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Geospatial Analysis of Land Use and Land Cover Change Using GIS and Remote Sensing: Implications for Earth Systems

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ABSTRACT

Land use and land cover (LULC) change is a major driver of environmental transformation, affecting climate regulation, hydrological processes, biodiversity, and ecosystem services. Rapid urbanization, agricultural expansion, deforestation, and climate variability have accelerated landscape modifications worldwide, creating significant challenges for sustainable development. Geographic Information Systems (GIS) and remote sensing technologies have become essential tools for monitoring and analysing these changes through satellite-based observations and spatial analysis. This narrative review examines global patterns and drivers of LULC change and highlights recent advances in geospatial technologies, including machine learning and artificial intelligence techniques for land cover mapping and change detection. The review further explores the implications of LULC dynamics for Earth system processes, such as carbon cycling, land surface temperature, water resources, ecosystem resilience, and biodiversity conservation. In addition, widely used geospatial indicators, including the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Built-up Index (NDBI), and Land Surface Temperature (LST), are discussed as valuable tools for environmental assessment. The review concludes that integrating GIS, remote sensing, and advanced analytical approaches provides a robust framework for understanding landscape transformations and supporting sustainable land management and environmental governance.

Keywords: *Land Use and Land Cover Change (LULC), GIS, Remote Sensing, Earth Systems, Machine Learning.*

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1. Introduction

One of the most prominent examples of anthropogenic impacts on the Earth system over the Anthropocene is land use and land cover change (LULC). Urbanization, agricultural expansion, industrial development, deforestation, infrastructure development and resource extraction are all pushing natural landscapes quickly to a stage of change, resulting in the modification of ecological processes and environmental conditions at local, regional and global scales (Roy et al., 2022). The changes impact climate regulation, hydrological cycles, conservation of biodiversity, carbon sequestration, soil quality and provision of ecosystem services, which impacts climate sustainability and human wellbeing. Considering the dynamics of LULC change is an important scientific and policy priority in the face of increasing population, economic development and climate change (Mir et al., 2025).

The world has seen unprecedented levels of land transformation in the last few decades. The forests have been turned into agricultural lands, wetlands have been filled in for urban development, and peri-urban areas have grown quickly with increasing population and industrial activities (Roy et al., 2022). Recent worldwide assessments indicate that almost 75% of the land surface that is not covered by ice has undergone significant alteration by human activities, leading to habitat destruction, fragmentation, and biodiversity loss (Gupta et al., 2024). The changes in land use are significant contributors to greenhouse gas emissions and a major factor in environmental change globally. Therefore, proper monitoring and assessment of LULC changes is vital for land use impact analysis, foreseeable change and to design appropriate land use management strategies (Tahir et al., 2025).

The use of Geographic Information Systems (GIS) and remote sensing technology has transformed the research of LULC change. Though useful, traditional ground-based surveys are often time- and cost-intensive and may be limited by spatial coverage (Dangayach and Pandey, 2025). Satellite remote sensing, on the other hand, is able to continuously observe the Earth's surface with repetitive and large-scale observations and monitor changes to the environment in unprecedented detail in terms of space and time (Milu et al., 2025). Since the launch of the Landsat program in 1972, satellite imagery has become one of the most important sources of information for detecting and quantifying land cover transformations. With the recent development of higher resolution satellite missions such as Sentinel, MODIS, Worldview and Planet missions, it is now possible to analyse the complex landscape dynamics at several spatial scales (Hemati et al., 2021).

GIS is used as an analytical framework that complements remote sensing observation-generated spatial data and aids in their storage, integration, visualization and interpretation. GIS and remote sensing can be used together to detect patterns of land transformation, assess environmental impacts, and create predictive models of future land use scenarios (Chatrabhuj et al., 2024). Moreover, the developments around geospatial technology have enabled increased analytical capabilities with machine learning, artificial intelligence, cloud computing and geospatial big-data analytics. The classification accuracy and change detection performance have also been greatly enhanced by techniques like Random Forest, Support Vector Machines, Artificial Neural Networks, and deep learning models, enabling more accurate mapping of the heterogeneous landscape (Gu and Zeng, 2024).

Beyond the changes in the composition of LULC, the effects of LULC change are far-reaching to the environment. Vegetation cover changes directly affect carbon storage, evapotranspiration and energy exchange processes and as such impact regional and global climate systems (Arroyo-Araujo et al., 2022). Urban development may lead to an increase in impervious surfaces, a decrease in infiltration and escalating land surface temperatures which can cause urban heat island conditions and increase flood risks. Likewise, deforestation and degradation of wetlands can further decrease the ecosystem's resistance, biodiversity and affect ecosystem services like water purification, nutrient cycling and climate regulation (Fu and Weng, 2016). The interconnections of these effects underscore the need to consider LULC dynamics in an Earth system context, accounting for the interplay between land, atmosphere, hydrosphere and biosphere (Mashala et al., 2023).

In recent years, geospatial indicators have also been increasingly used for the assessment of the environment thanks to the advances of technologies used for Earth observation. The Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Built-up Index (NDBI) and Land Surface Temperature (LST) are examples of spectral indices that have gained widespread use to assess vegetation health, water availability, urban growth and thermal conditions (Tsatsaris et al., 2021; Zhao and Yu, 2025). These indicators offer important information about the functioning of an ecosystem and about environmental change, which biologists use to correlate observed land changes to other processes that occur on Earth. In addition, technologies like Google Earth Engine have revolutionized large-scale geospatial analysis by providing access to vast archives of satellite imagery and powerful computing power (Steffen et al., 2020).

Monitoring and interpretation of LULC change is still faced with a number of challenges, despite the advances in technology. The different resolution and classification methods, temporal coverage, and validation process in data generation can create uncertainties that make it difficult to compare results from different studies (Macarringue et al., 2022). In addition, many investigations place emphasis on mapping land cover transitions, but do not consider the implications of these transitions for the ecological and Earth system impacts. Hence, the integration of recent advances in GIS, RS, machine learning, and Earth system science data into a single platform is a growing requirement to understand the dynamics of LULC and its effect (Pandey et al., 2021).

The aim of this narrative review is to critically discuss recent methods for assessing LULCC in GIS and remote sensing and to analyse their implications for processes in the Earth system. Specifically, the review integrates the state-of-the-art understanding of global trends and drivers of LULC change, recent developments in geospatial monitoring methods, new machine learning applications, environmental impacts of LULC change, and prospects for sustainable land management in the future. This review aims to offer the researchers, environmental managers and policy makers a summary of the findings from recent scientific publications that will help them understand the potential of geospatial technologies in helping to solve current environmental issues and evidence-based decision making for sustainable development**.**

2. Global Patterns and Drivers of Land Use and Land Cover Change

The change in land use and land cover (LULC) has become a benchmark of environmental change in the twenty first century, as the level of human footprint on the land has increased. Globally, there is a growing conversion of natural landscapes into agriculture, urban settlements, transportation and industrial areas (Radwan et al., 2021). Fast population growth, economic development, technological progress and globalization have been the main contributors to these changes since the mid-twentieth century (Dickinson, 2018). Today, over 75% of the Earth's terrestrial surface is altered by anthropogenic activities, and LULC change is one of the most significant factors contributing to biodiversity loss, ecosystem degradation and climate change (Beylich et al., 2024). LULC changes are highly variable between regions. Deforestation in the tropical areas of South America, Africa, and Southeast Asia still continues at a large scale, for the purposes of agriculture, livestock farming, logging, and the construction of roads and other infrastructure (Fagua and Ramsey, 2019). Significant deforestation has occurred in the Amazon Basin, Congo Basin and Southeast Asia rainforests leading to habitat fragmentation, carbon emissions and loss of ecosystem resilience (Tasya, 2025). Many developed areas, on the other hand, have seen high levels of urban growth and suburbanization and low rates of deforestation. In North America, Europe and East Asia, urbanization has significantly increased with urban areas replacing agricultural and natural landscapes, which has led to the alteration of hydrological and climatic processes due to increased impervious surfaces (Huang et al., 2024).

One of the most prominent causes of modern-day LULC transformation is urbanization. By 2050, almost 68% of the world's population is projected to live in urban areas (Rimal et al., 2025). This rapid urbanization creates growing demands for housing, transportation infrastructure, industrial areas and public services, resulting in the rampant sprawl of built-up areas at the expense of agricultural land and natural vegetation (Ishtiaque et al., 2017). In developing countries, urban sprawl is especially strong due to rapid economic development and population growth that can outpace planning frameworks. This results in often uncoordinated land use change in peri-urban areas, which leads to environmental degradation, reduction in agricultural productivity and heightened natural hazard risk (Akbar et al., 2019; Güneralp et al., 2020).

Another important global cause of global land cover change is agricultural expansion. Population growth and the shifting consumption habits have increased the pressure to the land resources, due to the growing food demand (Kanianska, 2016). Forests, grasslands and wetlands have been cleared away on a large scale to make way for crop fields and livestock farms, which are used to grow food and for export. While agricultural technology has enhanced productivity, there has been a continued process of land conversion in many areas as a result of economic incentives and market demand (Kan et al., 2026). Intensification can lead to degradation of soils, loss of water resources, pollution of the water, and loss of ecosystems biodiversity which impact environmental sustainability over time. Deforestation and forest degradation are significant elements of LULC changes on a global scale (Kan et al., 2025). The forests are essential for capturing carbon, regulating the climate, protecting biodiversity and maintaining water stability. But large-scale deforestation due to agriculture, mining, infrastructure development and logging remain a threat to these ecosystems (Potapov et al., 2022). Tropical forests are very sensitive due to their high biodiversity and carbon storage potential. Deforestation contributes significantly to greenhouse gas (GHG) emissions and weakens ecosystems' ability to buffer climate change impacts. Deforestation is an important contributor to greenhouse gas (GHG) emissions and to the capacity of ecosystems to cushion the effects of climate change. Furthermore, forest fragmentation affects the ecological connectivity and endangers many plant and animal species (Ren et al., 2024).

Climate change has become an increasingly salient force for LULC change. Changes in temperature, precipitation, droughts and extremes affect vegetation distribution, ecosystem production and land-use (Hassan et al. 2024). The effects of climate change on species composition and vegetation zones have been noted in many areas, including high latitudes, semi-arid and arid areas. Moreover, climate-related disasters like floods, wildfires, and storms can have a sudden effect on land cover, causing intricate interactions between land systems and climate processes (Saleem et al., 2025).

Local and regional scale LULC dynamics are also influenced by socioeconomic and political factors. Land resources are used and managed by factors such as population growth, economic policies, land tenure systems, governance structures, technological innovations and market forces. Weak institutional structures and poor land-use planning in many developing countries are responsible for unsustainable land conversion practices (Allan et al., 2022). On the other hand, good governance, proper conservation policies and sustainable development programs can decrease environmental degradation and facilitate equitable land management practices. Interactions between biophysical, socioeconomic and political drivers are thus crucial to understand to design effective strategies for tackling the challenges of LULC change (Cowie et al., 2018). The global LULC patterns are overall complex, intertwined process of human activities and environmental processes. The ongoing urbanization, intensification of agriculture, deforestation and land transformation due to climate change highlights the need for the development of comprehensive monitoring systems that are able to identify and evaluate landscape dynamics. These changes and their consequences for Earth systems sustainability can be understood with the help of geospatial technologies (Lei et al., 2024).

Table 1: *Major Drivers of Land Use and Land Cover Change and Their Environmental Impacts*

Driver of LULC Change	Major Activities	Environmental Impacts	Earth System Consequences
Urbanization	Expansion of cities, infrastructure development	Loss of vegetation, increased impervious surfaces	Urban heat island, increased runoff, reduced infiltration
Agricultural Expansion	Cropland and pasture development	Deforestation, soil degradation, habitat loss	Carbon emissions, biodiversity decline
Deforestation	Logging, land clearing	Forest fragmentation, ecosystem degradation	Reduced carbon sequestration, climate alteration
Industrial Development	Mining, manufacturing, transportation networks	Land degradation, pollution	Ecosystem disruption, increased greenhouse gases
Climate Change	Droughts, floods, wildfires	Vegetation shifts, ecosystem stress	Altered hydrological and ecological processes
Population Growth	Increased land demand	Resource pressure, land conversion	Accelerated landscape transformation

3. GIS and Remote Sensing Technologies for LULC Monitoring

Advances in Geographic Information Systems (GIS), remote sensing technologies (Ishtiaque et al., 2017) have completely changed the monitoring and assessment of land use and land cover (LULC) dynamics. These geospatial tools offer efficient, cost-effective and scientifically sound solutions to the collection, processing, analysis and visualization of spatial information on various temporal and spatial scales (Macarringue et al., 2022). The integration of these two has proven to be essential for environmental monitoring, resource management, urban planning, disaster assessment, biodiversity conservation, and climate change research (Lei et al., 2024). Aerial or satellite sensors are used to obtain information about the Earth's surface without direct contact; this is called remote sensing. Since the first Landsat satellite was launched in 1972, remote sensing has been one of the most important sources of data for monitoring environmental change. The Landsat program offers the longest uninterrupted record of Earth's observations that can be used to examine trends over 40 years of vegetation cover, urban growth, deforestation, wetland loss, and agriculture changes. The near-universal availability of freely available Landsat data has greatly increased the capacity to understand long-term LULC dynamics and environmental change on the global scale (Mir et al., 2025).

Newer satellite platforms have also added to the capacity for LULC monitoring. Sentinel missions offered by ESA deliver high resolution multispectral image data with better revisit time, supporting near real time monitoring of the environment (Roy et al., 2022). Sentinel-2 data at high spatial resolutions (10 to 60m) are very useful in vegetation mapping, agricultural monitoring, forest surveillance and water resource management (Roy et al., 2022). In a similar fashion, the Moderate Resolution Imaging Spectroradiometer (MODIS) provided high temporal resolution observations that allowed for global scale assessment of vegetation productivity, land cover dynamics and environmental changes related to climate (Saleem et al., 2025).

In recent years, the use of Synthetic Aperture Radar (SAR) technologies for LULC analysis has also been growing. In contrast to optical sensors, SAR systems can gather data even in cloudy conditions or even in the absence of sunlight, especially beneficial in tropical and humid areas (Zhao and Yu, 2025). Satellite missions like Sentinel-1, RADARSAT, ALOS-

PALSAR have opened up new possibilities for forest biomass monitoring, flood dynamics, soil moisture monitoring, and land deformation process monitoring. A combination of optical and radar data has led to better classification accuracy and better detection of environmental changes, which are subtle (Radwan et al., 2021). Geographic Information Systems are used as an analytical tool for processing and interpretation of remotely sensed data. GIS enables the collection, combination, analysis and visualization of spatial data from various sources such as satellite data, field survey data, topographic maps, socioeconomic data and environmental data (Rimal et al., 2025). GIS can be used for spatial overlay analysis, geostatistical modelling, and spatial decision-support systems, which can be used to detect patterns in land transformation, to quantify environmental impacts and to assess relationships between ecological and socioeconomic variables (Kan et al., 2026).

The incorporation of machine learning and artificial intelligence (AI) into LULC monitoring workflows has been one of the most important recent advancements in modern geospatial science. In addition to traditional classification methods, as mentioned above, more sophisticated machine learning algorithms such as Random Forest, Support Vector Machines, Artificial Neural Networks, Gradient Boosting Models, and Deep Learning models are becoming increasingly utilized to complement or replace traditional classification techniques (Hemati et al., 2021). Convolutional Neural Networks (CNNs) are an example of deep learning methods that have shown outstanding results in image segmentation, object detection and high-resolution land cover mapping.

Cloud computing platforms have also revolutionized geospatial analysis by enabling large-scale processing of satellite data. One of the most popular cloud-based geospatial platforms is Google Earth Engine (GEE), which currently has access to petabytes of satellite imagery and geospatial data (Mashala et al., 2023). Researchers can carry out complex analysis without downloading huge data or expensive computational infrastructure. GEE enables large scale environmental monitoring, automated change detection, machine learning applications and near real time environmental assessment, thus greatly speeding up geospatial research and decision-making processes. Unmanned Aerial Vehicles (UAVs) have become a more important source of high-resolution monitoring of the environment, in addition to satellite technology. The UAVs with centimeter-level spatial resolution can be used in detailed studies of agricultural systems, forest ecosystems, wetlands, coastal zones and urban areas with flexible data acquisition capabilities (Potapov et al., 2022). UAV derived imagery can be combined with satellite imagery and GIS analysis for more accurate and precise LULC assessment as well as to support the local scale environmental management (Saleem et al., 2025).

There are still some challenges to be addressed in implementing the use of GIS and remote sensing in LULC monitoring. Uncertainties can enter into land cover assessment because of variations in sensor characteristics, image quality, classification methodologies, and validation procedures. In addition, certain regions might lack data availability, computational resources, or technical expertise, restricting the potential implementation in those areas (Ren et al., 2024). However, the effectiveness of LULC monitoring and environmental assessment is still being enhanced through continued advances in Earth observation systems, artificial intelligence, cloud computing, and geospatial analytics. Geographic Information System (GIS) and remote sensing have become integral tools to understanding landscape dynamics and processes of the Earth system. They can deliver timely, accurate and geospatial information, which helps with evidence-based decision making, sustainable land use and environmental governance in a rapidly changing world (Roy et al., 2022).

4. Machine Learning and Artificial Intelligence in LULC Mapping

High resolution satellite images and geospatial big data have been growing in number, which has led to the widespread use of Machine Learning (ML) and Artificial Intelligence (AI) methods in Land Use and Land Cover (LULC) mapping. There have been several image classification methods used for decades such as Maximum Likelihood Classification (MLC) and Minimum

Distance Classification (MDC) and ISODATA clustering (Saleem et al., 2025). These methods however have difficulties in the accurate classification of complex and heterogeneous landscapes because of the spectral similarity among land cover classes and the growing amount of remotely sensed data. As a result, sophisticated ML and AI algorithms have become very promising alternatives that can enhance classification results, computation efficiency, and prediction potential (Steffen et al., 2020).

Random Forest (RF) is one of the most used algorithms in the field of LULC studies among the machine learning techniques. Random Forests (RF) is an ensemble learning method that merges several decision trees to produce powerful classification results and reduce overfitting (Tahir et al., 2025). Many studies have shown that RF consistently produces better results than traditional classification algorithms, especially in mixed land cover areas. Likewise Support Vector Machines (SVM) have been found to be excellent for processing high dimensional remote sensing data sets and classification of spectrally similar classes. Recent years have seen further improvements in the accuracy of classification and change detection using other machine learning algorithms such as Artificial Neural Networks (ANN), Gradient Boosting Machines (GBM), and Extreme Gradient Boosting (XGBoost) (Pandey et al., 2021; Tasya, 2025).

In recent years, artificial intelligence has led to great developments in deep learning, which can greatly enhance the interpretation and extraction of features from images. To classify land cover types automatically, detect objects, segment the semantic classes of interest, and analyze changes over time, Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are gaining significant use in fields such as remote sensing and Earth observation (Saleem et al., 2025). Deep learning models can learn hierarchical features directly from raw images which is beneficial compared to traditional machine learning methods, where feature engineering is required. These capacities are especially useful for high resolution satellite imagery, urban mapping, monitoring forests and assessing agricultural lands, among other applications (Fagua and Ramsey, 2019).

AI's ability to integrate with cloud computing technologies like Google Earth Engine has revolutionized the field of geospatial data analysis by providing the means to process massive amounts of satellite data at scale and automate these processes. AI's integration with cloud computing systems, like Google Earth Engine, has further revolutionized geospatial data analysis by streamlining the processing of extensive satellite imagery at scale and automating these tasks. These technological innovations enable almost real-time monitoring of environmental shifts and changes, enhance predictive modelling of future land use scenarios, and contribute to data-driven decision making for sustainable land use. AI technologies are poised to increase in influence on LULC mapping, offering ever more accurate and efficient instruments for environmental monitoring and Earth system assessment (Kan et al., 2026).

5. Earth System Implications of LULC Change

Changes in land use and land cover have significant effects on Earth system processes, which involves modification in the interactions between the atmosphere, hydrosphere, biosphere, and lithosphere. With the shift of natural landscapes into an urban environment, deforestation and agricultural and industrial development, essential environmental processes are changed and so are the environmental consequences, with effects that are not felt within the local ecosystem. Such knowledge is fundamental to understand the sustainability of land management systems and forecast future environmental pathways (Ishtiaque et al., 2017; Hemati et al., 2021).

LULC change affects the climate regulation and carbon dynamics, which is one of the most important impacts of LULC change. Forest, wetlands and natural grasslands are large carbon sinks that remove atmospheric carbon dioxide by fixing it in the biomass and soil through photosynthesis. This transformation into agriculture land or urban infrastructure releases significant amounts of carbon stored in these ecosystems into the atmosphere, and this release has led to a significant increase in greenhouse gases and global warming (Steffen et al., 2020). There is a relatively large portion of anthropogenic carbon emissions worldwide due to deforestation. In addition, deforestation decreases the ability of ecosystems to sequester carbon, which in turn decreases the ability of ecosystems to mitigate the effects of climate change. Land cover changes also have impacts on energy exchange processes, evapotranspiration rates, and surface albedo, which consequently influences regional and global climate systems (Radwan et al., 2021).

LULC changes also affect hydrological processes. Natural landscapes promote infiltration, groundwater recharge, and control surface runoff, but urban development creates a lot of impervious surfaces that alter natural water cycles. More roads, buildings, and other infrastructure replacing forests and farm land decreases infiltration capacity and increases the amount of runoff generated. Therefore, urbanized watersheds may have more intense peak discharges, more frequent flooding and be more susceptible to water-related disasters. The degradation of wetlands further enhances hydrology instability by destroying natural flood water storage areas and water purification functions. Intensification of agricultural practices can also impact streamflow, groundwater supplies, and water quality by increasing irrigation needs and nutrient load.

Another important Earth system impact of LULC change is the Land Surface Temperature (LST) and urban heat island (UHI) effects. Removal of vegetation decreases evaporative cooling and increases the amount of solar radiation absorbed and retained (Steffen et al., 2020). City surfaces like concrete, asphalt and roofing surfaces have high heat storage capacities, causing a rise in temperature, compared to the surrounding rural areas. Many studies have documented that urban expansion is correlated with appreciable LST increases, and that these increases can lead to the development of urban heat islands, or differences in temperature of several degrees Celsius. Rising temperatures affect consumption, air quality, public health, and ecosystem functions and exacerbate exposure to heat-related hazards in future climate change scenarios (Tahir et al., 2025).

Land transformation processes have also a strong impact on the integrity and biodiversity of ecosystems. Worldwide, habitat loss and fragmentation continue to be among the major threats to species decline. Obstacles to species movement, such as a reduction in ecological connectivity, due to increasing fragmentation of natural habitats by roads, urban development and agricultural activities (Fu and Weng, 2016). These changes have adverse impacts on population viability, genetic diversity and ecosystem resilience. The conversion of forests and degradation of wetlands is especially harmful as they are ecosystems which have high biodiversity and the essential functions. The degradation of habitats in previously undisturbed landscapes, due to the continued expansion of human activities, negatively affects many species and is a driver of global biodiversity loss (Beylich et al., 2024).

The effects of LULC change on ecosystem services that contribute to human well-being and economic development are also further influenced. Examples of ecosystem services include: carbon sequestration, water regulation, soil conservation, pollination, nutrient cycling, climate regulation, and recreational opportunities. When these services decline, due to degradation of natural ecosystems, there are environmental and socioeconomic challenges. For instance, deforestation can lead to soil erosion and sedimentation, which can lower agricultural productivity and water quality. Likewise, the disappearance of wetlands reduces the flood protection and groundwater recharge functions, resulting in higher disaster risks and management costs (Zhao and Yu, 2025).

A growing feature of Earth system science is that there are feedbacks between LULC change and environmental processes. Land cover changes lead to changes in the climatic conditions, which in turn lead to changes in vegetation, water availability and future land use (Pandey et al., 2021). These feedbacks can lead to complex interactions that can occur over time and amplify environmental change. For example, deforestation can lead to regional warming and a decrease in rainfall, also contributing to ecosystem deterioration and its rate of decline. Likewise, urban sprawl could exacerbate water shortages and heat stress, requiring further adjustments in land use and infrastructure (Chatrabhuj et al., 2024).

The cumulative effects of LULC change reveal the need to create an integrated system of geospatial technologies, Earth observation systems and environmental modeling methods for more effective understanding of LULC change-related interactions between the land and atmosphere, as well as ecosystem dynamics (Potapov et al., 2022). These changes can be effectively monitored to give essential data for climate adaptation, biodiversity conservation, disaster risk reduction and sustainable development planning. The implications of LULC change for the Earth system will continue to be key to environmental sustainability and resilience in the Anthropocene as human pressures on land continue to grow (Kan et al., 2026).

6. Geospatial Indicators for Environmental Monitoring

Satellite remote sensing-based geospatial indicators have emerged as valuable resources for understanding land use and land cover (LULC) change and its environmental impacts. They offer quantitative data on vegetation condition, water resources, urbanization and thermal conditions, allowing researchers to assess ecosystem health and track environmental change over time. Some of the most commonly used indicators are Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Difference Built-up Index (NDBI), and Land Surface Temperature (LST) (Saleem et al., 2025).

NDVI is one of the most widely used vegetation indices and is a good measure of vegetation density, biomass and photosynthetic activity. It is calculated using the reflectance values of the near-infrared (NIR) and red spectral bands (Kan et al., 2026). A higher value of NDVI suggests that the vegetation is healthy and dense while lower values are linked to vegetation sparseness, degraded landscapes and built-up areas. NDVI has been widely used to monitor deforestation, degradation of vegetation, agricultural productivity, the effects of drought, and the capacity of ecosystem to recover from different environmental changes (Saleem et al., 2025).

NDWI is a product created to improve the detection of surface water bodies and moisture conditions. The NDWI is designed to use the green and near-infrared spectral bands to separate water features from surrounding land surfaces. This index is used extensively for wetland mapping, monitoring for flood, drought assessment and water resource management. The trend of NDWI values can be indicative of variations in water availability, which may be due to changes in climate, or urbanization or land use changes (Chatrabhuj et al., 2024).

NDBI is specially designed for the identification of built-up and urbanized areas. It uses the shortwave infrared (SWIR) and near-infrared reflectance features to identify impervious surfaces, vegetation and water bodies (Gupta et al., 2024). Higher NDBI values are usually associated with urban development and construction. Thus, NDBI has emerged as an important tool to track urbanization, its land use, and environmental consequences of fast urbanization.

Land Surface Temperature (LST) is an important parameter that gives useful information on thermal conditions of landscapes. LST is derived from thermal infrared satellite data that is related to the energy balance of the Earth's surface and heavily dependent on land cover properties. The LST values are usually high in urban areas because of high impervious surface and less vegetation cover compared to forest areas and water bodies, which usually have low LST. LST is of great significance for studying the urban heat island effect, the impacts of climate change, and for the study of land-atmosphere interactions. The combination of NDVI, NDWI, NDBI, and LST provides a holistic approach to comprehend environmental processes and evaluate the consequences of LULC alteration on the functioning of the Earth system (Hemati et al., 2021; Saleem et al., 2025).

Table 2: *Common Geospatial Indicators Used in LULC and Environmental Monitoring*

Indicator	Formula	Purpose	Applications
NDVI (Normalized Difference Vegetation Index)	(NIR − Red)/(NIR + Red)	Assess vegetation health and biomass	Deforestation, agriculture, drought monitoring
NDWI (Normalized Difference Water Index)	(Green − NIR)/(Green + NIR)	Detect water bodies and moisture conditions	Flood mapping, wetland monitoring
NDBI (Normalized Difference Built-up Index)	(SWIR − NIR)/(SWIR + NIR)	Identify urban and built-up areas	Urban expansion assessment
SAVI (Soil Adjusted Vegetation Index)	[(NIR − Red)/(NIR + Red + L)] × (1 + L)	Reduce soil background effects	Sparse vegetation mapping
EVI (Enhanced Vegetation Index)	G × [(NIR − Red)/(NIR + C1×Red − C2×Blue + L)]	Improve vegetation analysis in dense canopies	Forest monitoring
LST (Land Surface Temperature)	Derived from thermal bands	Assess surface thermal conditions	Urban heat island and climate studies

7. Emerging Trends and Future Directions

Earth observation technology, artificial intelligence, cloud computing and geospatial data analysis are transforming the field of LULC monitoring. Such innovations are increasing monitoring capacity to detect environmental change more accurately, spatially and over time than ever before (Lei et al., 2024).

The one of the most impactful advances is the use of cloud-based geospatial platforms like Google Earth Engine (GEE). They offer access to huge archives of satellite data and advanced computational capabilities, allowing for comprehensive analyses of environmental processes that do not necessitate complex local computing resources. Automated classification, change detection and environmental modeling at regional, national and global scales is now possible (Ishtiaque et al., 2017).

The integration of Artificial Intelligence (AI) and deep learning into geospatial analysis is another transformative shift. Another paradigm shift is the incorporation of Artificial Intelligence (AI) and deep learning technologies in geospatial analysis. CNNs, RNNs, and transformer models have proven to be highly effective in image recognition, feature extraction, and land cover classification. These methods greatly enhance the accuracy of mapping at a reduced manual effort. Future developments are likely to combine the benefits of AI-driven predictive modelling and Earth system simulations to predict future land use scenarios and environmental impacts (Dangayach and Pandey, 2025; Güneralp et al., 2020).

A new trend is the use of multi-source geospatial data fusion. Combination of optical imagery, Synthetic Aperture Radar (SAR), LiDAR, UAV data and socioeconomic data allows a more comprehensive understanding of landscape dynamics. Multi-sensor approaches can enhance classification accuracy and enable monitoring of environmental processes under various climatic and geographical conditions (Huang et al., 2024).

Innovative approaches to environmental management include digital twins and Earth system modelling frameworks. Virtual representations of real landscapes are digital twins that can help researchers and policymakers simulate future scenarios, test policy interventions and determine sustainability outcomes. The technologies have great potential in the field of urban planning, disaster risk reduction, ecosystem restoration and climate adaptation (Gupta et al., 2024).

Future study is expected to concentrate on actual monitoring of the environment, automated change discovery systems, utilizing big-data analysis, and creating choice support systems for sustainable land administration. The progress in these fields will support the use of geospatial technologies to tackle global environmental issues and to inform evidence-based policy-making (Akbar et al., 2019).

8. Research Gaps and Challenges

While there have been significant advances in GIS and remote sensing technologies, there remain a number of research gaps and challenges for reducing the effectiveness of LULC monitoring and analysis. The issue of data resolution and consistency is one of the challenges. Many differences in spatial, spectral and temporal resolution between satellite sensors can cause uncertainty and make comparisons between different studies and regions difficult. Another concern is the accuracy of the classification. Recent machine learning and deep learning methods have led to huge gains in mapping accuracy, yet classification errors still occur in complex landscapes with land cover classes having similar spectral signatures. In some areas, especially in developing countries and remote areas, there are often no reliable validation datasets available.

One other important constraint is the lack of incorporating socioeconomic, institutional and governance aspects into LULC studies. Much of the research on investigations is often just concerned with land cover changes, and it ignores human dimension aspects which cause landscape change. The understanding of the land-use decision-making process would be enhanced by the incorporation of socioeconomic indicators, demographic trends, policy framework and economic drivers.

Future projections of land cover are further influenced by climate change. Climate variability and ecosystem responses, as well as human actions, interact dynamically to form complex feedbacks that are poorly captured by many models. There is therefore a need to enhance the coupling between LULC analyses and Earth system models. It's difficult to turn scientific research into actionable policies. While geospatial technologies provide a wealth of environmental information, the effective dissemination of information from researchers, planners and policy-makers is often lacking. Strengthening interdisciplinary collaboration and developing user-friendly decision-support systems will be essential for ensuring that geospatial research contributes meaningfully to sustainable land management and environmental governance.

Conclusion

Land use and land cover change is one of the major drivers of environmental changes in the Anthropocene that affect climate systems, hydrological processes, biodiversity, ecosystem services and human well-being. In this review, it has been emphasized that Geographic Information Systems (GIS) and remote sensing technologies have a vital role in monitoring, analyzing and understanding the multifaceted processes of land changes over multiple space and time scales. Rapid progress in satellite observation systems, machine learning algorithms, AI, and cloud computing platforms has significantly enhanced the precision and productivity of LULC mapping, leading to more detailed analyses of environmental change.

Conflict of Interest

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