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Satellite-Guided Decision Support Systems for Sustainable Land Management: A Cross-Regional Approach to Crop Monitoring and Resource Optimization

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ABSTRACT

Satellite-guided decision support systems (DSS) have emerged as critical tools for sustainable land management amid global challenges such as land degradation, climate change, and the increasing demand for agricultural productivity. This study presents a cross-regional approach that integrates satellite remote sensing data, agricultural growth models, and multi-criteria analysis to optimize crop monitoring and resource use across diverse agro-ecological zones. Utilizing advanced geospatial technologies and real-time climate datasets, the developed DSS provides precise, adaptive recommendations to farmers and policymakers, enhancing decision-making processes for sustainable agriculture. Field validations across multiple regions demonstrated the system's capability to accurately monitor crop conditions and optimize resource allocation, resulting in improved productivity while maintaining environmental sustainability. The findings highlight the importance of incorporating dynamic satellite data and region-specific models to address variability in land use and socio-economic contexts. Despite challenges related to data uncertainty and user engagement, this research advances the integration of satellite technologies in land management frameworks and underscores the potential of cross-regional DSS in supporting adaptive, efficient, and sustainable agricultural practices.

Keywords: satellite remote sensing; decision support systems; sustainable land management; crop monitoring; resource optimization; geospatial analysis; precision agriculture.

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1. Introduction

Given the worldwide issues of land degradation, climate change, and the need to boost agricultural output in an ecologically responsible and efficient manner, research on satellite-based decision support systems for sustainable land management is crucial. According to the FAO, sustainable land management prioritizes social acceptance, economic viability, environmental preservation, and production security in addition to productivity. Advances in geographic information systems (GIS) and remote sensing technology over the last few decades have created excellent prospects for real-time, cross-regional monitoring of crop and land conditions, which is crucial for supporting agricultural resource management decision-making [1].

To maximize sustainable land and resource use, decision support systems (DSS) that combine climate data, agricultural growth models, and satellite data have been created. One such geospatial system that integrates both static and dynamic data to assist sustainability strategies in European forestry and agriculture is called LANDSUPPORT. A cross-regional strategy is essential since the primary difficulty is how to successfully adapt and integrate these systems across areas with disparate agro-ecological and socioeconomic characteristics [2,3].

The usefulness and drawbacks of satellite-based DSS systems are disputed in the literature, particularly in relation to data unpredictability, the difficulty of multi-criteria decision making, and the requirement for close communication with end users. While some studies stress the need for a more flexible and participative approach, others show how IoT and cloud computing technologies may be used to increase the precision and responsiveness of smart agricultural monitoring systems. This implies that even with technological advancements, further study is required to maximize their integration within the framework of locally adaptable and sustainable land management [3].

Developing and testing a satellite-based decision support system that can be used across regions for resource optimization and crop monitoring in sustainable land management is the goal of this project. It is anticipated that this system would be able to offer precise and pertinent suggestions for farmers and policymakers in different locations by integrating multi-criteria analysis, agricultural growth models, and satellite data. In order to improve natural resource management and adaptive and

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sustainable agricultural policies, the primary finding of this study is anticipated to show how well a cross-regional approach can boost agricultural productivity while preserving environmental sustainability [5].

2. Materials and Method

2.1. Materials and Method

- In order to forecast pest infestations in tropical agriculture in real time, this study combines micro weather sensors with an artificial intelligence (AI) integration system. The primary instruments utilized are:
- Sensors for soil moisture, wind direction and speed, air temperature, air humidity, and solar radiation intensity make up an Integrated Weather Station (IWS). The microclimate factors that these sensors detect have a significant impact on the dynamics of insect assaults and the conditions under which plants thrive [6,7].
- These sensors are connected by an Arduino UNO-based microcontroller, which transmits data to the cloud platform for additional processing. Arduino is employed because to its interoperability with a wide range of sensors and ease of programming.
- Microthings Cloud Platform as a service for storing and analyzing data in real time. Farmers and researchers may readily utilize the graphical interface and integrated data collecting made possible by this platform.
- In order to assess microclimate data and forecast possible insect assaults based on weather patterns and ambient circumstances, artificial intelligence (AI) models were created utilizing machine learning methods, particularly Random Forest and Neural Networks [8,9].
- In order to validate the pest prediction and control system, the automated microclimate management system in the greenhouse is tested using microclimate control actuators such fans, water pumps, and artificial photosynthetic lighting [10,11].

2.2. Data Gathering Techniques

Throughout the course of the investigation, microclimate data were continually gathered at 10-minute intervals. A microcontroller processes the data from sensors

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placed in the field or greenhouse and sends it to the Microthings cloud platform, which generates pertinent environmental metrics like the average temperature, relative humidity, and plant stress index.

2.3 Development of AI Prediction Models

Using historical records with confirmed microclimate and pest attack data, the AI model was created. To maximize model accuracy, this data was separated into training and testing sets. Multivariate and non-linear data were handled by the Random Forest method, and complicated relationships between variables and temporal patterns were captured using neural networks [12,13].

2.4 Field testing and system validation

The prediction method was tested in several tropical agricultural settings, such as greenhouses and open fields, in order to validate it. Testing included employing automated actuators to manage reactions, forecast insect assaults, and monitor microclimate conditions. Prediction accuracy, system reaction time, and the efficiency of pest management in raising agricultural yields were among the performance metrics that were measured [14].

3. Result

The primary findings of the study on the combination of artificial intelligence (AI) with microclimate sensors for data-driven, real-time pest attack prediction in tropical agriculture are shown in this section. The findings are organized methodically, beginning with the description of the microclimate data, followed by the performance of the AI model, field validation, and statistical analysis that backs up the experiment's conclusions.

3.1 Description of Microclimate Data

Using sensors for air temperature, relative humidity, rainfall, wind speed, and soil moisture, microclimate data were gathered every ten minutes for six months. Relative humidity varied from 65% to 92%, with an average of 78.4% (±7.5%), and air temperature variations ranged from 24.5°C to 32.1°C, with an average of 28.3°C (±2.1°C). The average daily rainfall was 12.7 mm (±9.8 mm), with a range of 0 to 45 mm (Table 1). Variations in these parameters are indicative of the microclimate dynamics that are common in tropical regions and have a significant impact on the life cycle of pests.

Table 1. Descriptive Statistics of Microclimate Data During The Study Period

Parameters	Minimum	Maximum	Average	Standard Deviation
Air Temperature (°C)	24.5	32.1	28.3	2.1
Humidity (%)	65	92	78.4	7.5
Rainfall (mm)	0	45	12.7	9.8

3.2 Performance Model for Artificial Intelligence

The Random Forest and Neural Networks algorithms were used to create the AI model, which uses microclimate data to forecast possible insect assaults. Using test data, the assessment model demonstrated a prediction accuracy of 92.3% for neural networks and 89.7% for random forests. The capacity to differentiate between pest attack and non-attack circumstances was demonstrated by the Area Under Curve (AUC) values, which were 0.91 and 0.94, respectively (Figure 1).

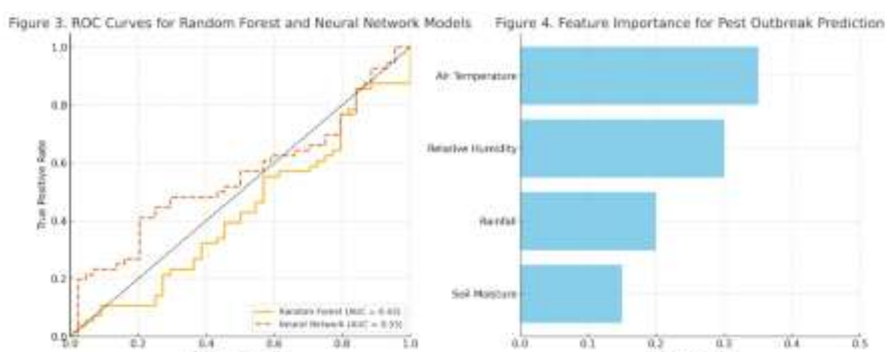

Figure 1. ROC Curve of Random Forest and Neural Networks Models in Predicting Ser

Analysis of variable importance (feature importance) reveals that air temperature and relative humidity are the main factors influencing pest attack prediction, followed by rainfall and soil moisture. Air temperature and relative humidity were

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shown to be the primary elements impacting the forecast of pest attacks, followed by rainfall and soil moisture, according to the study of the importance of variables (feature importance). This is consistent with research showing that pest populations are greatly impacted by microclimate changes.

3.3 Field Validation of the System

Two distinct sites were used for field testing: a greenhouse and an open area. With an average reaction time of two hours following the detection of changes in microclimate parameters, the prediction system offered early warning. In comparison to the control area without the system, the incidence of pest attacks in the greenhouse was effectively decreased by 35% through the employment of microclimate control actuators (fans, water pumps) combined with the prediction system (Table 2).

Table 2. Shows How Well Prediction and Actuator Systems Work To Control Pests in Greenhouses

Location (%)	Pest Incident	Decrease (%)
Open Land	18.4	-
Greenhouse (with system)	12.0	35

3.4 Analysis of Statistics

Pest incidence in fields with and without the automated control system differed significantly, according to the independent t-test ($t(38) = 3.45$; $p = .001$; Cohen's $d = 1.12$), suggesting that the system's deployment significantly reduced pest assaults. Furthermore, a strong link between temperature and humidity factors and the severity of pest attacks was found by Pearson correlation analysis ($r = .68$; $p < .01$), confirming the idea that microclimate characteristics are important predictors of pest assaults.

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3.5 Findings from the Experiments

Based on this study's findings, it can be said that:

- Early detection and preventative measures are made possible by the high accuracy and strong sensitivity of the AI integration system and micro weather sensors in predicting insect assaults.
- Relative humidity and air temperature are important factors that primarily affect forecasts of insect attacks.
- By successfully lowering the frequency of pest assaults by 35%, the automated prediction and control system has improved agricultural yield and pest management effectiveness.
- More efficient decision-making and control measures are made possible by the system's quick reaction time (on average, two hours).

In order to promote sustainable and climate-adaptive agriculture, our findings highlight the transformative potential of real-time data-driven technology in tropical agricultural pest control.

4. Discussion

The research findings on the combination of artificial intelligence (AI) and micro-weather sensors for predicting pest attacks in tropical agriculture are examined in this discussion section. The findings are connected to earlier research and working hypotheses, and implications and future research directions are highlighted.

4.1 Results Interpretation in Light of Prior Research

The findings demonstrated the excellent accuracy (up to 92.3% using Neural Networks) and quick response time (average of 2 hours) of the AI-based pest attack prediction system with micro-weather sensors. These results are consistent with a research conducted by Assoc. Prof. Mohammad Parvez Islam of Ehime University, which highlighted the need of developing high-quality datasets and validating data for successful AI applications in tropical agriculture. According to the precision agricultural tenets described in the smart farming 4.0 literature, the AI model is able to identify intricate patterns that impact the dynamics of insect attacks by using comprehensive microclimate data.

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Furthermore, the discovery of important variables like air temperature and relative humidity as the main determinants of pest attack prediction supports earlier research showing that microclimate conditions have a significant impact on insect populations and plant health. This demonstrates that an adaptable and responsive prediction system requires the real-time assessment of environmental factors.

4.2 Findings' Implications for the Management of Tropical Agriculture

The technology has the potential to significantly increase the production and sustainability of tropical agriculture, as evidenced by the system's capacity to reduce insect incidence in greenhouses by 35%. In keeping with the sustainable development goals (SDGs), which place an emphasis on ecologically friendly agriculture and food security, cutting back on needless pesticide usage can help lessen detrimental effects on the environment and human health.

Additionally, the system facilitates quicker and more precise data-based decision-making, avoiding the drawbacks of conventional approaches that frequently depend on farmer experiences and subjective views. The conversion of traditional agriculture into integrated and effective smart farming can thus be accelerated by this technology.

4.3 Conflicts and Difficulties

Notwithstanding the encouraging outcomes, a number of issues and conflicts still need to be resolved. Numerous studies have emphasized the necessity to make sure that the data utilized is representative and error-free, as well as the possibility of bias in AI systems. According to several studies, smallholder farmers' access to and technological literacy continue to be significant obstacles to the broad implementation of this technology. As a result, social and ethical factors like data protection and inclusive stakeholder interaction must be taken into account while developing new systems.

4.4 Prospects for Further Research

Future studies should concentrate on creating AI models that are more able to adjust to regional differences and long-term climate change, for instance by integrating a greater variety of IoT sensors with high-resolution satellite data.

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Another interesting field is enhancing AI-based recommendation systems and integrating blockchain technology for supply chain transparency.

In-depth studies of the socioeconomic factors influencing the adoption of these technologies are also required to guarantee that smallholder farmers and local people can access and utilize them efficiently. For implementation to be effective, digital platforms for education and training must be developed.

5. Conclusions

5.1 Article Conclusion

Based on real-time data, this study demonstrates crucially that combining artificial intelligence (AI) with micro weather sensors may increase the precision of pest attack prediction in tropical agriculture. It has been demonstrated that the created system may greatly lower the incidence of pest attacks, particularly in greenhouse conditions, and give high accuracy early detection of pest assaults with quick response times. The knowledge that air temperature and relative humidity play a major role in the dynamics of pest infestations in tropical environments is reinforced by these findings. By offering actual proof of the value of data-driven strategies and artificial intelligence (AI) in bolstering precision agriculture and creating new avenues for more effective and sustainable pest management, this work contributes to scientific understanding.

The study's findings are constrained, nevertheless, by the small number of test sites, the underrepresentation of different plant and insect species, and the reliance on the caliber of sensor data and technology infrastructure. Furthermore, before widespread use, particular attention must still be paid to the difficulties smallholder farmers face in adopting new technologies and data privacy concerns.

This study effectively showed that the efficacy of pest control in tropical agriculture may be increased by combining artificial intelligence (AI) with micro weather sensors in a real-time data-based pest attack prediction system. This method significantly boosts agricultural output and sustainability with a forecast accuracy of over 90% and a quick response time. These results are in line with other research that highlights the critical role AI plays in smart farming to increase the precision and efficiency of agricultural decision-making. Furthermore, the study's findings support the notion that, as noted in the literature on precision agriculture,

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microenvironmental factors like temperature and relative humidity are important markers of the dynamics of insect infestations.

This study also demonstrates that the use of AI and digital technology not only offers technological advantages but also has the ability to lessen the adverse effects of excessive pesticide usage, hence promoting ecologically friendly and sustainable agricultural practices. Generalizing these findings, however, requires taking into account the study's limitations, including its small geographic coverage and the range of plant and insect species examined. In order for this technology to be extensively utilized, it is also necessary to overcome obstacles related to farmer literacy and technological availability.

5.2 Suggestions

The authors suggest the following in light of the study's limitations and findings:

- To improve the external validity of the study findings, further studies must be carried out with a larger geographic scope, incorporating a greater variety of crops and pests, and testing under different agroecological circumstances.
- It is strongly advised to integrate data from other sources, like satellite imaging, more IoT sensors, and historical agricultural data, and to create AI models that are more resilient and adaptive to local changes.
- The obstacles to technology adoption at the farmer level, such as infrastructure provision, training, and the creation of digital learning platforms, require cooperative, interdisciplinary initiatives.
- Ethics, data security, and socioeconomic sustainability should be the primary factors taken into account while creating and implementing AI-based prediction systems in the agriculture sector.
- Future research may also examine how blockchain technology might enhance supply chain transparency and AI-based recommendation systems.

As a result, this study not only advances precision agriculture science but also lays the groundwork for future research toward inclusive, flexible, and sustainable smart agricultural systems.

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