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Remote Sensing and Geographic Information Systems in Agriculture: Applications and Challenges

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ABSTRACT: The agricultural sector faces numerous challenges, including climate change, resource scarcity and the growing need for food security. To address these challenges, the integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has become increasingly essential in modern farming practices. RS provides critical data through satellite imagery, drones and aerial sensors, allowing for the monitoring of crop health, soil conditions and environmental factors. GIS, on the other hand, helps analyze, manage and visualize this spatial data, supporting decision-making processes related to crop management, irrigation and resource allocation. Together, these technologies enable precision agriculture, optimizing input usage, enhancing productivity and promoting sustainability. However, their implementation is not without challenges, including high costs, technical complexity and the need for specialized skills. This review explores the applications of RS and GIS in agriculture, discussing their roles in crop monitoring, pest management, yield prediction and environmental monitoring. It also addresses the current limitations and barriers to widespread adoption, such as data accuracy and accessibility.

Keywords: Remote sensing, Geographic Information Systems, Agriculture, Crop monitoring, Precision farming.

INTRODUCTION

The agricultural sector is facing unprecedented challenges, including climate change, declining natural resources and the need to increase food production to meet the demands of a growing global population (FAO, 2017). Traditional farming methods, which often rely on broad, generalized approaches, are becoming increasingly insufficient to address these challenges. To ensure food security and environmental sustainability, there is a pressing need for the integration of advanced technologies into agricultural practices. Among these technologies, Remote Sensing (RS) and Geographic Information Systems (GIS) stand out as powerful tools that can transform agricultural management by providing detailed, real-time insights into crop and land conditions.

Remote Sensing (RS) refers to the process of obtaining data about the earth's surface without direct contact, typically through satellite or aerial platforms (Campbell & Wynne 2011). Thus, remote sensing provides a set of techniques for obtaining spatial, temporal, and spectral information using sensors that collect energy flows from electromagnetic spectrum bands for interpretation (Murillo-Sandoval and Carbonell-Gonzalez 2012). Remote sensing data in the optical, microwave, thermal and hyperspectral domains have proven to be powerful tools for assessing crop and soil properties across varying spatial and temporal scales, offering cost-effective solutions for natural resource management. Geographic Information Systems (GIS), which integrate, manage, analyze and visualize spatial data, have a critical role in enhancing agricultural productivity (Longley *et al.*, 2015). The application of GIS in agriculture enables farmers to precisely manage and monitor their lands, improving decision-making in areas like crop rotation, fertilization strategies, irrigation management and pest control (Bishop *et al.*, 2013) thus reducing costs and enhancing sustainability. By combining RS and GIS, farmers can monitor crop growth in real-time, predict yields, assess soil health and manage water resources more efficiently, resulting in sustainable agricultural practices.

Despite their promising potential, the adoption of RS and GIS in agriculture is not without challenges. High costs, data complexity, the need for specialized training and limited access to the required infrastructure remain significant barriers (Mulla, 2013). Furthermore, data accuracy, resolution and integration across various platforms and scales continue to pose technical challenges (Dandois *et al*., 2015). As these technologies evolve, new advancements such as the integration of artificial intelligence (AI) and machine learning (ML) hold the potential to further enhance the precision and predictive power of RS and GIS in agriculture (Liakos *et al*., 2018).

Geospatial tools have been employed efficiently for soil resource mapping, generating digital soil information systems and conducting spatial soil property assessments. These tools are particularly effective for monitoring soil environmental degradation, conducting quality assessments at varying spatial scales and covering large areas. Furthermore, geospatial applications have transformed the field of Agri-informatics, Agro-meteorology by facilitating crop monitoring, including crop classification, health monitoring, nutrient management, irrigation management, stress monitoring and yield mapping. These applications are also crucial for precision agriculture and supply chain management, where they contribute to optimized resource allocation. Advances in spectral sensing, through polar and geostationary satellites, offer the opportunity to capture near-real-time, synoptic and continuous coverage of crop conditions throughout the growing season. This capability enhances agro-meteorological advisory services, integrating satellite-derived agro-meteorological products and value-added information into existing frameworks to offer location-specific recommendations.

In India, programs such as Forecasting Agricultural Output using Space, Agro-meteorology and Land-based observations (FASAL) and the National Agricultural Drought Assessment and Monitoring System (NADAMS) utilize remote sensing and other data sources for agricultural monitoring and drought management (Ray *et al.,* 2014). Crop insurance schemes such as the Pradhan Mantri Fasal BimaYojana (PMFBY) and Yield Estimation Crop Insurance Scheme (YES-TECH) are crucial initiatives in India that rely on remote sensing technology.

Unprecedented demands are being placed on the world's soil re- sources (FAO-ITPS, 2015). At the same time, there is an increased evidence that world's soil are under threat (Montanarella *et al*., 2016) and there is an urgent need to put the soil at the crossroad of the sus-tainable development goals (SGDs) (e.g Bouma, 2019); putting soils and their governance in the global agenda is more urgent than ever (Montanarella, 2015). Understanding the importance of geospatial tools for four major contributors to food security and sustainable production-soil resource mapping, Agri-informatics, soil environmental monitoring and satellite agro-meteorology—has become a pressing need. This review aims to document the applications of space-based technologies in agriculture and soil assessment, promoting the sustainable development of agriculture.

Methodology for Standard Soil Survey and Mapping. A standard soil survey systematically collects information about soils, focusing on their origin, distribution, capabilities, limitations, and predicting their behavior for particular uses, as well as classifying them. The process of standard soil survey and mapping typically follows these steps.

1. Preliminary reconnaissance of the area to investigate the major soils and their pattern of occurrence.
2. Procurement of required base maps. Aerial photographs, satellite imagery and topographical maps are useful references and used as basemaps.
3. Preparation of mapping legend based on the preliminary field studies.
4. Stereoscopic study of aerial photographs and satellite imagery for the identification and delineation of land forms (hills, valley, terraces, flood plains, coastal plains, sand dunes etc.) based on the differences in tone, relief, vegetation etc.
5. Plotting of soil boundaries, mostly by RS data and verified by observations.
6. Classification of soils and naming of map units.
7. Preparation of final legend and finalization of soil map.

Soil survey and mapping have traditionally been done through fieldwork and manual sampling, but advancements in remote sensing (RS) and geographic information systems (GIS) have greatly enhanced the efficiency and accuracy of this process. The following outlines are standard methodology for soil survey and mapping using remote sensing and GIS:

Remote Sensing Data Acquisition

- **Satellite Imagery**: Obtain satellite imagery from sources like Landsat, MODIS or Sentinel, which provide multispectral data (e.g., visible, near-infrared and thermal bands) that can be used to analyze soil properties.
- **Aerial Photography**: High-resolution aerial imagery can be used for detailed soil mapping, especially in smaller areas or complex terrains.
- **LiDAR Data**: Light Detection and Ranging (LiDAR) provides elevation data that can assist in interpreting soil types based on topography.
- **Soil Spectral Signatures**: Remote sensing imagery is analyzed for specific spectral bands that correspond to soil characteristics (e.g., organic matter content, moisture, texture).

Field Survey for Ground Truthing

- **Sampling Locations**: Select ground truthing locations based on a stratified random sampling approach. The points should represent the variability of soil types across the area.
- **Soil Sample Collection**: Collect soil samples from each location to analyze physical, chemical and biological properties such as pH, texture, organic matter content and nutrient levels.
- **Georeferencing**: Record precise coordinates using GPS to ensure that soil samples correspond to the correct locations in the remote sensing imagery.

GIS Database Creation

- **Georeferencing of Remote Sensing Data**: Correct for spatial distortions in the satellite or aerial imagery and align it with the local coordinate system for accurate mapping.
- **Layer Creation**: Create GIS layers for each relevant variable, such as vegetation indices (NDVI, for instance), elevation and land cover.

• **Soil Classifications**: Develop soil maps based on the field observations and laboratory analysis of samples. Use standard classification systems, such as FAO or USDA soil classification systems, to categorize soils.

Data Integration and Analysis

• **Multispectral Analysis**: Spectral indices like the Normalized Difference Vegetation Index (NDVI) and the Soil-Adjusted Vegetation Index (SAVI) can be utilized to differentiate various soil properties.

• **Spatial Analysis**: Use spatial analysis tools in GIS to integrate remote sensing data with field data, creating predictive models of soil distribution.

• **Classification**: Apply machine learning or statistical classification techniques such as supervised classification, k-means clustering or random forests to generate a thematic map of soil types.

Soil Map Generation

• **Map Validation**: Validate the resulting soil map using ground truth data and assess accuracy using metrics such as confusion matrices and kappa statistics.

• **Map Refinement**: Refine the map based on feedback and recalibrate the models as necessary. The map should be integrated with environmental variables like vegetation and climate data to provide a comprehensive understanding of soil characteristics.

Visualization and Reporting

• **Map Visualization**: Produce high-resolution maps for presentation, considering both thematic and topographic features.

• **Interpretation**: Interpret the soil data in terms of practical applications (e.g., agricultural suitability, erosion risk or land degradation).

• **Reporting**: Generate reports that summarize the methodology, results, limitations and recommendations based on the soil mapping.

Final Deliverables

• **Soil Maps**: Provide digital maps in common formats such as GIS shape files or geodatabases.

• **Soil Properties Data**: Include tabular data for each soil unit with its corresponding properties.

• **Metadata**: Ensure that metadata is provided for all datasets, including remote sensing data, soil properties and mapping techniques used.

Application of Geospatial Technology in Soil Resource Mapping

Soil mapping refers to the systematic process of understanding and predicting the spatial distribution of soils. This procedure entails the collection of field observations—such as detailed soil profile descriptions—the laboratory analysis of soil properties, the characterization of landscape features, and the subsequent production of soil maps. **Soil resource inventories** provide comprehensive information on the types, attributes, and geographic distribution of soils within a specified area. Traditionally, soil mapping has relied on the development of a conceptual framework based on soil-forming processes to predict the spatial distribution of various soil classes. However, with advancements in geostatistics and the widespread availability of digital information concerning terrestrial features, it is now possible to map soil properties more effectively by integrating existing soil data with auxiliary information on environmental variables. This modern approach enables the transformation of legacy soil data into digital products, enhancing their accessibility and practical application. Furthermore, in alignment with initiatives such as Digital India and the Soil Health Mission, the creation of digital soil maps for different regions of the country is both timely and essential.

Use of Satellite RS for Soil Resource Mapping

Satellite remote sensing has become a powerful tool in conducting **soil resource surveys** and generating critical data to support **sustainable land-use planning**. This technology is applicable across scales—from regional to micro-level studies—making it indispensable in modern **soil analysis** and environmental monitoring.

Satellites equipped with various **sensors and cameras** capture both **analog and digital data** by detecting **electromagnetic radiation (EMR)** emitted or reflected by Earth's surface. The energy used in these observations comes from the **electromagnetic spectrum (EMS)**, which includes a range of wavelengths and frequencies.

Non-photographic sensors are capable of detecting EMR across a wide range of wavelengths—from **ultraviolet (UV)** light with wavelengths shorter than 0.38 µm to **microwaves** with wavelengths over 100 cm. Different **remote sensing (RS) techniques** utilize specific EMS regions such as:

• **Visible light** (0.4–0.7 µm)

• **Infrared** (0.7–3 µm)

• **Thermal infrared** (3–5 µm and 8–14 µm)

• **Microwave** (0.1–30 cm)

Regardless of the technique used, the core principle involves acquiring information based on the **radiation reflected or emitted** by objects on Earth's surface.

Two key advantages of satellite imaging are:

1. **Wide-area coverage** for large-scale assessments
2. **Repetitive imaging**, allowing for regular monitoring of the same location over time

This makes satellite imagery ideal for **reconnaissance and semi-detailed surveys**, such as those used in **regional planning** and **district-level soil studies**.

Through systematic interpretation of satellite images, researchers can accurately delineate soil boundaries. Advanced **digital image processing** techniques, including **supervised and unsupervised classification** (using the **maximum likelihood method**), are widely employed in **digital soil mapping**.

• In **supervised classification**, "training sets" of pixels with known soil properties (collected through fieldwork) are used to generate precise soil maps.

• In **unsupervised classification**, clusters of pixels with similar **digital numbers (DNs)** are grouped, and field verification is performed to determine the soil composition of each cluster. This **ground-truth data** is then used to finalize the soil maps.

Role of Geographical Information Systems (GIS) and Soil Information System (SIS) in Soil Resource Mapping

A Soil Information System (SIS) is a computerized database designed to manage extensive data related to soil and land resources. It enables the organization, storage, retrieval, analysis, and processing of soil information, presenting it to users in formats like maps and tables. The SIS is built upon a database compiled from remote sensing (RS) data and ground surveys, integrated with Geographic Information Systems (GIS) and Decision Support Systems (DSS). Initially the mapping was carried out manually and the generated resource maps were overlaid to study the soil resources in an integrated form. The various sources of locational information give us spatial data in different scale, time and format. This spatial data with location and shape of features along with its descriptive information in form of attributes are integrated to derive meaningful interpretation and assist the user for planning using the GIS tool. The concept of SIS is depicted in Fig. 1.

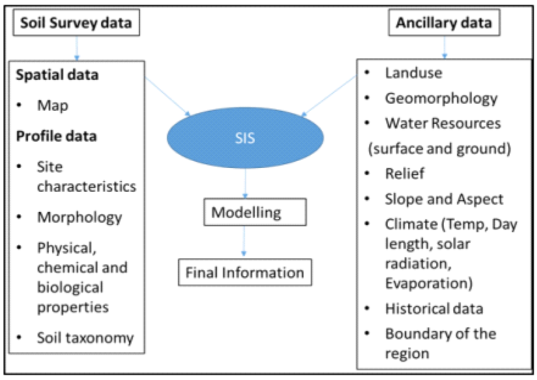

Fig. 1. Soil information system (SIS)-Concept (ref: Fundamentals of Soil Science, 2002).

SIS helps in easy handling of voluminous data; reproduction of maps derived suitability and other interpretative maps; Linkage with other georeferenced coverage to generate new composite overlays; Cost effective and time-saving periodic updating of map/information and quick monitoring and impact assessment of development measures. All of these make the SIS a useful tool for generating action plan and its implementation for land resource management of a region or watershed.

Digital Soil Mapping (DSM). Digital Soil Mapping (DSM) has its roots in the state-factor soil formation model introduced by Jenny (1941), which explains how soil formation and distribution are influenced by specific soil-forming factors. When the connection between soil profile features and these factors is established, it becomes possible to predict the distribution of soil characteristics based on the spatial distribution of the forming factors. Today, soil maps and spatial soil information systems are developed using mathematical models that incorporate spatial and temporal variability in soil properties, drawing on environmental proxies for soil-forming factors. This approach represents the modern paradigm in soil mapping (Mcbratney *et al.*, 2002).

Stages in DSM. The DSM process characteristically involves three stages (Fig. 2).

Stage I is concerned with development and assessment of inputs.

Stage II is where the choice of methods and tools is made.

Stage III is where the spatial inference system is developed and applied.

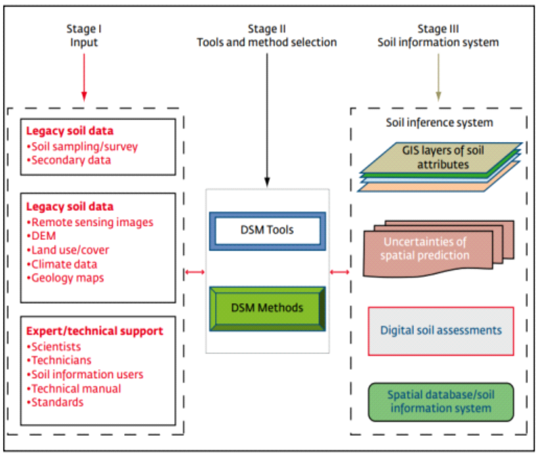

Fig. 2. Processes in DSM (Omuto *et al.*, 2013).

Spatial prediction methods for DSM

Spatial prediction methods are broadly categorized into three primary groups: non-geostatistical, geostatistical, and hybrid techniques. The non-geostatistical category includes methods like Nearest Neighbors, Inverse Distance Weighting (IDW), Natural Neighbors, Triangular Irregular Networks (TIN), Splines, Trend Surface Analysis, Classification and Regression Trees, Kalman Filters, and Regression Models. It also encompasses several kriging variants such as Simple, Ordinary, Universal Kriging, Cokriging, Kriging with an External Drift, and Block Kriging, along with Bayesian Maximum Entropy. Geostatistical approaches consist of Indicator Kriging, Factorial Kriging, Principal Component Kriging, Disjunctive Kriging, and Multivariate Factorial Kriging. The mixed or integrated methods combine elements from both previous categories, including Regression Kriging, Linear Mixed Models, combinations like Kriging with Regression Trees, or Trend Surface Analysis, as well as Bayesian Maximum Entropy within hybrid frameworks.

Global Soil Mapping Initiatives

Global efforts in soil mapping focus on producing updated soil maps, standardizing global soil data systems, and maintaining and sharing international soil databases.

1. Globalsoilmap.net (www.globalsoilmap.net) is an international collaboration established to create a high-resolution digital soil map of the planet. Leveraging modern and innovative mapping technologies, this project aims to estimate soil characteristics at a detailed spatial scale of approximately 100 meters. The initiative is led by the Digital Soil Mapping Working Group under the International Union of Soil Sciences (IUSS).

2. Global Soil Information Facilities (ISRIC) provides a range of soil data products, such as SoilGrids250m, which offers predictive soil property and classification maps. These are also available in generalized forms at 1 km and 5 km resolutions. Additional resources include the WoSIS Soil Profile

Database and the harmonized WISE v3.1 Global Soil Profile Dataset.

Digital Database on Soils of India

Some available digital soil databases of India are, Soil and terrain digital database (SOTER), National natural resource information system (NRIS) by the Department of Space, Govt. of India, National informatics centre (NIC) by the planning commission, Agricultural resource information system (AGRIS) by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP).

Soil Site Suitability Assessment

Soil site suitability assessment is a crucial step in agricultural planning and decision-making. Geospatial technology plays a significant role in analyzing soil characteristics and determining the suitability of a site for specific crops by integrating various data sources, creating detailed soil maps, conducting spatial analysis, applying multi-criteria evaluation techniques and supporting decision support systems. These capabilities enable farmers and agronomists to identify suitable areas for crop cultivation, optimize resource allocation, and make informed decisions regarding land use and agricultural practices. Geospatial analysis enhances the efficiency, accuracy and sustainability of crop area site suitability assessments, contributing to improved agricultural planning and management.

GEOSPATIAL TECHNOLOGY FOR AGRI-INFORMATICS

The integration of geospatial applications and Agri-informatics can enhance decision-making, increase productivity, and improve sustainability. For example, the use of GIS software can help to map crop health, optimize irrigation, fertilizer use, monitor and manage pests and diseases (Singh *et al*., 2020). RS can provide early warning of crop stress, monitor crop growth and development and assess soil properties and water availability. GPS can enable precision farming, track and optimize the movement of vehicles and machinery and monitor and control pest and disease outbreaks (Thenkabail & Knox 2016). Unmanned Aerial Vehicles (UAV) can provide high-resolution images of crops and fields, which can be used to assess crop health, detect weeds and count plants. RS data can be combined with ground-based data such as soil moisture measurements to provide more accurate information on crop stress factors. By combining these data sources, farmers can make more informed decisions about when to apply irrigation or fertilizer and in what quantity.

- **Components of Agri-Informatics**

Agri-informatics involves crop monitoring that include crop classification, stress detection, crop yield mapping; precision agriculture and supply chain management. Geospatial tools and techniques are of enormous importance when large area crop monitoring is required at different spatial scale, for variable rate application of fertilizer and irrigation in precision farming. The methodologies with few practical applications are given in separate section for each of these Agri-informatics components.

Crop Monitoring : Satellite data have been used to track a variety of elements of vegetation monitoring, including but not limited to: crop classification and assessment of crop acreage, estimation of biomass and yield, monitoring and detection of crop stress and assessment of crop phenology.

Crop Classification : Crop classification using RS is a technique that uses satellite or drone data to identify and map different types of crops across a field or region. RS data can be used to distinguish between different crops based on their spectral characteristics. Each crop has a unique spectral signature, which can be identified using algorithms that analyse the reflectance of different wavelengths of light. Optical and microwave sensors play a vital role in crop classification, providing valuable information about vegetation characteristics and crop types.

Optical sensors excel in capturing detailed spectral information, identifying crop types and assessing vegetation health. On the other hand, microwave sensors are effective in penetrating vegetation canopies, providing structural information and mapping soil moisture content. The most common approach for crop classification using RS is different types of supervised classification, including maximum likelihood, support vector machines, random forest (RF) and decision trees.

Crop Yield Mapping: Pre-harvest prediction of a crop yield may prevent a disastrous situation and help decision-makers to apply more reliable and accurate strategies regarding food security. RS helps in large area yield estimation at different spatial scale using multispectral and hyper spectral data, radar and LiDAR data. There are several techniques for crop yield mapping using RS such as:

1. Statistical empirical models that use spectral vegetation indices such as the normalized difference vegetation index (NDVI) or Enhanced Vegetation Index (EVI) or spectral profile characteristics, as the independent variable. Weather based regression model are also used for crop yield estimation where the weather data is derived from satellite input.

2. RS based semi-physical models that uses mostly input data from satellite RS for crop yield estimation. The Input data for the semi-physical model for crop yield estimation are maximum radiation use efficiency (RUE max), photosynthetically active radiation (PAR), Fraction of absorbed PAR by the crop (FAPAR), temperature scalar, water scalar and Harvest index of the crop (Tripathy *et al.*, 2021). There are several crop simulation models available for yield estimation, including the widely used WOFOST (World Food Studies), DSAAT series of models including CERES (Crop Environment Resource Synthesis), Cropsyst, Infocropetc (Singh *et al*., 2008).

3. AI-ML based approaches involve the use of machine learning algorithms and techniques to analyse and model the relationships between input data (such as weather, soil, and management practices) and crop yield output. The advantages of AI-ML based approaches for crop yield estimation include their ability to account for the non-linear behaviour of the relationship between the crop yield and the factors of

crop production. However, this requires large good quality training dataset at the required spatial scale (Kumar *et al.*, 2020).

Crop Health Monitoring: The objective of crop health monitoring is to detect early signs of abiotic stress like water and nutrient stress or biotic stress like disease in crops. The data captured by these sensors is used to generate spectral indices that are indicative of crop health. The most widely used spectral index for crop health monitoring is the NDVI, EVI, the green chlorophyll index (GCI) and the normalized difference water index (NDWI). These indices capture different aspects of crop health, including biomass production, chlorophyll content and water stress.

Geospatial Technology in Supply Chain Management

Geospatial technologies enable the tracking of trucks and other vehicles transporting agricultural goods, offering real-time updates on their position and estimated delivery times. This data supports better logistics planning and helps minimize the risk of product spoilage or damage. GPS systems, when integrated with logistics platforms, allow continuous monitoring of vehicle locations and shipment statuses. This integration aids in route optimization and reduces transportation expenses. Additionally, sensors can track environmental conditions like temperature and humidity, helping to maintain the quality of agricultural products throughout the shipping process (Mishra & Mishra 2017). By monitoring environmental conditions, supply chain managers can take corrective action to prevent spoilage or damage to products. Geospatial technology can also be used to monitor inventory levels and track the movement of products through the supply chain (Srinivasan *et al.*, 2020).

ENVIRONMENTAL MONITORING OF SOIL USING REMOTE SENSING

Soil quality can be defined as the ability of the soil to function within the boundaries of natural or managed ecosystems to sustain biological productivity, maintain water and air quality and support human habitation (NRCS, 2012). Unfortunately, human activities such as cropping, grazing and forestry have led to the degradation of soil quality, which poses a threat to the sustainability of these practices worldwide.

Awareness of the need to monitor soil degradation on a large scale emerged in the 1970s. By the late 1980s, the first major evaluation of human-driven soil degradation, called the Global Assessment of Human-Induced Soil Degradation (GLASOD), was completed. This initiative primarily aimed to raise awareness about the dangers of poor land resource management and to help prioritize efforts for remediation. Numerous researchers have since concentrated on mapping particular forms of degradation, similar to the GLASOD project, which categorized soil degradation into four types: erosion by water and wind, physical deterioration, and chemical deterioration. Physical deterioration refers to issues such as soil compaction, waterlogging, and the subsidence of organic soils, whereas chemical deterioration involves processes like nutrient depletion, salinization, acidification, and contamination.

Assessing Wind Erosion: Remote sensing is a powerful toolfor identifying wind erosion. Due to the expansion of agriculture to marginal areas, wind erosion has intensified in recent years. There are direct and indirect indicators of wind erosion that can be detected through remote sensing. Direct indicators include surface lowering, which can be identified through the use of Lidar and Interferometric Synthetic Aperture Radar (InSAR) techniques. Changes in soil roughness can also be detected through radar backscattering and LiDAR mapping. Indirect indicators of wind erosion include spectral information about surface properties.

Assessing Water Erosion : Water erosion can occur in three forms: sheet, rill and gully. Direct assessment of erosion intensities requires estimating the metric dimensions and volume of individual patches of sheet, rill and gully erosion, as well as their densities. Previous studies have relied on aerial photographs to interpret high-resolution data for mapping gullies. Barber and Mahler (2010) reported high-resolution mapping of gullies using 0.2 m resolution photographs with an RGB camera mounted on a light aircraft flying at a height of 800 m above the ground. Indirect methods for detecting water erosion involve wide-coverage assessment of surface changes from gully erosion. Studies have employed merging high-resolution imagery (QuickBird) with medium-resolution imagery (Landsat Enhanced Thematic Mapper (ETM) and Système Pour l'Observation de la Terre 5 (SPOT 5)) to detect gully erosion areas (Igbokwe *et al.*, 2008).

Mapping of Overall Soil Losses: Different modeling techniques are available to estimate soil loss caused by various forms of erosion, typically categorized as phenomenological, empirical, or a hybrid of both. Among these, the Universal Soil Loss Equation (USLE) is widely utilized to determine soil loss per unit area over a specified time frame. The USLE takes into account multiple factors, including the rainfall and runoff erosivity index, soil erodibility, slope length and steepness, surface cover and management practices, and conservation practices. Remote sensing (RS) technologies are crucial for collecting data to produce regional assessments of soil loss and to create maps over extensive areas. Methods such as photogrammetry, radar interferometry, and LiDAR are often employed to generate the topographic information necessary for calculating slope length and slope steepness parameters.

Mapping of Soil Drying and Crusting : Decreasing soil moisture (SM) can have a significant impact on agricultural production and soil crusting reduces water infiltration capacity (Wani *et al.*, 2009) hence these two factors need to be assessed and monitored for improving production. The major approaches for detecting SM content include radar techniques, radiation balance and surface temperature calculations, reflectance in the visible, near-infrared and shortwave-infrared regions and integrative methods that utilize more than one spectral range. Soil crusts can be identified by significant colour changes, which can be parameterized by the soil's spectral reflectance.

Monitoring Soil Quality Deterioration. Mapping degraded soil properties can be challenging because these chemical and physical properties primarily change within the soil at greater depths, often showing minimal variation at the surface. As a result, indirect methods, particularly those using plant properties to indicate subsoil conditions, are commonly employed.

• **Soil salinity :** Remote sensing methods have gained attention in the last decade for mapping soil salinization and its regional effects. There are two ways of mapping soil salinity: surface salinization mapping and subsurface salinization mapping.

Surface salinization mapping involves high-resolution aerial photographs and multispectral images such as IRS and Landsat. Hyperspectral sensors have also been used in this method.

Subsurface salinization mapping can be performed using indirect methods that implement passive sensors, which utilize spectral information from the soil surface or plants or active sensors such as electromagnetic induction meters.

• **Soil Organic Matter and Nutrients**: Soil organic matter (SOM) is a product of biological decomposition and has a major impact on agricultural production and climate change on a global scale and hence, SOM mapping is essential for evaluating land degradation and soil fertility. Techniques in this field were developed using two main approaches. The first approach involves studies that link spectral information from the soil surface to subsurface conditions. The second approach links plant properties to subsurface nutrient conditions, primarily assessing spectral indicators of nutrient content in leaves.

Assessing Soil Contamination: Soil contamination is a major environmental issue, with large areas of soil acting as sinks for both organic and inorganic pollutants. These contaminants, often released through fossil fuel use and various human activities, include petroleum hydrocarbons, heavy metals (such as nickel (Ni), chromium (Cr), copper (Cu), cadmium (Cd), mercury (Hg), lead (Pb), zinc (Zn), and arsenic (As)), acid mine drainage, and pesticides. The reflectance properties of soil make it possible to assess the presence of different contaminants. In particular, hyperspectral imaging technology has been successfully applied to monitor soil contamination caused by metal mining activities, notably through the oxidation of pyrite. Research indicates that heavy metals themselves do not show distinct absorption features within the visible, near-infrared, and short-wave infrared (VIS-NIR-SWIR) wavelength regions. Nevertheless, their presence can be identified indirectly through their interactions with organic matter or their association with detectable compounds such as hydroxides, sulphides, carbonates, or oxides. Additionally, heavy metals can be detected when they are adsorbed onto clays, which strongly absorb light within these spectral ranges.

Core Agromet Products from Indian Geostationary Satellite

• **Vegetation Index (VI)**: Vegetation index is a mathematical representation of spectral response of vegetation in different wavelength to know the vigour and health of vegetation. The "Normalized Difference Vegetation Index" (NDVI) is widely used for vegetation growth monitoring. NDVI is computed as per equation (1) NDVI = $\rho NIR - \rho RED \rho NIR + \rho RED$.

• **Surface insolation:** The amount of solar radiation reaching at ground surface between 300 to 3000 nm is known as surface insolation or global insolation and is the driving input for two important eco-physiological plant processes such as evapotranspiration and photosynthesis. In the present scenario surface insolation is one of the most important renewable energy resources. The daily insolation data is also used for estimation of crop biomass and yield. In past, interpolated data from the limited ground station was used to generate the spatial insolation maps. The regular observations from the geostationary satellite (high temporal sampling frequency) pay a way to compute 30-minute dynamics of the surface insolation. Instantaneous surface insolation was generated using spectrally integrated radiative transfer scheme and three-layer cloudy-sky model with cloud-top albedo, temperature, atmospheric water vapour from visible, thermal IR and water vapour spectral bands and vertical profile of aerosol and ozone (Bhattacharya and Nigam 2015). Surface insolation is provided through INSAT 3D and 3DR from MOSDAC geo-portal.

• **Land surface temperature (LST)**: The land surface temperature (LST) lead to characterizing the interaction between surface atmosphere energy fluxes, thus having great usage in agro-meteorology, hydrology and other environmental applications. A single (10.5-12.5 μm) and dual (10.2-11.3 μm and 11.5-12.5 μm) thermal spectral bands with Radiative Transfer (RT) model were used to retrieve LST from satellite. The basis of LST algorithm depends on transmissivity, upwelling and downwelling radiances of the atmosphere along with surface emissivity.

• **Surface Soil Moisture (SSM) Product:** The operational Soil Wetness Index (SWI) and volumetric Soil Moisture (SM) products were created using time series data from the SMAP L-band radiometer. Absolute soil moisture, denoted as W(t) at a specific time, was calculated based on SMAP L-band brightness temperature (Tb), along with the soil's permanent wilting point (PWP) and field capacity (FC), modeled through time series analysis (Pandey *et al*., 2021).

GEO-SPATIAL VALUE ADDED AGROMET PRODUCTS

• **Leaf area index (LAI):**LAI is defined as the single sided area of green, functioning leaves per unit ground area. LAI can play a vital role for determining vegetation physiological state and health. Agricultural crop LAI from satellite can be retrieved using forward and inversion modeling of one dimensional (1-D) canopy radiative transfer (CRT) model PROSAIL and satellite reflectance data. PROSAIL has two components (i) PROSPECT (Jacquemoud & Baret 1990) simulates reflectances at leaf level and(ii) SAIL address the directionality. The different statistical and machine learning inversion techniques are used to invert the satellite observed surface reflectance to get the unique crop LAI.

• Evapotranspiration

Potential Evapotranspiration: Reference or potential evapotranspiration (ET0) indicates the atmospheric demand for water over a vegetated surface. In this context, potential evapotranspiration—referred to as grass reference evapotranspiration (ET0)—is defined as the rate of water loss to the atmosphere from a surface that is uniformly moist and covered with short, actively growing grass, such as Alfalfa. Daily ET0 values, measured in millimeters, are estimated using solar radiation data from INSAT-3D and 3DR satellites, along with three-hourly meteorological forecasts derived from the WRF (Weather Research and Forecasting) model. The FAO56 model has been adapted to integrate INSAT data and weather inputs for this calculation. Currently, daily ET0 operational products are accessible to users via the MOSDAC portal.

Actual Evapotranspiration: The calculation of actual evapotranspiration (AET) involves the use of latent heat fluxes (Eλ or LE) and the latent heat of evaporation (L). Generally, satellite-based estimates of surface latent heat flux (Eλ) are obtained as the residual component of the surface energy balance approach (Kustas *et al*., 1994). Over the Indian subcontinent, this technique has been applied using INSAT satellite data to estimate AET (Bhattacharya and Nigam 2015).

• **Surface Dryness Index (SDI):** The Surface Dryness Index (SDI) serves as a metric to quantify the availability of precipitation relative to atmospheric water demand. It reflects the adequacy of precipitation in meeting the atmospheric vegetation water requirements. The weekly SDI can be calculated utilizing daily potential evapotranspiration (PET) data obtained from INSAT-3D and rainfall estimates derived from the Hydro Estimator (HEM) products.

Application of agromet products

Crop Sowing Date: The sowing date constitutes a vital input for initializing crop conditions within dynamic crop growth models. It delineates the temporal window for crop development and establishes essential boundary conditions for modeling crop yields and planning agronomic practices such as irrigation scheduling. Multiple methodologies have been developed to estimate sowing dates using time-series data from the Normalized Difference Vegetation Index (NDVI).

In-Season Crop Area Monitoring: In India, diverse methodologies have been developed over the past two decades to monitor crop area and production utilizing data from polar-orbiting satellites. However, these satellites are constrained by limited temporal resolution and revisit intervals, which hinder their ability to provide consistent intra-seasonal crop monitoring. Geostationary satellites, by contrast, offer the capacity for continuous observation over a fixed region, accommodating variations in solar zenith and azimuth angles. This characteristic positions geostationary satellite data as a promising tool for regular, high-frequency monitoring of crop progress under Indian agro-climatic conditions.

Agrometeorological Advisory Services: The current framework for agrometeorological advisories, developed under the Gramin Krishi Mausam Seva (GKMS) program by the India Meteorological Department (IMD), faces limitations in conducting near real-time assessments of soil and crop conditions. To improve the accuracy and geographic reach of these advisories, spectral data from geostationary and polar-orbiting satellites is being used to create agrometeorological products that enable real-time, continuous, and synoptic crop monitoring. In partnership with the Indian Space Research Organisation's (ISRO) Space Applications Centre, IMD has begun the routine application of daily agro-meteorological products in six Agro-Met Field Units (AFMUs), covering 382 blocks within 60 districts. These tools—including NDVI, Potential Evapotranspiration (PET), Standardized Drought Index (SDI), minimum and maximum Land Surface Temperature (LST), and Surface Soil Moisture (SSM)—are shared in a user-accessible format through the VEDAS (Visualization of Earth Observation Data and Archival System) portal (https://vedas.sac.gov.in). These time-series and near real-time datasets are used to evaluate crop sowing conditions, monitor plant health, determine irrigation requirements, and detect crop stress across block and district levels during the farming season (Nigam *et al*., 2023).

CONCLUSIONS

This paper concludes that geospatial technology plays a pivotal role in revolutionizing agriculture and soil management practices. Its applications, such as precision agriculture, crop monitoring, soil mapping, land use planning, yield prediction and decision support systems, provide valuable tools and information for farmers to make informed decisions and implement sustainable practices. Geospatial technology enables precision agriculture by allowing farmers to analyze spatial data and optimize resource management, leading to improved resource efficiency, reduced environmental impacts and increased crop yields. It facilitates continuous crop monitoring and management, aiding in the identification of crop health issues, stress factors and nutrient deficiencies, enabling timely interventions to optimize crop performance. By utilizing geospatial technology for soil mapping and analysis, farmers can characterize soil properties, assess land suitability and implement site-specific management practices. This approach supports effective soil conservation, nutrient optimization and erosion prevention, contributing to improved soil health and long-term sustainability. Geospatial technology also plays a critical role in land use planning and management, integrating data on land cover, topography, soil characteristics and climate patterns. This enables farmers to make informed decisions regarding crop selection, land allocation and zoning, leading to optimized land utilization, reduced land degradation and the promotion of sustainable agricultural practices.

Furthermore, geospatial technology aids in yield prediction and forecasting, facilitating production planning and risk management for farmers. By integrating historical data, weather information and crop growth models, farmers can estimate future yields and make proactive decisions to adjust planting strategies, optimize harvest schedules and identify market opportunities. The development of decision support systems in agriculture, incorporating geospatial technology, enhances overall farm management. These systems integrate various data sources, providing real-time information, recommendations and alerts to optimize resource allocation, reduce production costs and improve decision-making processes. Overall, geospatial technology empowers farmers with valuable spatial information and tools, enabling them to optimize resource utilization, improve crop productivity, reduce environmental impacts and foster sustainable agricultural practices.

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