**Geospatial Techniques - Mapping, Monitoring, and Modeling of Cultivable Soil**

A**bstract**

Cultivable soil is a vital resource for global food security, but its degradation and depletion pose significant threats to sustainable agriculture. Geospatial techniques offer a powerful tool for mapping, monitoring, and modelling cultivable soil, enabling data-driven decision-making for soil conservation and management to ultimately tackle the emerging challenges of cultivable soil that arise with the demands of a growing population, including land marginalisation, soil erosion, nutrient depletion, compaction, and degradation resulting from poor agricultural methods and severe climate change. This paper aims to emphasise the significance of these techniques in comprehending and managing cultivable soils. These technologies improve the accuracy and efficacy of soil evaluations, which are vital for sustainable agriculture operations. This evaluates Geospatial technologies encompass several techniques and methodologies, including remote sensing, Geographic Information Systems (GIS), and spatial modelling, to provide an integrated framework for assessing and forecasting soil cultivability. These techniques facilitate the efficient collection, analysis, and visualisation of spatial data, essential for successful soil management. Modelling cultivable soil incorporates geographical and temporal data to forecast soil behaviour under many environmental conditions. These geographic models simulate moisture dynamics, nutrient cycling, and the impacts of various agricultural techniques. This modelling functions as an essential decision-making tool, allowing stakeholders to evaluate interventions and adapt to the implications of climate change. This paper ultimately advocates for the incorporation of geospatial techniques into soil management policies to foster sustainable agriculture.

Keywords: sustainable agriculture, managing, remote sensing, Geographic Information Systems (GIS) and modeling.

**1. Introduction**

Technology has advanced significantly in recent years, particularly in the areas of geographical information systems and remote sensing. These developments have made it possible to use these technologies practically in a variety of tasks pertaining to the planning, execution and assessment of the agricultural sector in tropical nations. In the sector of agriculture, the use of geospatial methods has grown significantly (Tiwari et al., 2024). The rapid expansion of satellite-based observation capabilities has created new opportunities for more effective assistance in crop production estimation and agricultural output prediction. There is a great deal of promise to help poor countries achieve food security for their populations by integrating remote sensing, Geographic Information Systems (GIS) and Global Positioning Systems (GPS), while also mitigating rural poverty (Mitran et al., 2020).

Attempts are underway to use these cutting-edge technologies to improve agricultural decision-making. Farmers and other agricultural professionals may make well-informed decisions about irrigation, fertilization and pest control thanks to the capacity to remotely gather and analyze data, which offers insightful information on the health and conditions of crops (Reddy, 2018; Grishin & Timirgaleeva, 2020). Farmers can now monitor crop growth trends, identify water stress, and detect disease outbreaks by using remote sensing, GIS and GPS. This enables them to carry out focused interventions and maximize agricultural production (Bagwan, 2024; Raihan, 2024).

More accurate land management techniques have also been made possible by the application of such technology. It is possible to evaluate soil properties, map changes in land cover and land use, and track deforestation and land degradation by utilizing remote sensing data and GIS. Effective resource distribution, land tenure, and environmental protection all depend on this knowledge (Amato et al., 2022). Policymakers and agricultural stakeholders can create plans that support sustainable land use and conservation, which eventually helps to reduce poverty and ensure long-term food security, if they have access to timely and reliable data (Tziolas et al., 2021). Rapid technological breakthroughs, particularly in the fields of geographical information systems and remote sensing, present enormous prospects for the tropical agriculture industry (Roberts et al., 2021).

Better agricultural planning, execution and assessment are made possible by the integration of these instruments. Remote sensing, GIS and GPS are important tools for agricultural growth and poverty alleviation in rural areas because they may be used to evaluate crop output, anticipate yields and secure food for people. With its precise and affordable solutions, geospatial technology is essential for determining the amount of land utilized for pastureland, forest products, and agricultural production. The management of Earth's resources can be greatly enhanced by utilizing this technology. In order to track the condition of the vegetative environment, on which we mostly depend, this method offers instantaneous, through information on a broad scale that can be updated regularly (Reddy, 2018). Unfortunately, there is still very little use of this useful knowledge in the field of agriculture.

Despite its enormous potential, geospatial technology is still not widely used in this industry. When compared to current agricultural monitoring systems, the main emphasis is on developing methods for more efficient information extraction that are also cost-effective. It's interesting to note that the difficulties encountered in this undertaking frequently go beyond technical, scientific or financial issues. Rather, they usually have their roots in organizational, administrative and policy-related issues. To fully utilize geospatial technology in agriculture and ensure its widespread adoption for the benefit of all parties concerned, several challenges must be overcome. Because they allow farmers and agronomists to make well-informed decisions based on spatial data, geospatial methods have become indispensable tools in modern agriculture (Tiwari *et al.,* 2024). By utilizing Geographic Information Systems (GIS) and geostatistics, researchers can assess soil properties, spatial variability, and environmental risks, leading to informed decision-making in soil management practices (Sayed & Khalafalla, 2024).

This review study assesses geospatial methodologies for mapping, monitoring, and modelling arable soil. It combines technologies like remote sensing, GIS, and spatial modelling to evaluate and predict soil cultivability. The assessment highlights deficiencies in knowledge and promotes the use of geospatial methodologies in soil management plans for sustainable agriculture. It culminates with ramifications for further study.

**2. Key Components of Geospatial Techniques:**

**2.1. Geographic Information Systems (GIS):**

Spatial data may be collected, analyzed, and visualized with the help of GIS, a sophisticated tool. In agriculture, GIS is used to map various soil types, track crop health and efficiently manage resources. It enables farmers to analyze information about terrain, climate and soil characteristics in order to optimize farming operations. Making educated judgments in areas like resource management and emergency response requires examining geographic connections using methods like spatial analysis.

**2.2 Global Positioning Systems (GPS):**

Users may pinpoint their precise location (latitude, longitude, and altitude) anywhere on Earth with the use of GPS, a satellite-based navigation system. Through a network of satellites, signals are sent to GPS receivers, which use trilateration techniques to pinpoint the user's location. GPS technologies and GIS work together to provide precise location data. This makes it possible to map fields precisely and apply inputs, including fertilizer and insecticides, at different rates depending on the specific characteristics of the field. Numerous applications across several industries, including agriculture, depend on precise location data.

**2.3. Remote Sensing:**

Remote sensing is the technique of using satellites and drones fitted with sensors to gather data on crops and soils remotely. This method yields crucial insights into crop health, soil moisture levels and patterns of land use. By detecting temporal variations, remote sensing enables the timely execution of crop management strategies.

**3. Key techniques and their applications in Mapping, Monitoring, and Modeling Cultivable Soil**

**3.1. Soil Mapping Techniques:**

**3.1.1. Soil Sampling and Ground Truthing:** The practice of verifying remote sensing data by contrasting it with real-world field observations is known as "ground truthing." For soil maps created using satellite photography or other remote sensing technology to be accurate, this step is essential. Typically, ground truthing entails:

* Collecting physical samples from identified areas.
* Comparing these samples with predictions made by remote sensing data to assess accuracy.

In order to map, monitor, and simulate cultivable soil, sampling and ground truthing are crucial procedures. By following these procedures, agricultural stakeholders are guaranteed to be able to base their decisions on accurate and trustworthy information on the productivity and health of the land. Although remote sensing provides a comprehensive picture, soil sampling is necessary for ground truthing in order to validate remote data. The physical and chemical characteristics of soil samples are determined in labs and then integrated into GIS systems for in-depth mapping.

**3.1.2. Digital Elevation Models (DEMS):** In order to comprehend how topography affects soil distribution, DEMs offer three-dimensional depictions of terrain elevation. By depicting elements like slope, aspect and drainage patterns, they may be used with remote sensing data to improve the precision of soil maps. In geographic information systems (GIS), a digital elevation model (DEM) is a three-dimensional representation of terrain elevation data that is commonly used to show the Earth's surface. DEMs fall under a variety of categories, such as:

* *Digital Terrain Models (DTMs):* These represent the bare earth surface, excluding vegetation and man-made structures.
* *Digital Surface Models (DSMs):* These include all surface features, such as trees and buildings, providing a comprehensive view of the landscape.

DEMs are frequently created using a variety of data sources, such as aerial surveys, satellite photography, and ground-based measurements. Numerous applications, such as mapping soil properties, hydrological modeling, land use assessment, and environmental research, depend on them. Researchers may learn more about the distribution and behavior of soil by examining terrain variables like slope and aspect that are obtained from DEMs. This knowledge is essential for efficient land planning and agricultural management.

**3.1.3. Remote Sensing:** Fischer first used the term "remote sensing" in 1960 A.D. The process of gathering and documenting data about an object without coming into physical touch with it is known as remote sensing. In its widest definition, remote sensing is the process of gathering and analyzing data about a phenomenon or object's characteristics without having direct physical contact with it. It may be felt in day-to-day existence. A camera-captured image is a record that offers details about an object. We can learn several key remote sensing ideas from a single snapshot. Distinct elements in the picture have distinct colors. For instance, if the folder is blue and the tree is green in any given picture, the stone is red. Electromagnetic radiation carries this information about colors, which correspond to particular electromagnetic spectrum bands. A photograph can also reveal the spatial connections between various elements of a scene. However, it is necessary to know the photograph's scale or to include an item of known length in order to calculate quantitative spatial information. Remote sensing gathers information on soil properties across wide regions using satellite images and aerial photography. Using methods like multispectral and hyperspectral imaging, soil characteristics may be analyzed using spectral reflectance or spectral signatures (Figure. 1). Soil health and moisture content may be evaluated with the use of common indicators such as the Normalized Difference Vegetation Index (NDVI).

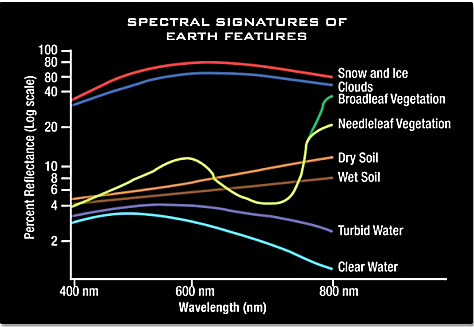


Figure. 1: Spectral signature of earth features

**3.1.4. Spatial Interpolation Techniques:**

The practice of assuming unknown values at certain places using known values from nearby points is known as spatial interpolation. It is based on Tobler's Law of Geography, which states that points near one another in space are probably going to have comparable values. In Geographic Information Systems (GIS), this method is frequently used to fold continuous representations of spatial phenomena, such soil characteristics.

**I. Common Spatial Interpolation Techniques:**

(i)*Inverse Distance Weighting (IDW)*

By giving known points weights according to their separation from the target position, IDW is able to estimate unknown values. Points that are closer have more of an impact than those that are farther away.   
Application: Since neighboring samples are likely to be more comparable, this approach works well for mapping soil characteristics like pH or nutrient levels.

(ii) *Kriging*

Kriging is a statistical technique that takes into account the degree of variation as well as the distance between known data points. It models geographic correlation using a variogram and offers estimates along with related error measures.  
Application: In precision agriculture, where knowledge of variability is essential for management strategies, kriging is very helpful for producing intricate soil maps.

(iii)*Shepard Interpolation Modified*  
This approach is an improvement on the classic Shepard technique, which uses distance-based weighted averages and can additionally take elevation into account.  
Application: It may be used in diverse locations where soil properties are greatly impacted by elevation variations.

(iv) *Nearest Neighbor*

The value of the nearest known point to an unknown point is assigned using this straightforward procedure. Although simple, it can cause predicted numbers to shift suddenly. Classifying land use categories based on neighboring observations is an example of an application that is best suited for categorical data or dense sample networks.

(v) *Triangulated Irregular Networks (TIN)*

By using triangles to join known points, TIN generates a surface representation that enables in-depth modeling of surface changes and topography.   
Application: Helpful in examining how topography affects drainage and soil erosion. As a result, continuous maps that depict the regional diversity of soil conditions may be produced.

**3.2. Monitoring Soil Conditions**

**3.2.1. Geostatistical Analysis:**

To comprehend the distribution and variability of soil characteristics, geostatistical analysis applies statistical techniques to spatial data. It usually uses methods like spatial interpolation, kriging, and variogram modeling to forecast values at unsampled places using known data points. Making precise soil maps that guide agricultural decisions requires this study. Important elements of geostatistical analysis include:

(i) *Variogram Modeling:*

By monitoring the change in soil qualities across distance, the variogram measures spatial autocorrelation. It aids in determining the range of correlations between soil parameters, which guides the selection of interpolation techniques. The variogram provides important metrics that characterize the extent of geographic variability, including the nugget effect, sill, and range.

(ii) *Machine Learning Algorithms:*

By examining the connections between different environmental variables and soil characteristics, machine learning techniques make it easier to create digital soil maps. Climate variables, remote sensing photos and topography data are frequently examples of these covariates. Compared to traditional techniques, the use of MLAs enables the creation of soil maps that are more precise and comprehensive.

**3.3. Modeling Soil Behavior**

(i) *Digital Soil Mapping (DSM):*

DSM involves creating spatial soil information systems using geospatial methods and field observations. It enables improved land management decisions by dynamically forecasting soil behavior in different environmental conditions.

(ii) *Integration with Other Data Sources*:

Enhancing predictions of soil behavior over time is possible by integrating soil data with hydrological, land use and climatic models. This comprehensive approach provides insights into soil responses to various management practices under changing conditions, thereby supporting sustainable agricultural practices.

4. **Applications of Geospatial Techniques in Agriculture:**

(i) *Precision Agriculture:*

Precision agriculture employs geospatial data to customize farming practices for distinct zones within a field. By examining soil variability and crop performance, farmers can fine-tune inputs like water, fertilizers, and pesticides to boost productivity and reduce waste (Akanbi *et al.,* 2024).

(ii) *Soil Mapping:*

Soil mapping is essential to grasp the spatial variability of soil attributes across a farm. In-depth soil maps assist farmers in making informed decisions about crop selection, irrigation methods, and fertilization plans (Sayed & Khalafalla, 2024). Advanced soil mapping integrates remote sensing data with on-the-ground soil sampling for precise soil characteristic depictions.

(iii) *Crop Monitoring:*

Ongoing crop monitoring through remote sensing enables farmers to identify stressors such as drought or disease promptly. This preemptive method aids in making timely management choices that can enhance yields and curtail losses.

(iv) *Farm Management:*

Geospatial technologies underpin extensive farm management by delivering instantaneous data on field conditions, equipment status, and resource usage. This data aids farmers in optimizing operations and elevating overall efficiency.

(v)*Improved Decision-Making:*

When geographical data is incorporated into agricultural operations, more intelligent choices about the distribution of resources and management tactics are made (Lanki *et al.,* 2023).   
(vi) *Enhanced Productivity:*

Farmers may drastically raise crop yields and save expenses related to resource abuse by optimizing inputs based on accurate data.  
(vii) *Sustainability:*

By encouraging effective resource use and reducing environmental impact, geospatial methods support sustainable agriculture operations.

6. **Challenges and Future Directions**

6.1. **Current Challenges in Implementing Geospatial Techniques in Agriculture**

The integration of geospatial techniques in agriculture holds the promise of significantly boosting productivity, sustainability, and efficiency (Singh *et al.,* 2023). Nonetheless, various challenges impede their successful deployment. The following are the principal challenges identified:

(i) *Limited Access to Technology*

* Infrastructure Shortcomings: Particularly in developing nations, many smallholder farmers lack modern agricultural technology due to insufficient infrastructure and resources, hindering the effective use of geospatial tools. –
* Cost Obstacles: Cutting-edge technologies like drones, GPS systems, and precision farming tools are often too costly for small and marginal farmers, complicating broad adoption.

(ii) *Gaps in Technical Knowledge*

* Training Deficiency: A notable technical knowledge gap exists among farmers in utilizing geospatial technologies, with many lacking the skills to interpret data or operate sophisticated tools efficiently.
* Data Interpretation Complexity: Geospatial technique-generated data can be intricate, necessitating a certain analytical ability to make informed choices. The lack of straightforward interfaces and educational programs worsens this problem.

(iii) *Issues with Data Accessibility and Fragmentation*

* Insufficient Data Exchange: Agricultural data is frequently scattered and inaccessible, hindering the creation of comprehensive solutions that meet farmers' needs and leading to decision-making inefficiencies.
* Ground Truthing Challenges: The accuracy of remote sensing data relies on ground truthing, which faces hurdles due to the limited availability of dependable in-situ data.

(iv) *Problems with Compatibility Integration Challenges*

It can be challenging to incorporate new agricultural technology into present systems since they aren't necessarily compatible with infrastructure or farming methods. Farmers used to old ways may become resistant as a result.

(v) *Reliance on outside variables, Reliability of External Data Sources*

A lot of geospatial technologies depend on outside data sources, including satellite images or weather predictions, which aren't necessarily reliable or accessible. Planning for agriculture may become unpredictable as a result of this dependence.

(vi) *Risks to Cybersecurity Vulnerability to Cyber Threats*

As digital technology becomes more and more integrated into agriculture, cybersecurity issues have surfaced. Cyberattacks can jeopardize sensitive data and cause operational disruptions in agricultural technology systems.

(vi) *Environmental Factors Impact of Climate Change*

* Farmers may find it difficult to make decisions on geospatial data alone due to climatic variability, which can compromise the accuracy of this data. For example, crop health and soil moisture levels might fluctuate according to shifting weather patterns.
* Climatic variability may challenge farmers' decision-making based solely on geospatial data, as it can affect the data's reliability. For instance, variations in weather patterns can cause fluctuations in crop health and soil moisture levels.
* Compatibility and Integration Issues: Newly introduced agricultural technologies may not always align with current farming methods or infrastructure, presenting difficulties.

6.2. **Emerging Technologies and Future Trends:**

Geospatial techniques hold substantial promise for enhancing agricultural practices, but overcoming certain challenges is essential for their effective deployment. Potential solutions involve increasing technology access via government initiatives, offering training for farmers, enhancing data exchange processes, and implementing strong cybersecurity protocols. The prospects for geospatial technology in agriculture are bright, with ongoing technological progress bolstering precision farming. The integration of tools such as drones, AI, IoT, and sophisticated GIS into farming operations will enable farmers to make informed decisions that boost productivity and foster sustainability. Addressing issues like data availability and bridging the technical knowledge divide is imperative to fully leverage these nascent technologies in agriculture. Active collaboration among technology creators, agronomists and policy makers is key to forging a sustainable agricultural future that can satisfy the global demand for food.

**Conclusion:**

Geospatial technologies have revolutionized agriculture by providing essential insights that enhance production and sustainability. The continuous advancement of technology is rendering the integration of Geographic Information Systems (GIS), Global Positioning Systems (GPS), and remote sensing essential for addressing the contemporary issues faced by the agriculture sector. By using these tools effectively, farmers may attain food security and promote environmental preservation for future generations.

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