



Digital Soil Mapping: Using GIS, Remote Sensing and AI to Understand Soil Variability

**Bhanu Pratap Singh
Raghubanshi¹, Imtilemla²
Sidhartha Mishra³
Ardhendu Swain⁴, Saikat Das⁵**

¹Sr.Technical Officer, Department of Soil Science, Rajmata Vijaya Raje Scindhia Krishi Vishwavidyalaya Gwalior, Krishi Vigyan Kendra Lahar, Bhind.

²SMS Soil Conservation, KVK Mokochung.

³Ph.D Scholar, Department of Soil Science, Sardar Vallabhbhai Patel University of Agriculture and Technology, Modipuram, Meerut 250110.

⁴M.Sc (Ag.) Scholar, Department of Soil Science and Agricultural Chemistry, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan-731236 West Bengal.

⁵M.Sc (Ag.) Scholar, Department of Soil Science and Agricultural Chemistry, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan-731236 West Bengal.



Open Access

*Corresponding Author

Bhanu Pratap Singh Raghubanshi*

Article History

Received: 04.09.2026

Revised: 09.09.2026

Accepted: 14.09.2026

This article is published under the terms of the [Creative Commons Attribution License 4.0](https://creativecommons.org/licenses/by/4.0/).

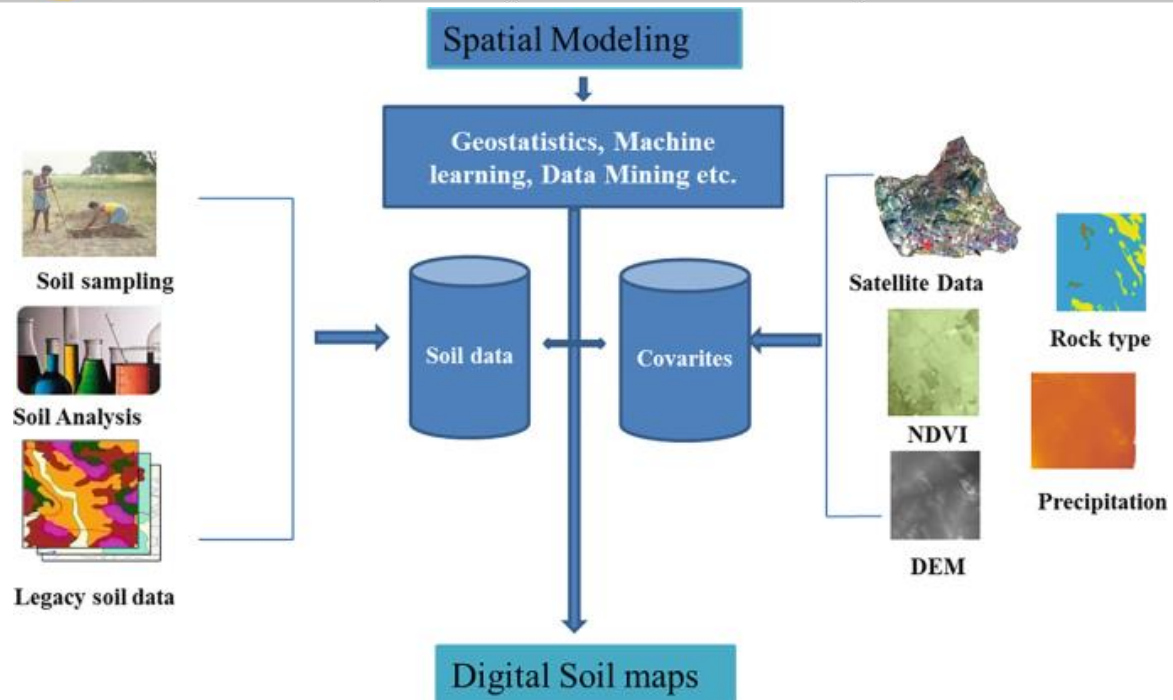
INTRODUCTION

The Hidden Diversity Beneath Our Feet

A field can look uniform to the eye, but the soil can vary dramatically from one point to another in the field. Shear strength, texture, depth, organic carbon, salinity, acidity, moisture, nutrient availability and water-holding capacity are all rarely homogeneous. These differences affect seed germination, root development, response to fertilizer, potential yield, and susceptibility to drought or erosion. Traditional soil surveys are informative, but they are time consuming, labor-intensive and too generalized to be of use in precision agriculture. Digital soil mapping provides an innovative approach by integrating field observations with environmental factors and computer-based predictions. It converts fragmented soil data into continuous, spatially explicit maps that characterize the spatial variability of soil properties at the farm, watershed and regional scales.

What is Digital Soil Mapping

Digital soil mapping is the computer-assisted prediction of soil classes and properties at locations where direct observations are unavailable. A digital soil map, unlike a traditional map that may represent land as a few large soil units, can represent continuous changes over the landscape. Values for pH, clay content, soil organic carbon, available nutrients, salinity or other characteristics may be predicted for each grid cell. These predictions are generated by investigating relationships between measured soil samples and environmental covariates such as terrain, climate, vegetation, land use and geological material. Digital maps are easily revised as new field observations, satellite images or improved analytical techniques become available, thus they are dynamic information resources instead of fixed records.



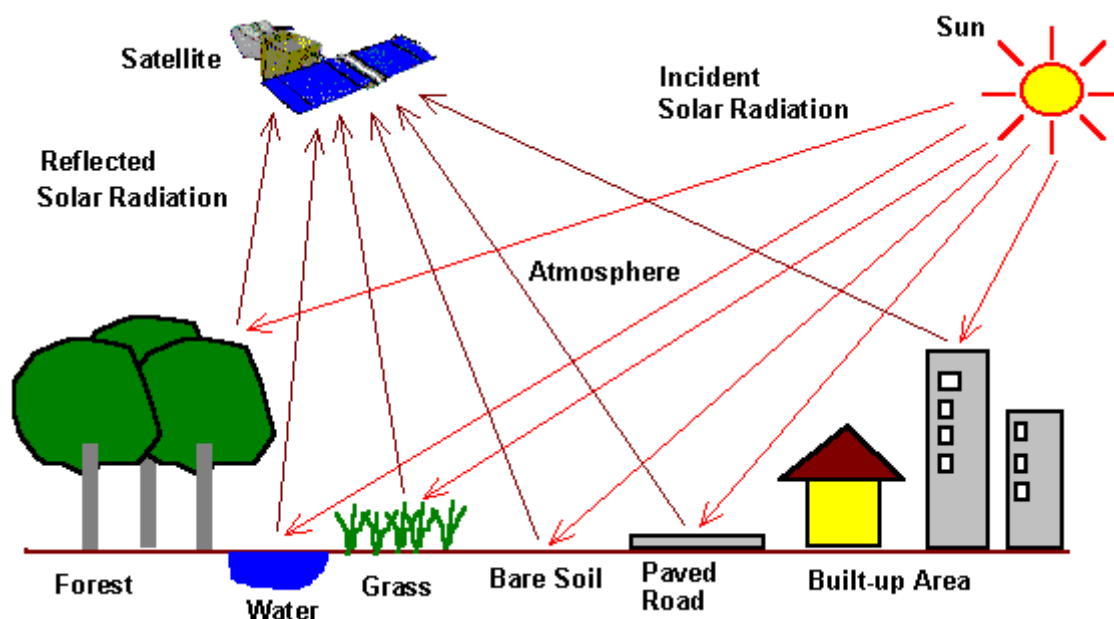
GIS: The Spatial Foundation

GIS (Geographic Information System) acts as a backbone for storing, analysing and visualising soil and environmental information. It associates soil sample points with layers of elevation, slope, rainfall, temperature, vegetation, land use, geology, and drainage to help locate spatial patterns and delineate useful management zones. This allows farmers to understand not only where soil fertility is low, but also the factors influencing it, such as erosion, poor drainage or sandy texture.

Digital soil mapping is based on the soil-landscape principle, which states that soil properties are functions of climate, organisms, relief, parent material, time and human activities. GIS expresses these factors as spatial variables such as slope, aspect, curvature, flow accumulation and wetness indices. GIS is the hub for digital soil mapping and decision-making by combining field observations, remote sensing and AI in a common coordinate system.

Remote Sensing: Observing the Land from Above

Remote sensing collects data about the earth at a distance without physical contact through the use of sensors mounted on satellites or in aircraft and Unmanned Aerial Vehicles (UAVs). Multispectral platforms, e.g. Landsat and Sentinel, provide repetitive coverage over large areas, while drones capture fine scale variability at the farm level. Bare-soil images may reveal soil colour, texture, moisture, organic matter and minerals, while crop vigour, canopy temperature and chlorophyll status offer indirect cues about nutrient status, salinity, drainage and water stress. Multi-date images allow to separate long-term soil patterns from short-term effects of weather, pests or farm operations. Hyperspectral sensors identify clay minerals, carbonates, iron oxides and pollutants, thermal sensors depict temperature and humidity, radar penetrates clouds and assesses surface roughness, and LiDAR captures microtopography influencing runoff and drainage. The integration of these synergistic approaches often leads to enhanced, more timely, and accurate soil variability predictions.



Field and Proximal Sensing Remain Essential

Digital technologies do not eliminate the need for soil sampling. Accurate maps start with accurate ground observations. Scientists take samples using designs that represent various landforms, soil types and management zones, and then they test them in labs. These outcomes are used to train and test predictive models. Badly positioned samples, inconsistent laboratory protocol or erroneous coordinates may give rise to errors which cannot be corrected by advanced algorithms, either. A good survey is therefore a compromise among the number of samples, their spatial distribution, the quality of analysis and the resolution required for the mapping.

Proximal sensing bridges the gap between laboratory analysis and remote sensing from the air. These devices are applied near to or on the soil surface and can measure electrical conductivity (EC), reflectance, gamma radiation, penetration resistance among others. Sensors mounted on tractors or hand-held enable them to gather much more data than traditional sampling methods. Advances in mobile soil spectroscopy are also allowing visible and near-infrared measurements to estimate

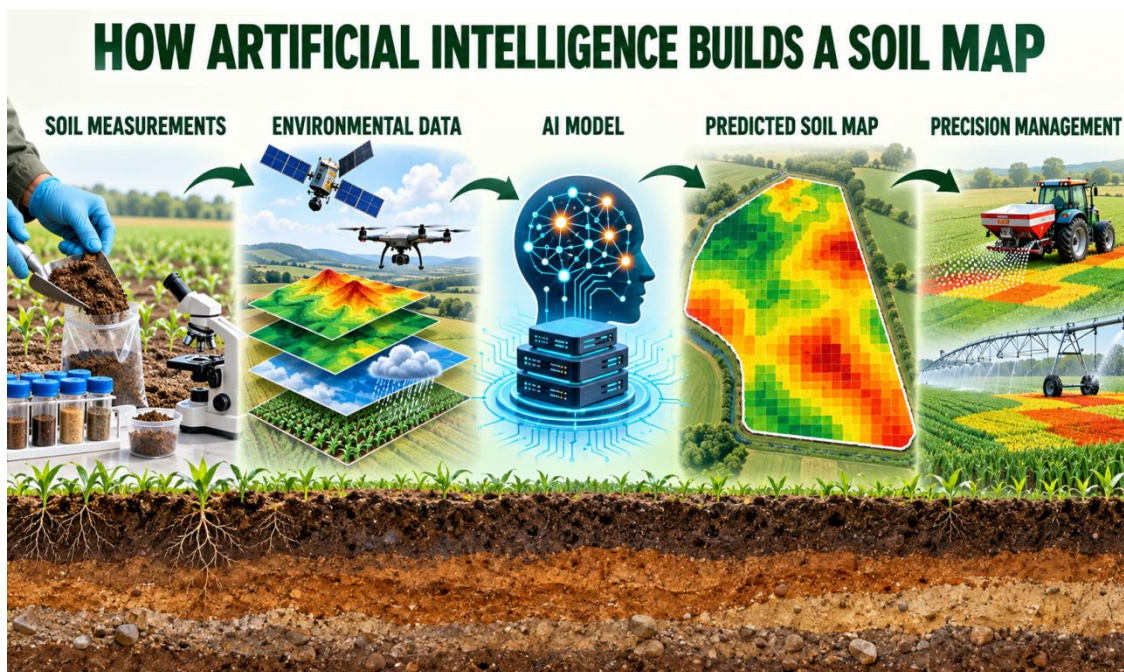
multiple properties after site-specific calibration. Strategic laboratory sampling along with dense sensor measurements can be used to effectively reduce costs and at the same time increase clarity in capturing within-field variation.

How Artificial Intelligence Builds a Soil Map

Machine learning, a core technology of artificial intelligence, is the basis of digital soil mapping, as the relationships between soil and the environment are often complex and nonlinear. Algorithms learn from sampled locations where soil measurements are matched with environmental variables to predict properties at unsampled grid locations. Common techniques include random forests, gradient boosting, support-vector machines, neural networks, ensemble models and geostatistics, which incorporates spatial dependence. Soil organic carbon, for instance, can be estimated from laboratory measurements, rainfall, temperature, elevation, slope, vegetation indices, cropping history and spectral data. Hybrid models combine machine learning, geostatistics and process-based knowledge, while deep learning analyses imagery with minimal manual feature selection. Active learning identifies where new

samples would bring the greatest reduction in uncertainty, and transfer learning helps to improve data-poor regions using knowledge from similar regions. Explainable AI is used to

explain which features influence predictions, allowing scientists to evaluate the biological plausibility of the predictions.



From Prediction to Practical Decisions

Digital soil maps provide spatially continuous soil information and have the potential to enhance farm management. The maps can be used to direct variable rate applications of fertilizer, lime, water, drainage and organic matter, saving on the costs and nutrients lost to the environment. Soil texture, water holding capacity, salinity, depth and risk of erosion maps also aid in scheduling irrigations, selecting crops and soil conservation measures.

On larger scales, digital soil maps enable watershed management, land capability analysis, drought preparedness, and land rehabilitation. They allow governments and extension providers to pinpoint soil constraints, align crops with agro-ecological zones, and predict soil carbon stocks and sequestration potential. When used with weather data and crop models, they also enhance decisions for climate resilience.

Benefits for Smallholders and Indian Agriculture

Digital soil mapping is especially relevant in India, where small land holdings, a variety of soils and highly variable monsoon rainfall result in heterogeneous recommendations. Village and farm-scale maps can augment soil test and Soil Health Card results by showing the expected variation of measured properties between sampled locations. Mobile apps can convert complicated maps into easy language maps for farmers to get recommendations on nutrient management, crops, irrigation and soil conservation. Regional language interfaces, simple legends and location-specific suggestions are required if digital products are to empower farmers instead of being limited to research institutions.

Effective uptake is further dependent on cost-effective sampling, trained local staff and collaboration between universities, government departments, remote-sensing agencies, extension services and farmers'

organisations. Community involvement may yield information on flooding, crop yields, erosion, historical land use, and problem soils which are not visible from a satellite. The amalgamation of such local intelligence with digital data can result in maps that are scientifically robust and operationally meaningful.

Accuracy, Uncertainty and Responsible Use

Digital soil maps are inherently uncertain, as they interpolate conditions between observations. Accuracy may decrease due to wide-spaced sampling, land use changes, inappropriate training data, and satellite interference (e.g., clouds, crops, moisture, or residues). Thus, maps should be required to incorporate independent validation, spatial cross-validation, and estimates of uncertainty to identify where additional sampling is needed. The resolution of the map should also be appropriate to the scale of the decision (e.g., fine-scale fertilizer placement requires much finer resolution data than regional scale land-use planning). Predictions should be frequently refreshed as soil conditions evolve as a result of erosion, irrigation, cropping, urbanization, and climate change.

Ownership, privacy, and access to data are also matters of concern. Data on farm soil may have commercial and personal value, so good policies are needed to protect farmers and ensure they receive fair benefits. The use of open standards, open methods, and interoperable databases can facilitate data sharing and avoid information silos. AI and digital soil maps are tools to be used to guide field verification and inform professional expertise and local knowledge, not substitute for these.

The Future: Living Maps of Soil Health

The next era in digital soil mapping will evolve from static property maps to a dynamic soil-health intelligence system. Satellite

constellations, drones, field sensors, farm machinery and weather stations will provide these repeated observations. Cloud computing will handle large data sets, and AI will identify changes, update predictions and warn users of potential problems. Maps might be made to represent biological activity, compaction, contamination, nutrient availability and even probability of crop response instead of basic soil properties alone.

Digital twins of farms and landscapes might integrate soil maps with weather and crop growth and management records to predict the implications of various courses of action prior to actual implementation. A producer also could assess the impact of irrigation techniques, fertilizer rates, cover crops or conservation practices on yield, water use, soil carbon and production expenses. Nevertheless, the trajectory of soil mapping will be determined by exceptional field science and strong, inclusive institutions as much as by powerful algorithms.

CONCLUSION

Digital soil mapping exposes the concealed variation that underpins agricultural production and environmental quality. GIS provides a framework for managing spatial data, remote sensing provides information on the dynamic land surface, field measurements supply reliable ground truth, and AI translates complex relationships into spatial predictions. Together, these advances have the potential to make soil management more precise, cost effective, and sustainable. but their greatest impact will be the delivery of comprehensible, locally relevant decisions, rather than colourful maps. With sufficient validation and farmer engagement and the underpinning responsible governance of data, digital soil mapping offers the opportunity for every portion of the landscape to be treated in line with its real capabilities and constraints.