



Digital Soil Mapping for Site-Specific Nutrient Management: Integration of GIS, Remote Sensing, Proximal Sensing and Machine Learning

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Soil fertility rarely follows the neat, uniform pattern assumed by blanket fertilizer recommendations; nutrient levels can vary sharply within the same field. Digital Soil Mapping (DSM) addresses this by integrating Geographic Information Systems (GIS), remote sensing, proximal soil sensing and machine learning to generate high-resolution, spatially explicit maps of soil properties. Satellite and drone imagery capture crop and soil reflectance patterns, proximal sensors such as electromagnetic induction meters and portable X-ray fluorescence devices measure soil attributes in the field, GIS organizes and overlays these datasets, and machine learning algorithms model the complex relationships between them to predict nutrient status across entire farms. Together, these tools enable Site-Specific Nutrient Management (SSNM), allowing farmers to apply the right nutrient, at the right rate, place and time. This article reviews how the four technologies work together, highlights practical applications, and discusses the challenges to wider adoption.

Keywords: Digital soil mapping, Site-specific nutrient management, GIS, Remote sensing, Proximal sensing, Machine learning

Introduction

For decades, fertilizer recommendations in most farming systems have been based on a single soil test result applied uniformly across an entire field, or even an entire block of fields. Yet soils rarely behave so simply. Differences in parent material, topography, drainage, and historic management create considerable variability in nutrient availability within short distances, sometimes within the same field. Applying a blanket recommendation under such conditions inevitably means over-fertilizing some zones, and under-fertilizing others, wasting inputs, reducing farm profitability, and contributing to nutrient runoff and greenhouse gas emissions. Site-Specific Nutrient Management (SSNM) was developed to address this problem by tailoring fertilizer application to the actual needs of small, homogeneous management zones within a field. Making SSNM practical at scale, however, requires the ability to map soil properties in fine spatial detail across large areas quickly and affordably. Digital Soil Mapping (DSM), built on the integration of Geographic Information Systems (GIS), remote sensing, proximal soil sensing and machine learning, has emerged as the technology capable of doing exactly that.

What is Digital Soil Mapping?

Digital Soil Mapping is the process of creating spatial soil information using field and laboratory observation data combined with environmental variables, statistical or machine learning models, and GIS. Instead of relying solely on sparse soil survey points and manual interpolation, DSM uses continuous data layers, such as terrain attributes, satellite imagery and sensor readings, to predict soil properties like nitrogen, phosphorus, potassium, organic

carbon, pH and electrical conductivity at every location across a field, not just where samples were physically collected.

Remote Sensing for Soil and Crop Assessment

Satellite platforms such as Sentinel-2 and Landsat, along with unmanned aerial vehicles (drones) fitted with multispectral and hyperspectral cameras, capture reflectance data from soil and crop canopies. Vegetation indices derived from this imagery, such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Red Edge Index (NDRE), are closely linked to chlorophyll content and nitrogen status, making them valuable indirect indicators of nutrient stress across a field. Bare-soil imagery, captured after tillage or before crop emergence, can also reveal patterns in organic matter and texture through subtle differences in surface reflectance, helping to delineate zones of differing fertility even before any crop is sown.

Proximal Soil Sensing

While remote sensing observes the field from above, proximal sensors are operated close to or in contact with the soil, offering more direct and often more accurate measurements. Tractor-mounted electromagnetic induction (EMI) sensors and electrical resistivity meters measure apparent soil electrical conductivity, which correlates with texture, moisture and salinity. Portable X-ray fluorescence (XRF) and near/mid-infrared spectroscopy devices allow rapid, on-the-go estimation of nutrient concentrations and organic carbon without the delays of conventional laboratory analysis. Because proximal sensors can be mounted on machinery already used for other field operations, they make it feasible to collect dense, farm-scale nutrient data at a fraction of the cost of conventional grid soil sampling.

GIS: The Integration Platform

GIS provides the spatial framework in which satellite imagery, proximal sensor readings, terrain data (such as elevation, slope and aspect derived from digital elevation models) and laboratory soil test results are layered, aligned and analyzed together. Through spatial interpolation techniques such as kriging and inverse distance weighting, GIS converts point-based soil test data into continuous surfaces, and through overlay analysis it helps identify management zones that share similar soil and terrain characteristics. GIS is also the platform on which the final nutrient prescription maps are generated, formatted, and exported for use in variable-rate fertilizer applicators.

Machine Learning: From Data to Decision

The relationships between remote sensing indices, proximal sensor readings, terrain attributes and actual soil nutrient concentrations are rarely simple or linear. Machine learning algorithms, including random forest, support vector regression, gradient boosting and increasingly deep learning models, are well suited to capturing these complex, non-linear patterns. Trained on soil samples that have been analyzed in the laboratory, these models learn to predict nutrient levels for every pixel of a field using only the more easily collected remote sensing and proximal sensor data, dramatically reducing the number of expensive laboratory tests needed while still producing a detailed, field-wide nutrient map.

Site-Specific Nutrient Management in Practice

Once a DSM-derived nutrient map is available, it can be converted into a variable-rate application (VRA) prescription map that instructs GPS-guided fertilizer spreaders or seed drills to automatically adjust application rates as the machine moves across the field, applying more fertilizer in nutrient-poor zones and less where soil fertility is already adequate. This targeted approach ensures crops receive nutrients matched to actual local requirements, improving nutrient use efficiency, reducing input costs, and minimizing the leaching and runoff losses associated with blanket over-application.

Benefits and Real-World Applications

The integration of these four technologies is already being applied in precision agriculture programmes worldwide, from large mechanized farms in North America and Europe to progressive farmer cooperatives in parts of Asia. Reported benefits include reduced fertilizer costs through more efficient input use, more uniform crop growth and yield across a field, and reduced environmental impact from nutrient runoff. Beyond nutrient management, the same DSM infrastructure supports soil health monitoring, carbon stock assessment, irrigation scheduling and yield prediction, making the initial investment in mapping technology valuable across many aspects of farm management.

Challenges and the Way Forward

Despite its promise, wider adoption of DSM-based SSNM faces several hurdles. High initial costs of sensors, drones and variable-rate equipment remain out of reach for many smallholder farmers. Model accuracy depends on adequate ground-truth soil sampling, which is still limited in many regions, and integrating data from multiple sensor types and platforms requires technical expertise not yet widespread among extension services. Cloud cover can limit optical satellite imagery availability, and rural connectivity constraints can hinder real-time data processing. Addressing these barriers will require continued investment in affordable sensor technology, farmer training, open-access soil databases, and stronger links between research institutions, extension agencies and equipment manufacturers.

Conclusion

Digital Soil Mapping, built on the combined strengths of GIS, remote sensing, proximal sensing and machine learning, is transforming nutrient management from a uniform, field-level practice into a precise, zone-specific science. By revealing the fine-scale variability that blanket soil testing overlooks, this integrated approach allows farmers to apply fertilizers more efficiently, protect the environment, and improve profitability. As sensor costs continue to fall and machine learning models improve, Site-Specific Nutrient Management guided by digital soil maps is set to become an increasingly practical and essential tool for sustainable, precision agriculture.

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