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Research Article

DEVELOPMENT OF TECHNOLOGICAL PRINCIPLES FOR THE INTEGRATED ANALYSIS AND ASSESSMENT OF THE STATE OF THE ENVIRONMENT BASED ON GIS TECHNOLOGIES AND MATHEMATICAL MODELING METHODS

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ABSTRACT
Modern environmental challenges such as land degradation, desertification, and climate change require innovative approaches to environmental assessment. In Uzbekistan, these issues have become particularly critical due to intensified anthropogenic pressure, inefficient management of land and water resources, and the desiccation of the Aral Sea. Consequently, there is an urgent need for scientifically grounded technologies capable of providing reliable ecological diagnostics and supporting sustainable decision-making.
This study aims to develop a comprehensive methodology for analyzing and assessing the environmental state of Uzbekistan using Geographic Information Systems (GIS), mathematical modeling, and the methodological framework of L. A. Zadeh's fuzzy set theory. The fuzzy logic approach allows the quantification of uncertainty in environmental data through degrees of membership, enabling the differentiation of transitional conditions between favorable and unfavorable ecological zones. By integrating expert and empirical data, this approach enhances the precision and interpretability of environmental evaluations.
The proposed methodology combines multiple thematic GIS layers representing climatic, soil-ecological, and anthropogenic parameters through the OVERLAY algorithm, supported by the calculation of informative weighting coefficients. Expert-defined membership functions are employed to determine the composite environmental condition of territories, ensuring more accurate spatial differentiation and environmental assessment.
Spatial analysis revealed that the most favorable zones for agricultural production are located in the Fergana, Surkhandarya, and Khorezm regions, while ecologically unstable areas are concentrated in Karakalpakstan, the Aral Sea basin, and northern Navoi. The developed integrated zoning maps reflect environmental stability levels and land suitability for agriculture, providing a spatial basis for rational land use planning.
Overall, the GIS-based analytical framework incorporating Zadeh's fuzzy set methodology enables the integration of diverse spatial data and supports objective environmental evaluation. The results have practical significance for environmental monitoring, sustainable land management, and strategic planning in Uzbekistan's agricultural sector.

Keywords: *Ecology, Agriculture, Gis Technologies, Mathematical Modeling Methods, Fuzzy Logic*

INTRODUCTION
Over the past decades, the intensification of anthropogenic impact on the natural environment has led to a serious deterioration of the ecological situation in Central Asia, creating a contradiction between the

objectives of agricultural development, nature conservation, and improving the quality of life of the population. These processes are particularly evident in the Republic of Uzbekistan. The most striking example of the negative consequences of irrational agricultural policy is the desiccation of the Aral Sea — the largest environmental catastrophe of modern history, which unfolded in less than half a century (Micklin, 2019). More than 60 million people living in the Aral Sea basin have been affected by this disaster. The dried seabed, covering an area of more than 5.7 million hectares, has turned into the Aralkum Desert — a source of saline and dust storms (Glantz, 2020).

Agriculture remains a key sector of Uzbekistan's economy: the republic ranks third in the world in cotton exports and sixth in overall production (FAO, 2021). In 2017, the sector accounted for 17.6% of GDP and employed about 44% of the working population. However, the expansion of irrigated lands, including saline areas, has led to secondary soil salinization. Even a slight increase in soil salinity reduces cotton yields by 10–15%, moderate salinization by 30–40%, severe salinization by 50–60%, and when salt content exceeds 2–3%, the yield is completely lost (Qadir *et al.,* 2019).

In recent years, the degradation of valuable irrigated lands and the decline in their productivity have been observed due to inefficient management of water resources and irrigation systems, as well as irrational land use (Zou *et al.,* 2020). In response, the republic has been implementing projects to mitigate the consequences of the Aral Sea catastrophe: afforestation of the dried seabed and the creation of protective forest zones are being carried out to reduce the intensity of dust storms in the next 10–12 years (World Bank, 2021). Over the past decade, investments aimed at combating salinization, desertification, and improving the agricultural environment have exceeded 1.2 billion USD.

For the rational use of natural resources, a comprehensive analysis and mapping of environmental conditions using modern geographic information technologies is required. Modeling the interaction between society and nature is becoming an essential tool for optimizing investments and improving the quality of life of the population.

ii. Relevance of the study

Improving the efficiency of agricultural production requires comprehensive studies of the state of the environment using Geographic Information Systems (GIS). Based on such analyses, it is possible to create maps that reflect the degree of suitability of territories for habitation and agricultural activities (Ahmed *et al.,* 2023). This approach makes it possible to identify areas with the greatest need for increasing soil fertility and agricultural productivity, as well as to determine priorities for investment. The obtained data provide a scientific basis for the rational allocation of resources within the agricultural sector. All these factors confirm the relevance of developing a technology for the integrated analysis and assessment of the state of the environment through the application of modern information technologies.

iii. Purpose and objectives of the study

The purpose of this study is to develop a technology for the integrated analysis and assessment of the state of the environment based on GIS technologies, with a focus on evaluating the suitability of territories for agricultural production (Chen *et al.,* 2022).

The main objectives include:

1. Development of a mathematical model for the differentiation of territories based on integrated environmental indicators using the theory of fuzzy sets (Zadeh, 2012).
2. Creation of thematic assessment maps for the regionalization of Uzbekistan's territory according to the degree of suitability for agriculture (Li *et al.,* 2021).
3. Formation of an integral map of the regionalization of natural conditions, taking into account the informativeness of thematic maps (Wang *et al.,* 2022).

In this study, the concept of *regionalization* is considered in sectoral, inductive, and formalized aspects (Smith & Johnson, 2019). The research is based on archival cartographic materials, reference data, literature sources, and digital topographic maps at a scale of 1:500,000, which meet modern standards for topographic data (UNEP, 2020).

MATERIALS AND METHODS

4.1. GENERAL APPROACHES

To assess the state of the environment in the Republic of Uzbekistan, a comprehensive approach was applied, incorporating methods of geoinformation analysis, mathematical modeling, and thematic mapping (Goodchild, 2020; Longley *et al.,* 2021). GIS technologies enable the integration of spatial data on natural and anthropogenic factors, facilitate the analysis of territorial heterogeneity, and allow for the visualization of results in the form of digital maps. This approach ensures high accuracy in evaluating the relationships between natural conditions and agricultural activities (Kurbanov, B. T. (2020), de Smith *et al.,* 2018).

The study employs geoecological and landscape-geographical methods based on the system analysis of territorial complexes, as well as the principles of sustainable environmental management. Particular attention is given to the spatial distribution of factors influencing the agroecological stability of territories, including climatic, soil-hydrological, and anthropogenic parameters (Wu *et al.,* 2022).

4.2. DATA AND SOURCES

The analysis used archival cartographic materials, digital topographic maps at a scale of 1:500,000, ICONOS satellite imagery, as well as statistical and reference data from national and international organizations (FAO, 2021; UNEP, 2020; World Bank, 2023). Spatial data were processed in ArcGIS Pro and QGIS environments using modules for spatial analysis and 3D modeling.

Additionally, long-term climatic datasets (temperature, precipitation, humidity, wind regime), data on soil resources, water availability, and land salinity were used. All datasets were normalized to a unified coordinate system (WGS-84), ensuring the comparability of heterogeneous sources.

4.3. ASSESSMENT AND MODELING METHODOLOGY

The research methodology is based on the construction of integrated indices characterizing the degree of favorability of natural conditions for agricultural activities. Calculations were performed using the principles of multicriteria analysis (Saaty, 2008; Malczewski, 2015). Each indicator (climate, relief, soil, water resources, etc.) was assigned weighting coefficients derived from expert evaluations and correlation analyses.

For integral assessment, the theory of fuzzy sets was applied (Zadeh, 2012; Chen *et al.,* 2022), which allows accounting for uncertainty and the vagueness of natural complex boundaries. The use of cluster analysis methods and the Land Suitability Index enabled the identification of territories with varying degrees of suitability for agricultural production (Zou *et al.,* 2020; Ahmed *et al.,* 2023).

Comparison of the resulting maps with actual data on crop yields and soil salinity confirmed the adequacy and reliability of the developed model (Qadir *et al.,* 2019).

4.4. RESEARCH METHODS

Modern studies of the state of the environment are actively developing through the integration of cartographic, mathematical, and geoinformation methods. The use of computational technologies and digital modeling ensures high accuracy in spatial analysis and data visualization (Das *et al.,* 2020; Pautz *et al.,* 2023; Goodchild, 2021). The cartographic method has proven its effectiveness in integrating data from diverse sources, making it a fundamental tool for ecological and geographical regionalization.

One of the key challenges of modeling lies in developing tools that account for both quantitative characteristics of the natural environment and imprecise expert judgments. This challenge is effectively addressed by the theory of fuzzy sets proposed by L. A. Zadeh (Zadeh, 1965; Zadeh, 1976; Zadeh, 2012). Recent studies confirm that the integration of fuzzy logic with GIS technologies and multicriteria analysis methods enhances the reliability and informativeness of assessment maps (Saatchi, 2024; Chen *et al.,* 2022).

In this study, following the recommendations of L. Zadeh, qualified experts in ecology and geoinformatics were engaged in the preparation of initial data. When necessary, artificial intelligence systems were employed to refine expert evaluations. Natural territories were classified according to a scale of ecological conditions (favorable / unfavorable), in accordance with modern approaches to geoecological regionalization (Nguyen, 2023).

Formally, the degree of membership of an element *x* in a fuzzy set *A* is defined by the membership function $\mu_a(x)$:
$\mu_a(x)$, $0 \leq \mu \leq 1$

- If $\mu_a(x) = 0$, the element *x* does not belong to the given set.
- If $\mu_a(x) = 1$, the element *x* fully belongs to the given set.
- For $0 < \mu_a(x) < 1$, the element *x* belongs to the set with a corresponding degree of certainty.

The developed method was applied for the scoring evaluation of initial data and the construction of thematic maps for the regionalization of the territory of Uzbekistan. Expert validation of the factor hierarchy confirmed the objectivity of the obtained results, although in some cases specialists adjusted certain assessments without disrupting the overall hierarchical structure of the factors.

V. DEVELOPMENT OF THE SYNTHETIC REGIONALIZATION MAP

In a comprehensive assessment of the state of the environment, its components exhibit varying resilience to anthropogenic impact. More resilient ecosystems are characterized by conservatism, while less resilient ones display dynamic responses. Thematic maps of individual components possess different levels of informativeness, and therefore, an integral approach is required to form a holistic picture (Smith *et al.,* 2018; Zhang & Wang, 2020).

The integral regionalization map based on agricultural suitability criteria was created through the analysis of several thematic layers using weighting coefficients that reflect their relative importance. To accomplish this task, the OVERLAY procedure developed by Intergraph Corporation was employed (Teng, Joseph & Shojaee, 1986), which allows for the superposition of thematic layers and the identification of spatial interrelationships (Johnson & Miller, 2023).

The initial data were organized into four main directions:

1. Processes of ecosystem desertification,
2. Assessment of soil and land resources,
3. Climatic characteristics,
4. Indicators of ecological stability.

For each direction, thematic maps were created and then integrated into a comprehensive synthetic map using the weighting coefficients. The resulting map reflects the spatial distribution of natural conditions and highlights territories with varying degrees of suitability for agricultural production, providing a foundation for rational natural resource management and ecological-geographical planning.

VI. INTEGRATED ANALYSIS OF REGIONALIZATION MAPS OF THE TERRITORY FROM THE PERSPECTIVE OF AGRICULTURAL SUITABILITY

6.1. ASSESSMENT OF CLIMATIC RESOURCES

Climatic resources are one of the key factors significantly influencing human economic activities. Effective agricultural production is only possible with a careful analysis and evaluation of climatic conditions. When assessing the suitability of climatic resources for various crops, it is necessary to consider the spatial distribution of the main parameters that determine their development, such as thermal resources and natural moisture availability of the territory.

A crucial aspect of this task is the development of criteria for evaluating climatic resources, which have the greatest influence on the growth and development of agricultural crops under the conditions of the Republic of Uzbekistan. The study employed a wide range of climatic indicators reflecting heat and moisture availability both during the growing season and throughout the year. Adverse weather phenomena, particularly in the winter period, were also taken into account.

Agroclimatic Factors

The main agroclimatic factors determining crop development include:

- Heat availability during the growing season. This indicator is characterized by the sum of positive daily average temperatures above 0 °C, 5 °C, 10 °C, and 15 °C. When the air temperature crosses 0 °C, the period of complete plant dormancy ends. The onset of spring growth for grasses and some semi-shrubs (e.g., wormwood) coincides with a stable air temperature crossing 5 °C. During this period, the vegetation of many woody plants begins, the growth of alfalfa, cereals, and most fruit crops resumes. Active vegetation for most crops starts when air temperature consistently exceeds 10 °C. The growth of melon crops is associated with a stable temperature above 15 °C.
- Moisture availability of the territory. Assessing natural moisture availability requires consideration not only of precipitation but also of the amount of water evaporated from the soil. Various methods can be used to determine evaporated moisture. Instrumental observations provide the most accurate results, but the limited number of meteorological stations in the country complicates their practical application. The most significant indicator of moisture availability is the hydrothermal coefficient (HTC) according to G. T. Selyaninov's method, defined as the ratio of precipitation during the growing season (at temperatures above 10 °C) to one-tenth of the sum of positive temperatures for the same period. Additionally, the frequency of days with relative air humidity of 30% and 80%, as well as dry wind events with air moisture deficit ≥ 50 mb (categorized as weak [50–60 mb], moderate [60.1–70 mb], and intense [>70 mb]) were considered. Annual moisture availability was assessed based on precipitation during the cold period.
- Wintering conditions. These indicators determine the survival and yield of winter crops. The most adverse factors are snowstorms, ice, and minimum temperatures below –20 °C. The study accounted for the recurrence of extremely low temperatures.
- Adverse climatic events. Dust storms and strong winds exceeding 15 m/s during the growing season cause significant damage to crops.

Each agroclimatic indicator was evaluated on a five-point scale. The weighting coefficients for the significance of parameters were determined using expert assessments with the application of fuzzy set theory (Zadeh, 2012) (see Table 1). Subsequently, the significance (weight coefficient) of each parameter affecting crop growth was calculated using fuzzy mathematics methods.

Note:

- Dry winds are considered for the period from April to September (180 days);
- Dust storms — from March to October (240 days);
- Strong winds — during the vegetation period (April–September, 180 days);
- Snow cover — from October to March (180 days);
- Average minimum air temperature of –20 °C is considered for the period from November to March (150 days).

Table 2 presents the weighting coefficients for each agroclimatic factor. Based on these data, an integral agroclimatic index $K_{agro}$was determined, taking all factors listed in Table 3 into account.

The values of K_{agro}at selected meteorological stations were plotted on the working topographic base at a scale of 1:500,000, after which isolines of equal K_{agro}values were constructed using interpolation.

According to the results of the integral agroclimatic assessment K_{agro}, the majority of the territory of the Republic of Uzbekistan falls into areas with low to moderately favorable agroclimatic conditions.

Table 1: Criteria for Scoring Agroclimatic Characteristics

Agroclimatic Characteristic	**Degree of Factor Influence**				
	Most Favorable	Favorable	Moderately Favorable	Slightly Favorable	Unfavorable
	1 point	2 points	3 points	4 points	5 points
Sum of positive air temperatures normalized to the maximum sum of temperatures for each threshold (Ti/Tmax) (>0 °,>5 °,>10 °,>15 °)	1.00-0.81	0.80-0.61	0.60-0.41	0.40-0.21	≤0,20
HTC, normalized to the maximum of the mean and maximum values	1,00-0,81	0,80-0,61	0,60-0,41	0,40-0,21	≤0,20
Precipitation: annual total (H≤600 m)	401-500	301-400	201-300	101-200	≤100
Precipitation: total amount during the cold period (XI-III) (H≤600 m)	>350	251-350	151-250	51-150	≤50
Average daily soil surface temperature, January, °C	>0	0 -5	-5 -10	-10 -15	<-15
Average daily soil surface temperature, July, °C	<20	20 -25	25 -30	30 -35	>35
Number of days					
Dry winds	≤20	20-60	61-100	101-140	141-180
Relative humidity ≤30%	<60	60-120	121-180	181-240	>240
Relative humidity ≥80%	<60	60-120	121-180	181-240	>240
Dust storms	≤80	81-120	121-160	161-200	201-240
Strong wind, ≥15 m/s	≤20	21-60	61-100	101-140	141-180
Frost-free period	>240	181-240	121-180	61-120	<60
Snow cover	≤20	21-60	61-100	101-140	141-180
Average minimum air temperature, ≤ 20 °C	≤10	11-45	46-80	81-115	116-150

Based on the obtained data, a map assessing climate resources in terms of suitability for agricultural production was developed (Figure 1).

The analysis of the map allowed the identification of the following agroclimatic regions based on the impact of climatic factors on agriculture:

• **Unfavorable conditions** are observed in the arid part of the Aral Sea coast, the territory of the Republic of Karakalpakstan, and the northern part of the Navoiy region.
• **Less favorable regions** cover most of the Bukhara region, the southern part of the Navoiy region, the northwestern part of the Kashkadarya region, and the floor of the Fergana Valley at elevations up to 100 m.
• **Moderately favorable regions** include the southwestern part of the Kashkadarya and Surkhandarya regions, the foothills of the Fergana Valley, as well as the Tashkent, Syrdarya, and Samarkand regions.
• **Favorable regions** are concentrated in the Surkhandarya Valley up to its lower part (up to Termez), in the Chirchik Valley (up to 2000 m), and in the western part of the Zarafshan Valley.

The territorial zoning scale based on agroclimatic conditions was developed considering the climatic characteristics of the Republic of Uzbekistan. Adaptation may be required for other regions. The developed map is of independent interest and can be used as primary information for the assessment of agroclimatic resources in Uzbekistan. The map analysis shows consistency with data from previous studies (Glazirin G.E. *et al.,* 1999).

Table 2: Significance coefficients of each agroclimatic factor

Agroclimatic factor	**Significance coefficient P**
HTC	1,0
Sum of positive temperatures	1,0
Soil surface temperature	1,0
Dry winds	0,9
Relative humidity, ≤30%	0,9
Average minimum air temperature ≤-20 ºC	0,9
Relative humidity ≥80%	0,85
Dust storms	0,8
Strong wind at a speed of ≥15 m/s	0,8
Precipitation	0,6
Snow cover	0,6
Frost-free period	0,6

Table 3: Integral agroclimatic assessment K_{agro}

Values of the integral agroclimatic assessment K_{agro}	Agroclimatic regions
≤3.20	Favorable
3,19-3,60	Moderately favorable
3,61-3,99	Less favorable
4,00-4,40	Unfavorable
>4.40	Highly unfavorable

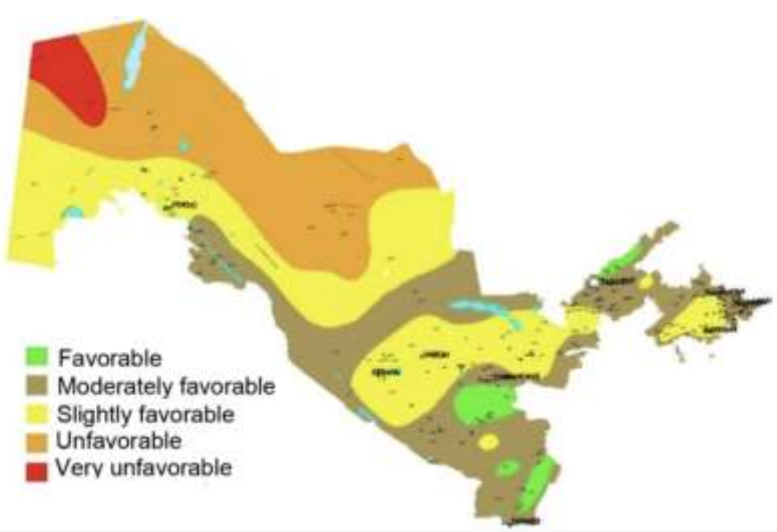

Fig. 1. Map of climate resource assessment by degree of suitability for agricultural production

6.2. DEVELOPMENT OF A SOIL–ECOLOGICAL ASSESSMENT ZONING MAP

One of the key challenges facing the modern world is ensuring food security under conditions of population growth and limited agricultural resources. To intensify agricultural production, many countries widely apply mineral fertilizers and pesticides, which—if used without a scientifically grounded approach—can lead to soil degradation and deterioration of environmental quality (Lal, 2020; FAO, 2020; Qadir *et al.,* 2018).

Pesticides have a positive effect on crop yields; however, their excessive use results in soil contamination and the formation of persistent toxic residues that pose a serious threat to human health. According to the World Health Organization, approximately 500,000 people are poisoned by pesticides each year, and more than 10,000 of these cases are fatal (HNB.com.ua, n.d.). Hundreds of compounds, particularly those containing heavy metals such as arsenic, lead, and mercury, are characterized by long decomposition periods and the ability to accumulate in food products (Tann.ru, n.d.; Zhang *et al.,* 2018). Their half-life may reach up to 20 years, as they are resistant to degradation under sunlight, microbial activity, and enzymatic processes.

The accumulation of pesticides in soils can result in trace amounts being present even in untreated agricultural products, which subsequently enter the human body. Furthermore, pests targeted by pesticides may become more numerous and harmful; for instance, due to pesticide use, the population of the Colorado potato beetle has increased fivefold, fruit mites elevenfold, and the cotton bollworm threefold (Tann.ru, n.d., 2021).

Residual quantities of persistent organochlorine pesticides, as well as the accumulation of heavy metals (cadmium, nickel, chromium) and radionuclides, are of particular ecological concern. The most vulnerable areas are irrigated lands, where the intensity of chemical use is especially high. As a result, soil productivity decreases and the area of the most valuable agricultural lands is reduced (FAO, 2020).

To identify spatial patterns of soil ecological conditions in Uzbekistan, a soil–ecological zoning map was developed using GIS technologies and fuzzy logic methods (Fig. 2). The cartographic materials were standardized and integrated into a unified system within which 14 soil–ecological groups were identified. A score-based evaluation of the map parameters (Table 4) made it possible to determine that the most favorable areas for agricultural activities are irrigated soils and alluvial territories of the Amu Darya Delta, whereas solonchaks (salt-affected soils) and mountain–forest soils are the least productive (Bünemann *et al.,* 2018).

The results of spatial analysis indicated that the most favorable conditions for agriculture are observed in the **Fergana Valley, Khorezm region, central Karakalpakstan, the eastern part of Tashkent region, and northern Syrdarya region**. The most environmentally degraded soils were identified in areas of long-term agricultural use—**the Khorezm and Lower Zeravshan oases**, where farming has been practiced for over 4,000 years, as well as in the **Amu Darya Delta** (UNEP, 2020).

The main causes of soil degradation are:

1. **Irrational use of irrigation systems**—excessive water consumption, soil salinization, and contamination (Sun *et al.,* 2020).

2. **Intensive application of mineral fertilizers and pesticides**, leading to a decline in natural soil fertility and disruption of soil microflora (Sharma *et al.,* 2019; Hussain *et al.,* 2021).

3. **Anthropogenic impacts**—mechanical destruction of soil structure and depletion of organic matter.

Restoring soil fertility requires the implementation of modern irrigation techniques, expanded use of organic fertilizers, application of biological plant protection methods, and the development of an ecological monitoring system (FAO, 2020).

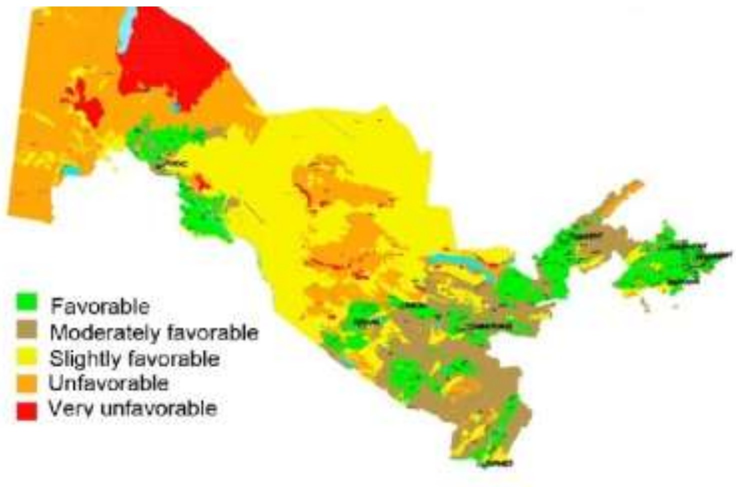

Fig. 2. Map of soil resource zoning by degree of suitability for agricultural cultivation

Table 4. Soil cover assessmen

Index	Soil–ecological groups	Points
I	Gray-brown soils	0,44
II	Gray-brown soils in combination with takyr soils and takyrs	0,4
III	Gray-brown soils in combination with takyr soils and takyrs	0,25
IV	Takyr soils and takyrs	0,33
V	Takyr soils in combination with various solonchaks	0,29
VI	Desert sandy soils and sands	0,47
VII	Meadow and marsh soils	0,87
VIII	Solonchaks and their complexes	0,21
IX	Light sierozems	0,67
X	Typical sierozems	0,53
XI	Dark sierozems	0,24
XII	Brown and dark brown mountain–forest soils	0,2
XIII	Non-soil formations (chinks, bozyngens, outcrops of bedrock, etc.)	0,18
XIV	Irrigated soils	1

6.3. BRIEF CONCLUSIONS ON THE INFLUENCE OF SOIL RESOURCES ON AGRICULTURAL ACTIVITIES

The analysis demonstrates that the effectiveness of mineral fertilizers and pesticides depends on the adherence to scientifically based recommendations and the technological management of agriculture (Zhang *et al.,* 2018; Hussain *et al.,* 2021). Exceeding permissible application rates leads to soil degradation, contamination of water sources, and adverse effects on human health.

In the context of rapid population growth and limited land resources, **rational use of fertilizers and reclamation technologies** remains a necessary condition for increasing crop yields (Lal, 2020; FAO, 2020). Global experience shows that strict adherence to recommended dosages and the use of adapted agrotechnologies can increase yields by 15–25% without negatively impacting ecosystems (Bünemann *et al.,* 2018).

The application of mineral fertilizers is a reliable means of improving crop yields and maintaining soil fertility. Considering the rapid population growth and the limited availability of irrigated lands, without fertilizers, the global community would face serious food security challenges. The use of fertilizers has effectively mitigated these consequences. Currently, the production and use of mineral fertilizers continue to grow worldwide, with leading countries including **Japan, the United Kingdom, the Netherlands, France, and the Republic of Korea**. There is a close relationship between fertilizer dosage and crop yield. The highest doses are applied in France, the UK, and the Netherlands, where grain yields reach **74, 70, and 83 centners per hectare**, respectively, among the highest levels globally (Lal, 2020; FAO, 2020).

Thus, **sustainable development of the agricultural sector** is possible through a combination of scientifically grounded soil fertility management, precise chemical application, and the adoption of environmentally safe agricultural technologies.

6.4. DEVELOPMENT OF AN ASSESSMENT MAP FOR ECOSYSTEM DESERTIFICATION

One of the most pressing environmental challenges in Uzbekistan remains the process of desertification, which affects substantial areas of both agricultural and natural landscapes. The main factors contributing to ecosystem degradation are anthropogenic pressures, including overgrazing, cultivation of marginal lands, irrational water use, as well as climatic changes that exacerbate the aridization of the territory.

The most illustrative example of anthropogenically induced desertification in Central Asia is associated with the shrinkage of the Aral Sea, which led to the formation of the Aralkum Desert. The dried seabed annually emits over 75 million tons of salts and dust, resulting in increased incidence of diseases among the population of the Aral Sea region, including anemia, respiratory diseases, kidney disorders, and gastrointestinal illnesses (Lioubimtseva & Henebry, 2009). According to research data, dioxin levels in the blood of pregnant women and in breast milk in Karakalpakstan exceed the average European levels by more than five times (Groll *et al.,* 2019).

To evaluate the ecological consequences and the degree of impact of desertification processes on agricultural production, zoning maps were developed (Fig. 3), constructed using mathematical modeling methods, fuzzy set theory, and expert assessments (Zadeh, 2018; Liu *et al.,* 2019; Kurbanov, 2019).

For the convenience of assessing environmental phenomena and processes related to desertification, the legend of the "Ecosystem Desertification" map was divided into four blocks:

1. Endogenous factors affecting desertification
2. Desertifying territorial complexes
3. Anthropogenic factors of desertification
4. Natural–anthropogenic factors of desertification

Desertification processes affecting territorial complexes have a significant impact on agricultural activities. This block is analyzed in greater detail. Table 5 presents the evaluation of desertification factors for territorial complexes from the perspective of their impact on agriculture, developed according to the Lotfi Zadeh methodology (Zadeh, L. A., 1965; Zadeh, L. A., 2012).

The analysis of this table indicates that the ecosystems most strongly affected by desertification are irrigated lands experiencing secondary salinization and waterlogging, where natural complexes have been entirely replaced by cultural landscapes (II-6). Desertification processes also have a significant, though somewhat lesser, impact on rice field ecosystems (II-7) and rainfed lands (II-8). The least affected areas are salt flats, takyrs, and outcrops of bedrock (II-1, II-2, and II-5, respectively), largely because these lands are practically unused in agriculture.

Among anthropogenic desertification factors, the most significant negative impacts arise from secondary salinization, technogenic soil degradation, and pasquale vegetation regression. Among the natural-anthropogenic factors negatively affecting agricultural activity, the aridization processes on the desiccated Aral Sea bed are particularly notable.

Table 5: Assessment of Territorial Complexes

Index	Desertifying Territorial Complexes	Баллы
II-1	Solonchaks	0,05
II-2	Takyrs	0,06
II-3	Unstabilized Sandy Massifs	0,18
II-4	Chinks	0,15
II-5	Bedrock Outcrops	0,08
II- 6	Irrigated Lands	1
II-7	Rice Fields	0,87
II-8	Dryland (Rainfed) Lands	0,83
II-9	Swampy Lands	0,5
II-10	Areas with Tree Plantations	0,3
II-11	Nature Reserves and Protected Areas	0,27
II-12	Pastures	0,57
II-13	Hayfields	0,33
II-14	Forests	0,29
II-15	Abandoned Lands	0,67
II-16	Discharge and Filtration Lakes	0,54
II-17	Flooded Areas	0,44
II-18	Ruins	0,31
II-19	Spoil Heaps, Tailings, and Quarries	0,63

Desert pasture ecosystems, where exploration, prospecting, and mining activities are currently conducted, are also heavily degraded. However, natural ecosystems in these areas have not yet been fully replaced by derivative landscapes. The least structural changes in natural ecosystems occurred in forested and shrubland areas. Although unsystematic tree and shrub cutting for economic needs occurs, these ecosystems still resist this type of anthropogenic pressure.

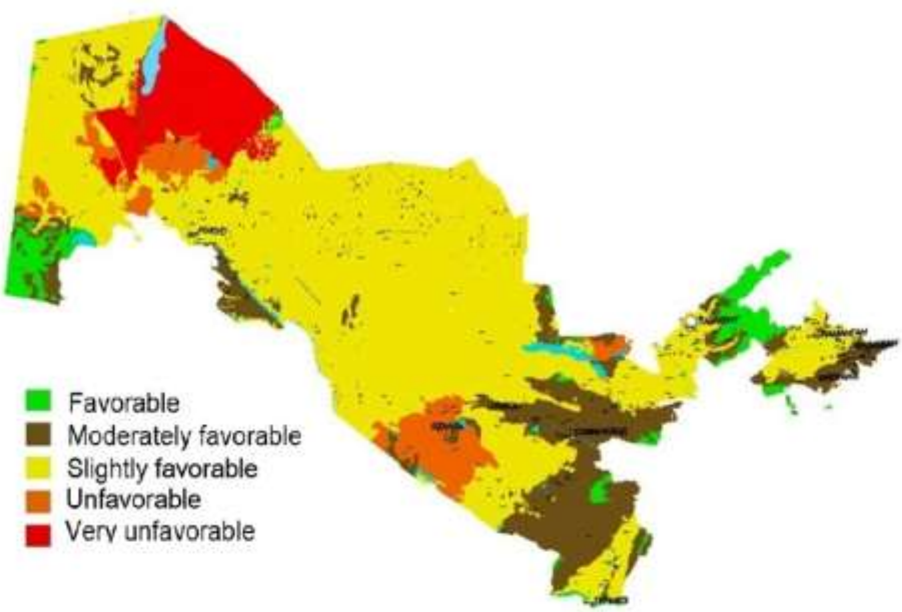

Fig. 3. Zoning map of desertification processes according to their degree of negative impact on crop cultivation

The most severe changes caused by natural-anthropogenic desertification factors occurred in areas formed by the drying of the Aral Sea. In terms of development and negative impact on agricultural activity, the most hazardous are active natural-anthropogenic processes, which cause significant damage to both the environment and economic activity.

Based on these findings, a **desertification zoning map** was developed to reflect the degree of negative impact on crop cultivation (Fig. 3).

A comparative analysis of the desertification map revealed that the lands of the Aral Sea region, the Kyzylkum, and the Karakum deserts are the most susceptible to degradation. These areas exhibit a reduction in vegetation cover, intensified deflation processes, and an expansion of saline soils. In the foothill regions, water erosion and humus depletion of soils are observed. The comprehensive assessment of desertification dynamics underscores the need for integrated approaches to restore degraded ecosystems, including the implementation of soil-conservation technologies, rational water management, and afforestation measures.

6.5. DEVELOPMENT OF AN EVALUATIVE ZONING MAP OF LAND RESOURCES

The land resources of Uzbekistan constitute one of the most important natural factors determining the development of the country's economy, particularly its agricultural sector. The total land area is approximately 44.8 million hectares, more than half of which is used for agricultural purposes (FAO, 2023). A distinctive feature of the land fund is the predominance of desert and semi-desert areas, which necessitates rational use and land reclamation to ensure sustainable agricultural production.

The role of land resources in Uzbekistan's agricultural sector is crucial, as they form the basis for the production of the majority of food and raw materials for the processing industry. Uzbekistan has become one of the leading agricultural producers in Central Asia. According to FAO (2023), the total area of irrigated lands is approximately 4.2 million hectares. According to Trading Economics (2023), agricultural land accounts for 58.06% of the country's total area. According to the USDA Foreign Agricultural Service, in the 2025/26 marketing year, Uzbekistan is expected to produce 620,000 metric tons of lint cotton. In addition, Kun.uz (2024) reports that the export volume of fruits and vegetables exceeded 2 million tons, generating $1.5 billion USD in revenue for the country.

High productivity on irrigated lands ensures not only the domestic needs of the population but also significant export potential for the agricultural sector. In recent years, particular attention has been given to enhancing soil fertility, implementing water-saving technologies, and transitioning to sustainable agricultural practices. Therefore, rational management of land resources is a strategic direction for ensuring food security and sustainable development of the country's agriculture.

Agriculture remains a strategic sector of Uzbekistan's economy, providing food security and employment. Efficient land use requires the adoption of modern spatial analysis and monitoring tools. In this context, an evaluative zoning map of land resources was developed, based on the application of geoinformation technologies and mathematical modeling methods (Zadeh, L. A., 2012).

The agricultural land block is the most important for agricultural operations. This block is subdivided into arable land, pastures, and hayfields. Among the arable land, distinctions are made between old-irrigated and newly irrigated fields, reflecting their level of reclamation and productivity. The seasonality of pasture use is represented by predominantly year-round and spring–autumn grazing areas.

The productivity of land resources for agricultural production was evaluated using fuzzy logic methods and expert analysis (Zadeh, 2018). The most productive land categories were identified as old-irrigated and newly irrigated arable lands, characterized by stable water supply and a high level of agrotechnical development (Table 6). The least effective lands for agricultural production were summer pastures and floodplain hayfields, which are characterized by low productivity and a limited period of use.

Table 6: Assessment of Major Categories of Agricultural Land

Index	Agricultural Land	Rating Points
A	Old-irrigated arable lands	1
B	New-irrigated arable lands	0,8
C	Rainfed lands (Bogarny)	0,47
D	Orchards (Perennial plantations / Gardens)	0,33
E	Vineyards	0,5
F	Year-round pastures	0,25
G	Spring–Summer Pastures	0,18
H	Summer Pastures	0,13
I	Floodplain Hayfields	0,1

Hereinafter, higher values of the assessment index correspond to lands with the greatest productivity for use in the agricultural sector. The scores were calculated using methodologies based on mathematical modeling, fuzzy set theory, and expert evaluations (Zadeh, L., 2012; Liu *et al.,* 2019).

6.6. ASSESSMENT OF MAJOR CATEGORIES OF AGRICULTURAL LAND

Based on the evaluation of the main categories of agricultural land, a land resource zoning map has been developed. This zoning map allows for a comprehensive assessment of land utilization and ecological status, as well as the identification of priority directions for rational land use (Fig. 4).

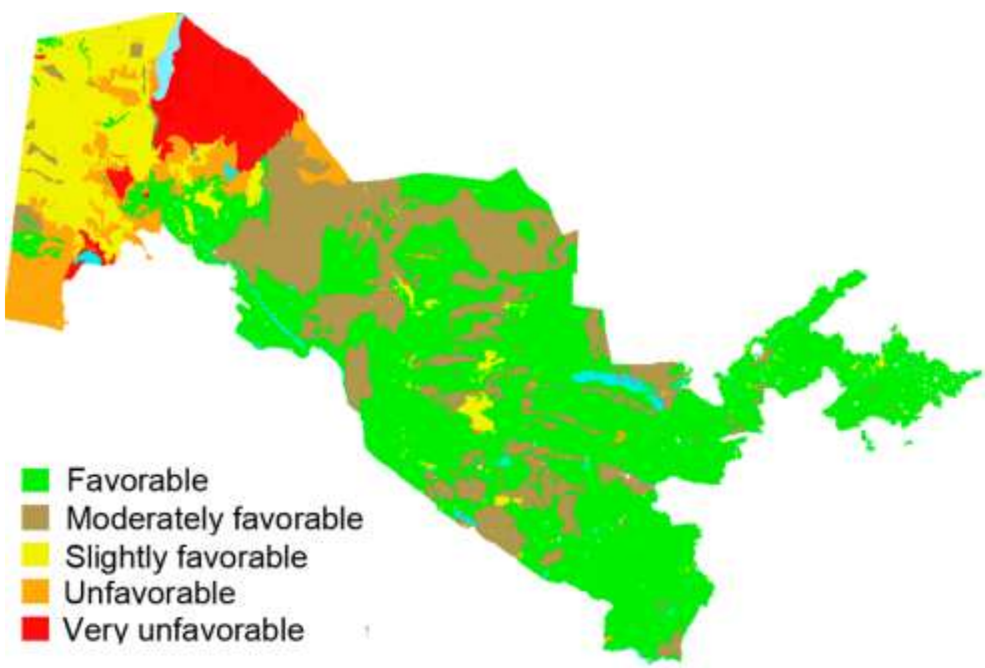

Fig. 4. Assessment map of land resource zoning

The map serves as a tool for optimizing agricultural planning, improving water use efficiency, and reducing anthropogenic pressure on ecosystems (FAO, 2020; Huang *et al.,* 2020).

VII. DEVELOPMENT OF AN EVALUATIVE SYNTHETIC ZONING MAP OF THE TERRITORY BASED ON A COMPREHENSIVE ANALYSIS OF THEMATIC MAPS CONSIDERING THEIR SIGNIFICANCE

As noted earlier, the components of the natural environment possess varying degrees of resilience to anthropogenic impact. This determines the differential response of natural and natural-technical systems to external pressures: the most stable systems maintain their structural organization and equilibrium, whereas less stable ones exhibit high dynamism and susceptibility to change. Thematic ecological maps reflecting individual aspects of the environmental condition contribute unequally to the formation of an integrated assessment of the regional ecological situation (Kurbanov, B. T., & Kurbanov, B. B., 2025; Topuz *et al.,* 2023; Chandel *et al.,* 2024).

In constructing the synthetic zoning map of the territory according to the degree of suitability for agricultural activities, each thematic map (layer) was weighted proportionally to the extent of its influence on the final result. The determination of weight coefficients was carried out using the **expert assessment method (brainstorming)** involving specialists in ecology, geoinformatics, and agriculture. To refine statistical correlations and improve model accuracy, **artificial intelligence systems** were applied (Alharbi *et al.,* 2024; Dossow *et al.,* 2025).

The obtained significance coefficients were incorporated during computer processing of thematic layers in the process of creating the synthetic zoning map of the territory, reflecting the degree of suitability for agricultural production. The weighting multipliers were defined for **climatic, soil, and land resource maps**, as well as for maps characterizing the **influence of desertification processes** on agriculture.

The methodological basis of this process was the **OVERLAY technology**, representing a spatial overlay operation that enables the integration, comparison, and comprehensive analysis of geospatial data (Teng *et al.,* 1986; Smith *et al.,* 2018). This approach allows the combination of thematic maps of different nature—climatic, soil, land use, and desertification—to produce a **higher-level resultant map** that reflects the cumulative impact of analyzed factors on the spatial organization of the territory (Zhang & Wang, 2020; Johnson & Miller, 2023).

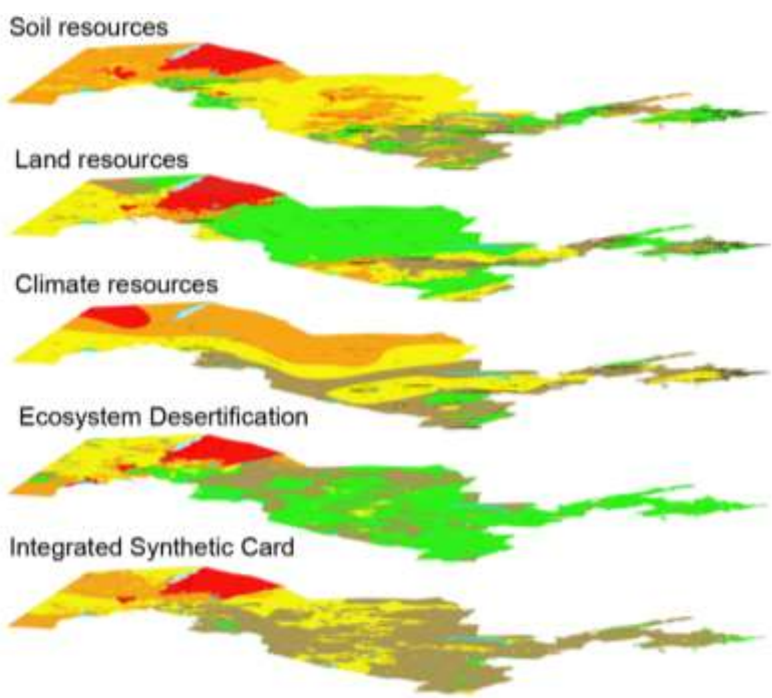

Fig. 5. Technology of the OVERLAY procedure application

Before implementing the overlay procedure, all input thematic maps were converted to a **unified cartographic projection (UTM — Universal Transverse Mercator)**, a **scale of 1:500,000**, and a **five-grade classification system**, which ensured the consistency and comparability of spatial data.

The **weight coefficients** of thematic layers, determined through expert evaluation, were as follows:

- climatic maps — **0.29**;
- soil maps — **0.27**;
- land resource maps — **0.24**;
- maps of desertification influence — **0.10**.

Based on these parameters, an integrated zoning map of Uzbekistan was developed, reflecting the degree of suitability of the territory for agricultural activities (Fig. 6).

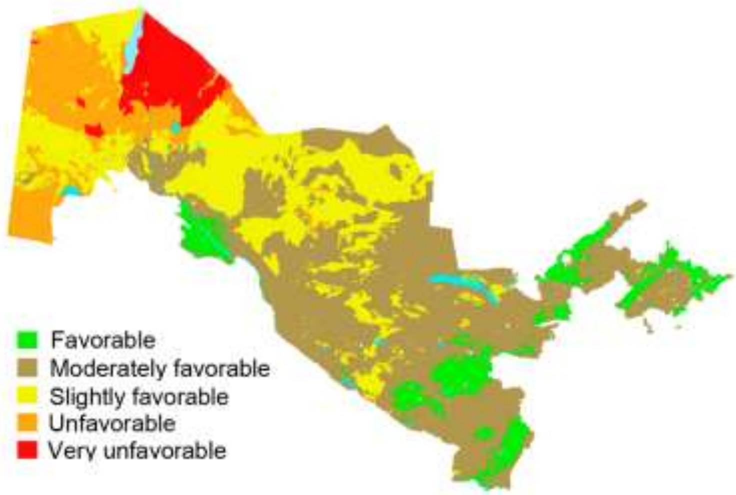

Fig. 6. Integrated zoning map of the territory of Uzbekistan by degree of suitability for agricultural activities

The results obtained made it possible to identify the most favorable zones for agricultural use — the Tashkent, Fergana, and Samarkand regions — as well as the least favorable areas, such as the Aral Sea region and desert territories (Sadaf *et al.,* 2025; Gao *et al.,* 2025). The application of the OVERLAY technology and multi-criteria analysis demonstrated that combining expert assessments, elements of fuzzy logic, and geoinformation modeling ensures a high level of objectivity in the synthetic evaluation of natural conditions. This approach allowed for the integration of data on land, climatic, and soil resources together with information on desertification processes into a unified assessment system, resulting in the development of an integrated zoning map of a higher analytical level that reveals territorial differences in the stability of natural complexes.

In the future, the proposed methodology may be enhanced by incorporating additional thematic layers that characterize water resource quality, air condition, geobotanical features, demographic parameters, and other indicators. This will broaden the applicability of the method for sustainable development, rational environmental management, environmental protection, and public health preservation (The Role of GIS Mapping in MCDA, 2025).

One of the key objectives of this study is to demonstrate the potential of modern geographic information systems and artificial intelligence technologies for integrated spatial data analysis. The application of these methods opens new opportunities for optimizing the allocation of investment resources aimed at solving ecological problems — such as desertification, land degradation, and salinization — as well as for restoring soil fertility and improving the quality of life of the population (Kurbanov, B. T., 2019).

VIII. CONCLUSION, FINDINGS, AND RECOMMENDATIONS

8.1. CONCLUSION

1. The conducted research made it possible to develop and substantiate the technological principles of comprehensive environmental analysis and assessment using geoinformation technologies and mathematical modeling methods. As a result of the study, a methodological framework was created to ensure the integration of diverse thematic data — climatic, land, soil–reclamation, and desertification processes — within a unified GIS environment. Implementation of the proposed approach enhances the objectivity and accuracy of assessing natural and anthropogenic processes, as well as enables the identification of spatial and temporal patterns in environmental changes. The use of mathematical modeling in combination with GIS tools facilitates the quantitative evaluation of impact factors and the prediction of environmental dynamics.
2. The developed technological principles are of a universal nature and can be applied to environmental zoning, monitoring of degradation processes, optimization of natural resource use, and assessment of ecosystem stability. The obtained results confirm the effectiveness of integrating GIS and mathematical modeling as a scientific and methodological foundation for evidence-based decision-making in environmental management and sustainable territorial development.

8.2. FINDINGS

The integration of geoinformation technologies and mathematical modeling methods has led to the development of technological principles for comprehensive analysis, ensuring a systematic approach to environmental assessment.

The proposed methodology allows for the integration of multidimensional thematic data (climatic, soil–reclamation, land use, and desertification processes) within a unified spatiotemporal framework, thereby increasing the reliability and informativeness of the analysis.

The application of GIS technologies contributes to identifying spatial regularities in the formation of natural and anthropogenic processes, while mathematical modeling enables the quantitative evaluation of influencing factors and the prediction of ecological dynamics.

As a result of modeling and spatial analysis, key factors determining the stability of natural systems were identified, forming the basis for optimizing resource use and planning environmental protection measures.

The developed technological approach provides a transition from descriptive to analytical and predictive methods for environmental assessment.

The practical significance of the results lies in their potential use for environmental zoning, evaluation of degradation processes, monitoring, and the development of regional sustainable development programs.

The integration of GIS and mathematical modeling has proven to be an effective scientific and methodological basis for decision-making in environmental protection and the rational use of natural resources.

8.3. RECOMMENDATIONS

To ensure objective environmental monitoring, it is recommended to implement geoinformation systems as a core platform for collecting, storing, processing, and visualizing spatially distributed natural and anthropogenic data.

In conducting regional environmental studies, it is advisable to employ mathematical modeling methods to forecast changes in natural complexes under the influence of climatic and anthropogenic factors.

The developed technological principles of comprehensive analysis can be applied in environmental planning, territorial management, and the creation of ecological–geographical and thematic maps of various levels of detail.
It is recommended to develop an automated environmental monitoring system using remote sensing and artificial intelligence technologies for rapid assessment and early warning of degradation processes.
The obtained results should be utilized in the development of sustainable development programs and environmental zoning of territories, as well as in improving the scientific and methodological framework for assessing natural resources and environmental safety.

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