Land-use dynamics and land fragmentation: ecological challenges and consequences-a review

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Abstract. Land fragmentation has emerged as a critical environmental challenge affecting ecosystem connectivity, land-use efficiency, and the sustainable management of natural resources. This review synthesizes and examines the drivers of land fragmentation, with particular emphasis on its ecological consequences, ecosystem connectivity, ecosystem services and landscape resilience, while assessing the geospatial approaches to detect fragmentation. A narrative review approach was employed using comprehensive literature from major academic databases, including Google Scholar, Scopus, and Web of Science. Key patterns were identified, reviewed and organized thematically under major dimensions in the analysis. The study revealed that land cover may cause changes under permanent, semi-permanent or temporary with their persistence and spatial characteristics influencing the fragmentation process. Large dams, expressways and reservoirs are man-made features that remain for a long time after construction and could generate fragmentation in the existing features of the land cover. Natural disturbances can also produce rapid and temporary but persistent changes in landscape structure. Geospatial and landscape metric approaches have progressively improved the detection and assessment of land cover change and fragmentation. Despite methodological advances, challenges remain in integrating spatial analysis with ecological interpretation and translating fragmentation assessments into coordinated land-management and policy decisions. The challenge lies in operationalizing these tools effectively for informed policy, institutional coordination, and evidence-based land management.

Keywords: ecological resilience, habitat fragmentation, land cover change, land use, landscape sustainability

Abbreviations

GIS- Geographic Information System
ENVI - Environment for Visualizing Imagery
FRAGSTATS- Fragmentation Statistics
LFT- Landscape Fragmentation Tool

1. Introduction

The term 'land' refers to the earth's surface in general. Since their arrival on the planet, humans have relied on land to meet their cultural, social, and spiritual needs, eventually contributing to

the development of civilizations. The land provided essential resources necessary for the sustenance and development of human societies, including water, food, and shelter. It has also been an asset for achieving social status and prestige, as well as for asserting territorial sovereignty within cultural societies. Beyond the natural events that alter the landscape, human-made changes have become significant agents of alteration and modification in the land and to varying degrees of intensity (Adam, 2023; Garg et al, 2019; Wijesekara et al, 2026). Furthermore, in the advanced setting, land has been utilized for traveling and delivering commodities, for recreation, leisure and for aesthetic pleasure (Schirpke et al, 2026). Gatahi (1976) pointed out that vegetation biomass, climate, slope, landform and soil texture as the attributes of lands, further noting that these characteristics interact dynamically under complex conditions. Natural flora, wildlife, human life, economic activity, and transportation and communication networks are all supported by the land and as a resource, land is a fundamental factor of production. Land can be identified as a multi-dimensional (economic resource, ecological system, cultural landscape, political territory) resource.

1.1 Conceptualizing land use, land cover and land fragmentation

The terms “land use” and “land cover” are conceptually related but their actual meanings stand distinct. The substance that covers the earth’s surface (vegetation, forest, glaciers, barren lands, water bodies, rocks etc) are generally known as land cover (Duhamel, ND). It may also be contributed by land uses such as buildings, roads, or water reservoirs (Cihlar et al, 2001). Land cover information further provides essential ground cover data for generating baseline thematic maps. In contrast, land use refers to the intended use or functions of the particular area, including production, recreation, development, conservation and agriculture. These maps establish a reference for assessing the spatial structure and composition of the landscape. Diverse land cover types can be used or managed in different ways. The land cover and land use maps establish a reference for assessing the spatial structure and composition of the landscape. Consequently, accurate land cover/ use information provides a critical foundation for long-term analysis of land use, land cover dynamics, landscape fragmentation patterns, habitat alterations and associated changes.

Land use and land cover interact with each other in many ways. A single land cover may be used for a single land use (Ex: grasslands used for animal husbandry). Or a single land cover can be utilized for several land uses (Ex: Forest for recreation and wildlife conservation/water areas for fisheries and recreation). Similarly, a single land use such as agriculture may be associated with several land covers such as cultivated lands, improved pasture or woodlands

(Turner & Mayer in Briassoulis, 2020). Consequently, studies on land changes are multidisciplinary by their nature. With prior knowledge and auxiliary data, information on land cover is used to ascertain land uses of the selected earth surface. Thus, in land change sciences, comprehending the differences between land covers and land use is crucial.

Fragmentation is a diverse phenomenon (Tejaswi, 2007). It occurs over time by dividing the homogeneous land cover into several units. Literature defines land fragmentation from diverse perspectives. While the most recent studies focus on land fragmentation as a result of morphological changes associated with the division of a continuous area of land (or habitat) into number of parcels/patches, smaller, more isolated. Another strand of studies focuses on land fragmentation in relation to its tenure (Demetriou, 2014). Land parcel fragmentation primarily refers to the subdivision of land into smaller cadastral units based on their tenure. This may often result from inheritance, land transactions or settlement policies. In contrast, in Ecology, the separation of habitats by barriers that impede the movement of organisms or ecological flows between areas due to human activities are defined as fragmentation. This may potentially reduce habitat connectivity and affect biodiversity. These two processes are distinct from each other. Therefore, this review will specifically address the ecological division and isolation of habitat patches.

Processes of land cover change including deforestation (Reddy et al, 2018; Ning et al, 2023), urban sprawl (Jiang, 2025; York, 2011; Bozkurt & Basaraner, 2024) and cropland expansion (de Oliveira, 2017; Ma et al, 2023) help to produce fragmentation patterns. Meanwhile, fragmentation can be both a cause and a consequence of broader landscape dynamics. The land cover must be identified, defined, and mapped to help with resource planning, management, monitoring and policymaking. Further, land use and land cover maps are utilized for planning implications such as simulating and assessing urban encroachment, sea level rise, wetland losses, prioritizing conservation needs and simulating new plans for future endeavors. Long-term changes in land cover could indicate regional climatic alterations, biodiversity loss, water cycle disturbance and serve as the foundation for global terrestrial changes. These data provide more insights into the traditional census databases. In recent years, many international policies have been formulated in alignment with the United Nations Sustainable Development Goals (SDGs). Advances in land-cover visualization are expected to generate more accurate datasets for assessing several SDG indicators, and these datasets can be used both to monitor progress and to support efforts toward achieving the SDGs (Feng et al., 2021). The specific goals pertaining directly to land are; Goal 2 (eradicating hunger), Goal 11 (sustainable cities) and

Goal 15 (ecosystem on land). Further, SDGs on infrastructure, clean water and climate action contribute indirectly to the land.

1.2 Rationale of land cover change studies

The science of land change came into discussion in the late 1990s. It has evolved over three decades and contributed to uncovering the causes and effects of land change in a broader perspective (Turner et al, 2020). Finding the principles that underlie land change and identifying a wide range of case-specific factors that mediate those factors are the key elements of land change science (Turner et al, 2020). Changes in the land surface are primarily driven by the combined effects of biophysical factors, such as the atmosphere, hydrosphere and human-induced activities. These forces alter both the structure and functioning of land systems. Briassoulis (2020) emphasizes that key biophysical components, including geology, landforms, soils, hydrology, regional climate, vegetation, and fauna, play a significant role in driving land-cover change. Ultimately, such changes often lead to land degradation (Nga et al, 2023).

Musa (2008) emphasizes that biodiversity, hydrological cycle, land productivity, and the sustainability of the natural environment are all impacted by changes in land cover, either directly or indirectly. He also highlights that land cover change entails mapping the baseline and monitoring or tracking the change over time. This real-time information is required to support the advancement of policies, to support the competing uses and to implement new regulations fulfilling the demand on land. Environmental monitoring, sustainable land management, urban and infrastructure planning, disaster risk reduction and climate change assessment are several reasons where detecting morphological changes in land cover is important. Decisions about land cover are affected by both formal and informal institutional structures. Land cover changes have the potential to cause significant and lasting effects on both natural and anthropogenic environments, with impacts that can be observed in the short term as well as over extended periods. These changes can have far-reaching consequences that require thorough consideration.

However, human-induced land-cover changes have had a variety of positive and negative effects on society, biosphere and land use (Aguilar & Hernandez-Lozano, 2024). **The most influential elements are probably land ownership and tenure.** Further, it has been directly affected by sociocultural factors and geographical (Bozkurt & Basaraner, 2024) and temporal scale interactions too. Rather than occurring in a vacuum, changes in the land may include intricate webs of time and place in particular relationships. Any biological, chemical contaminant change; physical change such as upgrading or installation of a new drainage

network, installation of irrigation networks or dams, emergence of new plantations, vegetation removal, spread of non-native plant species, or conversion of lands such as agricultural lands to industrial activities are defined as land use change (Quentin, 2006 in Meshesha et al, 2016). Individual land units may fluctuate depending on site-specific conditions such as accessibility, regional land use patterns, transportation costs, production costs, competition, size of the land, financial support by governmental and private bodies, laws and regulations by governments or local authorities, practices of land management, land tenure and ownership.

Within the broader context of land change science and land cover change, land fragmentation is grounded in landscape ecology, which focuses on the spatial configuration of landscapes and the interactions among ecosystems (Clark, 2010). Landscape fragmentation is influenced by human or natural forces and visible when the landscape tends to change into complex from simple landscape, showing complexity and heterogeneity in the spatial pattern (Montis, 2017). Further, the landscape fragmentation can be explained as the area decreases while the number of patches grows (Pu, 2024). Landscape fragmentation can adversely affect ecological processes and biodiversity, thereby compromising the sustainability, resilience, and overall quality of ecosystems (Gibson et al, 2013). Local level fragmentation can also scale up to regional and global effects, leading to huge disruptions in ecosystem connectivity, biodiversity loss, climate regulation, and human well-being. The BR-163 road in the Brazilian Amazon is one of the real-world examples which expanded regional deforestation to a significant level of Carbon emissions, ultimately contributing to global warming.

Concerning the ecological threats, land fragmentation can affect many types of ecosystems, including wet zone rainforests, by altering migration patterns, increasing population density within limited habitat patches, intensifying competition for food and reproduction, and isolating species within small fragmented areas (Abeyrathne et al., 2024). Asian elephants are a globally endangered species and Sri Lanka is an example of where the local fragmentation contributes to global conservation priority rankings. Natural vegetation fragmentation in the dry zone of Sri Lanka has contributed to habitat loss and the decline of elephant habitats and populations in the country. Kenya-Nairobi-Nakuru highway is also a local level fragmentation example that scales up to global effects. The highway runs through wildlife ranges which disrupts the movement of African elephants, zebra and lions. African elephants are also listed as globally threatened species. These cases directly demonstrate how anthropogenic pressure drives land fragmentation; the effects of fragmentation on connectivity, biodiversity and ecological processes; and why geospatial approaches are essential in assessing these changes. The contextual evidence presented here clearly highlights the importance of identifying the

spatial context and underlying drivers of land change and fragmentation. From an ecologist's perspective, ecologists face challenges in obtaining long-term field data, limited availability of site-specific records, variation among ecosystems, and challenges in finding reliable sources that directly support fragmentation-related impacts (Abeyrathne, et al, 2024).

In summary, land fragmentation brings immediate effects such as habitat loss and altered environmental conditions, while also exerting long-term impacts such as biodiversity loss, reduced ecosystem services, compromised resilience, and implications for land productivity, resource availability, and climate change (Curran-Cournane et al, 2020). To comprehensively address these effects, it is crucial to prioritize sustainable land management practices that minimize negative consequences and promote the conservation of ecosystems, ensuring the well-being of both the environment and society. Therefore, studying land cover change and changes in landscapes is required to understand the drivers and consequences of land fragmentation before moving to long-term regional planning and policymaking decisions.

This review aims to synthesize drivers, impacts and critically examine the tools in the existing literature on concepts of land fragmentation and land cover change. The main objective of this study is to synthesize a comprehensive understanding of land cover change and land fragmentation with particular emphasis on their ecological consequences.

The key research questions are,

- What is the relationship between land fragmentation and land cover change?
- What are the drivers of land fragmentation and landscape alteration?
- What are the ecological consequences of land fragmentation on biodiversity, ecosystem connectivity, ecosystem services and landscape resilience?
- How have technological advancements improved the detection and analysis of landscape fragmentation?

In this background, this study continues to bring together the scattered work on land cover change, land fragmentation and landscape change. Through a geographical lens, the review develops an integrated perspective on how social, economic, institutional and infrastructural drivers reshape land cover, land fragmentation, and how they lead to ecological, hydrological and socio-economic consequences. Particular attention is paid to the role of linear infrastructure and large development projects, and the implications for sustainable land management in both Global South and Northern settings. In the following sections, the paper first clarifies key concepts and situates land fragmentation within land-change debates; synthesizes evidence on drivers; impacts on ecosystem connectivity, ecosystem services and landscape resilience; and

the consequences and analytical tools. It concludes by identifying conceptual and methodological gaps and outlining directions for future research and land-use planning.

2. Methodology

This study adopted narrative review approach to synthesize the existing knowledge. A wide range of insights and perspectives essential for a comprehensive knowledge diagram on land change and fragmentation was identified using this narrative approach. Unlike systematic reviews, narrative reviews allow for interpretive synthesis across diverse theoretical and methodological perspectives.

A comprehensive and extensive literature search using the main academic databases, including Google Scholar, Scopus and Web of Science were used in this review. The search string “Land Fragmentation” was used in searching the databases. The thesis databases from universities which were closely related to the topic were taken for the study to improve academic integrity. In addition to journal articles and books, relevant grey literature such as reports from the Food and Agriculture Organization and the United Nations Development Programme was reviewed to capture practical and policy-oriented insights. Literature was selected if the document explicitly discussed land change and land fragmentation, regardless of the location of the study. Only the documents available in English were included. Most recent advancements relevant to the subject and fundamental studies were also considered, but the study was not restricted to a time frame or region. The scientific credibility and contribution to the existing knowledge structure were highly considered. Because this study is a narrative rather than a systematic review, the selection process was not intended to produce an exhaustive or statistically representative inventory of all publications on land fragmentation.

The selected studies were reviewed and organized thematically. Key patterns were identified under major dimensions and selected literature was grouped into three thematic domains: (1) drivers of land fragmentation and land cover change, (2) biodiversity, agriculture and ecosystem services consequences; and (3) methods and tools for detection and analysis. As a narrative review, this paper does not claim exhaustive coverage of all available sources. However, it aims to provide a comprehensive synthesis of the most relevant and influential literature to date. Figure 01 elaborates the conceptual diagram.

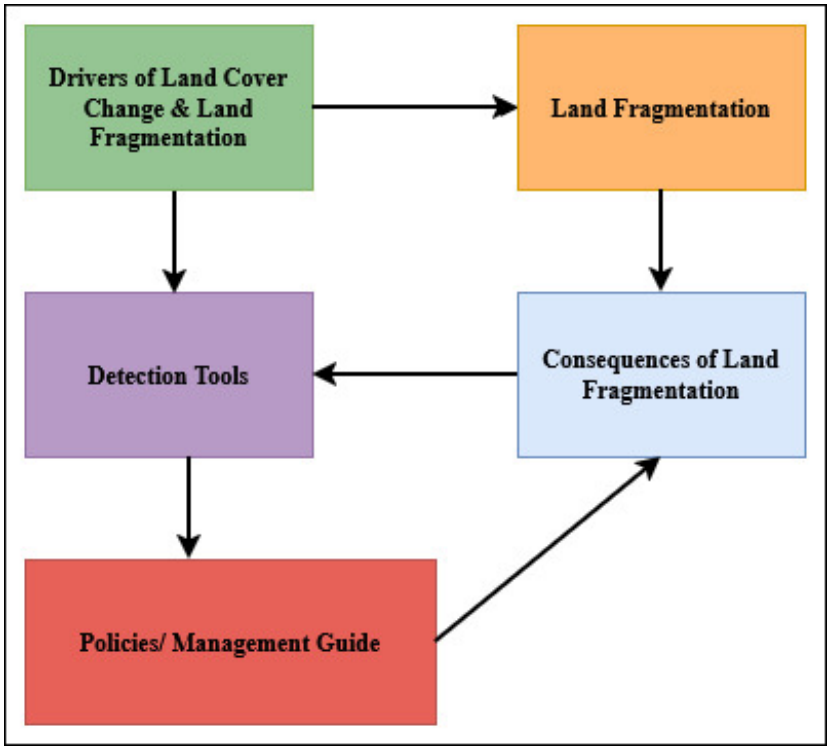


Fig. 1. Conceptual diagram

3. Results

3.1 Drivers of land fragmentation and landscape change

A land cover may cause changes under permanent, semi-permanent or temporary features. Permanent features are projected to be visible in the landscape for the foreseeable time in the landscape. Large dams, expressways and reservoirs are man-made features which may remain for a long time after construction could generate fragmentation in the existing features of the land cover. The effects of expressway construction projects lay on biota, and impacts such as landscape change and fragmentation, are cumulative (Wu et al, 2021).

Temporary features can last for a long time, but they are not maintained by humans and usually led to regenerate naturally. Seismic lines and commercial forest harvesting regions are among them. Some places quickly return to their old vegetation type, while others take considerable time to regenerate, depending on the type of plant harmed.

Linear infrastructure, including transportation (roads, waterways, airports, ports, bridges); water (water supply flows); sanitation infrastructure (rain drainage systems, sewage treatment systems); energy supply infrastructure (dams, power plants, power distribution and transmission facilities) and telecommunication infrastructure (internet facilities, fiber connections and recreation) are the main components of physical infrastructure. Tejaswi (2007)

reported that infrastructure developers and land settlement planners are one of the main reasons for edge fragmentation. Mansuroglu and others (2013) identified Antalya- Alanya expressway resulted in the removal of natural vegetation, extreme land consumption and fragmentation of agricultural lands. Southworth and others (2011) revealed that roads are the drivers of change in the Southwestern Amazon by studying the Tranz-oceanic highway connecting the Atlantic and Pacific oceans. Further, they found that access to roads was the determining factor of deforestation, while it also determines the spatial distribution. Sen & Kumar (2013) experienced that the expansion of the road network and expressways were the key point of expansion of the Gaya district in India.

As the infrastructure provisions have to deal with the biotic environment, it is essential to consider the demands of the natural systems as well as the needs of the population. The land use pattern of an area evolves in response to the changing needs of its population over time. Land values adjacent to roadways have also grown significantly due to the availability of infrastructure. Urbanization has caused fragmentation and heterogeneity of land (Demetriou et al., 2012; Tejaswi, 2007; Dadashpoor et al., 2019; Wu et al, 2021). Over time, urbanization tends to simultaneously reduce the amount of habitat and increase habitat fragmentation (Liu et al, 2016). Furthermore, the infrastructure acts as a barrier to spread of natural succession (Seiler & Folkeson, 2005). Growth of industries and industrial functions may ultimately lead to changes in landscape patterns from time to time in different aspects. According to their study, Dadashpoor and others (2019) mention that fragmentation and heterogeneity of the landscape are shaped by the growth and emergence of urban and industrial activities. Rapid urban expansion and population pressure have direct impacts on alterations in land uses and changing land cover patterns globally.

Considering natural sources, stormwater, mudflows, and avalanches are examples of swift-moving natural calamities that can significantly alter landscapes. These natural hazards are commonly observed in tropical regions experiencing heavy rainfall throughout the year. In addition, processes such as ice flows and ice melts in glacial and periglacial regions can reshape valleys, river systems, and low-lying areas through erosion, sediment deposition, and changes in water regimes in high-altitude and polar regions due to seasonal melting and glacial movements. Displacing soil and landmasses, creating new rivers, river channels, formation of new physical barriers can ultimately separate continuous habitats into smaller and isolated patches. Intense natural disturbances may result in altering the spatial connectivity of landscapes, influencing ecosystem structure and ecological processes.

Since culture creates landscapes and landscapes inoculate culture, landscapes have a significant impact on culture, with the influence of inheritance rules come across cultures (Nassauer, 1995 in Bürgi et al., 2005). Agricultural practices whether smallholder or commercial, land management and policies by governments also contribute significantly to the land fragmentation and landscape changes. Institutional, legal and tenure structures, property rights, customary tenure, zoning and planning systems can accelerate fragmentation and the land consolidation. Accordingly, it is evident that the driving forces behind landscape change is determined by the geographical, chronological and institutional scale (Bürgi et al, 2005).

3.2 Consequences for biodiversity, agriculture and ecosystem services

The structure and composition of land cover evolve over time and space. Changes in land cover structure can direct significant changes in ecological services such as connectedness and species movements. The loss of biological diversity and isolated natural biomes are the most detrimental effects of fragmentation. Apart from the increased risk of extinction for plant species and animals, fragmentation reduces their movements too (Seiler & Folkeson, 2005). Blocking the biological corridors of animal species in a habitat may result in the extinction of such species when their food and mating is disturbed. The availability and appropriateness of nearby areas for animals are also reduced as a result of habitat fragmentation generating a threat to biodiversity and ecological balance. After a certain point, the impact of fragmentation, generated by infrastructures becomes a barrier to continued development, preventing the fulfillment of ecological and landscape requirements (Pallag, 2000). Such developments not only increase habitat heterogeneity but also pose significant threats to micro-habitats by disrupting feeding and breeding patterns and diminishing the home ranges of smaller animal species, including insects. Fragmentation of water bodies can disrupt aquatic habitats by altering connectivity, water flow, access to breeding sites, and movement between feeding and spawning areas (Bell, 2001). These changes may strongly affect fish mating behavior, reproductive success, population structure, and long-term species survival.

Moreover, fragmentation affects faunal diversity and ecological processes too. The persistence of fauna depends on the size and the distribution of the patches (Offerman et al, 2011). Species diversity may increase within a fragmented land area, while the limited habitat space may also intensify food and mating competition. Such pressures can disturb species persistence and long-term ecological stability within fragmented habitats (Abeyrathne et al., 2024). Edge effects are also a significant outcome of land fragmentation (Fahrig, 2003), as they can alter microclimatic conditions and disrupt habitat integrity at patch boundaries. These effects often lead to

increased vulnerability to wind throw, desiccation, and the encroachment of invasive species, further threatening biodiversity and ecosystem stability (Murcia, 1995). Marcantonio and others (2013) prove that forest plant diversity is affected by the distance to roads from the forest land. Further, forest diversity is affected by environmental factors such as; Normalized Difference Vegetation Index (NDVI), slope, altitude etc, and climatic factors such as temperature, solar radiance and rainfall (Marcantonio et al, 2013).

Also, infrastructure (railroads, highways) contributes to the fragmentation of agricultural areas, resulting in reduced field sizes, increasing the number of agricultural land patches and various ecological disturbances important to farming. Increased transportation and production costs, as well as a drop in farmer revenue, are some of the implications of agricultural land fragmentation (Fentahun et al, 2022; Demetriou et al., 2012). At the same time, being an indicator of development, the density of linear infrastructure is a challenge in urbanized regions. Features like road networks, railways, liquid and gas distribution lines also contribute to the habitat fragmentation. The disruption caused by noise, visual, and chemical contamination, as well as habitat losses are the ultimate result caused by the infrastructure. Land fragmentation can have adverse effects on water quality runoff, infiltration, erosion, flood risk, landslide susceptibility (Dou et al, 2024; Cui et al, 2023), soil carbon sequestration and fire regime effects.

Fragmentation also contributes to the disruption of landscape aesthetics, cultural heritage, and the sense of place (Zeng et al, 2023). Social and cultural landscape changes may generate a possible impact on social conflicts, displacement and contested landscapes.

Most of the newest infrastructure development projects are more towards integrated planning, which allows multiple uses and as well generates less impact on the natural, social, and cultural environment. The Organization for Economic and Co-operation and Development (OECD) provide a good implication for quality infrastructure development by identifying potentials for establishing quality infrastructure while improving resilience and environmental and social outcomes (OECD, 2019).

3.3 Methods and tools for detecting land cover change and fragmentation

Landscape metrics are used to determine the spatial aspects of land in a quantitative aspect (Hastari, 2021). And it is used to measure the landscape's complexity and its structure. The alterations of land use/ land cover and landscape are linked to the total functional demand as well as changes in the physical environment (Musa, 2008). The landscape can be measured using metric analysis such as area, density, edge, shape, core area, proximity, evenness, connectivity and as well dominance (MacGarigal & Marks, 1995).

Demetriou and others (2012) emphasize that fragmentation of land has direct impacts on the regional scale, especially on sustainable development and agriculture. There are numerous tools and approaches available to detect landcover change, land fragmentation and landscape patterns available. No tool or application can apply to all types of ecosystems in land cover change detection studies. Satellite images indicate many benefits and are reliable for identifying land characteristics. They offer high temporal frequency, computational efficiency, consistency, and clarity, making them suitable for detailed analysis. As well they provide high resolution for more accurate analysis (Feng et al, 2021; Dong, 2021; Jia et al, 2019; Vigneshwaran, 2019; Vijay, 2017; Southworth, 2011). Further, some studies used ground verification using GPS to retain the accuracy of the satellite images (Rawat et al, 2013). These images are obtained through various satellites orbited around the globe and can be obtained images of 40 years. Further, land use/ land cover studies used cadastral maps (Ayazli, 2019) and orthophotos (Meneses et al, 2017) as well. Ortho imagery is a corrected aerial photograph which is geometrically corrected until the scale is uniform. Thus, it can be used to measure the true distances. The development of numerous sensor equipment with better radiometric, temporal, and spatial resolution which was facilitated by the advances in remote sensing science facilitated more accurate results interpretation for most parts of the world.

Remote sensing data integrated with Geographic Information System (Arc GIS), has been a tool for manipulating and managing spatial data sets for over 20 years of time (Lu et al, 2014). It has been updated to more new versions with significant development in its functions (Briassoulis, 2020; Feng et al, 2021; Dong, 2021; Southworth et al, 2011). Geographic Resources Analysis Support System (GRASS) (Rozon et al, 2015), Quantum GIS (QGIS) (Prabu & Dar, 2018), Earth Resources Data Analysis System (ERDAS) Imagine software (Vigneshwaran, 2019; Southworth et al, 2011; Sen & Kumar, 2013), Environment for Visualizing Images (ENVI) (Jia et al, 2019; Zhao et al, 2021), Idrisi or the TerrSet Land change modeler (Kumar et al, 2015; Zahir et al, 2021) were the most used software for land use/ land cover identification found in the literature. Technologies for data retrieval through remote sensing encouraged the development of land use/land cover investigations in many regions and scales and as well they have contributed to the evolution of land cover mapping preparation techniques (Meneses, 2017). Spectral mixture analysis and Artificial neutral networks also have significant value in applications of change detection (Lu et al, 2004). Land cover changes are effectively identified in both natural and social sciences integrated approaches. Social science researchers commonly employ interview methodsto collect data and opinions on land changes. Experience and the knowledge of the landowners or the local authorities are known

as most effective sources of information in this approach. Focus group discussions are also widely used techniques in Social Sciences. They successfully ascertain the political and socio-economic impacts on land change and are helpful in gaining human opinion and experiences on the land cover change.

For analyzing land fragmentation and landscape change, ArcGIS introduced a Vector-based landscape analysis tool named V-LATE 2.0 as an extension to ArcGIS 10.8 version (Tiede, 2020; Wadduwage et al, 2017; Rahman et al, 2016). Next, the Landscape Fragmentation Tool (LFT v2.0) which is developed by the Centre for Land Use Education and Research (CLEAR) (Rahman et al, 2016; Batar et al, 2021, Vogt, 2007). The University of Massachusetts introduces FRAGSTATS (McGarigal, 2012; McGarigal, 2015; Chen & Lannone, 2020; Ranaweera, 2021) for land fragmentation and landscape change analysis is also a systematic and effective tool. These are the commonly used tools found in the literature for effective landscape and fragmentation analysis.

Due to the wide range of software programs and data sources, research in the field of land sciences is dynamic. Additionally, there are many different methods for defining and identifying land use and land covers. Buffer analysis in GIS is one of the commonly used in determining the area or zone. It is used in identifying Geographic features of a particular location, within specific distances from a given point feature or line feature (Prabu & Dar, 2018; Zhang et al, 2013). Iso Cluster tool is used to classify and cluster the map cells into a specific number of classes. This is commonly used in unsupervised image classifications for identifying land covers where the minimum number of classification classes should be two and no limitation for the maximum number of classes (Vigneshwaran & Kumar, 2019: Dihkan, 2019).

Supervised classification is where the user can define the pixels of a raster image by assigning signatures for specific classes and software use the assigned signatures to classify the image (Prabu & Dar, 2018; Rawat et al, 2013). Principal component analysis (PCA) can be performed using several software (Excel, SPSS) which has high interpretability of data and used when there is a large amount of data per observation (Meneses, 2017). Normalized difference vegetation index (NDVI) is mostly used in agriculture or vegetation-related studies, which is used to easily quantify the greenness and the density of the vegetation (Feng et al, 2021; Dong et al, 2021; Jia et al, 2019; Rawat et al, 2013). Comparatively Normalized Different moisture index (NDMI), Normalized difference water index (NDWI) (Rawat et al, 2013). Normalized difference built-up index (NDBI) (Rawat et al, 2013), Object-based image classification techniques and visual analysis (Kara & Keçeli, 2017) were also mainly utilized in the land

change sciences. Further, the Tasseled Cap function which is also a function of the ArcGIS application and closely related to the NDVI analysis of the same application requires only three bands to perform an analysis. Principal component analysis (PCA) is also applicable to change detection analysis (Fung and LeDrew, 1987; Meneses, 2017).

The application of large datasets to conventional tools such as ArcGIS and Fragstats can be constrained by local computational capacity and data-processing requirements. Cloud-based platforms such as Google Earth Engine (GEE) and Microsoft Planetary Computer have expanded these capabilities by enabling the processing and analysis of large volumes of satellite imagery and geospatial datasets at regional and global scales without relying exclusively on local computing resources. Random forest, Support vector machine, Classification and regression trees are some machine learning algorithms that are undertaken on Google Earth Engine (Oo et al, 2022). These tools enable large-scale assessment of land cover dynamics, while facilitating integration of long-term, multisource observation data.

Thus, the spatial and temporal level of analysis determines the detection, measurement, and interpretation of land cover changes, land fragmentation and landscape pattern, the unequal access to these tools between the global North and South determines the major drawback of using these tools.

Table 1. Summary of empirical studies on land cover change/fragmentation detection tools.

Materials used	• Satellite images (Feng et al, 2021; Dong, 2021; Jia et al, 2019; Vigneshwaran, 2019; Vijay, 2017; Southworth, 2011) • GPS (Rawat et al, 2013) • Cadastral maps (Ayazli, 2019) • Orthophotos (Meneses et al, 2017)
Land use/ land cover change detection tools	• Arc GIS (Lu et al, 2014; Briassoulis, 2020; Feng et al, 2021; Dong, 2021; Southworth et al, 2011) • Geographic Resources Analysis Support System (GRASS) (Rozon et al, 2015) • Quantum GIS (QGIS) (Prabu & Dar, 2018) • ERDAS Imagine software (Vigneshwaran, 2019; Southworth et al, 2011; Sen & Kumar, 2013) • ENVI (Jia et al, 2019; Zhao et al, 2021)

Fragmentation detection tools	• V-LATE 2.0 as an extension to Arc GIS 10.8 (Tiede, 2020; Wadduwage et al, 2017; Rahman et al, 2016) • Landscape Fragmentation Tool (LFT) (Rahman et al, 2016; Batar et al, 2021; Vogt, 2007) • FRAGSTATS (McGarigal, 2012; McGarigal, 2015; Chen & Lannone, 2020; Ranaweera, 2021)

Note: Compiled by the authors

A few case studies reviewed for both land cover change detection and land fragmentation are briefed in Figure 2-7.

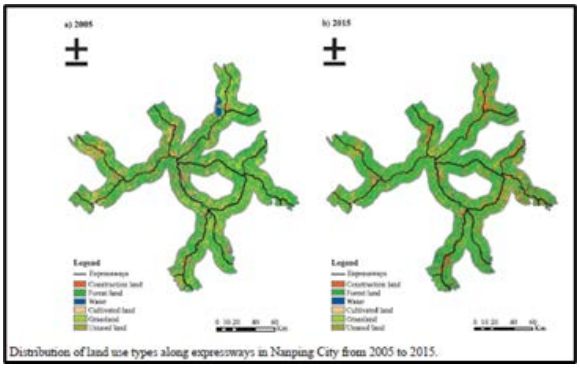


Fig. 2. Case Study 01(Zhao et al., 2021)

Zhao and others (2021) assess the changes in land use/ land cover and landscape patterns due to Expressways in Nanping City, China over 2005-2015 and evaluate their effects on ecosystem services. They used buffer zone analysis and calculated transfer matrix using ENVI software.

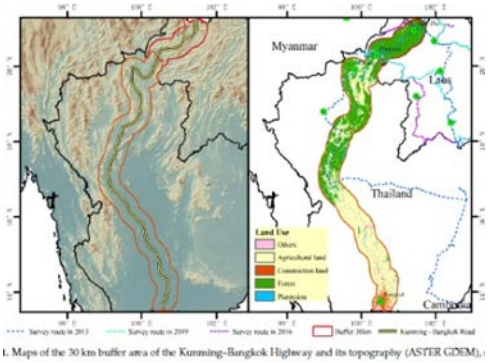


Fig. 3. Case Study 02 (Zheng, 2021)

In figure 3, Zheng (2021) examined dynamic changes in land use along the Kunming–Bangkok Highway running China to Bangkok by detecting changes in pixel values in ArcGIS 10 via raster iterators and buffer analysis and revealed, the dynamics of land use were much higher the before highway was opened to traffic.

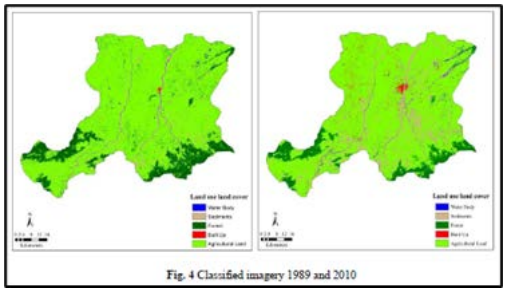


Fig. 4. Case Study 03 (Sen, 2017)

Sen (2017) revealed highways have been playing an important role in the expansion of the Gaya district in India and most of the development activities are taking place along the highways and directly connected regions (Figure 4).

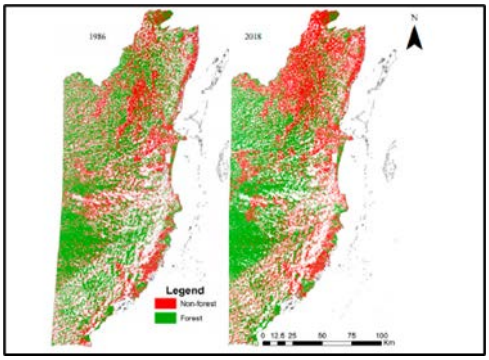


Fig. 5. Case Study 04 (Flowers et al, 2020)

Flowers and others (2020) assessed the extent and patterns of habitat fragmentation in Belize's ecosystems using landscape metrics. These metrics provide quantitative measures to analyse how habitat patches are fragmented and the resulting implications for biodiversity and ecosystem functioning (Figure 5).

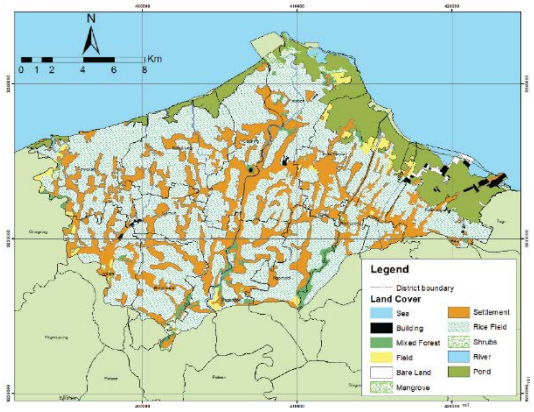


Fig. 6. Case Study 05 (Hastari et al, 2021)

Hastari and others (2021) quantify the Kendal delta landscape using patch density (PD), edge density (ED), mean shape index (MSI), mean nearest neighbor (MNN), and interspersion and juxtaposition index (IJI). Based on the overall calculation, a relationship between increase in PD and ED, leading to decrease in MNN and IJI were revealed (Figure 6).

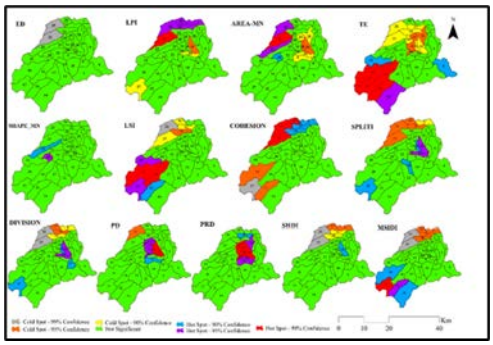


Fig. 7. Case Study 06 (Alaei et al, 2022)

Alaei and others (2022) have identified patterns of the land fragmentation through 36 sub-watersheds in Iran using FRAGSTATS Software and IIBM SPSS statistics (Figure 7).

Recent advances in land change science have expanded the analytical capacity beyond conventional desktop-based GIS workflows. While established tools such as ArcGIS and V-LATE remain useful for local-scale spatial analysis and landscape-metric assessment, cloud-based platforms such as Google Earth Engine and Microsoft Planetary Computer increasingly enable the processing of large volumes of remotely sensed data at regional and global scales with reduced dependence on local computational resources (Lukacz, 2024). In parallel, machine-learning algorithms, including Random Forest and XGBoost, have enhanced land-cover classification and change detection, particularly when combined with high-resolution and temporally extensive datasets such as Sentinel-2 and PlanetScope imagery. The integration of these technologies provides greater opportunities to detect fine-scale land-cover transitions and fragmentation patterns and to examine their ecological implications across broader spatial and temporal scales.

3.4 Towards integrated, sustainable land management under fragmentation

The rapid pace of infrastructure development and urban expansion has intensified land fragmentation and landscape alteration across many regions. While such developments are often justified in the name of economic growth, connectivity, and modernization, they also impose profound and often irreversible ecological costs. Striking a balance between the imperatives of development and the maintenance of ecological integrity remains one of the most pressing challenges in contemporary land-use planning and policy (Pu et al, 2024).

The dual nature of development: Infrastructure serves as both a catalyst and a constraint in regional development. On the one hand, linear infrastructures such as roads, railways, and canals enhance accessibility, stimulate trade, and improve socio-economic opportunities. On the other hand, they dissect continuous habitats into isolated patches, disrupt ecological corridors, and alter hydrological and geomorphological processes. This dual nature of development underscores the paradox where progress, if not guided by sustainability principles, can undermine the very environmental foundations on which long-term prosperity depends.

Fragmentation as a measure of landscape health: Land fragmentation can serve as ae critical indicator of landscape health. Fragmented landscapes exhibit reduced biodiversity, diminished ecosystem services, and weakened ecological connectivity. The findings across the literature (Tejaswi, 2007; Demetriou et al., 2012; Liu et al, 2016; Seiler & Folkeson, 2005) consistently reveal that fragmentation leads to habitat isolation, increased edge effects (Basu Roy and Dutta, 2025) and altered species composition. In agricultural landscapes, fragmentation results in smaller and less productive fields, higher production costs, and lower resilience to climatic and market shocks (Phan et al, 2022; FAO, 2002). Therefore, monitoring land fragmentation through spatial metrics provides valuable insights into the ecological costs of development (Das et al, 2025). Physical land fragmentation not only disrupts the spatial continuity of the landscape but also exerts adverse effects on the social life of local communities.

Infrastructure and the Spatial Dynamics of Change: Infrastructure-driven landscape change often demonstrates spatial dynamics. Expressways, highways, and industrial corridors stimulate secondary land-use changes in their surrounding zones, including increased urban sprawl, conversion of agricultural land, and loss of natural vegetation (Mansuroglu et al., 2013; Southworth et al, 2011). Beijing, China (Chu, 2022; Ye, 2024); Delhi, India (Jain & Pallagst, 2015); Jakarta, Indonesia (Rachman et al, 2024); Mexico City, Mexico (Aguilar & Hernandez-Lozano, 2024) are well known for uncontrolled suburban expansion and fragmented agricultural land due to infrastructure. São Paulo, Brazil has highly fragmented green and forest areas around the metropolitan periphery. Large-scale projects like expressways and reservoirs have reshaped land cover patterns, creating new economic nodes while simultaneously fragmenting ecosystems and agricultural mosaics. These secondary land use transformations can increase ecological fragmentation by reducing habitat continuity, increasing edge effects and weakening functional connectivity of the landscapes.

Toward a balanced development paradigm: Balancing development and ecological integrity requires a paradigm shift from reactive mitigation to proactive planning. The concept of

"quality infrastructure," as promoted by the OECD (2019), provides a promising direction by emphasizing resilience, inclusivity, and environmental performance. Advances in geospatial technologies have revolutionized the capacity to detect, measure, and model land cover and fragmentation dynamics, providing access to sustainable land management. However, technology alone cannot ensure sustainability unless it is embedded within participatory planning frameworks that integrate local knowledge, institutional collaboration, and environmental safeguards. A holistic approach combining scientific tools with governance mechanisms is vital for mitigating the ecological impacts of development. Development projects must incorporate ecological assessments at the design stage, maintain buffer zones around sensitive ecosystems, and promote multifunctional land uses that support both human and ecological needs. Moreover, integrating quality infrastructure such as green infrastructure, ecological corridors and urban green belts can help restore connectivity and mitigate fragmentation effects.

Absence of longitudinal or panel data for stronger evidence is a key limitation in land fragmentation studies. Cross-sectional data restricts the ability to establish a clear cause-and-effect relationship between land fragmentation and its outcomes. The impact and interpretation of fragmentation differ significantly based on location and terrain, therefore, generalizing findings of land fragmentation across diverse contexts is difficult. Fragmentation involves spatial, legal, social, economic, and environmental dimensions, requiring complex, integrated approaches that single studies often cannot fully address. These factors are the limitations and blind spots of fragmentation metrics and tools. Consequently, fragmentation research should focus beyond identifying functional connectivity, ecosystem service changes and effects of land use transformation. Instead, geospatial evidence should be incorporated into effective ecological conservation and sustainable land management strategies.

In many ecological studies, long-term and site-specific data are limited, which makes it challenging to clearly identify changes over time. Limited ecological data availability in national or regional monitoring systems is also a key threat in maintaining threatened habitats or species. This limitation is especially imperative for countries with rich biodiversity and high population density, where land-use change is rapid but ecological data may be incomplete, scattered, or difficult to access.

4. Conclusions

The synthesis of literature and case evidence indicates that development and ecological conservation are not mutually exclusive but are interdependent components of sustainable

progress. Though the analytical tools have improved over time, issues like land fragmentation, connectivity, and spatial delimitation continue to exist. Conceptual and methodological gaps exist in identifying the impacts of fragmentation on ecosystems, social, qualitative perspectives and functional connectivity.

The land is a non-replenishable resource where sustainable land use management is crucial to the growing population and their needs. Planning tools such as zoning, impact assessment and strategic planning should better account for fragmentation studies. The challenge lies in operationalizing this interdependence through informed policy, institutional coordination, and evidence-based land management. As countries continue to modernize, adopting an integrated landscape perspective that values ecological integrity alongside economic gain will be crucial to ensure that development today does not compromise the environmental security of tomorrow.

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Appendices

NA

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Conflicts Of Interest

The authors reported no potential conflicts of interest.

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