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The Principles, Applications, and Development Trends of GIS and Remote Sensing Technology in Precision Agriculture

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Abstract. Agriculture is a fundamental industry that ensures global food security and economic development, but it is confronted with multiple challenges such as climate change, land degradation, water shortage, and population growth. To address these issues, agriculture is increasingly shifting towards data-driven and precise management approaches. Hence, precision agriculture (PA) achieves the efficiency and sustainability of agricultural production through precise perception, data analysis, and intelligent decision-making. Geographic Information System (GIS) and Remote Sensing technology (RS), as key spatial information technologies for the implementation of precision agriculture, have been widely applied in fields such as crop monitoring, soil management, yield assessment, and variable input. This paper systematically reviews the typical applications of GIS and remote sensing technologies in agriculture, analyzes their advantages and limitations in combination with specific cases, and further explores the development trend of future technology integration, with the aim of providing theoretical support and practical reference for technological innovation in precision agriculture.

Keywords: Precision Agriculture, GIS, Remote Sensing, Spatial Analysis, Agricultural Zoning

1. Introduction

Under the combined pressure of climate change, land degradation, water shortage, and rapid population growth, global agriculture is undergoing a crucial transformation towards enhanced efficiency, precision, and sustainability. These challenges not only reduce the stability of food production, but also set higher demands on the sustainable development of rural communities. In recent years, climate change has become increasingly serious, and extreme weather events have significantly increased the risks of crop diseases and pests, soil degradation, and water resource shortages. Therefore, the agricultural system needs to adopt more advanced methods to enhance its adaptability [1]. Based this background, Geographic Information System (GIS) and Remote Sensing (RS) have become important tools for the development of modern precision agriculture. GIS provides an integrated platform for collecting, storing, analyzing and visualizing spatial data. At the same time, GIS can also integrate various types of information such as terrain, soil characteristics, climatic conditions and crop distribution [2]. Meanwhile, RS technology enables dynamic observations of the surface of the planet through satellite images and UAVs [3]. It plays a crucial

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role in monitoring key agricultural indicators such as soil moisture, crop growth conditions, and pests and diseases. GIS and RS have jointly significantly improved the timeliness and accuracy of agricultural information collection and made it possible to conduct real-time analysis and resource optimization at the regional level.

Although a large number of studies have explored the application of GIS and remote sensing in agriculture, most of these efforts remain fragmented, focusing on specific crops, regions, or technologies. Lack of comprehensive synthesis and in-depth comparative analysis. Therefore, it is clearly necessary to systematically review and evaluate the current progress in order to better understand the advantages and limitations of these technologies in the actual agricultural environment.

This review aims to explain the basic principles and functions of geographic information systems and remote sensing technology, summarize their typical applications in precision agriculture, analyze their advantages and limitations through practical examples and data, and explore the future development trend of agricultural comprehensive spatial information technology.

2. The synergistic role of GIS and remote sensing in smart agriculture

GIS and remote sensing (RS) technologies, as important components of spatial information technology systems, have been widely and deeply applied in agricultural production. Remote sensing technology acquires large-scale and high spatiotemporal resolution surface information rapidly and accurately in a non-contact manner through various observation platforms such as satellites, unmanned aerial vehicles, manned aircraft, vehicles, and ground sensors. This enables agricultural producers to monitor the growth status of crops, the outbreak trends of pests and diseases, as well as the moisture and nutrient conditions of the soil in real time [4].

GIS has a powerful ability for spatial data management and analysis. It can effectively integrate the image data obtained by remote sensing with multi-source spatial information such as farmland boundaries, soil properties, and topographic features. Through analysis methods such as layer superposition, spatial interpolation, and spatial modeling, it provides a precise and scientific basis for agricultural production zoning, variable input decision-making, and optimal resource allocation [5].

The organic combination of GIS and remote sensing integrates the advantages of remote sensing in large-scale and real-time data acquisition, as well as the strengths of GIS in in-depth analysis and interpretation of spatial data. This synergy has greatly enhanced the utilization efficiency of agricultural resources and the scientific nature of production decisions, providing a solid foundation and a complete framework for the technical practice of modern smart agriculture.

3. Applications of GIS and remote sensing in agriculture

3.1. Agricultural management zoning in ultra-arid environments

Elsharkawy et al. conducted a study in the extremely arid Salhiya region of Egypt to optimize the use of 67 hectares of irrigated peanut fields. The key challenge is to determine the spatial variations of soil and crop conditions to support variable rate fertilization (VRF) [6].

The team used Landsat 8 images to create enhanced Vegetation Index (EVI) maps and combined data from 33 soils and 37 yield sampling points. The key soil characteristics, including texture, pH value, organic matter, and micronutrients, were extracted using the Kriging interpolation method. These functions are integrated into the Integrated Land and Water Information System (ILWIS)

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platform through the Spatial Multiple Criteria Evaluation (SMCE) model, so building weighted overlay layers for zoning analysis.

The resulting areas show significant yield differences, with the best area reaching 7.2 tons per hectare and the overall classification accuracy reaching 86.49%. This study demonstrates that GIS has a high degree of complementarity in spatial modeling and remote sensing crop monitoring. It not only provides practical tools for efficient and precise agricultural management, but also helps farmers identify high-yield areas and potential problem regions [6]. At the same time, it can also optimize resource allocation, increase production, reduce input costs, and enhance the adaptability of the agricultural system to climate and environmental changes.

3.2. Crop identification and soil productivity assessment in irrigated arid zones

Hassan and colleagues used drone pictures, GIS tools, and deep learning to evaluate crops on over 40 acres of rice fields in Pakistan. This research investigates how to precisely measure plant density and how different fields vary, which cannot be effectively achieved by traditional manual methods [7]. Their team collected more than 1,200 high-resolution images within eight DJI Phantom 4 Pro drone flights. ArcGIS Pro 2.5 was used to process and analyze these pictures. The deep learning model detected rice plants with a 99% accuracy rate, confirmed by on-site inspections by experts.

According to the results, planting densities are 26,466 plants per acre (manual) and 29,823 plants per acre (mechanical), much lower than the recommended density of 80,000-150,000 plants. In order to provide information for variable-rate input decisions, spatial analysis also established the planting gap and established a correlation between crop density and soil properties [7].

3.3. Soil moisture and irrigation management in the mediterranean climate

In arid and semi-arid regions, soil moisture stress is the main constraint factor for crop yield and quality. Filintas et al. conducted a study in Thessaly, Greece, to combine the use of proximal sensing and GIS to address this issue.

Rain-reared agriculture in the Mediterranean climate is often affected by insufficient soil moisture at critical crop stages, which limits the productivity of coriander. The challenge lies in improving the irrigation time and efficiency under the condition of limited water [8].

The team used TDR soil moisture sensors to monitor the daily volumetric water content (0-75 cm) throughout the season. CoKriging interpolation is applied in ArcGIS to create the soil moisture distribution map, thereby achieving precise drip irrigation scheduling under rain-nurtured and supplementary irrigation schemes.

Limited drip irrigation during the critical growth stage increased the coriander seed yield from 422.37 kilograms per hectare to 1203.47 kilograms per hectare, an increase of 184.93%. The essential oil content increased by 25.4%, and the height of the umbellate inflorescence increased by 117.93%. Statistical analysis shows that the irrigation effect is very significant ($p < 0.001$). This study confirmed that combining TDR sensors with GIS modeling helps to use water efficiently and improve crop yields in arid areas [8].

3.4. Mapping of vegetable production suitability in subtropical humid regions

GIS and remote sensing technologies are also essential in maximizing the suitability of vegetable production on a regional scale. In North Dinajpur, India, Sarkar and associates mapped appropriate vegetable-growing regions using statistical models and geographical analysis [9]. An all-

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encompassing, data-driven strategy was applied to identify sites suited for growing vegetables in areas regarding environmental and sociological circumstances. Researchers also used Landsat-8 images and environmental factors (such as soil, groundwater, rainfall, topography, and market proximity) to calculate NDVI and NDWI. They applied frequency ratio (FR), entropy weight method (EWM), and evidence weight (WoE) in ArcGIS to create a weighted superposition suitability model based on 22 variables.

According to model estimation, 16.93% (531.95 km²) of the area was highly suitable and 26.64% (873.12 km²) was moderately suitable. The main influencing factors include soil type, rainfall, nitrogen content, groundwater depth, and distance to the market. High prediction accuracy (AUC: FR = 0.927, EWM = 0.888, WoE = 0.907) confirmed the reliability of the model and emphasized the value of GIS and remote sensing in guiding regional vegetable production planning [9].

4. Limitations and future directions

Although GIS and remote sensing technologies have played an important role in agricultural informatization and refined management, their application is still limited by problems such as insufficient technical adaptability, lack of data comprehensiveness, and weak promotion feasibility. The following will analyze the current deficiencies from three aspects: technical limitations, data shortcomings, and promotion obstacles. Based on cases from multiple countries, it proposes the future development directions of technology integration, data optimization, and policy coordination.

4.1. Limitations

4.1.1. Main deficiencies of the current research

One of the most significant deficiencies in current research are technical limitations, including single variable selection and insufficient model practicality. Most of the existing studies rely on a single remote sensing index (for example, the study of the Nile Delta in Egypt only uses the EVI index [6]) and fail to integrate key parameters such as crop moisture and soil moisture. Agricultural management elements such as the layout of irrigation systems and water resource allocation are often overlooked, resulting in limited application value of the model in arid areas.

4.1.2. Data shortcomings

The data processing process also suffers from missing time series. For instance, the rice identification research in Pakistan lacks cross-year data, making it difficult to analyze the growth dynamics of crops [10]. Moreover, high-resolution RGB images are highly dependent on data as they are vulnerable to environmental interference (illumination, flight altitude), and it is necessary to combine multispectral and temporal remote sensing to improve stability [10].

4.1.3. Promotion obstacles

The hardware is limited by a high technical threshold and social and economic constraints. The Greek application case requires drip irrigation systems and TDR sensors [8], while the Indian research relies on high-performance computing [9], making it difficult to replicate in resource-poor regions. Cost and institutional issues: Developing countries (such as Ethiopia) are confronted with challenges like high equipment costs, weak infrastructure, and insufficient training [1], and the problem of the "digital divide" is prominent in remote areas.

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4.2. Key paths for future development

Future development should focus on technological innovation, data optimization, and policy synergy. Introducing multispectral and hyperspectral remote sensing and Internet of Things (IoT) sensors can enhance data dimensions capturing key parameters such as leaf area index and soil moisture content. Developing low-cost solutions, such as open-source GIS platforms and mobile applications, will lower the technology adoption threshold for small-scale farmers [9]. Long-term remote sensing monitoring should be promoted to establish comprehensive crop growth cycle databases. Combining ground sensor data with satellite observations will enhance the robustness and reliability of predictive models [10]. Policy support is essential to promote technological inclusiveness through subsidy programs and training initiatives, as demonstrated in Ethiopia. Building agricultural data platforms based on cloud computing and blockchain technologies will optimize resource allocation and strengthen collaboration across the agricultural sector [11, 12].

5. Conclusion

GIS and remote sensing technologies have become core tools for promoting the sustainable transformation of agriculture, playing a key role in areas such as crop monitoring, land assessment, water resource management, and precise fertilization. Through the analysis of four typical cases, namely the Nile Delta in Egypt, the irrigated plains in Pakistan, the arid regions in Greece, and the water-rich areas in India, this study reveals the strong adaptability of these technologies in responding to different climatic and hydrological conditions. These practical achievements are of great value to all stakeholders: For farmers, they can optimize water and fertilizer input through precise field data and directly improve production efficiency; for policymakers, decision support systems based on spatial information are conducive to formulating more regionally adaptable agricultural and water resource policies. For technology developers, diverse application scenarios provide a valuable practical foundation for multi-source data fusion, intelligent algorithm optimization, and localized solution innovation.

However, the promotion of technology still faces multiple challenges: the high cost of obtaining high-precision remote sensing data, the insufficient cross-regional migration ability of models, the weak digital infrastructure in rural areas, and the limited acceptance of technology by farmers. To break through these bottlenecks, the future requires the collaborative efforts of all stakeholders: Technology developers should focus on developing low-cost sensors and lightweight analysis tools; policymakers need to increase investment in rural digital infrastructure and establish incentive mechanisms for technology promotion. The group of farmers needs to enhance their ability to apply technology through training. This multi-party collaboration model will accelerate the transformation of spatial information technology from "research-oriented" to "service-oriented."

In summary, against the backdrop of intensified global climate change and increasingly severe water shortages, GIS and remote sensing technologies are bound to play a more crucial role in the refined management of agriculture. Its successful application not only depends on technological innovation but also requires the establishment of a comprehensive promotion mechanism, including policy support, infrastructure improvement, and social recognition. Only through close cooperation among all key participants in the agricultural sector can the potential of these technologies be fully exploited to provide lasting impetus for sustainable global agriculture.

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