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MODELLING OF THE INTEGRAL INDEX OF ENVIRONMENTAL SUSTAINABILITY OF LAND USE IN EUROPEAN COUNTRIES

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Abstract. *The article examines the environmental sustainability of land use in European countries, taking into account the spatial provision of protected areas, land-use structure, the level of environmental stability, and anthropogenic pressure. The necessity of shifting from the assessment of individual environmental protection*

indicators to a comprehensive analysis of the capacity of territories to preserve natural potential, biodiversity, and ecosystem functions is substantiated. The methodological basis of the study comprises indicators of the development of the Natura 2000 and Emerald ecological networks, the protection coefficient, the indicator of anthropogenic saturation of natural territorial complexes, the share of arable land, the environmental stability coefficient, and the anthropogenic pressure coefficient. To make them comparable, normalization using the min-max transformation method and equal weighting of the indicators were applied. On this basis, an integral index of environmental sustainability of land use is proposed, which makes it possible to comprehensively assess the relationship between the environmental protection and economic components of territorial development. The index was modelled for the 27 European Union countries and Ukraine. Significant differentiation among countries in terms of environmental sustainability was established. The highest values of the integral index are characteristic of Slovenia, Finland, Sweden, Croatia, and Estonia, while the lowest values are observed in Denmark, Ukraine, Hungary, Malta, and Czechia. The average value of the index for the European Union countries is approximately 0.50, whereas for Ukraine it is 0.22. It is proved that a large area of protected territories alone does not ensure high environmental sustainability of land use if it is accompanied by a high share of arable land and significant anthropogenic pressure. The proposed index can be used for comparative assessment of countries, spatial planning, improvement of land and environmental protection policies, as well as substantiation of directions for the formation of environmentally balanced land-use systems.

Keywords: *environmental sustainability, land use, ecological network, biodiversity, protected areas, anthropogenic pressure, ecosystem services.*

Problem Statement. Modern environmental and socio-economic challenges necessitate a transition towards land-use models focused not only on achieving

economic outcomes but also on preserving natural capital, biodiversity, and the capacity of ecosystems to provide society with vital services. European practices for ensuring the provision of ecosystem services to the population are based on the comprehensive development of programs for the conservation, protection, and restoration of natural areas. An important element of this system is the formation of an interconnected ecological network that ensures the conservation of valuable natural complexes, the maintenance of ecological links between them, and the long-term functioning of ecosystems [8]. A key role in implementing this approach is played by the Natura 2000 network, established as the main instrument for biodiversity conservation in the European Union [14, 15]. Its spatial structure is formed on the basis of special protected areas designated in accordance with the Birds Directive and the Habitats Directive, for which appropriate measures are envisaged to manage and protect species and their natural habitats [10, 11]. The Natura 2000 network covers more than 18% of the European Union's terrestrial territory and more than 8% of marine areas and includes approximately 27 thousand protected sites [3].

At the same time, the spatial distribution of such territories differs considerably among countries. The highest shares of Natura 2000 areas are characteristic of Slovenia, Croatia, Bulgaria, and Slovakia, whereas in some other countries the corresponding share is significantly lower [21]. Such differentiation indicates the heterogeneity of environmental protection pressure and different approaches of states to integrating environmental priorities into land-use structures.

An important complement to Natura 2000 is the Emerald Network, established within the framework of the Bern Convention [5, 16]. It covers Areas of Special Conservation Interest and ensures the dissemination of pan-European biodiversity conservation standards beyond the European Union. The mutual compatibility of Natura 2000 and the Emerald Network forms an integrated spatial approach to the protection of natural habitats across the European continent.

For Ukraine, the implementation of European principles for developing the ecological network is of particular importance in the context of European integration and the need to restore natural resources [19]. The Emerald Network of Ukraine already includes 271 sites, covering approximately 12% of the country's territory [14]. Further improvement of its spatial structure, ensuring effective management of protected areas, and harmonizing land policy with European environmental protection standards are important prerequisites for increasing the environmental sustainability of territories.

The study is particularly relevant in the context of the implementation of the European Green Deal and the EU Biodiversity Strategy for 2030, which provide for expanding the scale of protection of natural areas and strengthening the role of ecosystems in ensuring sustainable development [12]. Therefore, studying the spatial characteristics of Natura 2000, assessing differences among European countries, and determining their relationship with land-use sustainability constitute an important scientific and practical task. Such an approach makes it possible to substantiate directions for improving environmental policy, spatial planning, and land-resource management systems based on biodiversity conservation and ensuring a stable flow of ecosystem services.

The purpose of the article is to develop an integral approach to assessing the environmental sustainability of land use in European countries based on indicators of ecological network development, environmental protection provision, land-use structure, environmental stability, and anthropogenic pressure, as well as to determine the differentiation in the level of environmental sustainability among European countries.

Materials and Methods of the Study. The research materials included statistical and spatial data on land-use structure, protected areas, and the Natura 2000 and Emerald ecological networks of EU countries and Ukraine, obtained from official EU sources, the World Bank, and the State Statistics Service of Ukraine. Six indicators were used for the comprehensive assessment of environmental sustainability of land use: the

ecological network development index (I_n), the protection coefficient (K_p), the indicator of anthropogenic saturation of natural territorial complexes (I_{as}), the share of arable land (P), the environmental stability coefficient (K_{es}), and the anthropogenic pressure coefficient (K_{ap}). These indicators characterize two interrelated components of environmental sustainability of land use. The first characterizes the environmental protection and ecological stabilization potential of a territory, while the second reflects the level of anthropogenic transformation of land.

The first group includes: the development index of the Natura 2000 and Emerald ecological networks (I_n); the protection coefficient (K_p); and the environmental stability coefficient (K_{es}). An increase in each of these indicators characterizes a positive trend from the perspective of the environmental sustainability of a territory. A high level of ecological network development indicates greater spatial provision for biodiversity conservation and ecosystem functions, an increase in the protection coefficient indicates an expansion of the protected-area system, while a high environmental stability coefficient reflects a more favourable land-use structure.

The second group includes indicators whose increase, conversely, indicates stronger anthropogenic pressure: anthropogenic saturation of natural territorial complexes (I_{as}); the share of arable land as the main destabilizing component of agricultural landscapes (P); and the anthropogenic pressure coefficient (K_{ap}). Thus, different directions of influence of the above indicators were taken into account when constructing the integral index.

Since at this stage of the study each indicator is considered an independent and methodologically equivalent characteristic of environmental sustainability of land use, equal weights ($1/6$) were applied to the six components of the integral index. This approach makes it possible to avoid subjective prioritization of individual components and ensures transparency and reproducibility of the integral assessment.

The indicators were normalized using the min-max transformation method [2]. For stimulators, the following relationship was used: $x_i' = (x_i - x_{\min}) / (x_{\max} - x_{\min})$, while for destimulators: $x_i' = (x_{\max} - x_i) / (x_{\max} - x_{\min})$.

As a result, the normalized values of all indicators range from 0 to 1, where a higher value corresponds to a higher level of environmental sustainability of land use.

To ensure a unified representation of the data in the calculations of the integral index, the ecological network development index (I_n) and the protection coefficient (K_p) were used as fractions of a unit in the range from 0 to 1 (Table 1). In our study, percentage values are used only to characterize areas and their structure.

The levels of the integral index of environmental sustainability of land use (I_{ESLU}) were determined according to the following intervals: 0–0.19 – critical; 0.20–0.39 – low; 0.40–0.59 – medium; 0.60–1.00 – high.

The integral index of environmental sustainability of land use (I_{ESLU}) was determined as the mean of the normalized values of the six indicators. The obtained values were used for comparative ranking of European countries and determining the levels of environmental sustainability of land use.

Analysis of Recent Research and Publications. Recent studies confirm the appropriateness of a comprehensive assessment of the environmental sustainability of land use, since the condition of European agricultural landscapes is determined not only by the area of protected territories but also by land-use structure, the intensity of agricultural production, fragmentation of natural habitats, and anthropogenic pressure.

Thus, the study by Nicholas and Scown (2024) demonstrates that rural land-use systems in Europe simultaneously contribute to and create barriers to achieving the Sustainable Development Goals [6]. The authors emphasize the need to consider environmental and socio-economic indicators simultaneously, which methodologically corresponds to the integral approach proposed in this article [13].

An important area of current research is the assessment of anthropogenic pressure on agricultural land. In particular, a 2024 study established that taking

agricultural intensity into account almost doubles the strength of the relationship between land use and the ecological condition of rivers in Europe [9].

Some publications focus on the role of landscape elements and ecological connectivity. According to JRC research, landscape elements occupy approximately 5.6% of EU agricultural land and are important for biodiversity conservation and ecosystem services. Other studies indicate that restoring connections between natural habitats and agroecosystems can increase the functionality of Natura 2000 [4].

Agricultural intensification remains a significant problem. A 2024 study showed an accelerated decline in populations of farmland birds in a number of European countries, with agricultural intensification identified as the main factor [13].

The problems of spatial provision for the conservation of biodiversity and ecosystem functions in European territories have been investigated in the works of Ukrainian researchers [1, 7, 21].

Thus, recent publications confirm the scientific validity of the proposed authorial approach, since environmental sustainability of land use should be considered as the result of interaction between environmental protection provision, land-use structure, environmental stability, and anthropogenic pressure.

Presentation of the Main Research Material. The pan-European ecological network is a complex territorial structure characterized by heterogeneity and uneven spatial distribution of protected areas. The implementation of the environmental protection component of the ecological network is complicated by the fact that its structure includes not only natural areas but also lands actively used for economic activities, particularly agricultural land.

The share of agroecosystems within national Natura 2000 networks varies considerably among countries. Analysis of its territorial structure indicates that significant areas of agricultural and forestry land are included in the ecological network, while simultaneously performing environmental protection and economic functions.

Within the EU, approximately 11% of agricultural land and 22.9% of forestry land are included in the ecological network (Fig. 1).

The largest shares of agricultural land included in Natura 2000 areas are observed in Croatia – 25.7%, Bulgaria – 22.4%, and Slovenia – 23.2%. In contrast, the lowest value of this indicator is recorded in Finland – only 1.2%.

Even more substantial differences exist among EU Member States in terms of the share of forestry areas covered by the Natura 2000 network: the corresponding indicator varies from 7.6% in Sweden to 53.2% in Bulgaria. These data indicate that forest-covered territories constitute a significant proportion of ecological network areas in EU countries.

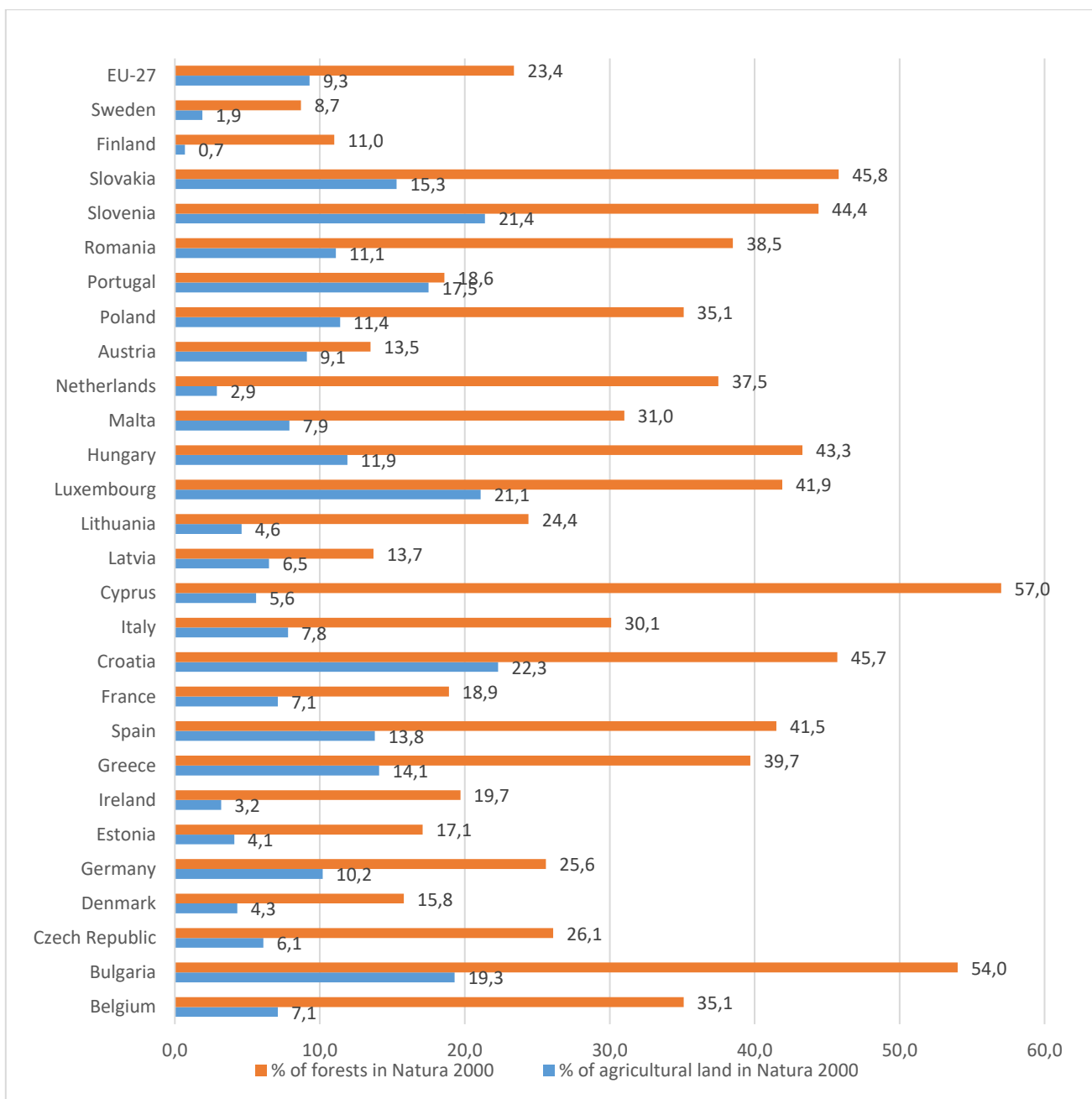


Fig. 1. Share of agricultural and forestry land in Natura 2000, % [5]

Given the active policy of the European Union aimed at expanding and developing environmental protection networks, an important task of the study is to assess the level of provision of European states with territories covered by the Natura 2000 and Emerald networks.

For EU countries, the study uses indicators of territorial coverage by the Natura 2000 network, whereas for Ukraine the corresponding indicator is based on the Emerald

Network. Their methodological comparability is determined by their common environmental protection orientation and focus on the conservation of biodiversity, natural habitats, and ecosystem functions. Therefore, within the integral model, they are considered different national and institutional forms of implementing the European approach to ecological network development.

To avoid terminological ambiguity, the study uses the unified term "ecological network development index" (I_n), which covers Natura 2000 for EU countries and the Emerald Network for Ukraine. In our opinion, this approach is consistent with the provision presented in the article regarding the mutual compatibility of Natura 2000 and the Emerald Network and their common environmental protection function.

For this purpose, an ecological network development index was developed and calculated within the study, making it possible to comprehensively assess the level of representation of protected areas within the land-use structure of European countries.

$$I_n = \frac{\sum S_c + \sum S_m}{\sum S_z}, \quad (1)$$

where:

$\sum S_c$ – total area of land plots covered by ecological network sites;
 $\sum S_m$ – total area of marine areas covered by ecological network sites;
 $\sum S_z$ – total area of the administrative unit.

The calculations produced the results presented in Table 1.

This indicator makes it possible to comprehensively assess the spatial provision of territories with conditions necessary for biodiversity conservation and maintenance of ecosystem functions. Within this study, the assessment was conducted for the Member States of the European Union and Ukraine.

The highest values of the index were recorded in Germany – 0.61 and Belgium – 0.50. The lowest level of provision is characteristic of Czechia – 0.14 and Ireland – 0.15. The average value of the indicator for the European Union countries is 0.26, whereas for Ukraine the Emerald index value is 0.12.

To assess the level of natural-resource provision of a territory, we calculated the protection coefficient as the share of protected areas (K_p), i.e., the ratio of the area of protected areas within a particular territory (S_{pt}) to its total area (S_t):

$$K_p = S_{pt}/S_t * 100\%. \quad (2)$$

The indicator reflects the level of natural-resource potential and ecosystem services of a country's territory. Among European countries, the highest level of territorial protection was recorded in Luxembourg – 51%, Bulgaria – 41%, and Slovenia – 40%. The lowest values of this indicator are characteristic of Ireland – 14% and Finland – 13%.

In Ukraine, the share of protected areas is only 7%, which is significantly lower than the European average of 26%. This ratio indicates insufficient provision of Ukraine's territory with protected areas compared with the Member States of the European Union.

To ensure a unified representation of the data in the calculations of the integral index, the indicator values were taken as fractions of a unit in the range from 0 to 1 (Table 1).

In our opinion, the structure of natural territorial complexes should be assessed using the indicator of anthropogenic saturation of natural territorial complexes – I_{as} (see Formula 5.3), which makes it possible to assess the share of anthropogenically loaded territories (agricultural land, urbanized areas) in the total structure of natural territorial complexes ($\sum S_a$), as well as specifically in forests, wetlands, water bodies, and dry areas with special vegetation cover ($\sum S_p$).

$$I_{as} = \frac{\sum S_a}{\sum S_p} \quad (3)$$

An increase in this indicator indicates the growing role of anthropogenically loaded territories in the structure of nature use and allows us to state that the interpenetration and, consequently, mutual influence of territorial components are approaching their maximum.

Thus, the highest indicators were identified in the land-use structures of Denmark (1.25), Luxembourg (1.22), Malta (1.00), Hungary (0.87), France (0.80), and Germany (0.79), indicating a high level of integration of the agricultural sector into the nature-use system, since the share of agricultural land is the largest.

The lowest indicators were identified in the land-use structures of Finland (0.02), Ukraine and Sweden (0.05), Estonia (0.14), Ireland (0.21), and Slovenia (0.24), indicating very low or low integration of agroecosystems into the natural territorial complexes of the respective countries.

One of the key areas of the study is a comprehensive environmental assessment of the territories of individual European countries and Ukraine. The information base of the study consisted of statistical and official data from the European Union, the World Bank, and the State Statistics Service of Ukraine.

The methodological basis for the agroecological assessment of territories was an approach involving the determination of the degree of disruption of ecological equilibrium between arable land, considered the main destabilizing component of agricultural landscapes, and the aggregate of natural landscape elements – forests, meadows, water bodies, hayfields, pastures, and other land categories performing an ecological stabilization function [17].

The calculation was performed using the following formulas:

$$P = \frac{S_p}{S_p + S_{ecu}} 100, \quad (4)$$

where:

P – share of arable land in the group of land categories;

S_p – area of arable land, ha;

S_{ecu} – total area of natural territories, ha.

The share of ecologically stabilizing land (ESL) within the land-use group is calculated according to the following formula:

$$ESL = \frac{Secu}{Sp+Secu} 100, \quad (5)$$

where ESL – share of ecologically stabilizing land within the P + ESL land-use group, %.

A five-point assessment scale was applied to characterize the degree of disruption of the ecological equilibrium of agricultural landscapes [18]. The results presented in Table 1 are given as fractions of a unit, ensuring the unification of the research results.

At the same time, the results of our study demonstrate that a significant proportion of the studied land-use systems of European countries are characterized by an optimal agroecological condition according to indicator P, within the range of 0–20. This group includes Malta, Sweden, Ireland, Finland, Slovenia, Portugal, Cyprus, Croatia, Estonia, Austria, and Greece.

A good agroecological condition, with P values ranging from 21 to 36, was established for Latvia, Italy, Spain, Luxembourg, France, Slovakia, the Netherlands, Bulgaria, Lithuania, and Belgium.

A satisfactory condition of territories, corresponding to a P range of 37–55, is characteristic of Germany, Poland, Romania, Czechia, and Hungary.

An unsatisfactory agroecological condition, with P values ranging from 56 to 70, was established in Ukraine – 56% and Denmark – 60%. This level of the indicator reflects significant anthropogenic pressure and excessive use of the natural potential of ecosystems.

At the same time, the average values of $P = 24.9$ and $ESL = 75.1$ for the European Union countries as a whole characterize their territories as having a good agroecological condition.

The assessment of environmental stability and the level of anthropogenic impact on territories was carried out in accordance with the methodological recommendations

for determining the environmental stability of agricultural landscapes and agricultural land use developed by A. M. Tretiak [18].

The impact of land-use structure on the environmental stability of a territory is characterized by the environmental stability coefficient – K_{es} , which was calculated according to the following formula:

$$K_{es} = \frac{\sum K_i * \Pi_i}{\sum \Pi_i} \quad (6)$$

where:

K_i – coefficient of environmental stability of the i -th type of land [18];

Π_i – area of the i -th type of land, thousand ha.

Analysis of the environmental balance of landscapes and the degree of their anthropogenic transformation showed that weakly stable environmental conditions have developed in Denmark, Malta, the Netherlands, Hungary, Belgium, and Ukraine.

The values of the environmental stability coefficient (K_{es}) in these countries range from 0.34 to 0.50. The highest level of positive influence of land-use structure on the environmental stability of territories is observed in Finland – 0.88, Sweden – 0.85, Slovenia – 0.78, and Estonia – 0.72.

The average value of the corresponding indicator for the European Union countries is 0.60, which corresponds to an average level of environmental stability of territories.

The environmental balance of landscapes and the impact of human activities on the condition of the environment, including land resources, are assessed using the anthropogenic pressure coefficient [20] (K_{ap}), which was calculated according to the following formula:

$$K_{ap} = \frac{\sum B_{ui} * \Pi_i}{\sum \Pi_i}, \quad (7)$$

where:

B_{ui} – score for the level of anthropogenic pressure on the i -th type of land;

Π_i – area of the i -th type of land, thousand ha.

Another area of the study was the determination of the level of anthropogenic pressure, which characterizes the intensity of human economic activity and its impact on the condition and functioning of territorial ecosystems.

The calculations showed that an increased level of anthropogenic pressure, corresponding to coefficient values from 3.1 to 4.0, is characteristic of Malta, Denmark, Belgium, the Netherlands, and Ukraine. For the remaining European countries under study, an average level of anthropogenic pressure was established (Table 1).

Since environmental sustainability of land use should be determined not by a single indicator but by a set of interrelated characteristics reflecting the ability of a territory to preserve its natural potential, ensure ecosystem functioning, and simultaneously withstand anthropogenic pressure, we propose using the integral index of environmental sustainability of land use (I_{ESLU}).

The use of only one indicator, such as the share of protected areas or the environmental stability coefficient, does not make it possible to comprehensively assess the condition of a country's land-use system.

In the present study, six indicators were used to form the integral assessment: the ecological network development index (I_n), the protection coefficient (K_p), the indicator of anthropogenic saturation of natural territorial complexes (I_{as}), the share of arable land in the land-use structure (P), the environmental stability coefficient of the territory (K_{es}), and the anthropogenic pressure coefficient (K_{ap}).

The integral index of environmental sustainability of land use was determined according to the following formula:

$$I_{ESLU} = \frac{ZI_n + ZK_p + ZI_{as} + ZP + ZK_{es} + ZK_{ap}}{6} \quad (8)$$

where I_{ESLU} – integral index of environmental sustainability of land use.

The proposed approach makes it possible to simultaneously account for the level of development of environmental protection infrastructure, the environmental stability of land-use structure, and the intensity of anthropogenic pressure.

Based on the data presented in the study, the integral index of environmental sustainability of land use was calculated for the 27 EU countries and Ukraine.

The modelling results demonstrate significant differentiation among European countries in terms of environmental sustainability of land use.

The highest value of the integral index was obtained for Slovenia – 0.786, which is due to the simultaneous combination of high environmental stability of land-use structure (0.78), a significant share of protected areas (0.40), a relatively low share of arable land (9.4%), and low anthropogenic pressure (2.5).

A high level of environmental sustainability is also characteristic of Finland (0.71), Sweden (0.71), Croatia (0.70), and Estonia (0.68). A common characteristic of these countries is a favourable land-use structure, significant areas of natural territories, high environmental stability, and relatively low anthropogenic pressure.

The situation in Finland and Sweden is particularly illustrative: despite relatively low values of the ecological network development index and protection coefficient, these are compensated for by very high values of the environmental stability coefficient and low levels of arable land and anthropogenic pressure.

Table 1

Modelling of the Integral Index of Environmental Sustainability of Land Use in European countries

Country	I _n	K _p	I _{as}	P	ESL	K _{es}	K _{ap}	I _{ESLU}	Level
Austria	0,15	0,29	0,41	0,17	0,83	0,67	2,80	0,54	medium
Belgium	0,50	0,15	0,58	0,35	0,65	0,44	3,40	0,38	low
Bulgaria	0,43	0,41	0,68	0,33	0,67	0,58	3,00	0,54	medium
Greece	0,32	0,35	0,46	0,17	0,83	0,64	2,80	0,60	medium
Denmark	0,24	0,15	1,25	0,61	0,39	0,34	3,60	0,07	critical
Estonia	0,36	0,21	0,14	0,16	0,84	0,77	2,50	0,68	high
Ireland	0,15	0,14	0,21	0,07	0,93	0,60	2,90	0,50	medium
Spain	0,35	0,28	0,38	0,24	0,76	0,60	2,90	0,55	medium
Italy	0,20	0,21	0,44	0,24	0,76	0,60	2,90	0,46	medium
Cyprus	0,29	0,38	0,41	0,12	0,88	0,57	3,00	0,58	medium
Latvia	0,27	0,18	0,33	0,22	0,78	0,72	2,60	0,57	medium
Lithuania	0,37	0,17	0,35	0,34	0,66	0,57	3,00	0,47	medium
Luxembourg	0,27	0,51	1,22	0,27	0,74	0,57	3,10	0,45	medium
Malta	0,18	0,29	1,00	0,05	0,95	0,38	3,60	0,32	low
Netherlands	0,40	0,26	0,36	0,30	0,70	0,43	3,40	0,43	medium
Germany	0,61	0,38	0,79	0,37	0,63	0,51	3,20	0,52	medium
Poland	0,41	0,40	0,78	0,38	0,63	0,54	3,10	0,48	medium
Portugal	0,23	0,22	0,63	0,11	0,89	0,68	2,70	0,54	medium
Romania	0,44	0,23	0,48	0,39	0,62	0,53	3,10	0,46	medium
Slovakia	0,30	0,37	0,32	0,29	0,71	0,63	2,90	0,57	medium
Slovenia	0,43	0,40	0,24	0,09	0,91	0,78	2,50	0,79	high
Hungary	0,21	0,22	0,87	0,50	0,50	0,43	3,30	0,23	low
Ukraine	0,12	0,07	0,05	0,56	0,44	0,40	3,40	0,22	low
Finland	0,21	0,13	0,02	0,07	0,93	0,88	2,20	0,71	high
France	0,44	0,27	0,80	0,29	0,71	0,55	3,10	0,47	medium
Croatia	0,46	0,38	0,41	0,15	0,85	0,70	2,70	0,70	high
Czechia	0,14	0,22	0,51	0,43	0,57	0,52	3,20	0,32	low
Sweden	0,25	0,14	0,05	0,06	0,94	0,85	2,30	0,71	high

Calculated by the authors using data [22].

A medium level of environmental sustainability was established for the majority of the countries under study. I_{ESLU} values ranging from 0.40 to 0.59 were obtained for Greece, Cyprus, Latvia, Slovakia, Spain, Bulgaria, Portugal, Austria, Germany, Ireland, Poland, Lithuania, France, Italy, Romania, Luxembourg, and the Netherlands.

Within this group, Germany deserves particular attention. It has the highest ecological network development index among the countries studied – 0.61; however,

its integral indicator is only 0.52. This is explained by the high anthropogenic saturation of natural territorial complexes (0.79), a significant share of arable land (36.7%), and relatively high anthropogenic pressure (3.2).

Therefore, a developed system of protected areas alone does not guarantee high environmental sustainability of land use if a significant level of anthropogenic transformation of the territory persists simultaneously.

A low level of environmental sustainability is characteristic of Belgium (0.38), Czechia (0.32), Malta (0.32), Hungary (0.23), and Ukraine (0.22). These countries are characterized by a combination of high anthropogenic pressure, a significant share of agricultural land use, and insufficient environmental stability of the land-use structure.

The result for Ukraine is particularly important. The IESLU value is 0.22, which is significantly lower than the average value for EU countries, which, according to the proposed model, is approximately 0.50. Thus, according to the model assessment, the integral level of environmental sustainability of land use in Ukraine is approximately 43% of the average level of EU countries.

The low I_{ESLU} value for Ukraine is formed under the influence of several interrelated factors. First of all, these include a low level of ecological network development (0.12), the lowest protection coefficient among the countries studied (0.07), a low environmental stability coefficient (0.40), a high share of arable land (56.3%), and an increased anthropogenic pressure coefficient (3.4).

At the same time, the low value of the indicator of anthropogenic saturation of natural territorial complexes (0.05) cannot compensate for the overall imbalance, since in the proposed model it is considered positive only provided that the natural components of the territory are sufficiently developed.

The lowest result was obtained for Denmark – 0.07. This is primarily associated with the highest share of arable land among the countries studied (60.6%), the highest indicator of anthropogenic saturation of natural territorial complexes (1.25), one of the

highest levels of anthropogenic pressure (3.6), and the lowest environmental stability coefficient (0.34).

The obtained result confirms that the high intensity of agricultural land use can significantly reduce the overall environmental sustainability of a territory even in the presence of a developed environmental protection policy.

The proposed integral index makes it possible to move from the analysis of individual environmental characteristics to a comprehensive assessment of the sustainability of the land-use system (Fig. 2). Its advantage is the combination of the spatial environmental protection component, represented by the ecological network and protected areas, with the structural characteristics of land and indicators of anthropogenic pressure.

It is important that the model does not equate environmental protection provision with environmental sustainability. For example, a country may have significant areas of Natura 2000 or protected areas but at the same time be characterized by a high share of arable land, significant anthropogenic pressure, and low environmental stability of agricultural landscapes.

Therefore, the integral assessment makes it possible to account for the compensatory effect of individual components and identify the actual imbalance between the environmental protection and economic functions of land.

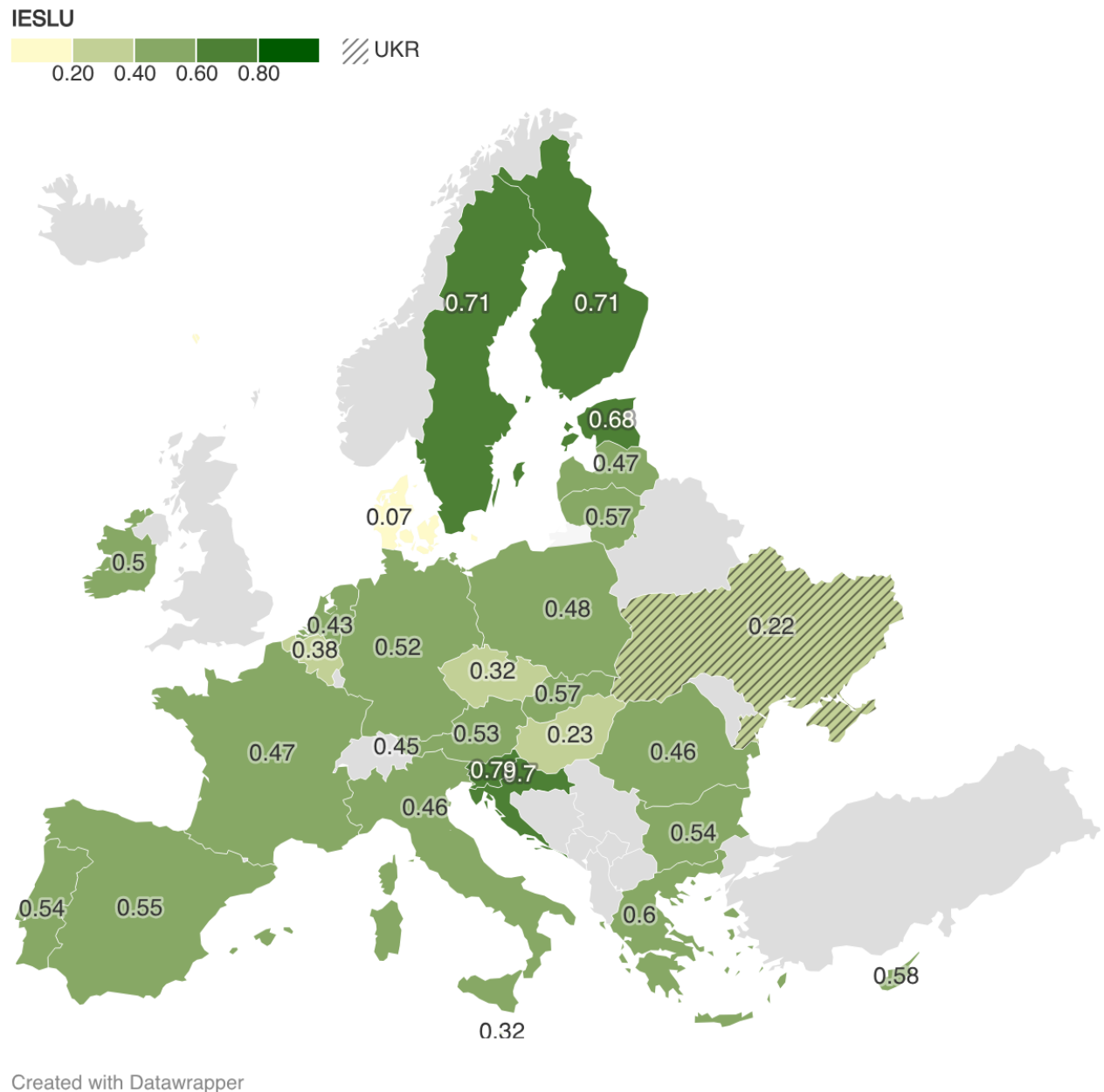


Fig. 2. Integral Index of Environmental Sustainability of Land Use in European Countries

Conclusions. Thus, the study demonstrated that the environmental sustainability of land use in European countries is shaped by three key components: environmental protection provision of the territory, environmental stability of the land-use structure, and the level of anthropogenic pressure.

The most balanced countries in terms of the combination of these characteristics are Slovenia, Finland, Sweden, Croatia, and Estonia. In contrast, the land-use systems

of Denmark, Ukraine, Hungary, Malta, and Czechia are characterized by the lowest values of the integral indicator.

For Ukraine, the priority directions for increasing the environmental sustainability of land use should include expanding the ecological network and protected areas, increasing the share of ecologically stabilizing land, optimizing the structure of agricultural land use, and reducing anthropogenic pressure on land resources.

In practical terms, the index can be used to compare the environmental sustainability of land use, identify problem areas, assess the effectiveness of land and environmental protection policies, substantiate directions for expanding ecological networks, optimize land-use structure, and determine priorities for the environmentalization of agricultural land use.

At the same time, the obtained results should be considered as an authorial model-based assessment, since the initial indicators characterize different aspects of the environmental condition of territories and have different underlying mechanisms of formation.

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МОДЕЛЮВАННЯ ІНТЕГРАЛЬНОГО ІНДЕКСУ ЕКОЛОГІЧНОЇ СТІЙКОСТІ ЗЕМЛЕКОРИСТУВАННЯ КРАЇН ЄВРОПИ

***Анотація.** У статті досліджено екологічну стійкість землекористування європейських країн з урахуванням просторової забезпеченості природоохоронними територіями, структури земельних угідь, рівня екологічної стабільності та антропогенного навантаження. Обґрунтовано необхідність переходу від оцінювання окремих природоохоронних показників до комплексного аналізу здатності територій зберігати природний потенціал, біологічне різноманіття та екосистемні функції. Методологічною основою дослідження стали показники розвитку екомережі Natura 2000 і Смарагдової мережі, коефіцієнт заповідності, показник антропогенного насичення природних територіальних комплексів, частка ріллі, коефіцієнт екологічної стабільності та коефіцієнт антропогенного навантаження. Для їх зіставлення застосовано нормалізацію за методом мінімаксного перетворення та рівнозначне зважування показників. На цій основі запропоновано інтегральний індекс екологічної стійкості землекористування, який дає змогу комплексно оцінювати співвідношення природоохоронної та господарської складових територіального розвитку. Здійснено моделювання індексу для 27 країн Європейського Союзу та України. Встановлено суттєву диференціацію країн за рівнем екологічної стійкості. Найвищі значення інтегрального індексу характерні для Словенії, Фінляндії, Швеції, Хорватії та Естонії, тоді як найнижчі - для Данії, України, Угорщини, Мальти та Чехії. Середнє значення індексу для країн Європейського Союзу становить близько 0,504, тоді як для України - 0,218. Доведено, що значна площа природоохоронних територій сама по собі не забезпечує високої екологічної стійкості землекористування, якщо супроводжується високою*

часткою ріллі та значним антропогенним навантаженням. Запропонований індекс може бути використаний для порівняльної оцінки країн, просторового планування, удосконалення земельної та природоохоронної політики, а також обґрунтування напрямів формування екологічно збалансованих систем землекористування.

Ключові слова: *екологічна стійкість, землекористування, екомережа, біорізноманіття, природоохоронні території, антропогенне навантаження, екосистемні послуги.*