

Artificial Intelligence and Remote Sensing in Soil Health Monitoring

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INTRODUCTION

Soil health is the capacity of soil to function as a living ecosystem that sustains plants, animals and humans. Healthy soils enable crop production, water regulation, nutrient recycling and carbon storage. Yet, soil quality has been negatively impacted by ever more intensive agriculture, soil degradation, climate change and poor management practices at a global scale. Conventional soil testing methods include field sampling and laboratory analysis, these offer precise results but are restricted by temporal and spatial scales. Due to the growing need of information on the soil at the site level, new technologies including Artificial Intelligence and Remote Sensing have been considered as useful tools for provision of soil health. The remote sensing instruments gather data at a distance, usually from satellites or aircraft, but can also be from unmanned aerial vehicles (drones) or ground-based platforms. Several AI methods have been applied to process large amount of spatial and temporal data to predict soil and terrain properties and soil health indicators with high accuracy. Collectively, these advances are transforming the soil management of the modern era.



2. Concept of Soil Health Monitoring

Soil health monitoring involves the systematic assessment of physical, chemical and biological properties of soil over time.

Physical Indicators

Soil texture, bulk density, aggregate stability, soil structure, water holding capacity and infiltration rate are physical indicators of soil health. These attributes influence the soil's capacity to hold and conduct water, to support root growth, to be aerated and to resist eroding. Collectively, they are essential for soil productivity and sustainability and hence for ecosystem function.

Chemical Indicators

Chemical properties (such as soil pH, EC, organic carbon, available N, P and K and cation exchange capacity or CEC) also indicate the health status of soil. These factors affect nutrient availability, soil fertility, salinity level and the soil water hold and supply essential nutrients to plants influence growth and yield of crops.

Biological Indicators

The biological air and water quality indicators range from microbial biomass, soil respiration,

enzyme activity and earthworm density to biodiversity indices. These indicators represent active soil life and the soil functioning processes, including the activity of the soil microflora and fauna, which affect nutrient cycling, organic matter breakdown, soil structure development and soil fertility and soil quality maintenance.

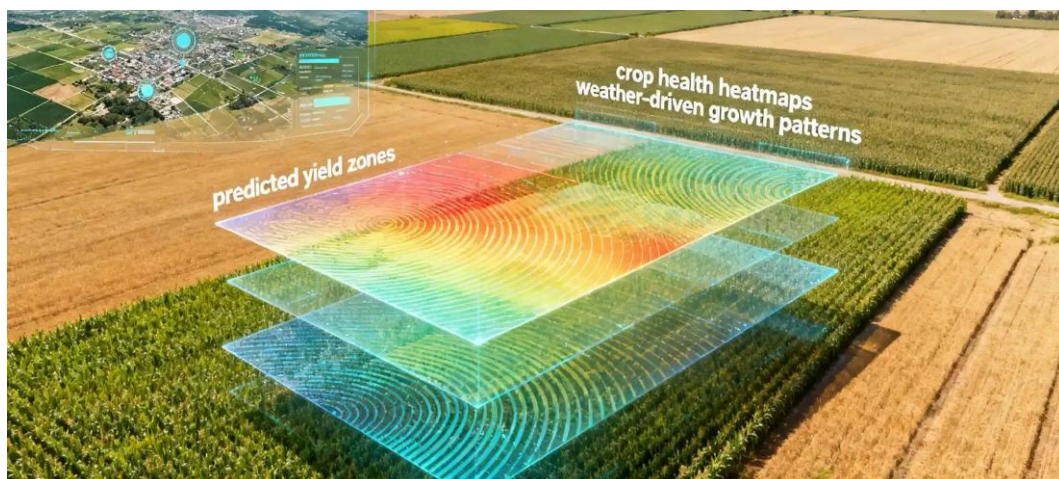
3. Artificial Intelligence in Soil Health Monitoring

Artificial Intelligence refers to computer systems capable of performing tasks that typically require human intelligence, including learning, pattern recognition, decision-making and prediction.

Major AI Techniques Used

1. Machine Learning (ML)

Machine learning techniques process past soil information to detect patterns and correlations between different soil attributes. They have been extensively utilized to predict soil properties, diagnose nutrient deficiencies, classify soils and forecast crop yields, leading to better, informed and more efficient soil management decisions.



2. Artificial Neural Networks (ANN)

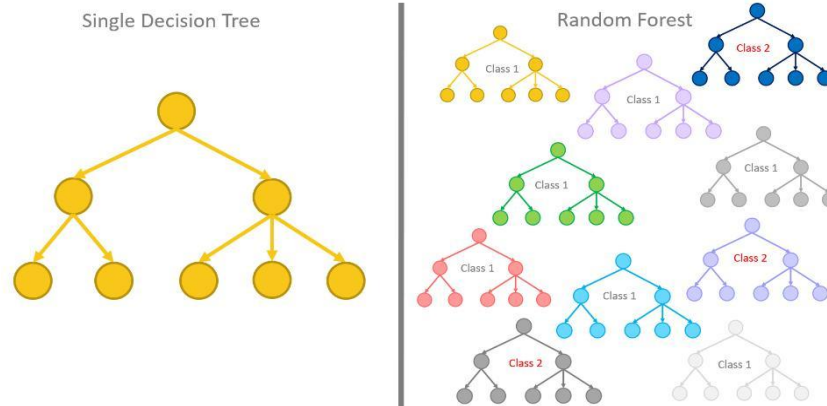
The artificial neural networks (ANNs) simulate the way that the human brain works and they are good in representing complex nonlinear relationships between soil properties. They

have been extensively used for predicting soil organic carbon, estimating soil moisture and mapping nutrients to accurately quantify the soil health for enhanced soil health monitoring and management.

3. Random Forest (RF)

Random Forest (RF) is a robust and reliable machine learning algorithm, which is commonly applied in digital soil mapping. It not only has high prediction accuracy but also can effectively manage large and complex data

sets and has a low risk of over fitting, which is the result of synthesizing the outputs of several decision trees and is very appropriate for predicting soil property and spatial soil modeling.



4. Support Vector Machines (SVM)

The Support Vector Machines (SVMs) is one of the most powerful ML algorithms which can be used for both classifications as well as regression problems. In soil health monitoring, they have been utilized for soil texture classification, salinity evaluation and soil fertility reconnaissance, with results that are deemed as accurate and dependable from the complexity of the soil data.

5. Deep Learning (DL)

Deep learning models enable sophisticated analysis of soil and land resources through automatic feature extraction from large and heterogeneous datasets. They are also used for image analysis, detection of soil erosion, and evaluation of land degradation with a high accuracy in the processing of remotely sensed and geospatial data for monitoring soil health.

Table 1: Remote Sensing Technologies for Soil Health Monitoring.

Remote Sensing Platform	Examples	Key Features/Applications	Advantages
Satellite-Based Remote Sensing	NASA Landsat, European Space Agency Sentinel, Indian Space Research Organisation Resourcesat, MODIS	Monitoring soil properties, vegetation status, land use changes and large-scale soil health assessment	Large area coverage, frequent monitoring, cost-effective, long-term data availability
UAV (Drone)-Based Remote Sensing	Multicopter and fixed-wing drones equipped with RGB, multispectral, or thermal sensors	Site-specific soil monitoring, crop stress detection, nutrient assessment and precision agriculture applications	High-resolution imagery, real-time observations, flexible deployment, detailed spatial analysis
Ground-Based Sensors	Spectroradiometers, soil moisture sensors, electrical conductivity sensors	Direct measurement of soil characteristics such as moisture content, salinity and spectral properties	High accuracy, continuous monitoring, immediate data collection, field-level assessment

5. Remote Sensing Indicators of Soil Health

Remote sensing instruments are now routinely employed to quantify important soil health indicators. Microwave sensors provide accurate estimates of soil moisture, which have been used for irrigation scheduling, drought monitoring and water resource management. Spectral reflectance can be used to estimate soil organic carbon and to support the assessment of carbon sequestration and soil fertility. Soil salinity is identified by typical spectral signatures, enabling mapping of salinity and planning of reclamation. Satellite images are used for locating areas susceptible to erosion and for sediment monitoring in soil erosion control. In addition, soil compaction can be monitored indirectly with vegetation and thermal indices, which reflect the stress of plants growing over compacted soils.

6. Integration of AI and Remote Sensing

The integration of AI and remote sensing enhances the efficiency and accuracy of soil health assessment.

Workflow

1. Data acquisition through satellites, drones and sensors
2. Data preprocessing
3. Feature extraction
4. Machine learning model training
5. Prediction and mapping
6. Decision support

Benefits

- Real-time monitoring
- Reduced sampling costs
- High spatial resolution
- Early problem detection

Table 2: Applications of AI and Remote Sensing in Soil Health Monitoring.

Soil Health Parameter	Remote Sensing Data Source	AI Technique Used	Outcome
Soil Moisture	Sentinel-1 SAR	Random Forest	Moisture mapping
Soil Organic Carbon	Hyperspectral imagery	ANN	Carbon estimation
Soil Salinity	Landsat imagery	SVM	Salinity classification
Soil Erosion	UAV imagery	Deep Learning	Erosion risk mapping
Soil Nutrients	Multispectral images	Random Forest	Fertility assessment
Soil Texture	Spectral data	KNN	Texture classification
Soil Compaction	Thermal imagery	CNN	Compaction detection
Soil Degradation	Satellite imagery	Deep Learning	Degradation assessment

7. Applications in Precision Agriculture

Variable rate fertilizer application with AI-based nutrient maps allows site-specific fertilizer management, increasing nutrient use efficiency and decreasing fertilizer costs and environmental pollution. Soil moisture monitoring in AI-based irrigation management leads to optimized irrigation scheduling for water saving and better crop growth. Soil fertility mapping offers high-resolution fertility maps that enable site-specific nutrient

management could Crop suitability Analyzes soil properties to identify the best crop(s) for the site, contributing productivity and resource-use efficiency.

8. AI and Remote Sensing for Soil Carbon Monitoring

Soil organic carbon is a key indicator of soil health and climate resilience.

Applications include:

- Carbon stock estimation
- Carbon sequestration assessment

- Climate-smart agriculture planning
- Greenhouse gas mitigation programs

9. Role in Sustainable Agriculture

AI and remote sensing play a vital role in the sustainable agriculture, yet they serve the resource conservation, including through efficient water use, reduced fertilizer losses and optimized pesticide applications. They assist in protecting the environment by reducing nutrient runoff, greenhouse gas emissions and soil erosion. Above all, they also deliver economic advantages such as reduced cost of monitoring, increased profitability of farms and superior effectiveness of data driven decision making for enhanced agricultural productivity and sustainability.

10. Challenges and Limitations

Despite the progress made, a number of challenges limit the application of AI and/or remote sensing to soil health monitoring. The technical challenges are that this requires processing large amounts of data, having high-performance computers and sensor calibration issues. Constraints on the data, such as small amount of ground-truth data, data heterogeneity, and missing observations, may influence the model accuracy. Financial constraints such as a high upfront cost and low accessibility for smallholder farmers, further limit the adoption. In addition, implementing this successfully would necessitate having experts in AI, GIS and data analysis, which may be in short supply in some areas.

11. Future Prospects

The next smart soil solutions is expected to be AI-based technology combined with remote sensing, cloud computing, IoT and big data analytics. Among new solutions are AI-driven

soil digital twins, which simulate soil systems to analyze real-time data and forecast changes and hyperspectral satellite missions permitting more precise assessment of soil nutrients and carbon. AI-enabled drone swarms will allow for the automation and continuous monitoring of soils and smart IoT-based sensors will capture real-time soil information tailored to precision agriculture. The emergence of Explainable Artificial Intelligence (XAI) would improve the transparency and trustworthiness of the AI-based decisions. In addition, climate-smart soil monitoring will contribute monitoring of drought, salinity, carbon sequestration and climate resilience, while generative AI-based soil advisory systems will provide intelligent recommendations on nutrient management, irrigation scheduling and sustainable land use planning.

CONCLUSION

Artificial Intelligence (AI) and Remote Sensing (RS) are revolutionizing the monitoring of soil health as they enable fast, accurate and holistic evaluation of soil attributes in various spatial scales. Soil moisture, fertility, salinity, erosion risk and organic carbon can be accurately estimated by applying machine learning and deep learning algorithms on complex datasets generated from satellite, drones and sensor networks. The convergence of AI and RS also empowers precision agriculture, sustainable land management, and climate-smart agriculture. While there are challenges linked to data accessibility, computational resources and adoption, it is anticipated that further progress in sensing techniques, cloud computing and intelligent analytics will render AI-based soil health monitoring as a cornerstone to achieving future sustainable agriculture.