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Revolutionising soil mapping with artificial intelligence and remote sensing

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Digital Soil Mapping (DSM) is transforming soil resource assessment in India by integrating advanced techniques such as remote sensing, geographic information systems (GIS) and machine learning. Traditional soil mapping methods, while foundational, are labour-intensive and often lack the spatial precision required for modern land management. DSM overcomes these limitations by providing high-resolution, updatable soil information which is very critical for precision agriculture, climate adaptation, and land use planning. This article highlights India's progress in soil mapping, including major initiatives by ICAR-NBSS&LUP and State Land Use Survey of India (SLUSI), as well as the role of the 'Bhoomi Geoportal' in making soil data accessible. With DSM, policymakers and farmers can make informed decisions to optimise land use, enhance agricultural productivity, and promote sustainable resource management. The integration of artificial intelligence and high-performance computing further strengthens DSM's predictive capabilities, ensuring its role in shaping India's future agricultural landscape.

Keywords: AI in agriculture, Crop planning, Digital soil mapping, Precision agriculture, Soil health, Sustainable farming

THE 21st century presents global challenges such as rapid population growth, food security concerns, deforestation, freshwater shortages, biodiversity loss, and climate change (FAO 2011). Soil functions, including biomass generation and carbon storage, play a vital role in addressing these challenges and significantly impact food production, climate regulation, carbon sequestration, water filtration, and biodiversity conservation. To effectively tackle these global and regional issues, there is a growing demand for up-to-date and reliable soil data to facilitate decision-making at all levels. High-quality, high-resolution soil data is essential for supporting land use management, precision agriculture and ecosystem research.

Traditional soil mapping methods rely heavily on extensive soil surveys which are labour-intensive, time-consuming, and expensive. These conventional methods also depend on expert knowledge for accurate interpretation. Additionally, soil maps based on taxonomic classification rather than direct quantification of soil properties pose challenges for non-experts in utilising the information effectively for land management. In response, Digital Soil Mapping (DSM) has emerged over the past two decades as a modern approach to predict soil properties.

Soil mapping efforts in India

Various organisations in India have conducted soil surveys at different intensities and scales. Under the Soil Resource Mapping Mission, the ICAR-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS&LUP) conducted a national soil survey at a 1:250,000 scale between 1986 and 1995, in collaboration with state soil survey and land use agencies. This three-tiered mapping approach involved image interpretation, field surveys with soil analysis, and cartography. The fundamental mapping unit at this scale is the soil family association, which helps identify predominant soil types at state and district levels. The survey used a sample area technique, with extrapolation applied to similar regions.

For more detailed mapping, ICAR-NBSS&LUP and the State Land Use Survey of India (SLUSI) conducted reconnaissance soil surveys at a 1:50,000 scale using topographic maps and Landsat/IRS satellite imagery, covering multiple districts nationwide. These maps typically delineate two to three associated soils per unit. Detailed soil surveys at scales ranging from 1:4,000 to 1:10,000 have also been conducted by ICAR-NBSS&LUP, SLUSI, and state agencies in catchment and command areas.

Through the Land Resource Inventory (LRI) programme, ICAR-NBSS&LUP recently mapped 50 blocks at a 1:10,000 scale across diverse agro-ecological zones, also surveying numerous research farms and watersheds. Additionally, ICAR-NBSS&LUP developed the 'Bhoomi Geoportal', a comprehensive soil database for India, providing users with a platform to visualise, access and query soil information.

A significant soil mapping initiative in Karnataka, the Sujala III project, funded by the World Bank, covered approximately 1 million acres using detailed soil mapping techniques. These high-resolution surveys provide site-specific land resource information at the farm level, using cadastral maps as a base.

Modern soil modelling increasingly requires spatially continuous and quantitative soil data. However, existing maps lack sufficient quantitative spatial data. DSM techniques address this gap by generating high-resolution spatial data on soil properties efficiently, gaining popularity among natural resource managers worldwide. Recently, ICAR-NBSS&LUP conducted DSM studies utilising LRI and legacy datasets in the Vidarbha region of Maharashtra, the Bundelkhand region of Central India and the Bikaner division of Rajasthan.

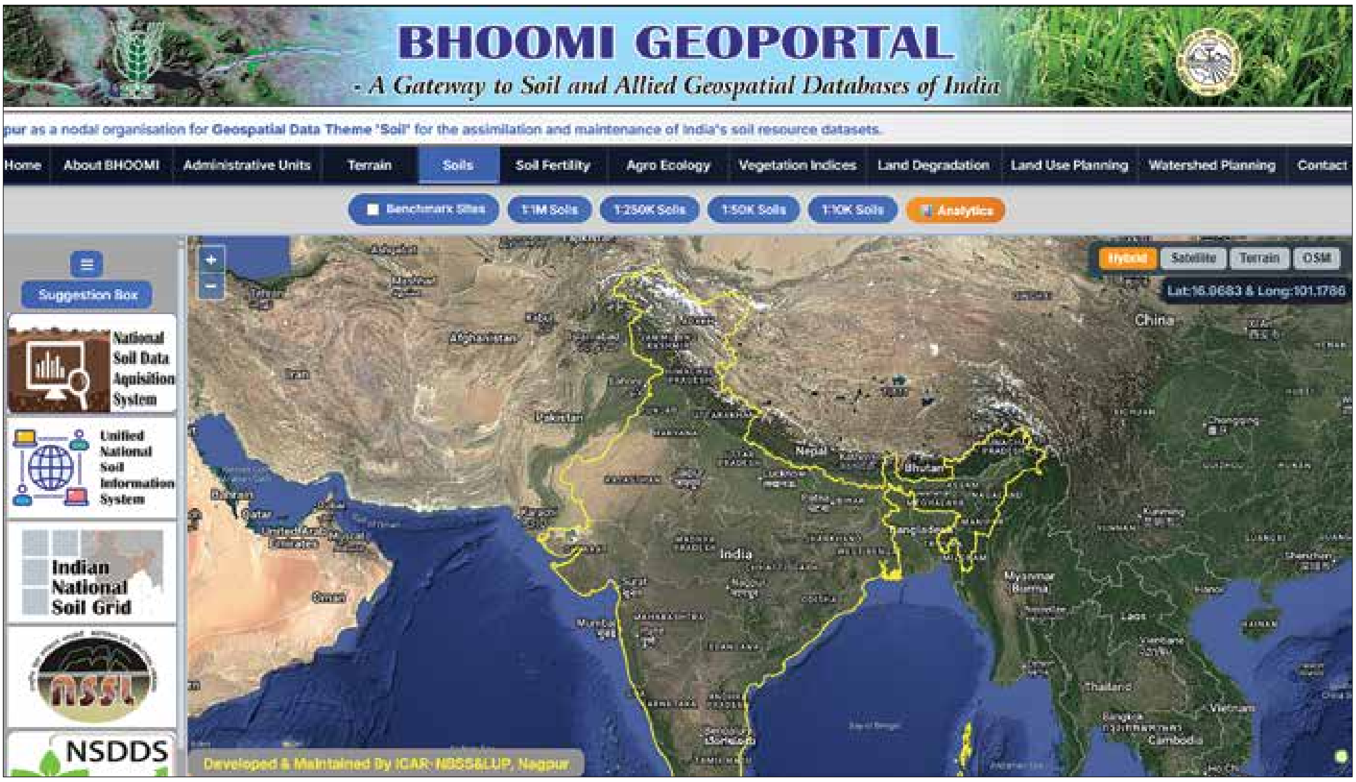
This extensive soil survey and mapping effort underscores India's commitment to improving land resource management through conventional and digital approaches. With DSM advancements, high-resolution, updatable soil information will enhance precision agriculture, ecosystem research, and sustainable land-use planning across the country.

Digital soil mapping

DSM, also known as predictive soil mapping, utilises numerical models to predict the spatial variations of soil properties using soil observations and environmental variables. It generates spatial soil information based on quantitative relationships between environmental covariates and soil data obtained from field observations and laboratory analysis (*See box*).

Table 1. Status of soil survey and mapping in India

Organisation	Type of survey and mapping	Area covered (mha)
NBSS&LUP	Small-scale soil mapping (1:250,000)	300.50
	Soil resource mapping (1:50,000)	198.40
	Detailed soil survey (1:4,000/1:15,000)	8.48
	Detailed soil survey (Sujala III project)	~1.0
	Detailed soil survey (LRI flagship programme)	>300 blocks
SLUSI	Rapid reconnaissance survey for watershed prioritization (1:50,000)	200.00
	Land degradation mapping (1:50,000)	65 districts
	Detailed soil survey (1:4,000/1:15,000)	13.50
	Soil resource mapping (1:50,000) under NRIS (DOS)	89 districts
National Remote Sensing Centre (NRSC)	Wasteland mapping (1:50,000)	Entire country
	Soil resource mapping (1:50,000) under NRIS (DOS)	200.00



Bhoomi Geoportal - Soil databases of India

Conventional vs. Digital soil mapping

From the 1950s through the early 2000s, conventional soil mapping (CSM) techniques dominated soil survey methodologies. CSM relied on aerial photo interpretation (API), and topographic analysis, complemented by the expertise of surveyors who conducted field assessments to interpret landscape and vegetation variations. This approach facilitated the development of a conceptual model capturing the spatial distribution of soil variations within a given region. Surveyors strategically selected locations for auger and pit observations based on their knowledge of characteristic soil types. However, CSM was inherently discontinuous, assuming distinct soil class boundaries rather than gradual transitions. This relies heavily on manual soil sampling and visual terrain interpretation to delineate soil polygons. Its primary limitations include labour-intensive field methods, the oversimplification of continuous soil variations into rigid boundaries, the assumption of homogeneity within mapping units, and the static nature of the resulting maps.

In contrast, DSM integrates soil attributes with environmental variables using computational techniques and numerical models. Widely adopted in soil mapping programmes worldwide, DSM employs environmental covariates to predict soil classes and attributes. Compared to conventional soil maps, DSM offers several advantages:

- Provides quantitative predictions of soil attributes.
- Enables reproducible and updatable mapping.
- Offers cost-efficient and faster map production compared to conventional methods.
- Includes uncertainty maps, which help identify data gaps requiring additional fieldwork to improve soil spatial variation analysis.

Traditional soil mapping demands extensive effort, expertise, and synthesis by soil surveyors, who rely on their understanding of soil-landscape relationships, lithology, land use, vegetation, and climatic influences. However, a major concern with machine-learning-based DSM techniques is their 'black box' nature in which pedological understanding may be obscured by the extensive use of environmental covariates and complex model structures. There is a real risk that machine-learning techniques could be applied without a thorough understanding of soil formation processes. Therefore, the role of soil scientists remains crucial in ensuring that DSM outputs enhance our understanding of soil spatial distribution and regulatory factors.

Environmental covariates and their selection

Environmental covariates influence soil formation either directly or indirectly. The main covariates include climate, vegetation, human activities, terrain, parent material, and time. Various studies have utilised multiple environmental factors to model soil spatial variability. Some commonly used covariates include:

- Legacy soil maps and data
- Geological and lithological maps
- Climate datasets (e.g. CHIRPS, MODIS land surface temperature, WorldClim)
- Remote sensing products (e.g. NDVI, EVI, NDWI, Landsat, MODIS, SPOT imagery)
- Terrain parameters (e.g. elevation, slope, curvature, topographic wetness index)

Key environmental factors in DSM

***Existing soil information*:** DSM relies heavily on legacy soil data, such as texture, bulk density, and mineralogy. In India, legacy maps exist at scales of 1:250,000 (nationwide), 1:50,000 (selected districts), and 1:10,000 (specific blocks). Studies have successfully used legacy maps for SOC mapping.

***Parent material*:** Bedrock and geomorphic processes shape parent material, influencing soil properties such as texture, depth, and mineralogy. Lithological and geological maps provide valuable insights into this factor.

***Climate*:** Climate significantly affects soil organic carbon prediction. Temperature, rainfall, and evapotranspiration datasets from CHIRPS, MODIS, and WorldClim are widely used in DSM.

***Organisms*:** Vegetation impacts soil organic carbon through organic matter contributions, erosion prevention, and moisture retention. Land use/land cover (LULC), NDVI, and EVI are important indicators in DSM modelling.

***Relief or topography*:** Elevation and terrain attributes significantly influence distribution of soil attributes in a region. DEM-derived topographic indices (e.g. slope, aspect, TWI, MrRTF, MrVBF) are critical for DSM.

Future implications in DSM

- Efficient and cost-effective soil sampling using proximal sensors.
- Integration of DSM into operational programmes and educational curricula.
- Combining pedological expertise with machine-learning techniques.

Framework of Digital Soil Mapping

Jenny (1941) CLORPT model [**S = f (cl, o, r, p, t)**] forms the basis of conventional soil mapping while McBratney *et al.* (2003) SCORPAN framework serves as the foundation for digital soil mapping.

S = f (s, c, o, r, p, a, n) + e

Where s is existing soil data, c/cl is climate, o represents organisms, r is relief, p is parent material, a/t denotes age or time, n is spatial location, and e accounts for spatially correlated residuals.

- Utilising high-resolution and high-temporal remote sensing data.
- Developing more intuitive criteria for uncertainty assessment.
- Enhancing the selection logic for relevant covariates.
- Mapping spatiotemporal soil moisture changes at the farm level using DSM techniques.

DSM continues to evolve, bridging traditional pedology with modern computational approaches, ensuring more accurate and reproducible soil information for sustainable land management.

SUMMARY

The integration of Artificial Intelligence (AI) and remote sensing in soil mapping and land use planning is revolutionising agriculture and environmental management. These advanced technologies enable high-resolution, data-driven insights that improve soil health assessment, optimise crop productivity, and support sustainable land use. Digital soil mapping, combined with AI-driven predictive modelling, enhances decision-making by providing accurate and timely information on soil properties and fertility. As India moves towards precision agriculture and sustainable development, embracing AI and remote sensing will be crucial in addressing challenges such as land degradation, soil fertility decline, and climate change. Future advancements in machine learning algorithms, satellite data processing, and big data analytics will further refine soil mapping techniques, making them more efficient and accessible. By leveraging these innovations, policymakers, researchers, and farmers can work together to achieve food security, environmental sustainability, and improved livelihoods for rural communities.

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