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Remote Sensing and GIS Applications in Soil Mapping and Classification

[1]Anil Kumar, [2] Shikha Ojha

[1]Research Scholar, Department of Soil Science, Sardarkrushinagar Dantiwada Agricultural University Gujarat

[2]Research Scholar, Department of Agronomy, Navsari Agricultural University, Navsari

Abstract

Soil mapping and classification are critical components of sustainable land use planning, precision agriculture, and environmental management. Traditional methods of soil surveys, though reliable, are often time-consuming, labor-intensive, and limited in spatial coverage. The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has revolutionized the process of soil data acquisition, interpretation, and spatial analysis, offering a rapid, cost-effective, and comprehensive approach to soil resource assessment. Remote sensing utilizes satellite and aerial platforms to capture multispectral and hyperspectral imagery that reflects the physical and chemical properties of soils. Variations in soil texture, moisture, salinity, organic matter, and erosion can be effectively detected and monitored using spectral signatures and image processing techniques. Platforms such as Landsat, Sentinel, and ASTER provide valuable temporal and spatial data that can support large-scale soil mapping efforts. GIS complements remote sensing by enabling the integration, storage, and analysis of spatial and non-spatial soil data. It facilitates the development of digital soil maps, the classification of soil types, and the generation of thematic layers such as pH, fertility, erosion risk, and land capability. Spatial interpolation techniques like kriging and inverse distance weighting (IDW) further enhance map accuracy and usability. Together, RS and GIS offer a powerful framework for generating detailed and dynamic soil information across diverse landscapes. They support decision-making in agriculture, land reclamation, irrigation management, and climate adaptation

strategies. Despite challenges such as image resolution limitations and the need for ground-truthing, advances in machine learning, drone-based sensing, and cloud-based GIS platforms are addressing many constraints.

Introduction

Soil is an essential natural resource, which serves agricultural output, ecological balance and sustainable stewardship of land. The knowledge of soil properties, distribution and classification are important to make informed decisions in agricultural, forestry management, water resource management and also in the environmental conservation. Land capability assessment, crop management practice planning, forecasting land degradation and site-specific interventions depend on a soil mapping and classification. Conventional ways of surveying soils include surveys done on large areas in the field, gathering of samples, testing in the laboratory and mapping by hand. Though these techniques can be trusted, they tend to be spatially and temporally limited, time consuming and costly. As demands within developing markets and densely populated areas grow which require and request timely and high-resolution soil data coverage more efficiently and cost-effective methods are required that are scalable. Here Remote Sensing (RS) and Geographic Information Systems (GIS) have come out as revolutionary instruments. Remote sensing is the process of getting information about the earth surface without making direct physical contact to it either by the use of satellite or aerial sensors. RS allows acquisition of real time or periodic measurements of vast surfaces, even discovering changes in measures of soil moisture, salinity, texture and organic matter as well as erosion and other physical parameters. The presence of the so-called multispectral and hyperspectral imaging advances gives the opportunity to interpret soil spectral signatures to be better interpreted, which means that it is possible to distinguish land types and conditions. Geographic Information Systems (GIS) are powerful tools of capturing storage, analyzing and visualizing geospatial data. Used together with remote sensing, GIS allows the creation of thematic soil maps, spatial analysis and modeling, as well as the interpretation of complicated data. Development of RS/GIS aids fast classification of soil, change detection of soil, and how the soil is compressed over a period.

Principles of Soil Mapping and Classification

Soil mapping and classification is basic element of soil science assisting in recognizing the location of the soil, physical and chemical properties and the possible use of soil resources. Such tools are important in planning agriculture, determining the ability of the land and environmental conservation. Although soil mapping is working on the geographic placement of the various soil types, soil classification is on the other hand showing a systematic use of determining and also classifying soils in line with their properties. The science of soil mapping is the activity by which area is surveyed, soil samples are gathered, their character used to make maps which show the kind, area, and quality of soils in a landscape. Such maps can contain data about soil texture, structure, drainage, soil pH, salinity, organic matter, and fertility level. The soil maps are drawn at various scales, i.e., the large-scale maps (1: 10,000-1:25,000) are capable to do assessments at the site, and the small-scale maps (1:250, 000, or smaller) are good to do planning of regions or the whole countries. Classification of soils, however, implies the division of soils into groups according to some common physical, chemical and biological peculiarities. Other internationally-recognized systems are the USDA Soil Taxonomy, the World Reference Base for Soil Resources (WRB) and the FAO soil classification. The hierarchical system applied by these systems involve that they are composed by soil orders, orders, great groups, subgroups, families and series. Classification contributes to the genesis of soil, its behavior and appearance or its suitability in different uses.

There are some soil properties which can be regarded as the key indicators when mapped and classified:

• **Texture**: This is the proportion of sand, silt and clay which influences keeping water and aeration.

• **Structure**: The organisation of soil particles into larger agglomerates that affects root penetration as well as water movement.

• **Color**: Shows content of organic matter and drainage.

• **Moisture levels:** Helpful to know how to irrigate and which crops can be grown.

• **pH and salinity**: Can influence the availability of nutrients and the tolerance of the crop.

The traditional soil survey is accurate, time-consuming, and a field sample-based laboratory examination followed by manual interpretation. These processes may be improved by the inclusion of Remote Sensing (RS) and Geographic Information Systems (GIS) to offer timely, consistent and large data of soil at improved spatial accuracies.

The place of Remote Sensing in Soil Studies

Remote sensing (RS) is essentially now central in the contemporary soil research in that it allows us to observe, examine and track properties of soils at broad spatial scales with high temporal resolution. As opposed to conventional approaches, where the soil is required to be measured under field conditions and then thoroughly examined with fresh samples in a laboratory, remote sensing is a quick, cost and scale-friendly method of measuring the soil. With the satellite imagement, aerial photos, and UAV (drone) systems, remote sensing will enable identifying the surface soil properties using the spectral reflectance behavior.

Depending on physical and chemical characteristics of soils, their spectral signatures are singular. The parameters moisture contents, organic matter, soil texture, salinity, and iron oxide contents simultaneously affect the influence of soils to diffuse the electromagnetic done in visible, near infrared (NIR), and short wave infrared (SWIR) frequencies. Using multispectral and hyperspectral sensors, differences between various types of soil and the changes in conditions can be identified by analyzing this reflectance.

Soil studies that utilize key remote sensing platforms are:

• Landsat (e.g. Landsat 8): Provides a moderate-resolution imagery applicable in regional soil mapping.

• Sentinel-2: Offers multispectral data (1020 m) of high resolution suitable in tracking agriculture and ground surveys.

• ASTER and MODIS: These are helpful in soil thermal and mineralogical studies.

• Hyperspectral sensors (e.g., Hyperion): Provide the ability to perform in depth spectral analysis to characterize soil.

• Drone-mounted sensors: they allow collecting highly resolved data, especially small-scale site-specific investigations.

The remote sensing applications in the study of soil are:

• Soil moisture estimation: To apply microwave and thermal waves to plan irrigation and to monitor drought.

Soil Salinity mapping: Using spectral derivations based on certain bands of wavelengths.

• Soil erosion evaluation: Over time land degradation is monitored through use of vegetation and bare soil indices.

• Mapping of soil organic carbon: Using reflectance variations owing to variation in the organic matter component.

GIS in Soil Mapping and Classification

The Geographic Information Systems (GIS) have gained prominence in soil mapping and classification which led to the successful acquisition, storage, exploration and mapping of spatial and non-spatial data of soils. Traditional soil survey processes have the advantage of GIS allowing integration of multiple datasets data such as remote sensing imagery, topographic maps, field observations and laboratory findings to be continued into a unified spatial context in order to carry out complete soil studies.

It is accompanied by the design of digital soil maps which is one of the major uses of GIS in soil studies. GIS allows the creation of detailed and precise maps of soil types and properties (e.g. pH, organic carbon, texture), soil suitability types (e.g. crop type and suitability classification, soil group and suitability classification, soil type and suitability classification), using geocoded field data and thematic layers. This type of maps may be prepared in different scales to assist in local to regional planning activities.

The other important attribute of GIS is spatial analysis. GIS with the use of overlay analysis, buffer regions, and spatial interpolation enables a researcher to analyze the correlation of soil characteristics and other environmental characteristics like slope, elevation, land use, and rainfall. Kriging, inverse distance weighting (IDW) and spline interpolation are useful methods that assist in determining the attributes of soil in the unsampled points and in turn enhancing the precision of map.

GIS can also serve a role in soil classification (see soil classification), associating attribute data (such as used by soil taxonomies systems) to areas. It is through this integration that the automatic categorization or even reclassification of soil data would occur depending on a particular criteria like land capability, fertility status or anything dealing with erosion.

GIS improves on decision-making in:

• Precision agriculture: Allowing the management of soil in a site-specific basis on spatial variability.

• Land use planning: Findings use that will possibly be ample to farming, grazing or determination.

• Soil degradation measuring: Observing the variation in the quality of soil in the long-run.

ArcGIS, QGIS, and Google Earth Engine are GIS platforms, which offer efficient features to manage and analyze soil data. The open-source GIS-tools have also decentralized the spatial analysis by ensuring that access to spatial soil information is more accessible to the researcher, government agencies, and farmers.

In spite of the benefits, GIS demands the quality data and technical competencies with respect to data management, spatial modeling and chart reading. When combined with remote sensing and field data, GIS has a significant performance in enhancing efficiency, accuracy, and scalability of soil mapping and soil classification exercises that eventually lead to sustainable soil and land resource management.

Soil mapping using RS and GIS Methodology

Combination of Remote Sensing (RS) and Geographic Information Systems (GIS) offers useful model in soil mapping and classification. The approach entails collection of field data combined with analysis of satellite images, processing of spatialized data and map production. This combined methodology provides cognizance about enhanced precision, effectiveness, and scalability in the evaluation of soil. The procedures followed are as given below:

1. Preparing data and Collection of data

Obtaining primary and secondary data is the first step of the process:

• Remote Sensing Data: Satellite imagery with satellites such as Landsat, Sentinel-2 or ASTER, or UAV/Drone higher resolution images.

• Ancillary Data: DEMs (Digital Elevation Models), Topographic maps, land use/landcover maps and climatic data.

• Field Survey Data: A ground-truth is necessary. The parameters that undergo the measurement are soil texture, pH, salinity, organic matter, and moisture, performed by soil samples.

2. Image Pre-processing

Satellite images clean up such issues as the distortion of atmosphere and sensor noise, as well as misalignment of the geometry of the images. Pre-processing includes:

Radiometric and geometric correction • Radiometric and geometric correction

• Image processing (e. g. contrast stretching)

- Subset or cut (also called clipping) the area of interest (AOI)

3. Classification and Meaning of the Images

The classification of the various kinds of soil types relies on the use of spectra signatures:

• Unsupervised Classification (e.g. K-means, ISODATA): Applied when little ground data exist.

• Supervised Classification (e.g., Maximum Likelihood, Random Forest): Since it needs training data based on field samples, it is not well suited for a high speed.

The Spectral Indices, i.e., NDVI, SAVI, and Salinity Index can be used to help in determining particular soil characteristics as well.

4. Spatial Analysis GIS Based

GIS is applied in terms of spatial layers processing and integration of data and geostatistical analysis. Functions include:

• Overlay analysis to match soil with slope, land use and geology

• Spatial interpolation (e.g., Kriging, IDW) to create an estimation of soil properties at locations where no samples were taken

Thematic mapping - reclassification and zonation

5. Generation and Verification of Map

This processed information is then recognized and produced into digital edition maps of the soil that is presented according to the soil types and categories in geographical clarity. Validation is done with:

• Accuracy evaluation (confusion matrix, coefficient kappa)

• Comparison to known reference information or ground-truth samples

Conclusion

The combination of Remote Sensing (RS) and Geographic Information Systems (GIS) has greatly changed the nature of soil mapping and soils classification to provide an efficient and more modern and data-based alternative to traditional soil survey projects. These earth observation tools offer capability to measure capture analyse and pilot picture the properties of the soil over large and inaccessible territories quicker, cheaper, and more accurately. The different soil parameters that can be detected by remote sensing through multispectral and hyperspectral imaging include the texture, salinity, moisture, and organic matter by the examination of spectral reflectance. Drone-based sensors, platforms such as Landsat, and Sentinel have allowed carrying out regular checks to monitor the soil over time. Such information is essential to the management of soil fertility, the fight against degradation and strategic land usage. GIS as opposed to it is an effective means of spatial soil data management, which allows putting together various layers of information (topography, land use, climate, etc.), as well as perform such sophisticated tasks as interpolation, classification, and models. GIS helps in evidence-based decision-making in agriculture, land capability measurement, watershed management and environmental protection by creating thematic maps and determining spatial patterns. Cumulatively, RS and GIS provide synergetic use in which the quality, resolution and usability of soil information is improved. Although certain limitations can be seen, including resolution limitations, vegetation interference, and the ground validation requirement, technologies, like machine learning, AI-based classification, and cloud computing, improve the means to overcome those limitations constantly and expand the boundaries of soil science. The extensive use of RS and GIS in soil research has colossal potential of attaining food security, reduction of the effects of climate change, and sustained development. Nevertheless, in order to fully capture the potential, there is need to invest in capacity building, open-access data and collaborative platforms. Unless innovations are made, and RS and GIS are regularly integrated within the country soil information systems, they will stay on the cutting edge of present-day soil resource evaluation and land management options.

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