualization of geospatial information [17, 18]. This necessitates the need to modernize databases using innovative digital technologies, which will improve the efficiency of analysis, management decisions, and the functioning of EEMLU. The priority is the development of digital infrastructure [15, 19], standardization of information flows, and improvement of information support to land resources management (Fig. 1).

The conceptual approach to the formation of the information support system of EEMLU involves the construction of a model that will provide all administrative and managerial levels

with comprehensive, reliable, and verified information for rational land use. The implementation of the proposed approach includes outlining the principles of the system's functioning, systematizing development factors, developing a structural and organizational model of the information infrastructure based on regional subsystems integrated into SIS, as well as determining the state body responsible for administration and data openness [15, 18]. In this context, a classification of the principles of the development of information support to EEMLU is outlined (Fig. 2).

The formulated principles made it possible to categorize the factors that determine the development of information support to the mechanism, and on the basis of factor analysis, to identify the most representative ones among them in terms of their impact on the efficiency of the system's functioning (Fig. 3).

To conduct factor analysis, a scale for assessing the level of influence of factors was proposed, which provides for three gradations – minimum, average, and maximum levels. Based

on this scale, a matrix for comparative assessment of influence factors was formed, which allows us to identify their relative significance and determine priority areas for improving information support to EEMLU (Fig. 4).

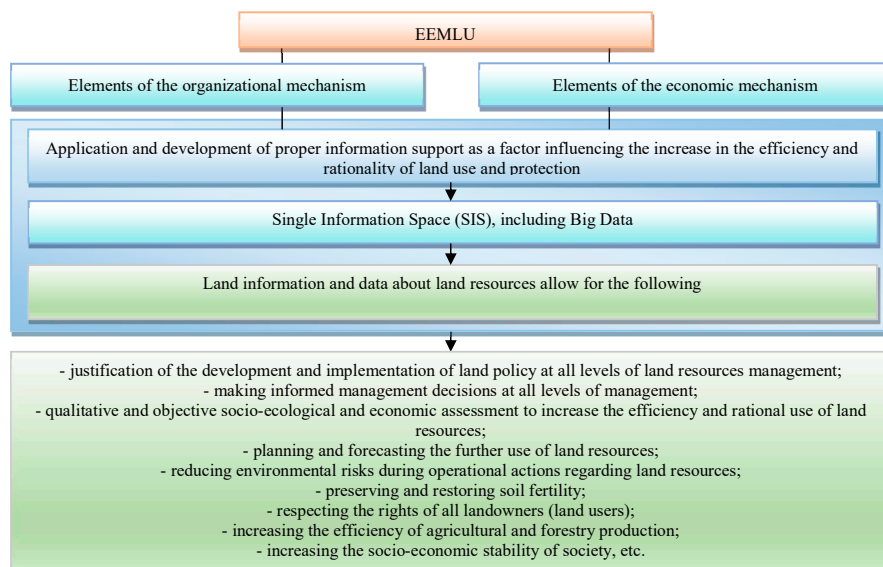


Fig. 1. Diagram for improving the ecological-economic mechanism of land use based on the development of information support

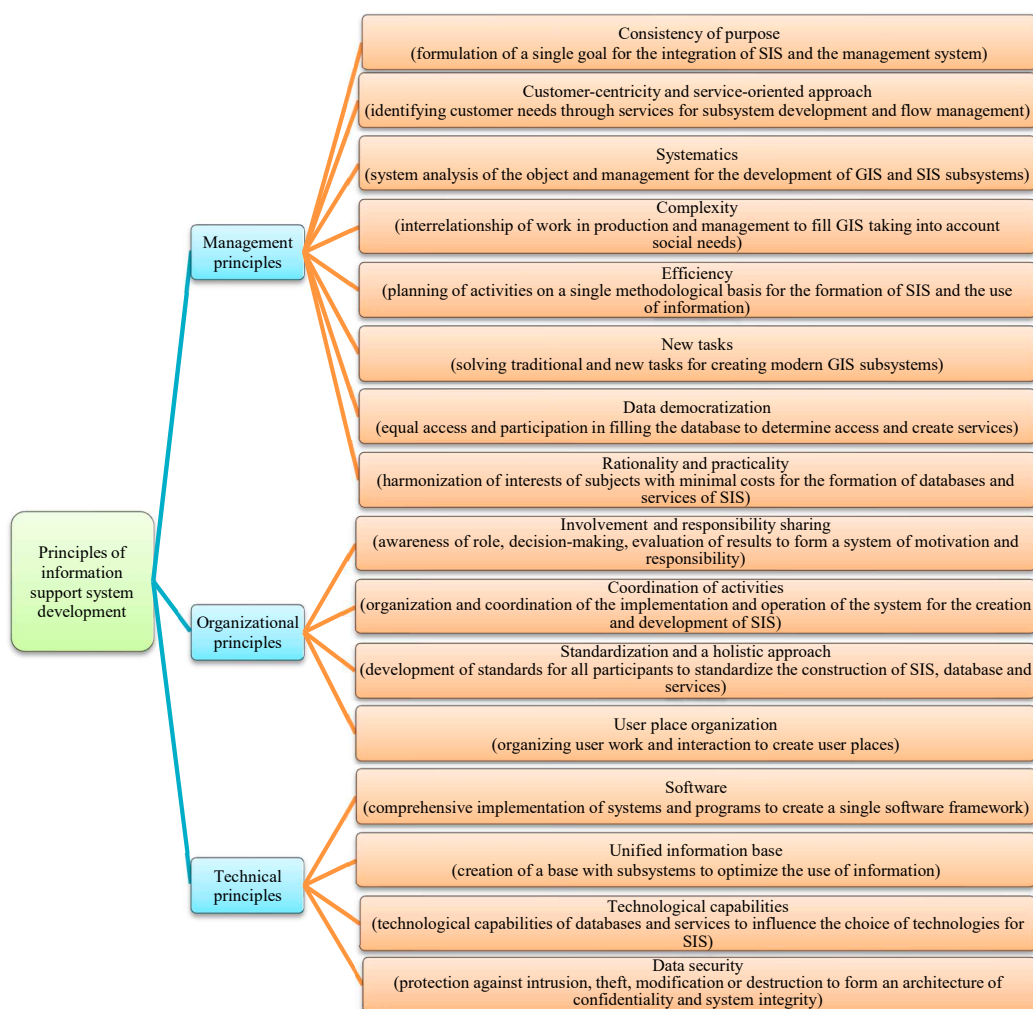


Fig. 2. Classification of principles for the development of an information support system

Thus, the greatest influence on the development of information support to EEMLU is exerted by factors 1–3.

In the context of the development of the information support system, the concept of the SIS of land information, created on the basis of modern software, digital GIS technologies and Big Data methods, is proposed. This approach ensures the integration, systematization, and accumulation of data on land resources in a single database and also provides for institutional support and administration of the system

through the services of the Ukrderzhregistry as a potential operator of SIS. The land information system, categorized by type – natural, economic, environmental, social, legal and geopolitical – is accumulated in a structured SIS database taking into account regional features of land use and the specifics of management tasks (Fig. 5).

To improve the efficiency of information support to EEMLU at the regional level, a model based on modern digital technologies has been proposed (Fig. 6).

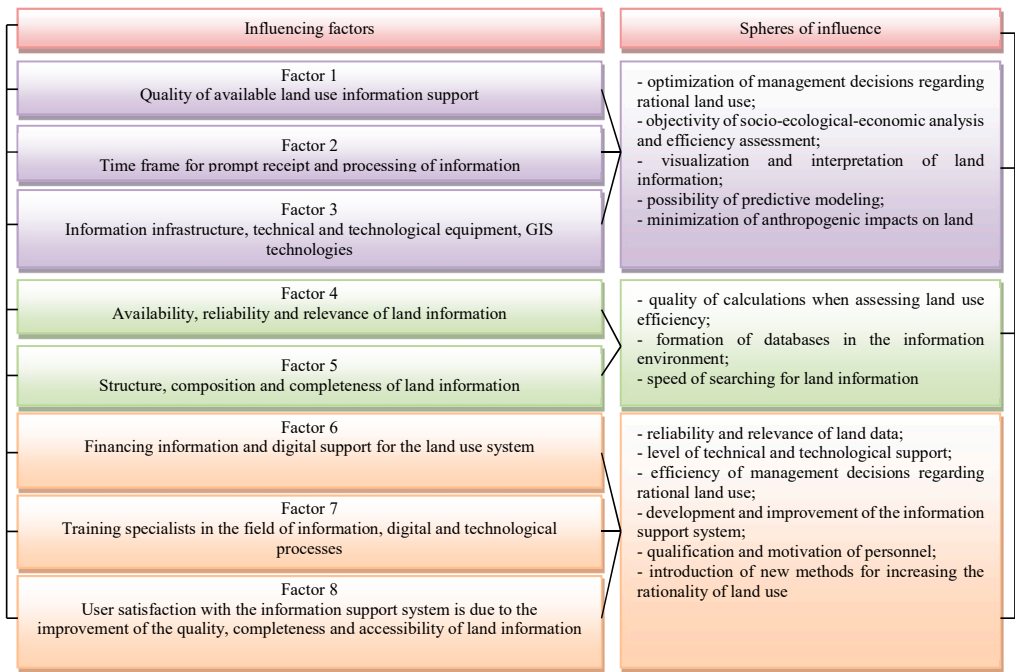


Fig. 3. Factors influencing the development of information support to the ecological-economic mechanism of land use

Factor No.	1	2	3	4	5	6	7	8
1		+++	++	+++	+++	+	+	+++
2	+++		+	+	+	++	+++	+++
3	+++	+++		+++	++	+	+	+
4	+++	+	++		+	+	+	+++
5	+++	++	++	+		+	+	+++
6	+++	+	+++	+	+		++	++
7	+++	+++	+++	+	+	+		+++
8	+++	+++	++	+++	+++	+	++	

Fig. 4. Matrix of comparative assessment of factors influencing the development of information support to the ecological-economic mechanism of land use: + – minimal impact; ++ – average; +++ – maximum

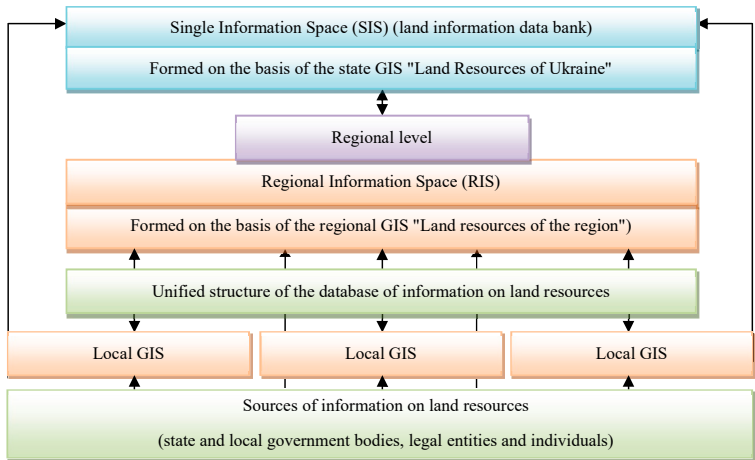


Fig. 5. Scheme for improving a single information space by organizing a regional information space based on the implementation of the latest digital data processing technologies

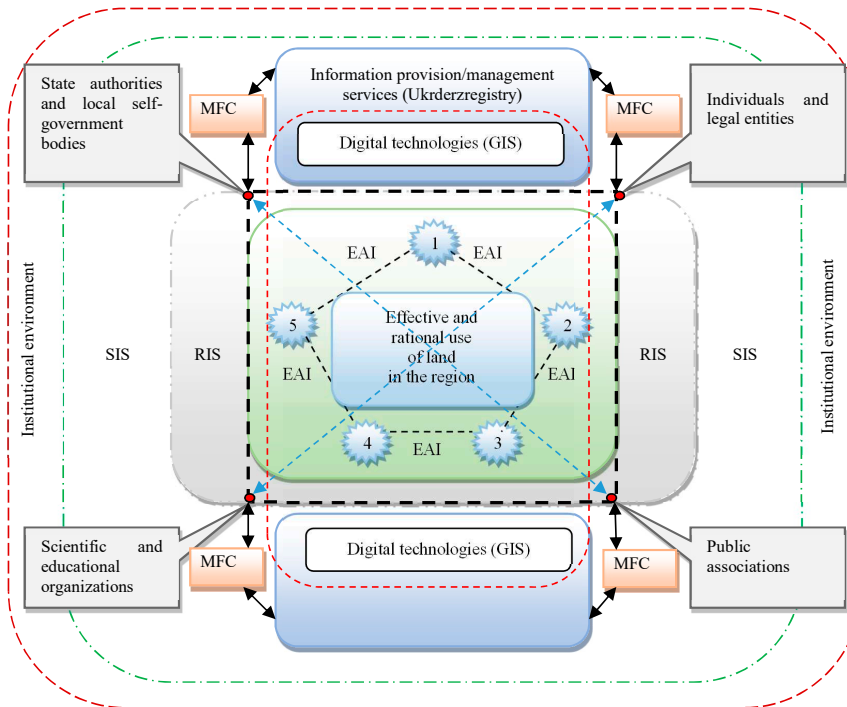


Fig. 6. Model of information support to the ecological-economic mechanism of land use based on the application of the latest digital information processing technologies: – efficiency (1 – economic; 2 – ecological; 3 – social; 4 – information and technical; 5 – socio-political); EAI – efficiency assessment indicators; MFC – multifunctional center

Its goal is to provide users with reliable, operational and accessible land information. The basis of the model is an organizationally structured information space, the functioning of which is expedient to implement through the services of the Ukrderzhregistry, using its existing technical, information, and communication resources.

The effectiveness of the proposed model is due to the formation of a synergistic effect that arises as a result of the coordination of diverse interests of entities that use information about land resources, as well as due to the integrated use of geographic information systems for its collection, processing and visualization. The key factor in the implementation of this effect is the formation of a new institutional environment and the emergence of hybrid institutional structures that ensure the effective integration of information flows.

5.2. Algorithm for increasing the relevance of methods for assessing land use efficiency

The developed model for improving the information system demonstrates new possibilities for integrating GIS technologies into management processes and rational land use. It is a key tool for increasing the efficiency of processing, analyzing and visualizing geospatial data, optimizing the interaction of participants in land relations and contributing to the formation of balanced EEMLU (Table 1).

The development of the information system allows land use participants to receive certain benefits

under the condition of rational use of land resources. This is possible only if there is high-quality and relevant information since the costs of its processing significantly affect the effectiveness of EEMLU. To assess the comprehensive effectiveness, an algorithm has been developed based on the improvement of information support and a system of indicators that reflect the relationship between management goals and the principles of sustainable land use (Fig. 7).

The step-by-step algorithm simplifies the comparison of expected and actual effects and can be applied in practice. Since land resources are a complex socio-ecological-economic object, for sound management and assessment of the functioning of EEMLU, it is necessary to determine the integrated efficiency of their use according to economic, environmental, and social criteria [10]. For this purpose, a system of integral indicators has been designed that complements the current cost and natural methods of assessment, based on the generalization of hierarchically structured information. The combination of generalizing and partial indicators allows us to calculate the integral indicator of land use efficiency and EEMLU effectiveness. The direct determination of the efficiency level is carried out through the integral indicator (E_{io}), which combines a system of generalized indicators of individual types of efficiency

$$E_{io} = \sum_{i=1}^n (E_{iGIS} + E_{iecol} + E_{isoc}), \quad (1)$$

where E_{iGIS} is an integral indicator of economic efficiency; E_{iecol} is an integral indicator of environmental efficiency; E_{isoc} is an integral indicator of social efficiency.

At the same time, the integral coefficient of land use efficiency is defined as a set of partial indicators of different types of efficiency (2), given in Table 2

$$K_{ieff} = \sum_{i=1}^n \left(\frac{E1 + E2 + E3 + E4 + E5 + E6 + C1 + C2 + C3}{E1 + E2 + E3 + E4 + E5 + E6 + C1 + C2 + C3} \right). \quad (2)$$

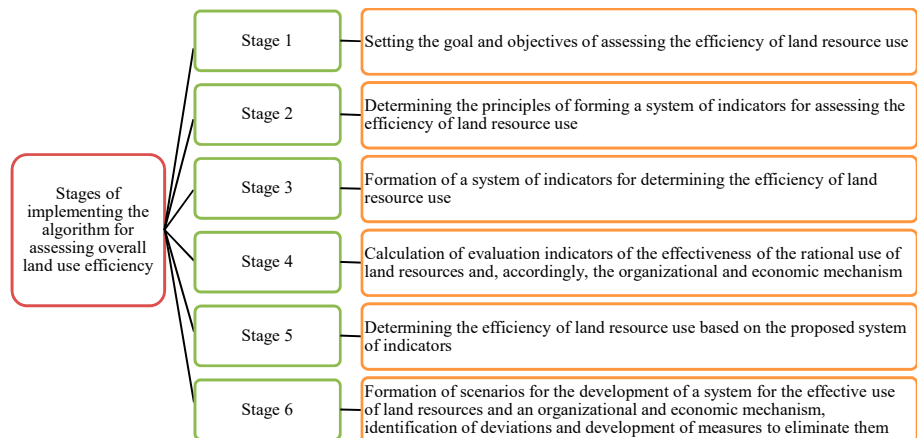


Fig. 7. Step-by-step algorithm for assessing overall land use efficiency

Table 1

Types of benefits for participants in land use processes as a result of the implementation of the information support system functioning model

Types of benefit	Their essence
Individual	Coordinated activities of participants in land use processes ensure the achievement of improved results, which include not only the growth of economic benefits, but also the implementation of socially significant non-commercial interests
Public	The results of such interaction contribute to an increase in the level of satisfaction of the population, communities and social associations, and the strengthening of their well-being
Common benefit	Common benefit (mutual benefit) lies in the impossibility of maximizing the profit of one participant at the expense of others, while the difference in benefits creates a synergy effect that enhances the efficiency of the land use system

Table 2

System of partial indicators and factors characterizing the state and development of information support to EEMLU

Type of efficiency	Name of the partial indicator	Factor name	Indicator designation	Type
Economical	Land tax	The quality of information support of the EEMLU, which determines the social and ecological and economic efficiency of lands	E1	Absolute
	Intensity of land market circulation		E2	
	Effectiveness of GIS application in the workplace of specialists		E3	
Ecological	Ecological quality of lands (degree of plowing and afforestation of territories, area of disturbed lands)	Technical and technological equipment and development of information infrastructure, application of GIS technologies	Ek1	
	Ecological state of the environment (environmental and ecological indices of the territory)		Ek2	
Social	Level of satisfaction of the population with information services in the consumer market of the region	Satisfaction of participants in land use processes with the information system, which is determined by the availability, completeness and quality of land information	C1	Relative
	Level of satisfaction of the population of the region with the availability and completeness of land information		C2	
	Time spent (duration) on obtaining information and services about land		C3	
	Level of satisfaction with the speed of information processing and timeliness of management decisions regarding rational land use		C4	

Partial indicators of each type of efficiency are systematized taking into account the key factors of information support development, which confirm the effectiveness of its functioning within EEMLU. The proposed system of indicators increases the objectivity of assessing overall efficiency and provides control over the achievement of set goals.

d_1 – funds allocated for education and science;
 d_2 – tax regime for individuals and legal entities;
 d_3 – funds allocated for the development of public associations.

The generalized types of player operations under the above conditions of the hierarchical game are given in Table 4.

Table 3

Designation of players in the process of ensuring maximum benefits within the framework of effective interaction among land use participants

Participants in land use processes	Designation
Government bodies	Player 1
Individuals and legal entities	Player 2
Public associations	Player 3
Scientific and educational institutions	Player 4

Table 4

Typical player operations in a hierarchical game

Player	Types of player transactions
Player 2	d_5 – level of production and services
Player 3	d_6 – level of development of public associations
Player 4	d_4 – level of development of educational services and scientific research

The expected values of the generalized types of operations of the specified players can be determined by the nu-

5. 3. Substantiating the effectiveness of the model of functioning of the ecological-economic mechanism of land use based on the introduction of digital technologies

To improve the ecological-economic mechanism of regulating land and property relations, a methodology for optimizing its parameters and assessing its effectiveness has been devised. The proposed approach, based on the relationship between payments and the costs of implementing GIS technologies, enables a uniform distribution of economic benefits between participants and contributes to increasing the effectiveness of the information support system.

The introduction of digital technologies provides individual benefits to participants in land and property relations and at the same time creates a synergistic effect of their interaction, increasing the efficiency and rationality of land use. To substantiate the effectiveness of the information support model aimed at improving EEMLU, game theory tools were used, in particular, the hierarchical game model, in which the authorities act as a higher-level player (Table 3).

The leader is the first Player, the others are followers; at the same time, in this game it is possible to distinguish the types of actions of the first Player:

merical scales of the corresponding indicators (in the ranges from 0 to 1 or from 0 to 100). It is obvious that

$$d_4 = d_4(d_1), \quad (3)$$

that is, the level of development of educational services and the volume of scientific research conducted is determined by the amount of funding for education and science.

Similarly

$$d_6 = d_6(d_3), \quad (4)$$

that is, the level of development of public associations depends on their funding.

Regarding the strategies of individuals and legal entities

$$d_5 = d_5(d_2, d_4, d_6), \quad (5)$$

that is, the level of production and provision of services is largely determined by tax regimes, as well as the amount of funding for scientific and educational institutions and public associations.

Taking into account formulas (3) and (4), we obtain

$$d_5 = d_5(d_1, d_2, d_3, d_4, d_6), \quad (6)$$

therefore, the final level of production and service provision is determined by the chosen options of action of the three other players.

According to the objective functions of the participants, for Player 1 the aggregate criterion (C) is the quality of land resources, which determines the socio-economic level of the population and the potential of government activities

$$C_1(d_1, d_2, d_3, d_4, d_6) \rightarrow \max_{d_1, d_2, d_3}. \quad (7)$$

In this context, the maximum values are determined on the set of possible actions of Player 1.

For Player 2, the criterion is the aggregated indicator of business functioning (agricultural production, recreation, tourism, etc.), which is determined by the profit from land use

$$C_2(d_2, d_4, d_1, d_5, d_6, d_3) \rightarrow \max_{d_5}. \quad (8)$$

The criterion for a generalized indicator of the state of development of public associations for Player 3 can be formulated as follows

$$C_3(d_3, d_6) \rightarrow \max_{d_6}. \quad (9)$$

For Player 4, the generalized indicator of the state of science and education takes the form

$$C_4(d_1, d_4) \rightarrow \max_{d_4}. \quad (10)$$

The criteria of the players can be measured both in real indicators and on a numerical scale [20].

The proposed approach ensures the implementation of an effective model of information support to EEMLU, adapted to domestic conditions, using digital technologies, the development of information spaces and the improvement of the regulatory and legal environment. Improving the EEMLU involves the formation of a system of economic incentives for rational land use and protection of natural resources through

a combination of compulsory and motivational measures of state environmental policy. The main areas include:

- economic interest: creating conditions under which it is economically profitable for enterprises and entrepreneurs to comply with environmental legislation and take into account the ecological functions of lands;

- promoting effective use: introducing a system of economic incentives that encourage a more careful attitude to the land, reducing anthropogenic pressure on ecosystems and increasing land productivity;

- improving public administration: forming an effective model of public administration in the field of ecology and land use, which meets the principles of a market economy and a democratic system;

- integrated approach: orientation towards a comprehensive solution to the problems of interaction of public opinion and nature in order to promote sustainable development, balancing economic and environmental factors in the process of land use;

- innovation and technology: use of innovative approaches and technologies to improve the efficiency of land use and reduce anthropogenic load on ecosystems.

6. Discussion of the results of the formation of an effective system of information support to the ecological-economic mechanism of land use

Our study demonstrates the feasibility of an integrated approach to land use, which combines the potential of the public sector, business structures, and territorial communities. The functions of the state are to form and implement land use policy, create regulatory and legal frameworks, support scientific research and ensure control over compliance with legislative norms. Business structures should focus their efforts on investing in efficient land use, introducing resource-saving technologies and increasing the level of environmental responsibility. The role of territorial communities is to participate in land resource management, observe land use traditions and increase environmental literacy.

Our study proposes a methodological approach to building an information support system to EEMLU, which ensures the holistic integration of information flows and increases the efficiency of land resource management (Fig. 2, 3). Unlike fragmentary solutions [16], the proposed approach focuses on the transparency of land-property relations, the validity of management decisions and the formation of a single information space in the context of sustainable development goals.

The results of the quantitative assessment carried out using the matrix comparison method of factors showed that the decisive influence on the development of information support is exerted by the quality of its functioning, the level of technical and technological infrastructure and user satisfaction with the accessibility and completeness of land information. The identified structure of factors justifies the priority of measures aimed at improving the information infrastructure and increasing trust in its services for effective land resource management (Fig. 4).

In the context of the development of the information support system, the SIS of land information was designed taking into account modern software, digital GIS technologies, and Big Data analytics methods (Fig. 5). This allows us to integrate, systematize, and quickly exchange data on land resources. The use of digital technologies, GIS, and services

of the Ukrderzhregistry ensures transparency, justification of management decisions and sustainable development of land use at the state and regional levels (Fig. 6).

It is appropriate to develop a system of integral indicators that complements existing assessment methods (cost and in-kind), ensuring the complexity and objectivity of assessing the effectiveness of land use. The proposed system is based on the generalization of interconnected information by hierarchy levels, which allows for multidimensional analysis of effectiveness. The integration of generalizing and partial indicators allows us to assess the effectiveness of EEMLU in the relationship of economic, social, and environmental aspects.

The algorithm for assessing comprehensive efficiency developed in our study is based on improving information support and forming a system of indicators that reflect the relationship between aspects of operational activities, management goals and principles of rational land use (Fig. 7). The proposed algorithm enhances the significance of socio-economic methods for assessing land through the integration of generalized indicators of the effectiveness of their use. Unlike traditional approaches, it provides a comprehensive assessment of economic, social, and environmental results of land use, based on modern management decisions. The implementation of the algorithm contributes to increasing the objectivity and quality of assessment, creating conditions for determining the effectiveness of the functioning of the improved EEMLU.

The methodological approach proposed in this study is to ensure a relatively even distribution of benefits between participants in land-property relations through a comprehensive approach to assessing the effectiveness of the model of functioning of the information support to EEMLU. This methodology takes into account the relationship between the costs of implementing modern information systems with socio-economic and environmental results. Unlike traditional methods, the proposed approach takes into account the relationships between economic, social and environmental aspects, which allows for a more objective determination of the range of benefits for each participant in the land use system (Table 1).

Practical use of the research results contributes to the creation of incentives for effective and environmentally safe land use, improvement of regulatory and legal regulation and increased loyalty of citizens to the state's land policy.

The development of the study is to use artificial intelligence and Big Data to automate land valuation, forecast management decisions, and increase transparency and efficiency of EEMLU.

Despite the results obtained and the methodological approach developed to improving the information support to EEMLU, our study has a number of limitations that determine the limits of application of the proposed solutions. The effectiveness of the developed model largely depends on the level of digital infrastructure and data integration capabilities in SIS, which may vary depending on regional conditions.

Along with the above limitations, the study is characterized by a separate drawback – the lack of modeling of risk scenarios. In particular, the work does not take into account scenario analysis of the impact of extreme external factors, such as economic crises, military actions, sharp transformations of the ownership structure, or unpredictable institutional changes. This drawback can be eliminated or significantly minimized within the framework of future research by applying stochastic modeling, Monte Carlo methods, and the development of complex scenario forecasts.

Awareness of the above limitations and shortcomings allows us to outline promising directions for deepening and

improving the model of information support to EEMLU. On this basis, more sustainable, scalable, and adaptive solutions for effective land management in the context of digital transformation can be formed in the future.

7. Conclusions

1. An approach to forming an information support system to EEMLU has been proposed. This approach includes determining the principles of the system's functioning, systematizing development factors, creating a structural and organizational model of information infrastructure based on regional subsystems integrated into SIS, as well as determining a state body responsible for administering and ensuring data openness. The approach ensures the holistic integration of information flows between state, business and public structures, enhances the transparency of land relations and the validity of management decisions, increasing the efficiency of land resource management. This creates the basis for a single information space in the field of land use and contributes to achieving sustainable development goals.

A concept for forming a single information space based on the use of geographic information systems and modern digital technologies has been formed, while ensuring the accumulation of data on land resources in a structured database. This approach contributes to increasing the accessibility of information for all interested users, which leads to an increase in its compliance with modern requirements and analytical significance. At the same time, prerequisites are created for the implementation of a comprehensive social and ecological-economic assessment of land resources, as a result of which management decisions in the field of land use become comprehensive and integrated. The introduction of a model of digital information support ensures the transparency of management processes, increases the validity of decisions, and contributes to the sustainable development of land use at the state and regional levels.

2. An algorithm has been built to enhance the significance of methods for social and economic assessment of lands through the use of generalized indicators of the effectiveness of their use. This algorithm makes it possible to carry out a comprehensive assessment of economic, social, and environmental results of land use based on creative management decisions. The implementation of the algorithm ensures an increase in the quality of land use efficiency assessment and creates opportunities for objectively determining the effectiveness of the functioning of EEMLU that we have improved.

3. To allow for a relatively even distribution of benefits between all participants in land-property relations, a model for assessing the effectiveness of the functioning of the EEMR information support and determining the spectrum of benefits for each of the participants. To increase the objectivity and complexity of land use efficiency assessment, a system of integral indicators has been developed that complements the current cost and in-kind assessment methods. It is based on the generalization of interconnected information by hierarchy levels, which allows for multidimensional analysis of efficiency. The integration of generalizing and partial indicators ensures the determination of an integral indicator of land use efficiency and the functioning of EEMLU in terms of economic, social, and environmental aspects. Partial indicators are systematized taking into account key factors in the

development of information support, which confirms the effectiveness and practical significance of the proposed model of EEMLU functioning.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors declare the use of generative AI in the manuscript preparation process. Tasks delegated to generative AI tools under full human supervision: checking grammar, spelling, punctuation without changing the context of the manuscript. Generative AI tool used: GPT-4.1.

The authors bear full responsibility for the final manuscript. The generative AI tools are not credited as authors and are not responsible for the final results.

Authors' contributions

Halyna Ostrovska: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing; Project administration; **Iryna Yasinetska:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing; **Tetiana Kushniruk:** Investigation, Data curation, Writing – review & editing; **Volodymyr Hryb:** Investigation, Visualization; **Oleksandr Kharchenko:** Investigation, Visualization.

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