Soil Fertility Mapping: A Scientific Approach for Soil Health Management

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Abstract

Soil fertility mapping is a scientific approach essential for sustainable soil health management and agricultural productivity in India. It involves assessing spatial variations in soil nutrients and properties using laboratory analysis, Geographic Information Systems (GIS), and remote sensing. Historically, soil surveys began in the 1950s, advancing with initiatives like the Soil Health Card Scheme. Modern methodologies include Digital Soil Mapping (DSM), which applies machine learning for high-resolution fertility prediction. Satellites such as Landsat and Sentinel-2 provide critical data on vegetation and land conditions. Benefits include optimized fertilizer use, increased yields, and environmental protection. However, challenges such as data inconsistency, limited infrastructure, and low farmer awareness persist. Future prospects lie in AI integration, real-time digital platforms, and enhanced policy support for precision agriculture in India. This scientific approach is essential for ensuring soil health, achieving food security, and fostering climate-resilient agricultural development in India.

Introduction

Soil fertility plays a pivotal role in sustainable agricultural development, as it directly influences crop productivity and consequently food security. Fertile soil possesses the physical, chemical and biological properties necessary to support robust plant growth, primarily through the adequate supply of macro- and micro-nutrients. In India, where nearly 58% of the population depends on agriculture for their livelihood, maintaining soil fertility is essential not only for economic stability but also for combating hunger and poverty. Given the pressures of increasing population, land degradation, intensive cropping, and climate change, a comprehensive understanding of soil fertility is essential for sustainable land use planning. Soil fertility mapping, therefore, provides a scientific foundation for evaluating spatial and temporal variations in soil quality parameters. This process involves collecting geo-referenced soil samples, analysing them in laboratories for nutrient content, pH, electrical conductivity (EC), organic carbon and other indicators and then integrating this data using geospatial techniques such as Geographic Information Systems (GIS), remote sensing, and spatial interpolation models. The integration of these data points into digital maps allows policymakers, researchers, and farmers to visualize the fertility status of soils at

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regional and local scales. Such maps are critical for implementing site-specific nutrient management (SSNM), reducing the overuse or misuse of fertilizers, enhancing crop yields, and mitigating environmental risks such as nutrient leaching and groundwater contamination. Therefore, soil fertility mapping is an indispensable tool in the promotion of resource-efficient, climate-resilient and economically viable agriculture in India.

Historical context and national initiatives

Systematic soil fertility mapping in India began with the institutionalization of soil science as a discipline in the early 20th century, but significant advancements occurred post-Independence, especially during and after the Green Revolution of the 1960s. The initial focus was on boosting food production through chemical fertilizers without detailed knowledge of soil nutrient status, which over time led to imbalanced fertilization and soil degradation. To address this, the Government of India established the Soil Survey Organisation in 1956, which later became part of the National Bureau of Soil Survey and Land Use Planning (NBSS &LUP) under the Indian Council of Agricultural Research (ICAR). The NBSS&LUP has since been instrumental in producing soil maps at 1:250,000 and 1:50,000 scales, integrating parameters like soil type, depth, texture, and nutrient status, and classifying Indian soils into major soil orders and agro-ecological zones. Their maps provide comprehensive data on soil orders, fertility status, and suitability for various crops. These efforts are now supported by emerging digital soil mapping (DSM) techniques and machine learning models that enhance prediction accuracy. A landmark initiative was the launch of the Soil Health Card (SHC) Scheme in 2015, aimed at providing farmers with detailed information on the fertility status of their land. Under this program, over 250 million samples were planned for testing across 638 districts, assessing 12 soil parameters including macro-nutrients (N, P, K), micronutrients (Zn, Fe, Cu, Mn, B), secondary nutrients (S), and physical properties like pH, EC, and organic carbon (DAC&FW, 2020). These data are digitized and linked to farmers' land records, facilitating customized fertilizer recomme-ndations and site-specific nutrient management.

Methodologies for soil fertility mapping

Soil fertility mapping is a multi-disciplinary process that integrates soil science, geospatial technology, and data analytics to assess the spatial variability of soil nutrients and other related properties. The methodologies employed aim to generate spatially explicit information about soil fertility status, enabling precise and location-specific soil management. In India, a combination of traditional and modern techniques is utilized for soil fertility mapping at various scales, from farm-level assessments to national surveys.

Soil sampling and laboratory analysis: The first step in soil fertility mapping is the systematic collection of soil samples, which can be done using different sampling designs:

✓ Grid sampling (e.g., 2.5 km × 2.5 km for district-

level mapping)

✓ Stratified sampling based on agro-ecological zones or land use

✓ Random or composite sampling for individual farm assessments

Each soil sample is geo-referenced using GPS to allow for spatial analysis. Samples are then analyzed in certified soil testing laboratories for key parameters such as macronutrients (N, P, K), micronutrients (Zn, Fe, Cu, Mn, B), secondary nutrients (S, Ca, Mg), soil pH, electrical conductivity (EC), organic carbon content, and cation exchange capacity (CEC).

Geospatial technologies: Geospatial technologies, particularly Remote Sensing and GIS tools, play a crucial role in soil fertility mapping by enabling the spatial analysis and visualization of soil data. GIS serves as a platform to manage geo-referenced soil sample data and integrate it with other spatial variables such as land use, slope, elevation, and rainfall. It facilitates the generation of fertility maps through spatial interpolation and overlay analysis. Remote sensing, on the other hand, provides multispectral satellite imagery (e.g., Landsat, Sentinel-2) that captures surface reflectance, enabling the derivation of vegetation indices like NDVI (Normalized Difference Vegetation Index), which are correlated with soil fertility. These indices help identify spatial variability in crop vigour, indirectly indicating underlying soil nutrient status and degradation trends.

Spatial Interpolation Techniques: Once soil data

are geo-referenced, spatial interpolation is used to generate continuous surface maps of soil properties. Common techniques include:

✓ **Inverse Distance Weighting (IDW):** Weights nearby observations more heavily than distant ones.

✓ **Ordinary Kriging:** A geo-statistical method that models spatial autocorrelation and provides uncertainty estimates.

✓ **Spline interpolation:** Used for smooth surface fitting of soil parameters.

The choice of method depends on data density, variability, and spatial structure. Kriging is often preferred due to its robustness and ability to model spatial patterns.

Digital Soil Mapping (DSM): Recent advancements include the application of Digital Soil Mapping, which employs machine learning algorithms (e.g., Random Forest, Support Vector Machines, Artificial Neural Networks) to predict soil fertility attributes based on covariates like topography, climate data, remote sensing indices, and existing soil observations. DSM enables the identification of spatial variability in soil properties with greater precision than traditional methods. In India, pilot implementations in states like Andhra Pradesh and Karnataka have demonstrated its potential in supporting precision agriculture, efficient fertilizer use, and informed land-use planning at local scales (Minasny and McBratney, 2016).

Data integration and validation: Validation of fertility maps involves cross-verifying predicted

values with independent field data using statistical accuracy measures such as RMSE (Root Mean Square Error), R^2, and MAE (Mean Absolute Error). Final maps are then integrated into decision-support systems for farmers and policymakers.

Satellites in soil fertility mapping

Satellite remote sensing plays a pivotal role in soil fertility mapping by providing large-scale, real-time, and multi-temporal data that support indirect assessment of soil properties. Satellite sensors capture reflected electromagnetic radiation from the Earth's surface, which can be processed to derive indicators relevant to soil fertility, such as vegetation health, land cover, and surface moisture. Key satellites and sensors used in soil fertility mapping include:

✓ Landsat series (e.g., Landsat 8, 9): Operated by NASA and USGS, Landsat provides medium-resolution multispectral imagery useful for calculating vegetation indices like NDVI and SAVI (Soil Adjusted Vegetation Index), which are proxies for plant health and, indirectly, soil nutrient status (Roy *et al.*, 2014).

✓ Sentinel-2: Part of the Copernicus Programme by ESA, Sentinel-2 offers high-resolution multi-spectral imagery at 10-20 m resolution. It captures reflectance in visible, near-infrared (NIR), and shortwave infrared (SWIR) bands, useful for assessing crop vigour, soil organic matter, and surface texture (Drusch *et al.*, 2012).

✓ MODIS (Moderate Resolution Imaging Spectroradiometer): Onboard NASA's Terra and Aqua satellites, MODIS provides daily observations with coarser resolution but high temporal frequency, suitable for regional-scale monitoring of crop dynamics and seasonal fertility trends (Löw *et al.*, 2018).

✓ SMAP (Soil Moisture Active Passive): Offers data on soil moisture content, which is a critical factor influencing nutrient availability and microbial activity in soils (Farahani *et al.*, 2022).

✓ PRISMA and Hyperspectral missions: Emerging hyperspectral satellites provide detailed spectral information that can detect specific minerals and organic matter in soils, enhancing direct soil property estimation.

These satellite datasets are integrated with GIS platforms and machine learning models in DSM frameworks to predict and map soil fertility parameters at fine spatial scales. In India, agencies such as ISRO and ICAR collaborate to utilize satellite data for national soil mapping projects, contributing to better resource management and precision farming.

Benefits of soil fertility mapping

Soil fertility maps aid in:

✓ Customized fertilizer recommendations

✓ Integrated Nutrient Management (INM) planning

✓ Monitoring degradation and land use changes

✓ Supporting climate-resilient agriculture

✓ Empowerment of farmers through initiatives like the Soil Health Card scheme

Common challenges associated with soil fertility mapping

- ✓ Soil heterogeneity across diverse agro-climatic zones complicates uniform mapping strategies
- ✓ Inadequate soil testing labs and lack of trained personnel reduce data quality
- ✓ Low sampling density leads to poor spatial resolution and inaccurate predictions
- ✓ Limited farmer awareness hinders the adoption of map-based nutrient recommendations
- ✓ Data integration challenges from multiple sources affect standardization and usability
- ✓ Temporal variability in soil properties is not captured in static maps
- ✓ Underutilization of advanced technologies like DSM and hyperspectral imaging
- ✓ Weak institutional coordination limits effective implementation and policy integration

Future prospects for Indian agriculture

The future of soil fertility mapping in Indian agriculture is promising, driven by advancements in geospatial technologies, machine learning, and digital platforms. Precision agriculture will benefit from high-resolution, site-specific fertility maps that optimize nutrient use and enhance crop productivity. Integration with AI and mobile applications will empower farmers with real-time, location-based recommendations. Emerging technologies such as hyperspectral imaging and UAVs offer rapid, non-invasive soil assessment methods. Furthermore, dynamic mapping will allow for monitoring of seasonal and climatic changes in soil health, promoting climate-resilient farming. National initiatives can be strengthened through public-private partnerships and centralized soil information systems to support research and policy. Enhanced farmer participation and training, alongside refined subsidy targeting, will ensure the effective application of soil fertility data, supporting sustainable and productive agricultural growth in India.

Conclusion

Soil fertility mapping, grounded in a scientific approach, is a transformative tool for effective soil health management and sustainable agriculture in India. By integrating traditional soil analysis with advanced geospatial technologies, remote sensing, and digital soil mapping techniques, it enables precise assessment of nutrient status across diverse agro-ecological zones. This spatial under-standing supports site-specific nutrient management, enhances fertilizer efficiency, and mitigates environmental degradation. National initiatives like the Soil Health Card Scheme have laid the groundwork for widespread implementation, but future success depends on strengthening infrastru-cture, farmer awareness, and data integration. As climate change and resource constraints intensify, soil fertility mapping will be indispensable for ensuring food security, promoting climate-resilient practices, and achieving long-term agricultural sustainability. A collaborative, technology-driven, and farmer-centric approach will be key to harnessing its full potential.

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