Assessment of Land Degradation Risk in Ukraine Using Analytic Hierarchy Process (AHP) and GIS Modeling

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Оцінка Ризику Деградації Земель в Україні за Допомогою Методу Аналізу Ієрархій та ГІС Моделювання

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***Abstract* — The paper proposes a methodology for multi-criteria decision analysis to assess land degradation risk in Ukraine. The approach is based on the Analytic Hierarchy Process method, which allows for the evaluation of degradation risk using quantitative and qualitative indicators of spatial-functional impact of processes and/or objects located in this territory, represented as a set of criteria layers in GIS. The main stages of the analysis are described: development of the hierarchical structure of the model, preparation of a set of criteria and alternatives, standardization and weighting of criteria, selection of combination rules, and others. The model's feature is the consideration of military-technogenic factors.**

***Анотація* — В роботі запропонована методологія багатокритеріального аналізу рішень для оцінки ризику деградації земель в Україні. Підхід ґрунтується на методі аналізу ієрархій, який дозволяє виконати оцінку ризику деградації за кількісними та якісними показниками просторово-функціонального впливу процесів та/або об'єктів, які розташовані на цій території, представленими у вигляді набору шарів критеріїв в ГІС. Надано опис основних етапів аналізу: розроблення ієрархічної структури моделі, підготовки множини критеріїв та альтернатив, стандартизації та зважування критеріїв, вибору правил комбінування та інші. Особливістю моделі є врахування воєнно-техногенних факторів.**

Keywords — geoinformation system (GIS); land degradation; multi-criteria decision analysis (MCDA); spatial modeling methods

Ключові слова—геоінформаційні системи; деградація земель, багаторитеріальній аналіз рішень; просторові методи моделювання

I. Introduction

Land degradation is a serious environmental problem influenced by both natural and anthropogenic factors. Ukraine today is a military-technogenically tense region of Europe with negative consequences for the environment generally and the soil cover in particular.

Land degradation is defined as the process of deteriorating land quality, reducing its fertility, and decreasing the content of nutrients within it. According to the estimates of the Food and Agriculture Organization of the United Nations, about 20% of agricultural land in Ukraine has already experienced significant degradation. The ongoing hostilities have an additional destructive impact on soil productivity. The main negative factors include craters from aerial bombs and artillery shelling, mined areas, destroyed heavy military equipment, oil spills, scorched areas from fires, landslides, etc.[1]

The functional properties of the soil may be restored and productivity increased depending on soil type, level of degradation and landscape conditions of the territory. This requires an interdisciplinary and integrated approach to sustainable land management. This project proposes the methodology for soil degradation risk assessment, which will be based on the application of geospatial multi-criteria decision analysis (MCDA) [2] using analytic hierarchy process (AHP) [3]. The methodology will make it possible to determine the spatial distribution of a soil degradation risk using an index that is based on the factors (criteria) influencing degradation risk, including military-technogenic factors.

II. Problem Statement

In a generalized form, the decision-making problem is represented by a tuple of sets of conditions:

$$\langle A, C, F, P; D \rangle, \quad (1)$$

where $A=\{a_1,a_2,\ldots,a_m\}$ is the set of alternatives; $C=\{C_1,C_2,\ldots,C_n\}$ is the set of criteria for evaluating alternatives; F is the evaluation procedure; P is the preference system, containing information about the evaluations of alternatives for each criterion; D is the decision rule specifies the procedure of action over the set of alternatives (selection, ranking, sorting, etc.). If we consider the territory as a complex system, the decision-making process can be reduced to evaluating a model representation of the system and its properties, which most closely correspond to the real state of the territory under specified conditions. In accordance with (1), the evaluation goals, methods, scales, evaluation criteria and evaluation procedure should be defined. Thus, decision-making technology involves obtaining or generating alternatives, comparing them based on specific criteria, and ranking them depending on the goals [4]. The diagram of the multi-criteria decision analysis procedure is presented in Fig. 1.

Thematic layers of objects are preferably represented as a set of cells (pixels) in a raster GIS model, which takes the form of a two-dimensional discrete rectangular grid of mx×my cells, where $\Delta x=\Delta y=\Delta r$ – cell size. Each cell is an alternative described by its spatial data (geographic coordinates) and attribute data (criterion values).

III. Research Methodology

After selecting the territory boundaries and quantization step, it is necessary to define a set of criteria. At this stage, the set of objects (processes) that determine the properties of the territory is decomposed into a subset of thematic layers (factors) influencing land degradation. Among the main exogenous geological processes causing land degradation in Ukraine, wind and water erosion are often considered. Indicators of land degradation may include changes in vegetation and soil erosion dynamics. To map them, relevant source data need to be prepared: besides multispectral satellite imagery, auxiliary geospatial data such as digital elevation models, various soil, and climate maps are required. Additionally, the negative impact of military-technological factors should be taken into account, manifested by mechanical deformation of soil cover and changes in its physical properties due to military vehicle movements, bombings, demining activities, construction of defense infrastructure, and thermal effects from numerous fires [1]. The thematic layers can be created based on open cartographic information, for example, available through the API of the Fire Information for Resource Management System (FIRMS) by NASA and the European Forest Fire Information System (EFFIS), or the Institute for the Study of War (ISW). The discretization of vector thematic layers into rasters can be performed using various GIS analysis methods, such as geostatistical interpolation, fractal analysis, computation of distances using Euclidean metrics, etc.

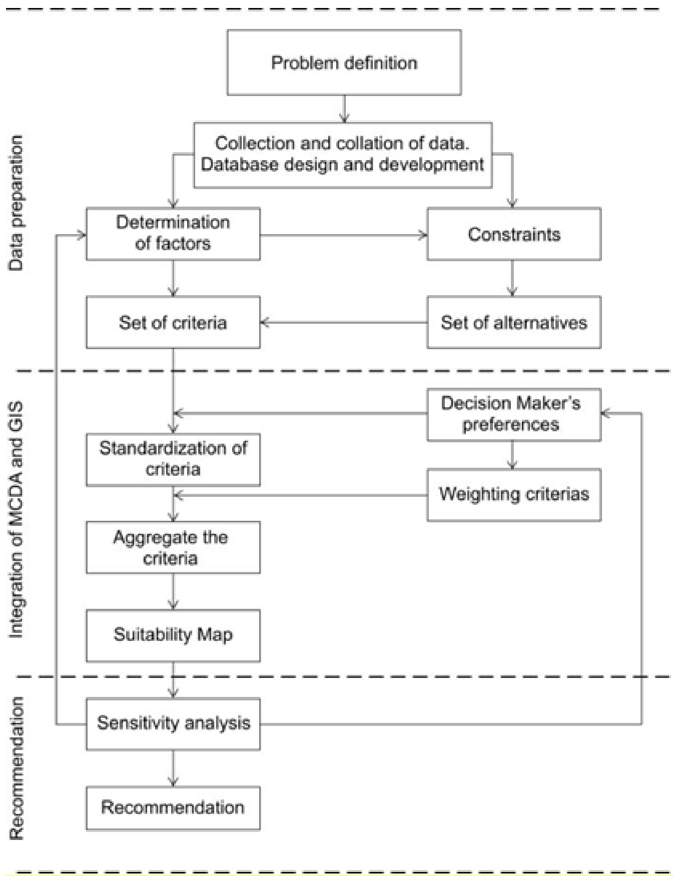

Fig.1 The diagram of the multi-criteria decision analysis procedure in GIS

In accordance with AHP, a hierarchical decision-making structure was developed, which at the first level consists of 7 criteria (topography, physical quality index of soil, chemical quality index of soil, wind erosion index, water erosion index, vegetation index, military-technogenic impact index). At the second level of the hierarchical structure, subcriteria characterizing the main indices are added. The detailed structure of the decision-making model with a description of the criteria is presented in Table 1.

Standardization of thematic layers of criteria involves scaling or reclassifying attribute values of thematic layers from raw scales into comparative units. At this stage, reclassification of attributes based on fuzzy membership functions constructed from expert knowledge and judgments is preferred [5]. Such fuzzification of attributes will allow reclassifying values into the range [0,1].

TABLE I. CRITERIA FOR ASSESSING LAND DEGRADATION RISK

Indexes	**Subcriteria (layers in GIS)**	**Description**
Topography	Slope (%)	Calculated based on the digital elevation model (DEM) using data from the SRTM space mission
	Topographic Wetness Index (TWI)	
	Erosion Relief Index (ER)	
Physical soil quality	Texture	Digital maps reclassified in GIS based on expert assessments. Transformed into raster data format for MCDA procedure.
	Soil filtration	
	Humus content in the arable soil layer (%)	
	Humus reserves (t/ha)	
Chemical soil quality	pH value	
	Soil salinity	
	Heavy metals content (mg/kg)	
	Soil fertility	
Wind Erosion	Intensity of wind field	Calculated based on the average wind speed with Kriging interpolation
	Terrain roughness coefficient	Calculated based on the digital elevation model (DEM)
	Soil erodibility	Digital maps reclassified in GIS based on expert assessments
	Intensity of dust storm	
Water Erosion	Rainfall (mm)	
	Land use type	
Vegetation	Normalized Difference Vegetation Index (NDVI)	Calculated using multispectral imagery from Landsat and Sentinel satellites
Military-Technogenic Impact	Density of fire distribution	Calculated using archived data from NASA FIRMS and EFFIS systems
	Distance from fortifications and minefields	Used data from the Institute for the Study of War (ISW) mapping service and high-resolution satellite imagery from Google Earth
	Intensity of combat actions	

The determination of weight coefficients of criteria importance was carried out based on the linguistic assessment scale of the AHP method. A weight is a value assigned to an evaluation criterion that indicates its importance relative to the other criteria under consideration. The method requires that decision-making agents specify their preferences with respect to the evaluation criteria. The greater the weight, the more important is the criterion. In the case of n criteria, the weights should possess the following properties:

$$W = \left\{ w_i \mid \sum w = 1,\ i = \overline{1, n} \right\}. \quad (2)$$

For aggregation - combining criteria attributes according to certain decision-making rules, overlay operations can be used: minimum, maximum, arithmetic mean, weighted sum. The aggregation operator can also take into account acceptable forms of compromise between alternative assessments based on different criteria, such as the OWA Yager operator [6, 7]. The application of various non-compensatory and compensatory aggregation operators allows conducting multi-criteria analysis for different decision-making strategies.

Sensitivity analysis allows assessing the influence of changes in the initial parameters of the model on its final characteristics and actually checking the reliability of the obtained solution. As shown in Fig. 1, in case of unsatisfactory results, it is necessary to return to the beginning of the MCDA procedure and possibly adjust the goals, set of criteria, and/or criteria weighting algorithm.

IV. CONCLUSIONS

Proposed is an approach to mapping land degradation risk in Ukraine based on multi-criteria decision analysis and the Analytic Hierarchy Process method. The set of criteria was adapted considering climatic, mechanical, and anthropogenic factors influencing the process of land degradation. Military-technogenic factors, which currently have a significant negative impact on soil conditions, were separately considered. The feature of this approach is its reliance on expert knowledge and judgments and its easy integration into GIS processing environment.

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