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The role of Geographic Information Systems (GIS) in sustainable agriculture: Assessing soil fertility and land use changes

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Abstract

Sustainable agriculture demands accurate, spatially explicit, and timely information about soil fertility and land-use dynamics. Geographic Information Systems (GIS), often combined with remote sensing (RS), have emerged as powerful tools for mapping, monitoring, and analysing soil properties and land-use/land-cover (LULC) changes over time. This review synthesises recent advances in the use of GIS for soil fertility assessment and land use change analysis within the context of sustainable agriculture. We examine methodologies for generating soil-fertility maps, conducting land suitability analysis, and detecting changes; discuss applications such as precision agriculture, land management, and resource allocation; and evaluate their limitations and prospects. Drawing on global studies and examples from India —including watershed-scale fertility mapping and agricultural land loss due to urbanisation —we demonstrate how GIS-driven insights support decision-making for agricultural sustainability. The review concludes by highlighting future directions: integration with other technologies, improved data collection, and institutional adoption for large-scale sustainable land management.

Keywords: GIS, soil fertility, land use change, sustainable agriculture, land suitability analysis

1. Introduction

Sustainable agriculture aims to meet present food and fibre needs without compromising future productivity or ecosystem health. Achieving this requires accurate, detailed and up-to-date information about soil conditions and how land use evolves ^[1, 2]. Traditional soil surveys and field-based monitoring alone fall short in terms of spatial coverage, frequency, and scalability, especially on large, heterogeneous landscapes. GIS, often in combination with remote sensing, offers a data-driven, spatially explicit, and cost-effective alternative. By overlaying multiple layers — soil data, topography, land use, climate, and cadastral boundaries — GIS enables mapping of soil fertility and land suitability, as well as detecting temporal changes in land use. This review explores how GIS contributes to sustainable agriculture via fertility assessment and land-use monitoring, and how it supports informed decision-making for resource-efficient land management ^[3, 4].

2. Soil Fertility and Land Use Change: Definitions and Importance

Soil fertility refers to the capacity of soil to supply essential nutrients and water to crops, maintain adequate structure and porosity, and support biological activity for healthy plant growth. Key fertility parameters include nutrient content (macro and micro), soil organic matter, pH, texture, structure, bulk density, and moisture-holding capacity. Fertile soils underpin yield stability, crop quality, and long-term sustainability of agriculture ^[5, 6].

Land use change (LUC) involves the conversion or alteration of land cover —for example, from forest or wasteland to agricultural land, or from agricultural use to urban built-up areas. LUC affects soil fertility and ecosystem services. Unsustainable or unplanned conversions may lead to soil degradation, erosion, nutrient depletion, loss of organic matter, compaction, or decline in water-holding capacity. Monitoring such changes is critical to safeguard soil health, maintain

productivity, and balance land-use demand with environmental sustainability.^[7, 8]

In a rapidly changing socio-economic context, with population growth, urbanisation, changing diets, and climate pressures, reliable data on soil fertility and land-use dynamics are essential for planning, sustainable intensification, land conservation, and policy-making^[9, 10].

3. GIS and Remote Sensing in Soil Fertility Assessment

GIS and remote sensing (RS) together allow spatially explicit mapping of soil fertility parameters over large areas, filling gaps left by traditional point-based sampling^[11, 12].

3.1 Methodological Principles

- **Overlay and layer approach:** GIS overlays multiple thematic layers — soil laboratory data, soil type maps, topography (DEM), land use/land cover (LULC), climate, and management history — to spatially represent fertility-related attributes^[13, 14].
- **Interpolation and spatial modelling:** For unsampled locations, GIS uses interpolation (e.g., kriging) or model-based spatial prediction to generate continuous fertility maps. For example, researchers applied spatial modelling and ordinary kriging, along with RS-derived variables, to develop soil quality maps in arid lands^[14, 15].
- **Indices-based soil quality modelling:** Some studies

combine multiple soil attributes (chemical, physical, geomorphologic, and fertility indices) into composite Soil Quality or Soil Fertility Indices (SQI/SFI). GIS integrates these indices to classify land into different fertility categories^[16, 17].

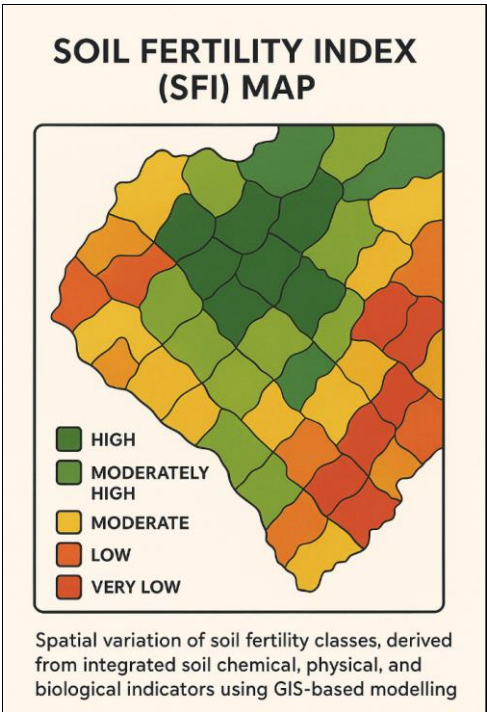
- **Remote sensing data integration:** Satellite imagery, spectral indices (e.g., vegetation indexes, spectral reflectance), and terrain data complement soil sampling to infer fertility-related conditions —such as moisture, organic matter content, and degradation or erosion risk^[17, 18].

3.2 Benefits for Fertility Assessment

- **Large-scale coverage and landscape-level insights:** GIS enables fertility mapping over entire districts, watersheds or regions, beyond what is feasible through only soil sampling^[19, 20].
- **Frequent monitoring and updates:** With updated soil-sample data and RS layers, fertility maps can be revised periodically to reflect changes due to land use, cropping, and soil management^[21, 22].
- **Supporting decision-making:** Fertility maps help identify zones of high fertility, degraded zones needing intervention, or variability within farms — enabling targeted soil management, fertiliser application, and sustainable practices^[23, 24].

Table 1: Soil Fertility Indicators and Measurement Techniques

Soil Fertility Indicator	Measurement Technique	Traditional Method	GIS/Remote Sensing Method	Advantages of GIS/Remote Sensing	Limitations
Soil Organic Carbon (SOC)	Soil sampling, Lab analysis	Gravimetric analysis	Satellite-based NDVI, Vegetation indices	Large-area monitoring, frequent updates	Surface-only measurement, vegetation interference
Bulk Density	Soil coring, Field sampling	Soil core method	GIS-based interpolation	Large-scale prediction of compaction zones	Point-based, can miss localised variation
Soil Moisture	In-situ sensors, Gravimetric	TDR, Gravimetric sampling	SAR, Optical imagery	High-resolution, cloud-independent moisture monitoring	Limited depth measurement
pH	pH meter, Lab testing	Standard laboratory method	GIS overlay of pH maps	Integration with other environmental factors	Depth variability
Nutrient Content (N, P)	Soil test kits, Laboratory	Chemical analysis in the lab	Spectral indices, SoilGrids	Quick mapping, real-time monitoring	Limited by soil types and spectral calibration



4. GIS-Based Land Suitability and Land Use Change Analysis

GIS has proven critical for assessing land suitability for agriculture and tracking land-use/land-cover (LULC) changes core components of sustainable land management^[25, 26].

4.1 Land Suitability Assessment

Land suitability assessment uses GIS to evaluate multiple criteria —soil properties (texture, depth, pH), topography (slope, aspect), climate, water availability — to classify land into suitability categories for specific crops. Techniques often include multi-criteria decision analysis (MCDA), weighted overlay, and suitability scoring. Recent studies proposed combining analytic frameworks (e.g., AHP) with GIS for rigorous land suitability evaluation^[27, 28].

Such suitability maps guide farmers and planners in allocating land for agriculture optimally, choosing crops suited to local soil and climate, avoiding cultivation on marginal or degradation-prone land, and reducing environmental stress^[29, 30].

4.2 Land Use / Land Cover Change Analysis

By comparing classified satellite imagery across different time periods, GIS enables the detection of LULC transitions — e.g.,

agricultural land converted to built-up areas, forest-to-cropland conversion, cropping intensification, and increased fallow land. This provides evidence of land-use pressures, degradation trends, and urbanisation-driven agricultural land loss ^[3, 31].

An Indian study covering 2000-2018 used Landsat imagery and

GIS-based classification to quantify the shrinkage of agricultural land and the expansion of non-agricultural uses in the Allahabad district. r Other studies globally and in developing regions apply similar methods for land-use change detection and impact assessment on soil health and ecosystem services ^[32, 33].

Table 2: Land Suitability Categories for Crops

Crop Type	Soil Suitability Criteria	Topographic Conditions	GIS-based Methods	Land Suitability Classification
Rice	High SOC, Low pH, Clay to Loam soil	Flat to gently sloping areas	Weighted overlay analysis, AHP-based suitability maps	High suitability in plains, low in hilly regions
Wheat	Moderate SOC, Neutral pH, Loam	Slightly sloped, well-drained	GIS-based suitability, spatial modelling	Suitable for moderately sloped lands
Maize	Moderate SOC, Slightly acidic pH, Loamy soil	Moderate slope, dry climate	Land suitability analysis, Spatial Decision Support Systems (SDSS)	Medium suitability, high irrigation demand
Cotton	Low SOC, Alkaline soil, Sandy Loam	Flat, well-irrigated land	Multi-criteria GIS-based decision analysis	Suitable for arid regions with irrigation
Soybean	High organic content, pH 6-7	Gently sloping, well-drained	GIS-based overlay, zoning	Suitable for well-drained soils with a moderate slope

5. Applications in Sustainable Agriculture and Land Management

GIS-driven soil fertility mapping and land-use change analysis support various applications critical to sustainable agriculture:

- **Precision agriculture and site-specific management:** Fertility maps guide variable-rate fertiliser application, optimising nutrient use, reducing waste, protecting soil health and the environment. GIS enables resource-efficient farm management tailored to intra-field variability ^[33, 34].
- **Land-use planning and policy support:** Land suitability maps inform crop planning, land allocation, zoning decisions, and sustainable land-use policy at regional and national levels. They help prevent the overexploitation of fragile soils ^[35, 36].
- **Soil degradation detection and conservation prioritisation:** LULC change detection reveals zones of deforestation, land degradation, urban encroachment or soil fertility loss - informing conservation, reforestation, or restoration efforts ^[37, 38].
- **Supporting resource-efficient and sustainable water, fertiliser, and land management:** By correlating soil fertility data with land use, water availability, and cropping patterns, GIS helps optimise irrigation scheduling, cropping intensity, and soil amendment, thereby improving sustainability and reducing environmental footprint ^[39, 40].
- **Food security, yield optimisation, and environmental sustainability:** Accurate spatial data helps maintain soil health, prevent degradation, and support long-term yield stability, crucial under pressures of growing population, climate change, and limited arable land ^[41, 42].

6. Case Studies (with Emphasis on Indian Context)

This section highlights empirical applications of GIS-based fertility assessment and land-use change monitoring, especially in Indian agroecological settings ^[43, 44].

6.1 Soil Fertility and Land Suitability in a Hilly Himalayan Region

Researchers used GIS to integrate soil sampling data, physiography, land use and terrain attributes to generate soil fertility and land suitability maps. The results informed optimal land-use allocation, fertiliser recommendations, and sustainable farming practices in a terrain otherwise rugged to survey manually. The study demonstrated that GIS-based interpolation

and overlay analysis reduce time, cost, and labour. Out of different physiographic units, the “intermontane valley” zones were found most suitable for high-value crops, owing to deeper soils, adequate organic carbon, moderate slope, and favourable soil texture. Soils in other units (hills, plateaus) required caution or amelioration before cultivation ^[45, 46].

6.2 Agricultural Land Use Change in Allahabad (Prayagraj), India (2000-2018)

A long-term study tracked the conversion of agricultural land to non-agricultural uses (urbanisation, built-up areas, wastelands) using multi-temporal Landsat satellite imagery and GIS classification. The analysis revealed a steady shrinkage of agricultural land over 18 years, reflecting population pressure and urban sprawl ^[47, 48].

Quantifying such land loss is critical for sustainable agriculture planning. The study provided a spatial baseline, enabling policymakers to assess land-use trends, manage urban encroachment, and protect fertile soils from irreversible conversion ^[34, 35].

6.3 Soil Attribute Mapping and Spatial Variability Assessment in Siliguri, West Bengal, India

In a district-level study, soil samples were collected at multiple points, and GIS was used to map the spatial variability of soil properties (e.g., texture, pH, fertility parameters). The resulting soil attribute maps helped identify zones with high fertility, degraded areas, or regions needing targeted soil management ^[43, 45].

This spatial understanding supported local agricultural planning, guiding fertiliser use, crop selection, and soil amendment, and helped detect potential risks of overuse, soil depletion, or mismanagement ^[32, 33].

6.4 Soil Quality Index Mapping in Semi-arid Region (International Example)

Although conducted outside India, a study in a semi-arid region used a GIS-based model combining chemical, physical, fertility, and geomorphological indices with RS data (satellite imagery, DEM) to classify soil quality across the landscape. Soil quality classes ranged from high to very low, providing a spatial decision-support tool for sustainable land use.

This demonstrates that GIS-driven soil quality assessment is viable even under challenging climatic and edaphic conditions a

model that can be emulated in arid or semi-arid areas of India [49, 50].

7. Challenges, Limitations, and Uncertainties

Despite clear advantages, GIS-based soil fertility and land-use analysis face several constraints.

- **Data quality and ground-truth dependency:** GIS-based fertility assessment relies on soil sample data for calibration and validation. In regions with sparse or outdated sampling, fertility maps may misrepresent actual conditions. Sampling depth, frequency, and lab standardisation remain limiting factors [51, 52].
- **Temporal limitations and dynamics:** Soil fertility and land use evolve due to cropping, management, erosion, urbanisation, and climate influences. Unless soil data are updated periodically, GIS maps may become obsolete, limiting their utility for dynamic decision-making [53, 54].
- **Heterogeneity and scale issues:** Soil properties vary at fine spatial scales. Interpolation or suitability analysis at coarse resolution may overlook micro-scale variability or local pockets of poor soil, leading to suboptimal recommendations [55, 56].
- **Integration complexity:** Combining multiple layers, soil, topography, climate, land use, management history, demands computational resources, technical expertise, and institutional capacity. Smallholder farmers or under-resourced regions may lack access to such capacity [57, 58].
- **Uncertainty and classification errors in LULC change detection:** Satellite image classification, change detection and interpretation are prone to mistakes, e.g., misclassification between land-use categories, seasonal variation, cloud cover, or image resolution limitations. These errors propagate into analyses and decision tools [49, 50].
- **Adoption and implementation barriers:** Even when GIS-based maps exist, actual integration into farm management, policy planning, or extension services remains limited. Institutional inertia, lack of awareness, or insufficient capacity hinder the translation of GIS insights into action [51, 52].

8. Future Directions and Recommendations

To enhance the role of GIS in sustainable agriculture, the following directions are essential:

- **Develop periodic and standardised soil-sampling networks:** Establishing systematic soil sampling and monitoring across agro-ecological zones, including sample depth, frequency, and standardised lab protocols will strengthen GIS-based fertility mapping accuracy [52, 53].
- **Integrate GIS with other technologies:** Combine GIS with remote sensing, drone imagery, IoT-based soil sensors, and crop modelling tools (e.g., coupling with crop simulation software) to create dynamic, high-resolution decision-support systems [54, 55].
- **Promote land suitability and agricultural zoning at the policy level:** Government and planning agencies should adopt GIS-based land suitability assessments to regulate land use, prevent overexploitation of fragile soils, and align agricultural practices with long-term sustainability [51, 52].
- **Capacity building and democratisation of GIS tools:** Provide training and affordable GIS/RS tools (open-source GIS, mobile GIS apps) to local planners, extension workers, and farmers. Encourage participatory GIS (PGIS) to involve

stakeholders in land-use planning and soil management [51, 52].

- **Continuous monitoring and time-series analysis of land use change:** Maintain and update land-use classification maps periodically to detect urban encroachment, agricultural land loss, deforestation, or degradation — enabling early intervention and conservation planning [48, 50].
- **Research and model refinement:** Develop and validate models (e.g., soil quality indices, land suitability, risk of degradation) adapted to local contexts, cropping systems, and soil-climate conditions. Validate these models with ground data and long-term monitoring [41, 50].

9. Conclusion

GIS, often integrated with remote sensing and spatial modelling, plays a critical role in advancing sustainable agriculture through detailed, spatially explicit assessments of soil fertility and land-use dynamics. It enables large-scale soil fertility mapping, soil quality classification, land suitability analysis, and land-use change detection, all essential for informed decision-making in agriculture, land management, and policy [53, 54].

Empirical studies, including those from India, demonstrate that GIS-based approaches help identify fertile zones, degraded soils, land suitability for specific crops, and trends of shrinking agricultural land. Such insights support precision agriculture, resource-efficient farming, soil conservation, and sustainable land-use planning.

However, the full potential of GIS remains underutilised due to constraints around data, sampling, capacity, and institutional adoption. Overcoming these challenges through systematic sampling, technological integration, stakeholder engagement, and policy support can unlock GIS's capacity to support sustainable, resilient, and productive agriculture — crucial in a world facing increasing population, land pressure, and environmental change [55].

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