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Role of GIS in Data-Driven Agricultural Planning and Sustainability Enhancement

Amlanjyoti Khuntia[1], Rahul Kumar Meher[2] and Ajay Kumar Upadhay[3]

Abstract: -

The aim of this review was to compile and evaluate existing evidence on the use of Geographic Information Systems (GIS) and Remote Sensing (RS) in agriculture, with a focus on strengthening evidence-based policy and practice to enhance agricultural sustainability and to identify constraints to their adoption, particularly in low- and middle-income countries. The application of GIS in agriculture has increased markedly over the past decade, with approximately 66% of the selected studies published within the last six years. Major areas of GIS application included crop yield estimation, soil fertility evaluation, monitoring of cropping patterns, drought assessment, pest and crop disease detection and management, precision agriculture, and fertilizer and weed management. GIS technologies offer significant potential to promote agricultural sustainability by incorporating spatial information into agricultural policy frameworks. Moreover, the role of GIS in supporting evidence-informed decision-making is expanding. However, a substantial disparity exists in the geographical distribution of GIS applications, particularly in sub-Saharan Africa, from which only a single study was identified. Given the escalating impacts of climate change on agriculture and food security, there is an urgent need to further integrate GIS into policy formulation and decision-making processes to support sustainable agricultural development.

Introduction:

Global food demand has increased sharply and is projected to rise by approximately 59–98% by 2050. A major concern, however, is that current agricultural

Amlanjyoti Khuntia[1], Rahul Kumar Meher[2] and Ajay Kumar Upadhay[3]

[1]Assistant Manager Livelihood (Agriculture), CBSAE Development Project, Odisha University of Agriculture & Technology, Odisha

[2]System Manager, Geo - Spatial Lab, LRI-OUAT (REWARD) Project, College of Agriculture, OUAT, Chiplima, Sambalpur

[3]M.Sc. Scholar, Department of Soil Science, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar

production systems are struggling to keep pace with this growing demand, particularly in low-income countries, thereby exacerbating food insecurity. Inefficiencies within food production systems further contribute to this challenge. Identifying strategies to boost food production without degrading land and water resources, increasing energy use, or harming the environment remains a critical responsibility for governments and policymakers. In many low- and middle-income countries (LMICs), food production is largely rural-based and dominated by smallholder and subsistence farmers. Improving the sustainability of these farming systems requires equipping farmers with practical, reliable information that enables them to make and apply evidence-based decisions aimed at enhancing productivity and long-term sustainability. To move away from weak and inefficient traditional subsistence practices, there is a need for sustainable production strategies that promote efficiency gains and improved agronomic management. Such strategies include the adoption of climate-resilient and high-yielding crop varieties, crop yield forecasting, integrated pest management, and the incorporation of biodiversity-based solutions into sustainable food systems. Implementing these approaches depends heavily on access to comprehensive and up-to-date datasets, both spatial and non-spatial, as well as the use of advanced GIS technologies capable of integrating social, spatial, economic, demographic, and environmental data. The resulting spatially explicit, evidence-based information can significantly enhance understanding of agricultural sustainability and support more effective policy formulation and decision-making.

Recent advancements in Geographic Information Systems (GIS), Remote Sensing (RS), and Global Positioning System (GPS) technologies have created new opportunities for acquiring and utilizing high-resolution satellite imagery and digital spatial data. Within the agricultural sector, these datasets have facilitated the analysis of spatial relationships among social, physical, agroecological, and environmental factors and their influence on agricultural sustainability. GIS offers a suite of tools for managing geospatial information, enabling the collection, storage, integration, querying, visualization, and analysis of spatial data across multiple scales. Remote sensing technologies capture crop- and soil-related information using sensors mounted on satellites, manned aircraft, unmanned aerial vehicles, and ground-based platforms; these data are subsequently processed to support agricultural decision-making systems. Agriculture’s spatial dimension can also be understood through variations in farmers' access to livelihood assets, local resources, infrastructure, and essential services within specific locations. In GIS environments, these components can be represented as multiple, nested spatial layers, each linked to geographic coordinates obtained through GPS. By analyzing these layers collectively, GIS can be used to assess crop and soil conditions, identify spatial interactions, forecast crop trends, monitor land-use changes, track pest dynamics, and support biodiversity conservation efforts. Additionally, such analyses can help identify spatial constraints to agricultural production and generate new insights to strengthen agricultural sustainability.

GIS in Agriculture and Policy Implications

The major research themes emerging from the existing literature on the application of GIS in agriculture. Overall, seven key areas of GIS application in the agricultural sector have been identified. These include crop yield estimation and forecasting, soil fertility evaluation, analysis of cropping patterns and agricultural monitoring, drought assessment, pest and crop disease detection and management, adoption of precision agriculture practices, and fertilizer and weed management. GIS plays a significant role in supporting the implementation of agricultural policies through multiple pathways. It can aid regulatory enforcement and provide clear spatial visualizations of the economic impacts of policy decisions. In addition, GIS tools are effective in identifying environmental health risks and addressing concerns related to animal health and welfare. The technology also contributes to resolving land-use conflicts by offering objective, spatially explicit evidence. Furthermore, GIS software enables detailed soil analysis and supports the monitoring and evaluation of project progress. By improving land resource planning and management, GIS can enhance agricultural productivity while reducing operational costs. The integration of satellite imagery, thermal sensors, and multispectral data within GIS platforms allows organizations to assess crop health more accurately and in a timely manner. In addition, GIS-based tools assist farmers in selecting suitable locations and environmental conditions for cultivating different crops. GIS-driven models also provide evidence-based solutions for improving soil quality and promoting sustainable soil management practices. The following subsections elaborate on the principal research domains addressed in the literature concerning the application of GIS and remote sensing in agriculture.

Crop Yield Estimation and Forecasting

Monitoring crop growth and generating early yield forecasts are essential for ensuring food security, guiding agricultural planning, and estimating economic returns from farming systems. Advances in remote sensing (RS) and GIS technologies have significantly improved the techniques used to track agricultural development and estimate crop yields with greater accuracy and efficiency. Remote sensing data are widely used to develop spatially explicit crop yield maps. A growing body of research demonstrates the effectiveness of integrating GIS and RS for crop production estimation. For instance, Memon et al. (2019) highlighted the usefulness of multispectral Landsat imagery and various remotely sensed spectral indices in quantifying wheat straw cover and assessing its influence on rice yield. Such insights are valuable for formulating long-term strategies to enhance sustainability in rice–wheat cropping systems. Similarly, Hassan and Goheer (2021) reported that wheat yields can be reliably predicted prior to harvest by combining vegetation indices derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data with observed yield records and GIS-based modeling techniques. In another study, Muslim et al. (2015) developed a GIS-driven framework that integrated climate modeling with environmental policy considerations to forecast rice yields. Their approach employed a comprehensive regional-scale model that combined crop-specific data, soil characteristics, farm management practices, and climatic variables to capture spatial variations in crop productivity. Together, these studies underscore the critical role of GIS and RS in supporting timely, accurate, and policy-relevant crop yield estimation and forecasting.

Assessment of Soil Fertility

Evaluating soil quality is a critical component of developing sustainable agricultural strategies that can narrow the gap between food supply and demand and, in turn, strengthen food security. The integration of remote sensing (RS) data with GIS-based spatial modeling has opened new opportunities for measuring and analyzing soil fertility and overall soil quality across different spatial scales. Several studies highlight the effectiveness of these approaches. Shokr et al. (2021) developed a spatially explicit soil quality model that combined physical, chemical, and biological soil properties. By integrating a digital elevation model with Sentinel-2 satellite imagery, the study produced detailed digital soil maps. Similarly, Abdelfattah and Kumar (2015) demonstrated the application of a GIS-supported, web-based soil information system that provides a comprehensive database of descriptive, quantitative, and spatial soil data through an accessible interface, enabling assessments of soil suitability for crop growth and sustainable management. In another example, Abdellatif et al. (2021) applied GIS and RS techniques to create a spatial soil quality assessment model based on four key indicators: soil fertility, physical condition, chemical properties, and geomorphological characteristics. Using conventional GIS kriging interpolation methods, the model generated an integrated soil quality index map. Such GIS-based models offer empirically grounded tools for improving soil quality management and guiding sustainable land-use decisions. The adoption of these approaches equips policymakers, land-use planners, agricultural practitioners, and decision-makers with robust information to monitor soil resources and promote the sustainable use of agricultural land in accordance with its inherent potential. Consequently, systematic assessment of soil quality indicators is essential for formulating sustainable agricultural policies, improving management practices, and ensuring long-term food security.

Analysis of Cropping Patterns and Agricultural Monitoring

Under conditions of increasing climate variability, agricultural crop monitoring and cropping pattern analysis can support both policymakers and farmers in developing adaptive strategies for crop planning and design that account for fluctuations in water availability. Agricultural monitoring systems integrate diverse geospatial datasets with cropping system models and computational algorithms to spatially simulate and identify optimal, site-specific scenarios for crop production. Several studies highlight the value of GIS and RS integration in this context. Shafi et al. (2020) developed a crop monitoring framework that combines high-resolution remote sensing data with a web-based GIS geoportal, enabling efficient visualization and analysis of crop conditions. The literature further emphasizes the effectiveness of GIS–RS-based tools for crop selection and crop rotation analysis at the farm level, which can significantly improve decision-making in crop management. Cropping pattern modeling is strongly shaped by irrigation water availability, which itself is influenced by climate variability and policies governing water extraction. According to Singha et al. (2020), such systems have wide-ranging applications in agronomic decision-making, including improving land and labor use efficiency, increasing cropping intensity, and boosting crop yields. Over the long term, the adoption of GIS- and RS-based monitoring approaches can enhance agricultural productivity and refine crop management practices, particularly through improved precision irrigation management.

Weed and Fertilizer Management

Precise spatial mapping of weed infestations can greatly improve the effectiveness of weed control interventions. By enabling site-specific management, such approaches reduce crop yield losses due to weeds, lower herbicide application costs, and support the more efficient use of fertilizers. Previous studies have shown that GIS-based weed distribution maps in rice-growing areas enhance the accuracy of input application, leading to reduced reliance on herbicides, fungicides, and manual labor for weeding. These improvements collectively contribute to decreased weed infestation levels and lower overall production costs. Existing research further emphasizes the importance of GIS in the development of Fertilizer Decision Support Systems (FDSS). Such systems combine remote sensing information, field-level data, and expert knowledge to guide fertilizer application decisions. The creation of spatial soil databases, including those developed using platforms such as SuperMap, has facilitated more targeted and efficient crop management practices. The application of FDSS in agriculture has been associated with improved fertilizer use efficiency, reduced nutrient losses, and a consequent decline in production expenditures.

Conclusions

This review explored the various ways in which GIS has been integrated into agricultural systems to strengthen decision-making and support policy formulation. Compared with approaches that do not explicitly incorporate spatial information, GIS and RS technologies provide more robust tools for analyzing the geographic factors influencing agricultural production. When applied effectively, the spatially integrated insights generated through GIS and RS can support agricultural policies and evidence-based interventions aimed at improving sustainability. Despite their considerable potential to advance agronomic practices, the adoption of GIS and RS technologies remains limited across many low- and middle-income countries (LMICs). This gap is particularly alarming given the urgent need in these regions to modernize agricultural and food production systems. To maximize the benefits of GIS and RS, governments, institutions, and farmers in LMICs must improve their awareness, technical capacity, and practical use of spatial agricultural data. Furthermore, ongoing advances in geoinformatics techniques and computing infrastructure can foster stronger collaboration among key stakeholders, including scientists, researchers, policymakers, academics, crop advisors, extension personnel, and agricultural input providers. Such collaborative frameworks can help translate spatial data into actionable guidance for managing crop yield estimation, soil fertility, cropping pattern analysis and monitoring, drought risk assessment, and fertilizer and weed management, thereby supporting more sustainable agricultural development.

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