Mapping Our Soils Digitally for a Sustainable Agricultural Future

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ABSTRACT

Digital Soil Mapping (DSM) is a transformative tool in sustainable agriculture; where the goal is to optimize productivity while conserving resources and minimizing environmental impacts. By providing high-resolution, data-rich insights into soil properties and their spatial variability, DSM supports the principles of sustainability in several key ways. DSM is a modern approach to understanding and representing the spatial variability of soil properties using computer-based techniques, geographic information systems (GIS) and remote sensing. It builds on traditional soil surveys but offers more flexibility and precision.

INTRODUCTION:

Machine learning techniques (Digital soil mapping) offer advantages in managing complexity with limited number of soil samples. However, Digital soil mapping (DSM) is an internationally recognized approach to quickly map the soil properties at higher resolution based on the observed values at the sampled sites and other environmental covariates along with the estimates of accuracy and uncertainty. DSM is the development of spatial information system on soil properties and soil classes based on the relationship between soil properties and environment covariates. DSM works based on SCORPAN model was proposed by McBratney *et al.* (2003) where soil class or

soil property (S) at particular location are derived indirectly from the environmental variables: climate (c), organisms (o), relief (r), parent material (p), age (a) and spatial location (n)

$$S = f(S, C, O, R, P, A, N)$$

Selection of environmental covariates related to soil development is important in digital soil mapping. Legacy soil data, remotely sensed imageries, land use land cover map, lithology map, Digital elevation model, long term climatic datasets are the important environmental covariates represented for SCORPAN variables. In general, the relationship between soil and co-variables are always not linear, but the non-linear relationship between the variables can be captured using machine learning methods in DSM approach.

Importance of Digital Soil Mapping in Sustainable Agriculture

1. Precision in Resource Use: DSM allows for detailed understanding of soil characteristics such as texture, organic matter content, pH and nutrient levels. Detail soil resources information of South Gujarat, India was developed using digital soil mapping techniques (Jangir et al., 2024). This information enables farmers to apply water, fertilizers and pesticides exactly where and when they are needed, reducing overuse and wastage of these resources. This is vital for conserving natural resources and reducing the environmental footprint of agriculture.

2. Soil Health Management: Sustainable agriculture hinges on maintaining healthy, fertile soils. DSM helps monitor and manage soil health by identifying areas prone to erosion, compaction, or nutrient depletion. This allows for targeted interventions like crop rotation, cover cropping, or soil amendment, preserving long-term productivity.

3. Adaptation to Climate Change: As climate change affects soil conditions (e.g., through increased salinity, altered moisture regimes), DSM provides up-to-date maps that reflect these changes. This helps farmers adapt their practices to sustain yields in a changing climate while protecting the soil from degradation.

4. Minimizing Environmental Impact: DSM helps in implementing practices like precision fertilization and irrigation, which minimize nutrient runoff and soil erosion. By applying inputs more efficiently, DSM reduces the risk of water contamination, loss of biodiversity and greenhouse gas emissions, contributing to the overall sustainability of agricultural practices.

5. Uncertainty Quantification: DSM also offers the ability to quantify uncertainties in soil predictions. This is crucial in sustainable agriculture, as it helps farmers and land managers make informed decisions, especially in areas where data might be sparse, thereby reducing risks associated with soil variability.

Applications of Digital Soil Mapping in Sustainable Agriculture

1. Precision Agriculture:

- DSM is the foundation of precision agriculture, which involves variable-rate applications of fertilizers, pesticides and irrigation based on soil conditions. This targeted approach reduces input use, enhances soil health, and improves yield, aligning perfectly with sustainable agricultural practices.

2. *Soil Conservation Planning*:

- DSM can identify areas that are susceptible to soil erosion, degradation, or compaction.

Farmers can use this information to implement conservation techniques like contour plowing, no-till farming, or planting cover crops to protect vulnerable soils, thereby preventing soil loss and maintaining fertility over time.

3. *Water Management:*

- Water is a critical resource in sustainable agriculture, and DSM provides detailed maps of soil moisture retention and drainage characteristics. This helps farmers develop efficient irrigation systems that minimize water usage, prevent waterlogging and reduce the strain on water resources, particularly in drought-prone regions.

4. *Nutrient Management:*

- DSM enables precise mapping of soil nutrient levels, allowing farmers to apply the right amount of fertilizers exactly where they are needed. This prevents nutrient leaching into water bodies, reducing the risk of eutrophication, while maintaining soil fertility. Efficient nutrient management also reduces the carbon footprint associated with fertilizer production and use.

5. *Carbon Sequestration:*

- Sustainable agriculture practices often focus on increasing soil organic carbon, a key component in improving soil structure and fertility and mitigating climate change. DSM can map soil organic carbon levels across landscapes, helping land managers target areas where carbon sequestration efforts will be most effective.

6. *Land-Use Planning:*

- Sustainable agriculture involves careful planning to ensure that the most suitable areas are used for farming while protecting ecosystems and biodiversity. DSM provides data for zoning decisions, guiding where agriculture should take place and where land should be set aside for conservation or restoration. This helps balance agricultural productivity with environmental preservation.

7. *Erosion Control:*

- By identifying areas with high erosion risk, DSM supports the adoption of soil conservation techniques. Farmers can implement erosion-control strategies such as terracing, buffer strips, or reduced tillage in areas identified as erosion-prone, preventing the loss of topsoil and maintaining soil fertility.

8. *Monitoring and Restoration of Degraded Lands:*

- DSM can be used to assess the current state of degraded lands and monitor changes over time. It helps in planning land restoration efforts by pinpointing the most degraded areas and guiding the application of amendments or conservation practices to restore soil health and ecosystem function.

9. *Climate Resilience:*

- DSM can help farmers adapt to climate variability by providing real-time or predictive data on soil moisture, temperature and fertility under changing conditions. This helps in adjusting planting schedules, irrigation plans and crop choices to maintain productivity while protecting the environment.

10. *Supporting Sustainable Certification:*

- For farmers aiming to achieve sustainability certifications (e.g., organic farming or regenerative agriculture), DSM can provide the detailed soil information needed to meet the certification criteria. It allows for continuous monitoring of soil

health indicators, ensuring compliance with sustainable farming standards.

CONCLUSION

Digital Soil Mapping is a powerful tool in sustainable agriculture, offering precise and actionable insights into soil properties that allow for more efficient and environmentally responsible farming. Its applications range from precision agriculture and water management to soil conservation and carbon sequestration, all of which are critical for maintaining soil health and productivity while minimizing negative environmental impacts. By integrating DSM into agricultural practices, farmers can achieve higher productivity, adapt to climate change and contribute to the long-term sustainability of global food systems.

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