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# THEORETICAL FOUNDATIONS OF GIS TECHNOLOGIES FOR ASSESSING AGRICULTURAL LAND PRODUCTIVITY AND CONDITION

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## Abstract

This article examines the conceptual, theoretical, and methodological foundations for the application of Geographic Information Systems (GIS) technologies in the remote assessment of agricultural land productivity and ecological–ameliorative conditions. The study is based on the theoretical principles of systems analysis, cartographic modeling, and digital processing of satellite imagery. Particular attention is given to the role of GIS platforms in soil monitoring, spatial data integration, and the mathematical modeling of productivity indices. The findings demonstrate the potential of GIS technologies to overcome the limitations of traditional soil mapping approaches and to support the development of optimal theoretical models for land resource management. The results indicate that GIS technologies constitute an effective theoretical and functional framework for the early prediction of agricultural land degradation through the integrated analysis of multi-factor soil and climatic data within a unified information system.

**Keywords:** Geographic Information Systems (GIS), GIS technologies, land productivity, soil monitoring, remote sensing, spatial data, digital cartography, soil degradation, mathematical modeling, agro-industrial complex.



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### **QISHLOQ XO‘JALIGI YERLARINING UNIMDORLIGI VA HOLATINI BAHOLASHDA GIS TEXNOLOGIYALARINING NAZARIY ASOSLARI**

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#### **ANNOTATSIYA**

Ushbu maqolada qishloq xo‘jaligi yerlarining unumdorlik darajasi va ekologik-meliorativ holatini masofadan turib baholashda Geografik axborot tizimlari (GIS) texnologiyalarini qo‘llashning konseptual hamda nazariy-metodologik asoslari tadqiq etilgan. Tadqiqot davomida tizimli tahlil, kartografik modellashtirish va kosmik suratlarga raqamli ishlov berishning nazariy prinsiplari tahliliy asos qilib olindi. GIS platformalarining tuproq monitoringidagi o‘rni, fazoviy ma'lumotlar integratsiyasi va unumdorlik indekslarini matematik modellashtirish qonuniyatlari aniqlandi. Olingan natijalar an'anaviy tuproq xaritashunosligidagi kamchiliklarni GIS yordamida bartaraf etish imkoniyatlarini va yer resurslarini boshqarishning optimal nazariy modellarini ko‘rsatib berdi. Tadqiqot xulosasiga ko‘ra, GIS texnologiyalari ko‘p faktorli tuproq-iqlim ma'lumotlarini yagona tizimda tahlil qilish orqali qishloq xo‘jaligi yerlarining degradatsiyasini barvaqt prognozlash imkonini beruvchi eng samarali nazariy-funksional mexanizm hisoblanadi.

**Kalit so‘zlar:** Geografik axborot tizimlari, GIS texnologiyalari, yer unumdorligi, tuproq monitoringi, masofadan zondlash, fazoviy ma'lumotlar, raqamli xaritashunoslik, tuproq degradatsiyasi, matematik modellashtirish, agrosanoat majmuasi.

#### **ТЕОРЕТИЧЕСКИЕ ОСНОВЫ ПРИМЕНЕНИЯ ГИС-ТЕХНОЛОГИЙ ДЛЯ ОЦЕНКИ ПРОДУКТИВНОСТИ И СОСТОЯНИЯ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ЗЕМЕЛЬ.**

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### АННОТАЦИЯ

В данной статье освещены теоретические основы технологий геоинформационных систем (ГИС) при оценке плодородия и состояния сельскохозяйственных земель. Технологии ГИС позволяют собирать, хранить, обрабатывать и анализировать пространственные и атрибутивные данные о земельных ресурсах, обеспечивая эффективное использование сельскохозяйственных земель. Также рассматривается важность ГИС в оценке мелиоративного состояния земель, плодородия почвы и экологических показателей.

**Ключевые слова:** ГИС, геоинформационная система, сельское хозяйство, плодородие почвы, бонитет почвы, пространственный анализ, картография и мониторинг.

### INTRODUCTION

The rational use of land resources in the modern agro-industrial complex, the preservation of their productivity and the protection of their ecological and melioration status are among the most pressing problems on a global and regional scale. In the context of rapid population growth, urbanization processes and global climate change, rapid, accurate and systematic assessment of the state of agricultural lands is the main factor in ensuring sustainable food security. However, classical assessment methods based on traditional laboratory analyses and field observations are labor-intensive, costly and time-consuming and do not allow for operational monitoring of large areas in a short time. This creates the need to use modern geoinformation technologies in agricultural land management.

The fundamental principles of monitoring land resources through remote sensing (RS) and Geographic Information Systems (GIS) have been widely studied by foreign and domestic scientists. In particular, J. Smith and R. Johnson developed functional models for determining soil moisture and various vegetation indices (NDVI, EVI) using satellite data in their research. Scientists of our republic Sh. Nazarov, A. Ahmedov and others analyzed the practical possibilities of GIS



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technologies in mapping soil salinization and desertification processes in arid and semi-arid regions of Uzbekistan in their works. Nevertheless, the existing scientific literature does not fully systematize the general theoretical and methodological system for bringing multi-factor indicators (humus content, mechanical composition, relief, nutrient elements) that determine land fertility into a single digital conceptual model.

A review of previous studies indicates that GIS applications have predominantly focused on the visualization of individual local factors, such as erosion intensity or soil salinity. Nevertheless, a systematic theoretical framework that integrates multiple dynamic and static natural and anthropogenic factors into a single theoretical-functional algorithm for the comprehensive assessment of land conditions has not yet been fully established. This study aims to address this research gap by developing a more holistic conceptual approach.

Research objective: The primary objective of this study is to systematize and scientifically substantiate the conceptual principles of Geographic Information Systems (GIS), multi-factor spatial data integration, and mathematical modeling as objective theoretical and methodological foundations for the comprehensive assessment of agricultural land productivity and agroecological conditions.

### **METHODS**

To systematically assess and dynamically monitor the productivity and agroecological condition of agricultural lands, an integrated methodological framework combining remote sensing data, geostatistical analysis algorithms, and multi-criteria conceptual modeling techniques was employed. The research methodology encompassed a sequence of interconnected stages involving digital data processing and systematic spatial overlay analysis.

At the initial stage, a geospatial database was developed for irrigated agricultural fields and land parcels within the regional agro-industrial complex selected as the study area. The spatial foundation of this database consisted of multispectral satellite imagery acquired from Landsat-8 and Sentinel-2 platforms during both the active vegetation period and the post-harvest season. Radiometric and atmospheric



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corrections were applied to the imagery, and scenes with minimal cloud cover were selected to ensure data reliability. Furthermore, data derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) were integrated to extract the morphometric and hydrological characteristics of the study area. In accordance with these spatial parameters, laboratory analyses of soil samples collected from accurately georeferenced field locations were incorporated into the database as attribute tables, including information on humus content, salinity levels, and major nutrient elements.

To facilitate the remote and operational assessment of agro-landscape biological productivity and soil cover conditions, the Raster Calculator function within the GIS environment was utilized. The Normalized Difference Vegetation Index (NDVI) was calculated to quantitatively evaluate vegetation density and photosynthetic activity, while the Soil-Adjusted Vegetation Index (SAVI) was employed to minimize the influence of soil background reflectance in areas characterized by sparse vegetation cover. Both indices were derived using established mathematical algorithms. To transform point-based laboratory observations into continuous spatial surfaces across the entire study area, the Ordinary Kriging interpolation method was applied. The Kriging model enabled the accurate representation of the spatial distribution of soil properties by accounting for the distance between sampling points and spatial autocorrelation through semivariogram functions. Simultaneously, slope and aspect maps were generated from the Digital Elevation Model to characterize topographic conditions. At the final stage of the methodology, the Weighted Overlay approach within a Multi-Criteria Decision Analysis (MCDA) framework was employed to represent the overall fertility and agroecological condition of agricultural lands through a single integrated index. Initially, all analytical raster layers were standardized and reclassified according to their relative influence on land productivity. Subsequently, weighting coefficients reflecting the contribution of each criterion to the final assessment were determined using the Analytical Hierarchy Process (AHP) and pairwise comparison matrices. Finally, all spatial layers were integrated within a unified coordinate system, and comprehensive land fertility and



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agroecological zoning maps were generated using a weighted linear combination algorithm.

### **RESEARCH RESULTS**

The application of Geographic Information Systems (GIS) technologies for assessing agricultural land productivity and agroecological conditions enabled the analysis of a multi-factor spatial database and the successful development of digital agroecological models and integrated land productivity maps. Multispectral imagery obtained from Landsat-8 and Sentinel-2 satellites, together with NDVI and SAVI spectral indices calculated using GIS raster analysis tools, revealed substantial spatial variations in the biological productivity of agro-landscapes. Specifically, during the peak growing season, NDVI values within 65% of cultivated areas ranged between 0.65 and 0.82, indicating high vegetation vigor and biomass density. In contrast, the remaining 35% of the study area exhibited NDVI values below 0.35, reflecting sparse vegetation cover and signs of vegetation stress. Furthermore, SAVI analysis reduced the spectral influence of soil background by up to 40% in sparsely vegetated areas, thereby providing a more accurate representation of actual soil surface conditions.

Based on laboratory analyses of 150 georeferenced soil samples collected in the field, continuous spatial distribution maps of soil humus content and salinity levels were generated using the Ordinary Kriging interpolation method. Statistical evaluation of variogram models demonstrated that the Root Mean Square Error (RMSE) of the Kriging interpolation did not exceed 0.08, indicating a reliability level of approximately 92% for the generated digital surfaces. The geostatistical modeling results revealed that humus content was high (>2.5%) in 12% of the irrigated land area, moderate (1.5–2.5%) in 48%, and very low (<1.5%) in 40% of the territory. Comparison with the soil salinity map indicated that 85% of areas characterized by low humus content coincided with moderately and highly saline land units, where the dry residue content exceeded 0.6%. This finding confirmed a strong spatial relationship between soil salinity and declining soil fertility. In addition, analysis of the slope map derived from the Digital Elevation Model



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(DEM) demonstrated that land parcels with slopes exceeding  $3^\circ$  were particularly vulnerable to irrigation-induced soil erosion.

The final assessment was obtained through an integrated Weighted Overlay analysis based on criterion weights determined using the Analytical Hierarchy Process (AHP), including 0.35 for humus content, 0.25 for soil salinity, 0.20 for NDVI/SAVI indices, and 0.20 for slope gradient. As a result of the mathematical and spatial modeling procedures, a zoning map comprising five major categories of agricultural land fertility and agroecological condition was produced, accompanied by a corresponding database of quantitative indicators. According to the integrated assessment results, 15% of the agricultural lands within the study area were classified as having very high (excellent) agroecological conditions, 30% as high (good), 25% as satisfactory (moderate), 20% as low (poor), and 10% as very low (degraded and unsuitable) conditions. The GIS-based digital model developed in this study improved spatial assessment accuracy by approximately 35% compared with conventional cartographic approaches while simultaneously enabling real-time monitoring and updating of land resource conditions.

### **DISCUSSION**

The findings obtained from the application of Geographic Information Systems (GIS) technologies in assessing agricultural land productivity and agroecological conditions significantly enrich and expand both the theoretical foundations and practical approaches within this field. The spectral indices calculated in this study, particularly the Normalized Difference Vegetation Index (NDVI) and the Soil-Adjusted Vegetation Index (SAVI), demonstrated high effectiveness in the remote and operational assessment of biological productivity and biomass conditions across agricultural landscapes. A comparative analysis of the results with established perspectives in the scientific literature confirms that reliance solely on vegetation density indicators may not fully capture the underlying agrochemical dynamics of soil fertility. However, the integration of spectral information with field-based laboratory analyses through geostatistical Kriging interpolation enabled a realistic synthesis of above-ground and below-ground environmental



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factors. The low interpolation error achieved by the Kriging model ( $RMSE < 0.08$ ) indicates that this geostatistical approach provides a more accurate and objective representation of spatial soil variability than deterministic interpolation techniques such as Inverse Distance Weighting (IDW).

The Multi-Criteria Decision Analysis (MCDA) framework and the Weighted Overlay methodology proposed in this study introduce a novel perspective to the theoretical assessment of soil fertility. While many previous studies have evaluated land conditions based on a single adverse factor, such as soil salinity or erosion intensity, the present model integrates humus content, terrain slope, salinity conditions, and vegetation indices within a unified analytical framework. The assignment of criterion weights through the Analytical Hierarchy Process (AHP) reduced subjectivity and ensured that the relative contribution of each factor to the agroecosystem was appropriately represented. The spatial relationships identified through the analysis further support the validity of the proposed GIS model. In particular, the finding that 85% of low-humus areas corresponded to moderately and highly saline land units provides strong evidence of the model's capability to accurately represent agroecological processes. Moreover, the incorporation of Digital Elevation Model (DEM) data enabled the successful identification and prediction of irrigation-induced erosion risks in areas where slope gradients exceeded  $3^\circ$ , demonstrating the model's practical value for sustainable land management and environmental monitoring.

Despite its methodological and practical contributions, the study has several limitations that should be considered in future research. First, the spatial resolution of the Landsat-8 and Sentinel-2 imagery used in this study (10–30 m) may introduce mixed-pixel effects when evaluating very small land parcels at a local scale, thereby limiting assessment accuracy in highly fragmented agricultural landscapes. Second, optical remote sensing data are inherently dependent on atmospheric conditions, particularly cloud cover during the growing season, which may temporarily restrict operational monitoring activities. To overcome these limitations and further enhance the assessment framework, future studies should integrate the proposed GIS model with radar-based satellite data, such as Sentinel-



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1, as well as ultra-high-resolution imagery acquired from Unmanned Aerial Vehicles (UAVs). Furthermore, linking the multi-factor spatial database developed in this research with Artificial Intelligence (AI) and Machine Learning techniques, including Random Forest algorithms and Artificial Neural Networks (ANNs), offers a promising direction for the development of intelligent monitoring systems capable of automatically predicting land fertility degradation and supporting advanced decision-making processes within the agro-industrial sector.

### **CONCLUSION**

This study, based on the integration of Geographic Information Systems (GIS) and remote sensing data in assessing the fertility level and agro-ecological condition of agricultural lands, demonstrated conceptual and practical approaches to overcoming existing problems in the traditional cartography and land monitoring system. NDVI and SAVI spectral indices calculated using Landsat-8 and Sentinel-2 space images made it possible to operationally determine the state of biological productivity and biomass of agrolandscapes in real time and over large areas. The results of point laboratory analyses obtained from field conditions were transformed into a continuous surface using the simple kriging interpolation method of geostatistics, and served as the basis for modeling the spatial distribution of macroelements and humus in the soil with minimal error (RMSE < 0.08) and high reliability (92%).

The multi-criteria decision-making (MCDA) system and the Weighted Overlay methodology used in the study served to provide a highly objective and comprehensive assessment of the state of land resources by combining relief slope, salinity, humus content and vegetation indicators in a single systematic algorithm. As a result of the integrated analysis, a digital map of the area was formed, divided into five categories according to the agro-ecological condition, and it was spatially confirmed that 30 percent of irrigated lands (low and very low categories) were subjected to various degrees of degradation and salinization processes. This proposed digital GIS model is distinguished by the fact that it increases the level



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of spatial accuracy by 35 percent compared to traditional methods of assessment and mapping.

In conclusion, it should be noted that the introduction of this methodology into the management of the agro-industrial complex is the most effective mechanism for early forecasting of negative environmental and land reclamation changes in agricultural lands and making prompt management decisions on the rational use of land resources. In future studies, the enrichment of this multi-factor database with data from radar satellites (Sentinel-1) and images from unmanned aerial vehicles (drones), as well as the formation of fully automated intelligent soil monitoring systems (Smart Agriculture) through the integration of machine learning algorithms, will remain a promising scientific and practical direction in the field.

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