

14. Remote Sensing-Based Assessment of Soil Nutrient Status for Precision and Site-Specific Fertilization

Palak Mehra¹

¹Research Scholar, Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu

Introduction

The escalating global demand for food production, coupled with the need to maintain soil fertility and protect natural resources, underscores the importance of efficient nutrient management in modern agriculture. Traditional soil testing methods, though reliable, are often labour-intensive, time-consuming, and limited in capturing the spatial variability of nutrients within a field. This limitation frequently leads to blanket fertiliser applications, resulting in nutrient imbalances, reduced input efficiency, and environmental concerns such as nutrient leaching and greenhouse gas emissions.

Remote sensing technology offers a powerful alternative by enabling rapid, large-scale, and non-destructive assessment of soil nutrient status. By capturing spectral signatures from the soil surface or crop canopy through satellite, drone, or proximal sensors, remote sensing provides critical information on nutrient distribution and crop health. These data can be integrated into precision agriculture frameworks to develop site-specific fertilisation strategies,

optimising nutrient use while enhancing crop yields and environmental sustainability. As advances in sensor resolution, data analytics, and machine learning continue to evolve, remote sensing is emerging as a cornerstone of next-generation nutrient management systems.

Principles of Remote Sensing in Soil Nutrient Assessment

Remote sensing is founded on the principle that soil and vegetation interact with electromagnetic radiation in ways that vary according to their physical and chemical properties. When sunlight or emitted radiation strikes the Earth's surface, different materials absorb, transmit, or reflect specific wavelengths. Soil characteristics such as texture, organic matter, moisture content, and nutrient composition influence these reflectance patterns. Similarly, the nutrient status of plants affects pigment concentration (particularly chlorophyll), leaf structure, and canopy density, which collectively modify the spectral response of crops. By capturing and analysing these subtle differences, remote sensing allows the

detection and quantification of soil nutrient variability across large areas without direct physical contact.

Sensors mounted on satellites, uncrewed aerial vehicles (UAVs), aircraft, or ground-based platforms record reflected energy across various regions of the electromagnetic spectrum, including visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) bands. Each band carries unique information:

- **Visible light (400–700 nm)** is sensitive to chlorophyll content and soil colour, making it helpful in detecting nutrient-induced changes in greenness.
- **Near-infrared (700–1300 nm)** responds strongly to internal leaf structure and canopy density, both of which are influenced by nutrient availability.
- **Shortwave infrared (1300–2500 nm)** is affected by soil moisture and organic matter, aiding in the estimation of soil chemical properties such as carbon and clay content that correlate with nutrient levels.

To translate raw spectral data into meaningful indicators of nutrient status, researchers calculate vegetation indices, which are mathematical combinations of reflectance values from different spectral bands. Commonly used indices include:

- **Normalised Difference Vegetation Index (NDVI):** Reflects chlorophyll concentration and biomass, making it particularly effective for detecting nitrogen deficiency.
- **Red Edge Position (REP):** Sensitive to changes in leaf pigment and structure, aiding in early detection of nutrient stress before visible symptoms appear.
- **Soil Adjusted Vegetation Index (SAVI):** Reduces the influence of bare soil, improving accuracy in sparsely vegetated fields.

These indices serve as proxies for key plant physiological processes that are affected by nutrient availability. For example, nitrogen deficiency leads to reduced chlorophyll content, which in turn lowers NDVI values. Conversely, phosphorus or potassium imbalances may restrict leaf expansion or alter canopy geometry, influencing REP and SAVI.

To obtain reliable nutrient estimates, calibration models are developed by correlating vegetation indices and spectral signatures with laboratory-analysed soil and plant nutrient data. Statistical techniques, such as partial least squares regression (PLSR), random forest, and machine learning algorithms, are commonly applied to enhance prediction accuracy. Once calibrated, these models can be used to generate spatial nutrient

maps at various scales, ranging from individual farm plots to entire regions, thereby supporting site-specific management decisions.

Remote Sensing Platforms and Data

Sources

The effectiveness of remote sensing in assessing soil nutrient status depends mainly on the type of platform used to collect spectral data. Each platform, including satellites, uncrewed aerial vehicles (UAVs), aircraft, or ground-based sensors, offers unique advantages in terms of spatial resolution, temporal coverage, and cost, making it suitable for different scales of precision agriculture. Understanding these platforms and their data sources is essential for designing accurate and efficient nutrient monitoring systems.

Satellite-Based Platforms:

Satellites provide broad, repeated coverage of agricultural landscapes, making them ideal for regional or national nutrient mapping. Widely used satellite missions include:

- **Landsat (NASA/USGS):** Offers moderate spatial resolution (30 m) with a historical archive spanning decades, useful for long-term nutrient trend analysis.
- **Sentinel-2 (ESA):** Provides higher spatial resolution (10–20 m) and

frequent revisit times (5 days), enabling near real-time crop monitoring.

- **WorldView, PlanetScope, and MODIS:** Deliver high-resolution imagery (sub-meter to 250 m) for field-level assessments and large-scale nutrient surveillance.

Satellite imagery is especially valuable for monitoring nutrient-related vegetation changes over entire growing seasons. However, cloud cover, atmospheric disturbances, and fixed revisit intervals can limit the acquisition of timely data in specific regions or seasons.

UAV/Drone-Based Platforms: Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, are gaining popularity for high-resolution nutrient assessments at the farm scale. Equipped with multispectral or hyperspectral cameras, drones can capture imagery at centimetre-level resolution, allowing detection of subtle nutrient variability within a single field. Their flexibility in flight scheduling makes them ideal for on-demand data collection, particularly in cloudy or time-sensitive situations. Drones are especially valuable for generating prescription maps that guide variable-rate fertiliser applications with remarkable spatial precision.

Aircraft-Based Remote Sensing: Human-crewed aircraft equipped with advanced hyperspectral sensors provide a middle

ground between satellite and UAV platforms. They cover larger areas than drones but offer finer resolution and more flexible scheduling than satellites. Aircraft missions are often employed for research or large-scale nutrient mapping projects that require very high spectral detail.

Proximal and Ground-Based Sensors: Proximal sensors, such as field spectroradiometers, handheld NDVI meters, and tractor-mounted active sensors (e.g., GreenSeeker, Crop Circle), provide point-based or strip-level measurements. Although limited in spatial coverage, these sensors are invaluable for ground-truthing and calibrating satellite or UAV-derived models. They can also be integrated with farm machinery for real-time nutrient monitoring and variable-rate application during fertiliser operations.

Workflow for Site-Specific Fertilisation Using Remote Sensing

The successful application of remote sensing for soil nutrient assessment relies on a systematic workflow that transforms raw spectral data into actionable fertiliser recommendations. This workflow integrates data collection, processing, and interpretation with agronomic decision-making to create precise nutrient management plans. The key stages include:

Data Acquisition: The process begins with the collection of multispectral or

hyperspectral imagery from satellites, UAVs, or ground-based sensors. The timing of data acquisition is critical, as nutrient-related changes in soil or crop canopies are often season- or growth-stage-dependent. For example, nitrogen deficiency is most effectively detected during the early vegetative stage, when chlorophyll content has a significant influence on reflectance patterns.

Preprocessing and Calibration: Raw remote sensing data require careful preprocessing to remove noise and atmospheric effects. This step typically involves radiometric calibration, geometric correction, and atmospheric correction to ensure that the spectral information accurately represents on-ground conditions. Ground-truth data collected through soil sampling and laboratory analyses are essential for calibrating spectral indices and validating nutrient prediction models.

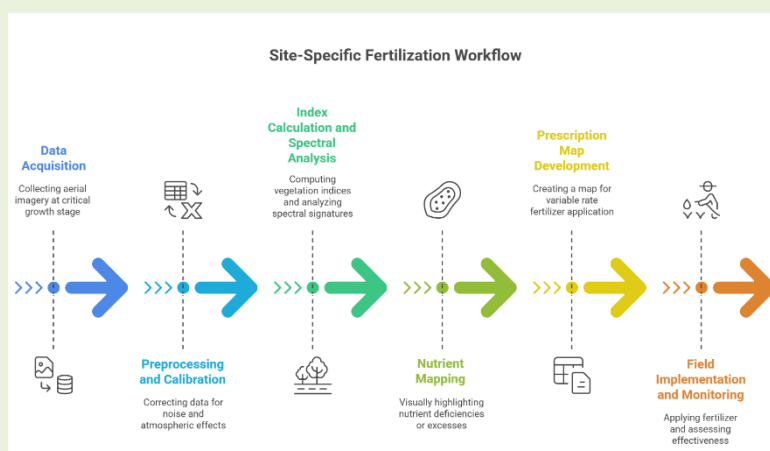
1. **Index Calculation and Spectral Analysis:** Once the imagery is corrected, relevant vegetation indices such as NDVI, REP, or SAVI are computed to highlight nutrient-related variations in crop health or soil reflectance. Advanced spectral features, such as absorption bands in the shortwave infrared region, can also be extracted for more detailed analysis of nutrients. Machine learning algorithms

(e.g., random forest, support vector machines) and chemometric techniques (e.g., partial least squares regression) are then applied to establish relationships between spectral signatures and nutrient concentrations.

2. Nutrient Mapping: The calibrated models generate spatial nutrient maps, identifying areas of nutrient sufficiency,

applicators, prescription maps are uploaded to farm machinery for site-specific fertiliser application. Post-application monitoring through subsequent remote sensing imagery helps evaluate the effectiveness of fertilisation and allows for mid-season adjustments if necessary.

Advantages and Challenges of Remote Sensing for Soil Nutrient Management



deficiency, or excess across the field. These maps visually depict intra-field variability, enabling farmers to pinpoint specific management zones and apply targeted fertiliser rates.

3. Prescription Map Development: Based on the nutrient maps, prescription maps are created to guide variable rate fertilisation (VRF). These maps specify the exact type, amount, and location of fertilisers to be applied, ensuring that each management zone receives only what is required to meet crop nutrient demands.

Field Implementation and Monitoring: Using GPS-enabled variable-rate

The integration of remote sensing into soil nutrient assessment and site-specific fertilisation provides numerous benefits for both farmers and the environment. At the same time, particular technical and operational challenges must be addressed to realise its potential fully.

• Advantages

1. Large-Scale and Rapid Monitoring: Remote sensing enables nutrient assessment across vast agricultural landscapes in a fraction of the time required for traditional soil sampling. Satellite platforms, for example, can monitor thousands of hectares in a single pass, making it

highly efficient for regional and national nutrient surveillance.

2. **Non-Destructive and Cost-Effective:** Unlike conventional methods that require extensive soil collection and laboratory testing, remote sensing collects data without disturbing the soil or crops. Over time, this reduces the cost of repeated sampling and chemical analyses.
3. **High Spatial and Temporal Resolution:** Advanced sensors, particularly UAV-mounted multispectral and hyperspectral cameras, capture fine-scale variability within fields, allowing the detection of subtle nutrient deficiencies before visible symptoms appear. Frequent revisit times from satellites, such as Sentinel-2, enable near-real-time monitoring throughout the growing season.
4. **Support for Precision Fertilisation:** Nutrient maps generated from remote sensing data guide variable-rate fertiliser applications, ensuring that inputs are matched to site-specific crop requirements. This optimises nutrient use efficiency, enhances crop productivity, and

minimises nutrient losses to water bodies or the atmosphere.

5. **Environmental Sustainability:** By reducing the over-application of fertilisers, remote sensing-based management helps lower greenhouse gas emissions, prevent eutrophication of water bodies, and maintain long-term soil health.

Challenges

1. **Need for Calibration and Ground-Truthing:** Remote sensing models must be calibrated with field data to account for local soil and crop conditions. Variations in soil moisture, organic matter, and surface roughness can alter spectral signatures, making the accurate estimation of nutrients challenging without robust ground-based measurements.
2. **Atmospheric and Weather Constraints:** Cloud cover, haze, and atmospheric disturbances can reduce the quality of satellite imagery, especially during critical crop growth stages. Although UAVs and proximal sensors can overcome some of these limitations, their use may be restricted by weather conditions or regulatory constraints.

3. Complex Data Processing:

Transforming raw spectral data into reliable nutrient maps requires expertise in image preprocessing, statistical modelling, and geospatial analysis. Farmers often require support from trained professionals or decision-support platforms to interpret the results effectively.

4. Cost of Advanced Sensors: High-

resolution hyperspectral sensors and UAV platforms involve significant initial investment. While costs are declining, smallholder farmers may still find the technology financially demanding without the support of institutions or governments.

5. Dynamic Nutrient Interactions:

Nutrient deficiencies or toxicities rarely occur in isolation. Remote sensing indices may be influenced by multiple interacting factors, including pests, diseases, or water stress, complicating the interpretation of spectral signatures.

Moving Forward: The Future of

Remote Sensing in Nutrient

Management

The continued evolution of remote sensing technologies promises to reshape the way soil nutrients are monitored and managed, making precision agriculture more

accessible, efficient, and sustainable.

Several key trends and innovations are driving this transformation, offering opportunities to overcome current limitations and expand the adoption of site-specific fertilisation.

1. Advances in Sensor Technology: Next-

generation sensors are rapidly improving in terms of spatial, spectral, and temporal resolution. Hyperspectral satellites—such as NASA’s Surface Biology and Geology (SBG) mission and ESA’s upcoming EnMAP—will capture hundreds of narrow spectral bands, enabling more precise detection of subtle soil and crop nutrient variations. Similarly, miniaturised multispectral cameras are making UAV-based imaging more affordable and scalable, allowing farmers to collect ultra-high-resolution data on demand.

2. Integration with Machine Learning and

Artificial Intelligence (AI): Machine learning algorithms are increasingly used to process large, complex datasets generated by remote sensing platforms. Techniques such as random forest, support vector machines, and deep neural networks can identify patterns and relationships between spectral signatures and nutrient concentrations that traditional regression models may

overlook. AI-driven systems can also automate image preprocessing, nutrient mapping, and fertiliser prescription development, thereby reducing the need for extensive technical expertise.

3. **Synergy with Internet of Things (IoT) and Ground Sensors:** The combination of remote sensing with IoT-enabled soil moisture probes, nutrient sensors, and weather stations creates a powerful, real-time decision-support system. Ground sensors provide continuous, point-based data that can be used to calibrate and validate satellite or UAV imagery, thereby improving accuracy. Farmers can receive instant updates on nutrient status through mobile apps, enabling them to make timely fertiliser applications that respond to changing crop needs.
4. **Cloud-Based Data Processing and Decision Platforms:** Cloud computing and open-access platforms are democratizing access to remote sensing data. Services like Google Earth Engine, Sentinel Hub, and commercial precision agriculture dashboards allow users to analyse large datasets without the need for expensive software or high-performance computing infrastructure. These platforms facilitate near-real-time nutrient monitoring and the generation of user-friendly prescription

maps, making advanced analytics more accessible to small and medium-scale farmers.

5. **Policy Support and Capacity Building:** Government initiatives and institutional partnerships are essential for scaling the adoption of remote sensing-based nutrient management. Subsidies for UAV services, training programs for farmers, and the development of open-source nutrient models can bridge the technological gap, particularly in smallholder-dominated agricultural regions. Public-private collaborations can further accelerate technology transfer and ensure equitable access to high-quality remote sensing tools.
6. **Towards Predictive and Dynamic Fertilisation:** The future of nutrient management lies not only in diagnosing current deficiencies but also in predicting future nutrient demands. By integrating remote sensing data with crop growth models, weather forecasts, and soil nutrient dynamics, predictive systems can recommend proactive fertiliser applications to optimise crop growth. Such dynamic fertilisation strategies will help maintain optimal nutrient availability throughout the growing season, thereby improving crop yields while minimising environmental losses.

7. Sustainability and Climate Resilience: Remote sensing will play a critical role in building climate-resilient agricultural systems. Enabling site-specific nutrient applications reduces greenhouse gas emissions from over-fertilisation, conserves natural resources, and promotes soil health. As climate change increases the frequency of extreme weather events, the ability to rapidly assess nutrient status and adjust management practices will be vital for maintaining food security.

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