Geographic Information Systems and Remote Sensing for Sustainable Development: Implications for Land Tenure Governance

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ABSTRACT

Land is a critical resource for livelihoods, food production, settlement, infrastructure and environmental sustainability. Yet, land administration in many developing countries continues to be constrained by incomplete cadastral coverage, fragmented records, competing statutory and customary claims, weak institutional coordination and limited access to reliable spatial information. This paper examines how geographic information systems (GIS) and remote sensing can support sustainable development through improved land information management and more responsible land tenure governance. It adopts a narrative review approach, drawing on established conceptual literature, recent peer-reviewed studies and guidance from international land-governance institutions. The discussion considers the contribution of satellite imagery, aerial photography, unmanned aerial vehicles, global navigation satellite systems, participatory mapping and spatial databases to land-use and land-cover monitoring, cadastral mapping, boundary identification, tenure-rights documentation, land degradation assessment and spatial planning. Recent studies indicate that geospatial technologies can improve the coverage, timeliness and accessibility of land information, while fit-for-purpose approaches can make land-rights recording more inclusive and affordable (Enemark et al., 2021, Tan et al., 2021 & Eshetie et al., 2024). Evidence from Nigeria also suggests that high-resolution aerial imagery can provide a practical complement to conventional cadastral survey methods, although regulatory, institutional and technical constraints remain (Taiwo et al., 2025). The paper argues, however, that technology alone cannot guarantee tenure security or sustainable development. Its effectiveness depends on legal recognition, institutional capacity, data quality, interoperability, public participation, protection of vulnerable groups and respect for customary and collective rights. The paper concludes that integrating GIS and remote sensing with participatory and rights-based land administration offers a promising pathway towards transparent land governance, sustainable land management and progress towards the Sustainable Development Goals.

Keywords: Geographic information systems; remote sensing; land tenure; land administration; tenure security; sustainable development; fit-for-purpose land administration.

INTRODUCTION

Land is central to economic activity, social identity, food security, housing and environmental protection. The way land is accessed, used, transferred and governed therefore has direct implications for sustainable development. Population growth, urban expansion, agricultural intensification, infrastructure development and climate-related pressures have increased competition for land and placed additional demands on land administration institutions. In many developing countries, these pressures occur alongside incomplete land records, overlapping claims, costly surveying procedures and limited institutional capacity. Where reliable information about land parcels, rights, land use and environmental conditions is unavailable, public agencies and communities may find it difficult to make informed and equitable decisions.

Sustainable development requires more than increasing the economic output obtained from land. It involves balancing productive use with environmental protection, social inclusion and the needs of future generations.

The widely accepted definition of sustainable development emphasizes meeting present needs without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development [WCED], 1987). In land governance, this principle requires land-use decisions to account for ecological limits, legitimate tenure rights, local livelihoods and long-term public interests.

Geographic information systems (GIS) and remote sensing have become important sources of information for understanding the location, extent, condition and changing use of land. Remote sensing provides repeated observations of the Earth's surface from satellite, aircraft and unmanned aerial platforms, while GIS supports the storage, integration, analysis and presentation of spatial and attribute information. When combined with field surveys, cadastral records and community-generated information, these technologies can strengthen land-use planning, environmental monitoring and land administration.

The relevance of geospatial technologies to land tenure governance has become more prominent in recent years. A systematic review by Eshetie et al. (2024) found that geospatial technologies can contribute positively to responsible land governance, particularly in developing countries, but highlighted the need to integrate indigenous knowledge and institutions into technology-supported approaches. Similarly, the Food and Agriculture Organization (FAO, 2022) emphasizes combining geospatial technologies with participatory methods to record and protect legitimate tenure rights. These developments suggest that the relationship between GIS, remote sensing and land tenure should be understood not simply as a technical matter of mapping parcels, but as part of a broader process of improving the fairness, transparency and sustainability of land governance.

Against this background, this paper examines the contribution of GIS and remote sensing to sustainable development, with particular attention to land tenure systems. It discusses the conceptual foundations of sustainable development and tenure security, reviews major geospatial applications in land administration and environmental management, identifies implementation challenges and proposes policy directions relevant to developing countries, including Nigeria.

Review Approach and Scope

This paper is a narrative review and conceptual discussion rather than an empirical field study or a systematic review. It develops the themes contained in the original paper by bringing together foundational literature on GIS, remote sensing, sustainable land management and land tenure with more recent research and institutional guidance published principally between 2021 and 2025.

The literature was selected for its relevance to geospatial technologies, cadastral mapping, land administration, tenure security and land degradation monitoring. Recent Nigerian evidence is included to connect international developments with the national context.

Because no original field data, database search protocol, screening flow diagram or statistical synthesis was supplied in the source manuscript, the paper does not claim to have conducted a systematic review. Its conclusions are interpretive and should be read as a synthesis of the cited literature rather than as findings from a new survey or spatial analysis.

CONCEPTUAL FOUNDATIONS

Geographic Information Systems and Remote Sensing

A GIS is an organized framework for capturing, storing, managing, integrating, analysing and displaying geographically referenced information. Its main value lies in the ability to relate spatial features—such as land parcels, roads, rivers, settlements and vegetation—to descriptive information, including ownership or tenure claims, land-use categories, soil characteristics, population and infrastructure. GIS therefore supports the examination of relationships that may not be apparent from non-spatial records alone.

Remote sensing is the acquisition of information about the Earth's surface without direct physical contact, commonly through sensors mounted on satellites, aircraft or unmanned aerial vehicles. Optical sensors record reflected electromagnetic energy, while radar systems can provide observations under cloud cover and at night. The resulting imagery can be processed to classify land cover, identify surface changes, assess vegetation condition, map built-up areas and support the monitoring of environmental processes.

The two technologies are complementary. Remote sensing supplies repeated and spatially extensive observations, whereas GIS provides the environment in which imagery can be combined with cadastral, demographic, legal, environmental and socio-economic information. Global navigation satellite systems and field-based positioning further support the collection and verification of spatial coordinates. Their integration can improve the evidence available for land-use planning and land administration, provided that the data are appropriately validated and interpreted.

Sustainable Development and Sustainable Land Management

Sustainable development is commonly understood through the interconnected dimensions of environmental integrity, economic viability and social equity. Applied to land, these dimensions require that land resources support livelihoods and productive activity without undermining soil, water, biodiversity and ecosystem functions. Sustainable land management involves the use of appropriate technologies, planning arrangements and institutional policies to maintain or improve land productivity while reducing degradation and social costs (Hurni, 1997).

Land sustainability is influenced by the condition of the resource and by the institutions that regulate access and use. Soil erosion, salinization, compaction, vegetation loss, waterlogging and declining soil fertility can reduce the capacity of land to support agriculture and other uses. Remote sensing and GIS can help identify the location and extent of such pressures, compare conditions over time and support the prioritization of interventions. However, the interpretation of remotely sensed indicators should be supported by field observations and relevant local knowledge, since a spectral change does not automatically demonstrate a particular cause or level of degradation.

The Sustainable Development Goals (SDGs) provide a relevant policy framework. Geospatial information can contribute to monitoring progress on food security, sustainable cities, climate action and life on land, among other goals. Its value depends on whether information is converted into accountable planning and management decisions rather than simply producing maps.

Land Tenure, Property Rights and Tenure Security

Land tenure refers to the relationships, whether legally or customarily defined, among individuals or groups with respect to land. These relationships are governed by rules that determine who may access, use, control, manage, inherit or transfer land, and under what conditions. Tenure arrangements may include statutory, customary, communal, leasehold, freehold and other locally recognized forms. The FAO Voluntary Guidelines on the Responsible Governance of Tenure recognize that legitimate tenure rights may exist under formal, informal, customary and collective arrangements and should be governed in a responsible and inclusive manner (FAO, 2012).

Tenure security concerns the extent to which people can enjoy their legitimate land rights without arbitrary interference, eviction or competing claims. It is multidimensional: it may involve the legal recognition of rights, the duration and enforceability of claims, the ability to use and benefit from land, and confidence that rights will be respected by public institutions and other actors. A title document may strengthen evidence of a claim, but tenure security cannot be reduced to possession of a formal certificate. Customary and community rights may also be legitimate and require appropriate recognition.

Secure tenure can encourage long-term investment, improve incentives for land stewardship and reduce uncertainty. Conversely, overlapping claims, unclear boundaries, weak dispute-resolution mechanisms and exclusion from registration processes can discourage investment and contribute to conflict. Geospatial tools

can help document the spatial dimensions of rights, but the legal and social legitimacy of those rights must be established through appropriate procedures and inclusive engagement.

Applications of GIS and Remote Sensing to Sustainable Development and Land Tenure

Land-Use and Land-Cover Mapping and Change Detection

One of the most established applications of remote sensing and GIS is the mapping and monitoring of land use and land cover (LULC). Multi-temporal satellite images can be classified to identify changes in cultivated land, forest, grassland, wetlands, water bodies and built-up areas. GIS can then quantify the location, extent and pattern of change and relate these changes to population growth, infrastructure development, agricultural expansion or environmental pressures.

Change detection is particularly useful where conventional ground surveys are expensive, slow or difficult to repeat over large areas. However, reliable change analysis requires comparable images, suitable classification methods, attention to seasonal variation and an assessment of classification accuracy. Researchers should report the imagery dates, spatial resolution, classification scheme, validation data and accuracy measures so that the results can be interpreted and reproduced.

For land administration, LULC information can help identify encroachment on agricultural land, expansion into wetlands or flood-prone areas, and changes around settlement boundaries. Such information can inform development control and land-use planning, but it does not by itself determine ownership or legal rights. A land-cover map and a cadastral map answer different questions and should not be treated as interchangeable.

Cadastral Mapping and Land Rights Recordation

Cadastral systems describe land parcels and their spatial relationships, usually linking parcel geometry with information about rights, restrictions and responsibilities. GIS provides a platform for managing parcel maps and associated records, while high-resolution satellite imagery, aerial photographs and UAV-derived orthomosaics can assist in identifying visible parcel boundaries and settlement features. GNSS and conventional survey methods may be used to establish or verify coordinates according to the accuracy and legal requirements of the task.

Fit-for-purpose land administration (FFPLA) offers an approach for extending the coverage of land-rights information by matching the level of spatial accuracy, legal formality and institutional procedure to local needs and available resources. It does not imply abandoning professional standards; rather, it encourages flexible, inclusive and scalable methods that can be upgraded over time. Enemark et al. (2021) discuss the role of fit-for-purpose approaches in providing secure land rights at scale, while Tan et al. (2021) show that successful adoption of UAV technology depends on legal, political, operational, social and technical capacity.

Recent Nigerian research provides relevant evidence. Taiwo et al. (2025) compared aerial imagery with conventional cadastral mapping methods in Ekiti State and reported that high-resolution aerial imagery could provide comparable results in terms of accuracy, with wider coverage and potential time and cost advantages. The authors also identified regulatory and institutional issues affecting the use of UAVs. This evidence supports the potential of aerial imagery as a complement to established surveying practice, not as an automatic substitute for legally required cadastral surveys.

Geospatial tools may also support participatory boundary delineation. Community members can help identify customary boundaries, shared resources, seasonal access routes and locally recognized rights that may not be visible in satellite imagery. FAO (2022) emphasizes the combination of geospatial technologies and participatory methods for recording legitimate tenure rights. This is important where formal cadastral systems have limited coverage or do not adequately represent customary and collective tenure.

Land Information Systems and Digital Land Administration

A land information system integrates spatial data with textual and administrative records relating to parcels, tenure rights, land value, land use, planning controls and transactions. A well-maintained system can help public agencies retrieve records, monitor changes, reduce duplication and provide more consistent information to landholders and investors. Digital systems can also improve transparency when access rules, audit trails and procedures for correcting records are clearly established.

Modern land administration increasingly requires interoperability among cadastral databases, planning systems, valuation records, registration platforms and environmental datasets. Data standards and consistent parcel identifiers are important for preventing fragmented databases and enabling information exchange. The FAO's current guidance on modernizing land administration highlights the need to strengthen spatial data systems, support both cadastral and non-cadastral records, use fit-for-purpose and participatory mapping, and recognize customary and collective tenure rights (FAO, 2026).

Digitalization should not be understood as merely scanning paper records or transferring existing institutional weaknesses into software. Data must be checked, records updated, staff trained, responsibilities clarified and procedures made accessible. Systems should also include safeguards for privacy, data security and the protection of vulnerable rights holders.

Monitoring Land Degradation and Supporting Sustainable Land Management

Remote sensing can support the assessment of vegetation condition, bare-soil exposure, surface moisture, land-cover change and other indicators associated with land degradation. Common indices include the Normalized Difference Vegetation Index (NDVI), which is used to assess vegetation greenness; the Normalized Difference Water Index (NDWI), which can support analysis of water-related characteristics; and soil-adjusted or bare-soil indices used in specific land-cover contexts. These indices are proxies and must be interpreted with regard to local climate, soil, crop type, season and sensor characteristics.

Optical imagery can be affected by cloud cover and atmospheric conditions. Synthetic Aperture Radar (SAR) can provide complementary information and is less dependent on daylight and cloud-free conditions. Sengani et al. (2023), reviewing optical and SAR data fusion for land degradation monitoring in semi-arid regions, highlight the potential of combining sensor types to improve the information available for sustainable land management. Such approaches are relevant to dryland and semi-arid environments where vegetation cover and soil conditions vary considerably over time.

GIS can integrate remotely sensed indicators with field measurements of soil properties, slope, drainage, irrigation infrastructure and land management practices. This combination can help identify areas requiring soil conservation, erosion control, improved drainage, vegetation restoration or changes in agricultural practices. For policy purposes, repeated monitoring can provide a basis for prioritizing interventions and evaluating whether land-management programmes are producing the intended results.

Urban and Regional Planning

Urban growth changes the demand for residential, commercial, industrial and infrastructure land. GIS and remote sensing can map built-up expansion, monitor the conversion of agricultural land and wetlands, and identify patterns of dispersed development. Spatial analysis can support the allocation of public facilities, transport corridors, green spaces and basic infrastructure. When combined with population and socio-economic data, these tools can help planners assess the likely consequences of alternative development scenarios.

The land-tenure dimension is important because urban expansion may affect customary holdings, peri-urban farming, communal resources and informal occupants. Mapping land-use change without examining tenure rights may overlook displacement risks and competing claims. Responsible planning should therefore connect

spatial evidence with transparent land acquisition procedures, consultation, compensation where applicable and accessible grievance mechanisms.

Agriculture, Food Security and Rural Development

In agricultural areas, geospatial technologies can support crop-area mapping, monitoring of vegetation conditions, irrigation planning, soil and water conservation, and the identification of land-use constraints. Combining soil, terrain, rainfall, water availability and access-to-market information can assist in assessing agricultural suitability and planning infrastructure. Remote sensing can also provide repeated observations that help identify changes in cultivated areas and the condition of agricultural landscapes.

The relationship between tenure and agricultural sustainability should be considered alongside these technical applications. Farmers who have confidence in their rights may be more willing to make long-term improvements, although the strength of this relationship depends on local institutions, access to finance, markets, extension services and the type of investment. Spatial information can help identify where tenure claims overlap with agricultural infrastructure or natural resources, but tenure-related decisions require legal and participatory validation.

Opportunities and Benefits

The integration of GIS and remote sensing into land governance offers several potential benefits. First, it can improve the availability and currency of spatial information by providing repeat observations and a common platform for integrating different datasets. Second, it can support more informed decisions by showing the spatial distribution of land resources, infrastructure, environmental risks and competing land uses. Third, geospatial methods can reduce the time and cost of some mapping activities, particularly when aerial or satellite imagery is used to support fieldwork and prioritize ground verification.

Fourth, participatory geospatial approaches can improve the visibility of customary and community-held rights that may be absent from formal records. Fifth, spatial databases can support more transparent administration by improving record retrieval, enabling monitoring of transactions and helping identify inconsistencies. Finally, geospatial monitoring can support environmental accountability by providing evidence on land-cover change and degradation trends. These benefits are most likely to be realized when the technologies are integrated into functioning institutions and linked to enforceable rights and practical land-management decisions (Eshetie et al., 2024 & FAO, 2026).

Challenges and Limitations

Technical and Data Constraints

The usefulness of geospatial information depends on image resolution, positional accuracy, classification quality, temporal consistency and the availability of reliable reference data. Cloud cover can limit optical imagery in some seasons, while differences in sensor characteristics can complicate comparisons. High-resolution imagery and UAV surveys may be costly, and their acquisition may be constrained by technical expertise, equipment availability and regulatory requirements. Errors in parcel boundaries or attribute records can also create serious consequences when maps are used for administrative or legal decisions.

Institutional and Legal Constraints

Land administration responsibilities are often distributed across multiple agencies with different mandates and databases. Weak coordination, unclear procedures and limited resources can undermine the maintenance and exchange of land information. In addition, a spatial representation of a parcel does not itself confer legal ownership or resolve a contested claim. The legal status of records, the authority responsible for validating rights and the procedures for appeals and dispute resolution must be clearly defined.

Social Inclusion and Customary Rights

A technology-led programme may reproduce existing inequalities if participation is limited to people who can afford formal documentation, access digital services or engage with public institutions. Women, tenants, pastoralists, youth, people with disabilities and customary communities may be inadequately represented in formal records. Eshetie et al. (2024) specifically identify the need to integrate indigenous institutions and knowledge with geospatial technologies. Participatory mapping should therefore include safeguards to ensure that local power differences do not silence less influential rights holders.

Privacy, Data Governance and Conflict Sensitivity

Digital land records may contain sensitive information about individuals, households, property interests and locations. Unrestricted disclosure can expose rights holders to fraud, discrimination or other harms. Data governance arrangements should specify who may access, change and share information, how consent is obtained, how errors are corrected and how sensitive records are protected. In areas affected by land disputes or insecurity, the publication of detailed parcel information should be assessed for potential risks to communities.

Sustainability of Digital Systems

Geospatial projects can fail when they depend on short-term funding, proprietary software, external consultants or equipment that local institutions cannot maintain. Long-term sustainability requires recurrent budgets, staff development, clear institutional ownership, open standards where appropriate, maintenance plans and reliable arrangements for data updating. Capacity development should address not only technical skills but also legal, organizational and community-engagement capabilities (Tan et al., 2021).

Implications for Land Administration in Nigeria

Nigeria's land administration environment is shaped by the coexistence of statutory and customary practices, varied institutional capacities and differing levels of cadastral coverage. The Land Use Act of 1978 provides the principal statutory framework for landholding and administration, while customary practices continue to influence access, allocation, inheritance and transfer in many communities. This institutional complexity makes it important for geospatial modernization to recognize the range of legitimate tenure relationships rather than focusing exclusively on formal title documentation.

The Nigerian case also demonstrates the importance of adapting geospatial approaches to local conditions. The study by Taiwo et al. (2025) in Ekiti State shows the potential of aerial imagery to support cadastral mapping, while also identifying regulatory and institutional issues that affect implementation. The broader fit-for-purpose literature similarly indicates that the adoption of new technologies requires attention to legal frameworks, operational arrangements, social norms and technical capacity (Enemark et al., 2021& Tan et al., 2021).

For Nigeria, a practical approach would combine existing cadastral and registry records with satellite imagery, aerial photography, GNSS observations, field verification and participatory mapping. Priority could be given to areas experiencing rapid urban expansion, land disputes, agricultural investment, infrastructure development or environmental degradation. Any resulting database should distinguish between verified registered interests, customary claims, leases, occupancy information and disputed or unresolved claims. This distinction is necessary to avoid presenting uncertain claims as settled legal facts.

Geospatial modernization should also be linked to institutional reforms that improve transparency, reduce administrative delays, strengthen public access to information and provide fair mechanisms for resolving disputes. The recognition of women's land rights, communal interests and other potentially marginalized claims should be treated as a core governance objective. In this respect, technology should support the responsible governance of tenure rather than become a substitute for legal reform, public accountability or meaningful participation.

Policy and Practical Recommendations

Adopt a fit-for-purpose and incremental approach to land information modernization, matching mapping methods and accuracy requirements to the intended legal and administrative use.

Integrate satellite imagery, aerial photography, GNSS observations, cadastral records and field verification within interoperable spatial databases, using clear standards and consistent parcel identifiers.

Combine geospatial mapping with participatory methods so that customary, collective, informal and other legitimate tenure claims are identified and assessed through inclusive procedures.

Establish clear legal and institutional rules for the validation, updating, sharing and correction of digital land records, including accessible procedures for complaints and dispute resolution.

Invest in staff training, equipment maintenance, recurrent funding and institutional coordination to ensure that geospatial systems remain operational beyond individual projects.

Apply privacy, cybersecurity and conflict-sensitive safeguards when collecting, storing and publishing land-related information.

Use multi-temporal remote sensing and field-based indicators to monitor land degradation, urban expansion and changes in agricultural land, and connect the results to land-use planning and environmental management. Evaluate geospatial interventions not only by the number of parcels mapped or records digitized, but also by improvements in tenure security, inclusion, service delivery, dispute reduction and sustainable land management.

CONCLUSION

GIS and remote sensing provide important opportunities to strengthen sustainable development and land tenure governance. Their capacity to integrate spatial and descriptive information, monitor land-use and land-cover change, support cadastral mapping and identify environmental pressures can improve the evidence available to land administrators, planners and communities. Recent literature demonstrates growing interest in the use of geospatial technologies for responsible tenure governance, fit-for-purpose land administration and land degradation monitoring (Eshetie et al., 2024, Sengani et al., 2023 & Taiwo et al., 2025).

Nevertheless, the benefits of these technologies are not automatic. Accurate maps do not independently establish legitimate rights, resolve disputes or ensure equitable access to land. Sustainable outcomes depend on the quality of data, institutional capacity, appropriate legal recognition, interoperability, public participation and protection of vulnerable groups. In particular, customary and collective tenure arrangements must be represented through processes that respect local institutions and rights.

The paper therefore concludes that GIS and remote sensing should be treated as enabling components of a broader, rights-based and fit-for-purpose land administration system. When combined with participatory mapping, effective legal institutions and sustained investment in capacity, these technologies can contribute to more transparent land governance, better environmental management and more inclusive sustainable development.

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