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Digital Soil Mapping and Smart Soil Monitoring Technologies

Bhanu Pratap Singh Raghubanshi[1], Amrutrao Hindurao Patil[2], Satish[3], Imtilemla[4], Shashikant[5]

[1]Sr.Technical Officer, Soil Science, Rajmata Vijya Raje Scindhia Krishi Vishwavidyalaya, Gwalior, Krishi Vigyan Kendra, Lahar, Bhind.
[2]Assitant Professor, Department of Soil Science, BV's LMK College of Agriculture, Kadegaon.
[3]Ph.D Scholar, Department of Farm Machinery and Power Engineering, University of Agricultural Sciences, Raichur,
[4]SMS, Soil Conservation KVK, Mokokchung.
[5]Ph.D Research Scholar, Division Soil Science and Agricultural Chemistry, University Banaras Hindu University, Varanasi.

*Corresponding Author
Bhanu Pratap Singh Raghubanshi*

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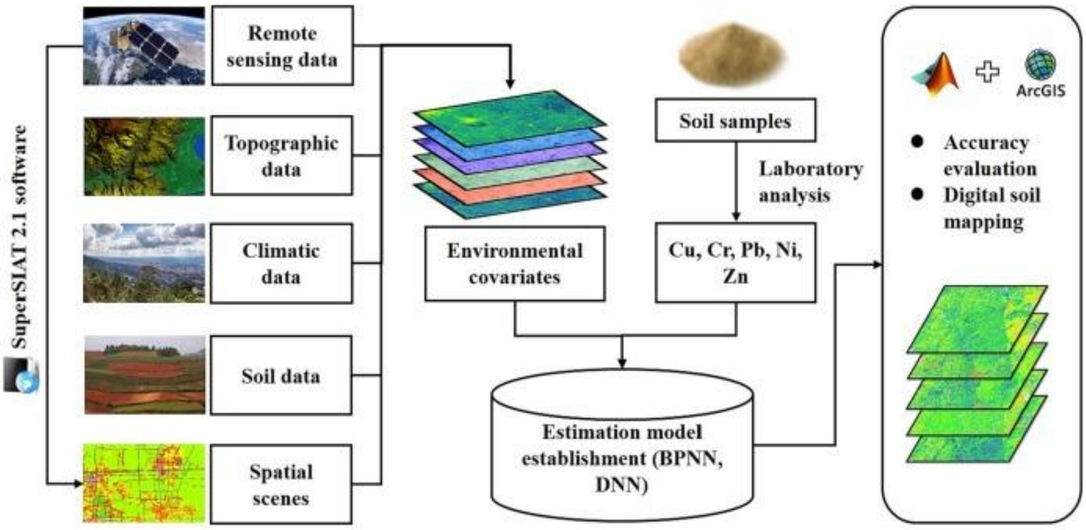
INTRODUCTION

Soil is essential to agricultural production and to the sustainability of the environment and functioning of ecosystems. It is the medium of plant growth; it controls the water cycle, is a reservoir of carbon, and is the home of biodiversity. Nevertheless, growing population demands, climate change, land degradation and non-sustainable agriculture have led to an even greater soil information demand. Conventional soil surveys, while useful, are costly and often cover small spatial extents. Traditional methodologies for monitoring soils (such as analysis of laboratory-based samples) are based on periodic sampling, which may not capture temporal changes on agricultural lands, or detect agricultural management-induced soil dynamics. Therefore, new techniques are essential for modern agriculture to meet its challenge of delivering soil information continuously and with spatial specificity.

The advent of DSM and Smart Soil Monitoring Technologies represents a new era for soil-based knowledge and solutions. These novel technologies, which combine geospatial, remote sensing, machine learning algorithms, sensor networks, and artificial intelligence, offer unprecedented detail in soil property and health over large extents, and allow for optimal soil management.

2. Concept of Digital Soil Mapping

DSM is a modern method for producing detailed soil information at fine spatial scales, based on quantification of the relationships between environmental variables and observed soil properties. In contrast with traditional soil surveys, DSM relies on integration of field observations and laboratory analyses with geospatial technologies and predictive modeling to generate soil maps in a timely and accurate manner at a much higher resolution.



A widely accepted framework for DSM is the SCORPAN model proposed by McBratney, which states that soil properties can be predicted as a function of existing soil characteristics (s), climate (c), organisms and vegetation (o), relief or topography (r), parent material (p), age (a), and spatial location (n). By combining soil observations with these environmental covariates, DSM enables the prediction and mapping of important soil attributes across landscapes. These attributes include soil organic carbon, soil texture, soil pH, electrical conductivity, nutrient availability, soil moisture, and bulk density. The integration of remote sensing, Geographic Information Systems (GIS), machine learning, and environmental data in DSM has significantly enhanced the accuracy and efficiency of soil resource assessment, making it an essential tool for precision agriculture, land-use planning, and sustainable soil management.

3. Components of Digital Soil Mapping

DSM is based on three pillars: soil data, environmental covariates, and a predictive model. Reliable observations of soils underpin DSM and are acquired by field survey and sampling, soil profile description, laboratory soil analyses, and soil sensing. Soils observations are accompanied by environmental covariates (factors of soil formation and spatial variability) such as topographic features (elevation, slope, aspect), climatic factors (temperature, precipitation), vegetation proxies (NDVI, biomass), lithologic proxies (parent material), or remote sensing-based products (spectral reflectance). Quantitative relationships between soil properties and associated environmental variables are derived by predictive modeling approaches, including advanced machine learning algorithms, and subsequently used to predict accurate and high-resolution soil maps for efficient soil resource evaluation and management.

4. Role of Remote Sensing in Digital Soil Mapping

Remote sensing has great potential in DMS as it can supply quickly, inexpensively, and homogeneously spatial information for soil evaluation and monitoring. Soil and land surface information can also be derived from satellite platforms of the U.S. NASA’s series of Landsat and MODIS, the European Space Agency’s Sentinel-1, Sentinel-2 and others. These are the remotely sensed products that have been extensively analyzed for retrieving soil moisture, estimating soil organic carbon, assessing land degradation, detecting salinity and investigating crop-soil interactions. In addition, satellite systems afford repeated observations, enabling temporal surveillance of soil condition, which contributes to enhanced soil resource and precision agriculture.

5. Artificial Intelligence and Machine Learning in DSM

Artificial Intelligence (AI) and machine learning have greatly improved the accuracy, efficiency, and predictive power of Digital Soil Mapping (DSM) by facilitating the modeling of complex interactions among soil properties and environmental variables. Random Forest (RF) is one of the most popular algorithms because it not only has a high prediction accuracy, but also can handle large datasets and high dimensional data, and is less prone to overfitting, and can effectively model nonlinear relationships between dependent and independent variables. Support Vector Machine (SVM) is widely used for soil classification, nutrient estimation, and land suitability evaluation, and Artifcial Neural Networks (ANNs) repay special attention for their potential in pattern recognition and in simulation of nonlinear soil processes in multidimensional data. More recently, Deep Learning (DL) methods have emerged as the best choice for applications including soil image classification, analysis of hyperspectral data, and prediction of soil properties. These AI based approaches have been instrumental in enhancing the accuracy and dependability of soil mapping that in turn facilitates evidence-based decision making in precision agriculture and sustainable land management.

6. Smart Soil Monitoring Technologies

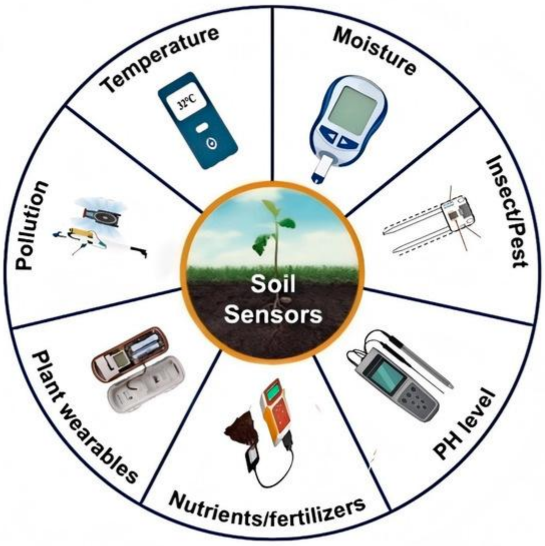
Smart soil monitoring is the monitoring of soil through the use of sensors, communication networks, cloud computing, and artificial intelligence in an automatic, continuous and real-time manner. These systems employ a collection of sensors to capture relevant information such as soil moisture or temperature, and visibly report on soil health and fertility indicators such as moisture content, temperature, pH, electrical conductivity, and levels of nutrient. The accumulated information is sent using wireless communication techniques such as Wi-Fi, Bluetooth, ZigBee, LoRaWAN, and NB-IoT, making it possible for field sensor and data management platform to connect well with each other. Cloud-based storage and computing enable collection, processing, visualization and the remote access of large amounts of soil data, durability of sensors-generated data is improved by artificial intelligence (AI) and advanced analytics, offering actionable outputs in scheduling irrigation, nutrient management, and disease risk prediction. These integrated systems are instrumental in precision agriculture, contributing to improved resource-use efficiency, crop productivity, and sustainable soil management.

7. Internet of Things (IoT) in Soil Monitoring

The Future Internet of Things (IoT) has been recognized as one of the important technologies for the development of soil monitoring systems as it allows the integration of multiple sensors, devices and communication systems over the internet to realize on-line data acquisition, analysis and automated decisions. IoT-enabled soil monitoring systems monitor essential soil factors in real-time and the data gathered are sent to cloud platforms for analysis and storage. This technique has many benefits such as continuous monitoring of soil, less labor and prompt notifications for early intervention, precision irrigation, efficient fertilizer management etc. Generally, the overall workflow of an IoT-enabled soil monitoring system contains data sensing by field sensors and then sending readings to a gateway, data storage and processing using cloud platforms, data analysis with AI and ML techniques, and finally offering actionable recommendations for farmers. By enabling timely management decisions that are specific to the site, IoT can greatly improve resource use the efficiency, crop productivity, and sustainability in precision agriculture.

8. Smart Sensors for Soil Health Monitoring

Smart sensors are also the basic units of current soil monitoring systems, which allow monitoring soil health in real time and aid in the development of precision agriculture. Soil moisture sensors have found wide applicability in irrigation scheduling, water conservation and drought monitoring by offering real-time data on soil water condition. pH sensors are used to measure soil acidity or alkalinity, aiding liming recommendations and the evaluation of nutrient availability for the best crop growth. Electrical conductivity (EC) sensors can be used to identify salinity problems in soil and soil fertility conditions, since EC correlates with the concentration of soluble salts and nutrients in the soil. In addition, nutrient sensors can also detect major plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K), providing the farmers with on-the-go updates on nutrient dynamics. These sensor-based smart soil monitoring systems enable site-specific nutrient management, enhance resource-use efficiency, reduce input waste, increase crop productivity, and support sustainable soil management.



9. Integration of DSM and Smart Monitoring Systems

The combination of Digital Soil Mapping (DSM) and real-time soil monitoring via smart soil probes brings new possibilities in soil management and precision agriculture. Although DSM is concerned with mapping the spatial variability of soil properties and at the same time assists in long term planning, soil resource inventory and land evaluation, smart monitoring technologies monitor temporal variations of soil conditions and enable soil management decisions in real time. Monitoring systems based on sensors offer dynamic evaluations of soil quality, adding to the static information about space produced by digital soil maps. Collectively, these technologies facilitate the exploration of knowledge in the temporal and spatial heterogeneity of the soil resource to promote precision farming, site-specific management and decision making. The synergetic application of these two technologies holds great promise for increasing agricultural productivity and efficient use of resources while mitigating negative impacts on the environment and fostering sustainable development of modern farming systems.

10. Applications in Precision Agriculture

Digital soil mapping (DSM) and smart-soil monitoring technology are expected to be key technologies for precision agriculture to realize accurate, location-based, and real-time service for farm management. These technologies enable nutrient management at site level through variable rate application of fertilizers according to spatial variation in properties of soils, which contribute to increase in efficiency of nutrient use and decrease of input cost. Precision irrigation is performed based on continuous measurement of soil moisture to apply water optimally and reduce water use. In addition, the monitoring of major indexes of soil health including pH, moisture, salinity and nutrients status in a near continuous manner enable sound soil health management. Combined with machine learning algorithms, the soil, weather, and crop data can also be used to predict yields accurately, giving farmers an additional incentive to make production decisions. In addition, DSM and smart monitoring technologies contribute to climate-smart agriculture (CSA) by enabling a range of adaptation and mitigation strategies and improving resource use efficiency, building resilience to climate variability and facilitating sustainable agricultural production systems.

11. Benefits of Digital Soil Mapping and Smart Monitoring

DSM and smart soil monitoring are the source for the significant economic, environmental and societal benefits of the Green Revolution and promise to do so also for the next generation; they are clearly the most important factors for sustainable agricultural development. In terms of economics, these technologies contribute to the reduction of input cost by efficient use of fertilizers, water and other inputs, and by increasing crop productivity and farm profitability. Environmentally, they promote sustainable resource management by preventing nutrient depletion, decreasing emissions of greenhouse gases related to overuse of inputs, and enhancing site-specific management practices for soil conservation. From a social perspective, the use of these technologies improves food security through higher productivity and greater resilience of agriculture, and enables farmers with real-time, data-driven advice for affected decision-making. They also promote sustainable land management practices, which contribute to the production and health of soil resources for future generations.

12. Challenges and Limitations

Nevertheless, there exist a number of technical, economic, and operational challenges DSM and smart soil monitoring techniques face that may prevent them from being widely used. Technical challenges include sensor calibration, measurement accuracy and data reliability and limited network connectivity mainly in rural areas. Economic limitations like initial high investment, need of infrastructure and maintenance may be strong impediment, particularly for small scale farmers. Furthermore, the vast amount of data collected from sensors, satellites and other monitoring platforms present challenges for data storage, processing, standardization, and inter-operability across various technology and system. To fully benefit from these technologies, a certain level of technical know-how is also necessary, which makes farmer training, capacity building, and extension support all the more imperative. Overcoming these challenges is key to guarantee that digital soil management systems are successfully introduced and maintained in the agriculture of the future.

13. Future Perspectives

Soil management is poised to become more digital, data intensive and smart with the fast evolution of new technologies. AI-based soil intelligence is also posited to improve predictive analytics by allowing for better prediction of the behavior of soil characteristics, nutrients, and suggestions for management. The building of digital twins of soil systems, virtual constructs of actual soil environments, will enable simulation, forecasting and decision-making over agricultural and climatic conditions. Drone-based soil surveying and monitoring with UAVs will generate high-resolution spatial data for accurate evaluation of soil and crops, and hyperspectral imaging techniques will contribute to improving it by spectral profiling of soil properties. Moreover, the development of autonomous sensor networks, integrated with self-powered sensors and real-time communication technology, will allow for continuous and effective soil monitoring with less human involvement. The coupling of DSM and smart monitoring system with climate models will further facilitate climate-smart agriculture, sustainable land-use planning, and adaptive management. Together, these advances in managing the soil resource are expected to have a transformative effect on soil management practices and to a large extent on sustainable agricultural intensification and global food security.

CONCLUSION

DSM and Smart Soil Monitoring technologies bring a new era of soil science and precision agriculture. Integrating geospatial technology, remote sensing, IoT, AI, ML, and sensor network, these methodologies offer reliable, timely, and spatially explicit information about various soil properties and soil health. Their utilization leads to substantial increases in resource use efficiency, crop production, environmental sustainability and climate resilience. While cost and data management and technical capacity issues still persist, these are anticipated to be overtaken by further developments in AI, cloud computing and sensor technologies signifying a ramping up of their application globally. Such innovations are expected to be instrumental for sustainable agriculture and global food security in the next decades.