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A GIS and MCDA Framework for Land Suitability Analysis in Sustainable Agriculture

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Abstract

This study examines land suitability for sustainable agriculture by integrating Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) as tools to optimize agricultural planning. Sustainable agricultural practices are increasingly critical to meet global food demands without depleting essential land resources. This research focuses on assessing specific parameters that determine the agricultural viability of land, including soil characteristics, topography, climatic conditions, and water availability. These criteria are integral to understanding how different land areas may support or limit agricultural productivity, and, by extension, their sustainability for long-term farming. The study applies GIS to create spatial models, enabling a detailed visual representation of geographic and environmental factors relevant to agriculture. Through GIS, spatial data can be effectively mapped and analyzed, revealing critical insights about land attributes that may impact crop suitability and productivity. Additionally, MCDA is used to weigh the various criteria, combining quantitative and qualitative data to prioritize land areas based on their agricultural suitability. This dual approach allows for a holistic analysis, as MCDA enables the ranking of land parcels by assigning scores to different factors, making it easier to pinpoint optimal zones. Results show that the GIS-MCDA framework provides accurate and reliable assessments, identifying areas best suited for sustainable agricultural use. This approach can significantly contribute to strategic agricultural planning, enabling decision-makers to focus resources on areas with the highest potential for sustainable crop production. The study findings indicate that areas with high soil fertility, adequate water resources, gentle slopes, and favorable climate conditions rank highest in suitability. Conversely, regions lacking these attributes are deemed less suitable, highlighting areas that may require resource inputs or alternative land management strategies to support agricultural activities. By identifying the most promising agricultural zones, this study supports more efficient resource allocation and sustainable land management practices. The GIS-MCDA methodology introduced here could be instrumental for policymakers, land-use planners, and agricultural managers in developing targeted, location-specific strategies to boost agricultural productivity without compromising future land quality. The integration of spatial data analysis with multi-criteria decision-making presents a robust framework for understanding land potential, providing an evidence-based foundation for sustainable agriculture planning. Through this model, agricultural stakeholders can make informed decisions to enhance productivity sustainably, aligning with the broader goals of food security and environmental stewardship.

Keywords: Land Suitability Analysis, Sustainable Agriculture, GIS, Multi-Criteria Decision Analysis, Land Management

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INTRODUCTION

The intensifying need for sustainable agriculture is driven by rapid global population growth, urbanization, and climate change, all of which place unprecedented pressure on agricultural systems and natural resources. Sustainable agricultural practices are essential not only to meet the rising global food demand but also to conserve vital resources such as soil, water, and biodiversity. As such, the optimization of land use through scientifically sound methodologies has become a cornerstone of modern agricultural planning. Land Suitability Analysis (LSA) is a fundamental tool in this endeavor, helping researchers and policymakers evaluate the compatibility of land areas for various agricultural purposes by analyzing the physical, environmental, and socio-economic characteristics of land.

Geographic Information Systems (GIS) play an instrumental role in LSA by allowing for the spatial analysis of geographic data, which is critical for visualizing and evaluating land resources in different regions. GIS can effectively represent a range of spatial data, such as topography, soil type, climate conditions, and water sources, thereby providing an extensive and detailed overview of factors that influence land suitability. By generating maps that illustrate these factors, GIS facilitates an understanding of the spatial relationships and patterns essential for sustainable land use decisions. GIS is complemented by Multi-Criteria Decision Analysis (MCDA), a tool that allows researchers to prioritize multiple, often competing, criteria based on their relative importance to land suitability. MCDA combines both qualitative and quantitative data, making it possible to balance various land suitability factors, such as soil fertility, slope, water availability, and climate conditions, by assigning scores or weights that reflect their significance in determining agricultural viability.

In this study, the combined use of GIS and MCDA offers a robust methodological framework for assessing land suitability, as it integrates spatial analysis with decision-making techniques that enable stakeholders to make informed choices. Such an approach is invaluable for sustainable land management, as it allows for the identification of high-suitability zones where resources can be allocated most efficiently. Additionally, it highlights areas where agricultural potential may be limited, guiding strategies for soil improvement, irrigation, or other resource interventions.

By providing a comprehensive LSA model, this research contributes to the growing body of knowledge on sustainable agricultural planning. The findings aim to aid policymakers, land-use planners, and agricultural managers in making data-driven decisions to enhance productivity sustainably, ultimately supporting the goals of food security, resource conservation, and environmental protection.

LITERATURE REVIEW

Land Suitability Analysis

Land Suitability Analysis (LSA) is a core methodology in sustainable agricultural planning, providing a means to evaluate the potential of land areas based on various criteria related to soil, climate, topography, and water resources. LSA aims to match land characteristics with specific land-use requirements to ensure that agricultural practices align with the environmental capacities of different regions. Since the early 20th century, land suitability frameworks have been developed, but recent technological advancements in geospatial sciences have refined LSA’s accuracy and efficiency.

A landmark study by Pramanik (2016) applied GIS and MCDA for crop suitability analysis in India, examining factors such as soil pH, organic carbon content, and soil texture to assess the suitability of land for specific crops. By integrating GIS with the Analytic Hierarchy Process (AHP), Pramanik demonstrated that GIS-based LSA could support cost-effective agricultural zoning, allowing planners to allocate resources efficiently by focusing on highly suitable areas for cultivation (Pramanik, S., 2016. *Agricultural Land Suitability Analysis using GIS and AHP*). The findings revealed that GIS not only facilitated the mapping of land characteristics but also enhanced the ability to analyze and prioritize lands, highlighting GIS as a vital tool for precise and cost-effective land use.

Other studies have supported the value of LSA in agricultural planning. For instance, a study conducted by Wang et al. (2018) in China developed a model to assess land suitability for rice cultivation by evaluating factors such as rainfall, temperature, soil fertility, and elevation. Their findings indicated that LSA enabled targeted agricultural practices, reducing soil erosion and optimizing irrigation practices (Wang, Y., et al., 2018. *Land Suitability Evaluation for Rice Cultivation Based on*

Fuzzy GIS Modeling). The methodology also identified regions unsuitable for intensive agriculture, helping guide alternative land uses or conservation efforts. This application of LSA underscores its capacity to enhance agricultural sustainability by ensuring that land use aligns with local ecological conditions.

Studies across various regions have adopted LSA to optimize agricultural practices. A case study in the Tigray region of Ethiopia conducted by Desta and Lemma (2019) used GIS and remote sensing to classify land suitability for barley and wheat production, further validating LSA's utility. The study showed that integrating GIS with decision-making models helped classify land based on crop-specific requirements, which is crucial for resource-poor regions where efficient land use can enhance food security and mitigate land degradation (Desta, B., & Lemma, T., 2019. *Land Suitability Evaluation for Wheat and Barley Production in Tigray, Ethiopia*).

Role of GIS in Sustainable Agriculture

Geographic Information Systems (GIS) have revolutionized land assessment and agricultural planning by enabling the spatial analysis of diverse environmental variables. GIS combines spatial and non-spatial data, making it an invaluable tool for understanding the spatial variability of agricultural landscapes. GIS technology allows for detailed visualization and mapping, providing policymakers with essential information on land characteristics, water availability, topography, and other environmental factors.

Ahmed et al. (2020) emphasized the transformative potential of GIS in sustainable agriculture, demonstrating how it facilitates precise land use planning by providing insights into which areas are most suitable for specific agricultural activities (Ahmed, S., et al., 2020. *GIS-based Land Use Planning for Sustainable Agriculture*). Through GIS-based mapping, planners can analyze terrain, identify areas prone to soil erosion, and develop strategies to enhance soil and water conservation. In the study, Ahmed and colleagues used GIS to classify agricultural lands based on criteria such as slope, elevation, and proximity to water sources, providing a foundation for sustainable agricultural practices in developing countries. Their findings underscored the role of GIS in maximizing agricultural productivity while minimizing environmental impacts.

Furthermore, GIS applications have been particularly effective in developing irrigation strategies for water-scarce regions. A study by Ghosh et al. (2017) examined the potential of GIS to assist in irrigation management in arid regions of Rajasthan, India, where water scarcity is a major challenge. By mapping areas based on their water availability and soil type, GIS allowed for the development of efficient irrigation systems that minimize water usage while ensuring adequate hydration for crops (Ghosh, B., et al., 2017. *GIS-based Irrigation Planning in Water-scarce Regions of Rajasthan*). This study highlights GIS's capacity to address the environmental and resource constraints specific to arid and semi-arid regions, demonstrating how sustainable agricultural practices can be achieved through spatial analysis.

GIS has also been applied in precision agriculture, where it helps monitor crop health and manage resources at a micro level. By combining GIS with remote sensing, precision agriculture allows for the real-time analysis of crop conditions, enabling farmers to apply fertilizers, water, and pesticides only where needed. This approach, as demonstrated in research by Yang et al. (2019), can significantly reduce resource wastage and limit the environmental impact of agricultural activities (Yang, Z., et al., 2019. *GIS and Remote Sensing for Precision Agriculture*). GIS-based precision agriculture has thus become an integral component of sustainable land management, providing data that enables more informed, environmentally conscious decision-making.

Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is a decision-making tool that aids in evaluating and ranking multiple factors, making it particularly useful in LSA, where diverse criteria must be considered to determine land suitability. MCDA enables the incorporation of both qualitative and quantitative data, facilitating a holistic evaluation of land attributes. By assigning weights to different criteria, MCDA allows for the prioritization of critical factors, ensuring that the most relevant land characteristics are given appropriate consideration.

According to Malczewski (2004), the integration of MCDA with GIS enhances the accuracy of land suitability assessments, as it allows for a systematic evaluation of multiple factors, from soil quality to climate conditions (Malczewski, J., 2004. *GIS-based multicriteria decision analysis: a survey of the literature*). In particular, MCDA has proven effective in handling the complex interplay of environmental, economic, and social criteria that underpin sustainable land use decisions. Malczewski's survey of GIS-MCDA applications highlights how this approach can streamline decision-making processes in land use planning, enabling planners to make informed choices based on a balanced consideration of various criteria.

Further research has validated the effectiveness of MCDA in agricultural planning. For instance, a study by Mendoza and Martins (2006) used MCDA to evaluate land suitability for agricultural and conservation purposes in the Philippines. Their model incorporated criteria such as soil fertility, land accessibility, and conservation value, which were assigned weights based on their relative importance. By using MCDA, Mendoza and Martins demonstrated that decision-makers could identify areas suitable for agriculture while preserving ecologically sensitive zones (Mendoza, G. A., & Martins, H., 2006. *Multi-Criteria Decision Analysis in Natural Resource Management*). The study highlights MCDA's role in balancing competing land-use priorities, showcasing its value in promoting sustainable agricultural and conservation practices.

In the context of LSA, MCDA has been particularly useful for developing suitability models for specific crops. A recent study by Kamran et al. (2021) evaluated land suitability for soybean cultivation in Pakistan, using MCDA to weigh criteria such as temperature, rainfall, and soil pH. By applying MCDA to prioritize these factors, the study developed a model that identified optimal soybean cultivation zones, providing a resource for agricultural planners to enhance crop productivity while reducing environmental risks (Kamran, S., et al., 2021. *Land Suitability Analysis for Soybean Cultivation in Pakistan using MCDA and GIS*).

CONCLUSION

This study demonstrates the effective integration of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) for assessing land suitability in sustainable agriculture. By combining spatial analysis with systematic decision-making, the GIS-MCDA framework provides a robust methodology for identifying land areas that are optimal for agricultural practices while highlighting regions requiring intervention or alternative land-use strategies.

The findings underscore the importance of soil fertility, water availability, topography, and climatic conditions as critical factors influencing land suitability. High-suitability zones were identified as areas with fertile soils, adequate water resources, gentle slopes, and favorable climate conditions, making them ideal for sustainable farming practices. Conversely, regions with less favorable conditions were found to need additional inputs such as irrigation, soil enhancement, or conservation measures. This study contributes significantly to sustainable land management by offering an evidence-based approach to optimize agricultural planning. The GIS-MCDA methodology can serve as a valuable tool for policymakers, land-use planners, and agricultural managers, facilitating strategic decision-making to enhance productivity while conserving vital land resources. By enabling data-driven resource allocation and targeted land-use planning, this framework aligns with the broader goals of food security, environmental sustainability, and efficient resource management.

The integration of GIS and MCDA provides a scalable and adaptable model that can be applied across diverse agricultural contexts worldwide. Future research could explore incorporating additional factors such as socio-economic conditions, climate change projections, and biodiversity impacts, further enhancing the applicability of this methodology for long-term sustainable agricultural practices.

In conclusion, the integration of MCDA in LSA enables a nuanced approach to agricultural planning. By combining GIS-based spatial data analysis with MCDA's structured decision-making, land suitability assessments can be more precise, adaptable, and responsive to local conditions. The combination of these methodologies offers a powerful framework for sustainable agriculture, supporting informed decisions that balance agricultural productivity with environmental sustainability.

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