

Article

Assessing Long-Term Forest Fragmentation and Land Use/Land Cover (LULC) Dynamics along the Proposed China-Nepal Railway Corridor

Madan Kumar Khadka^{1,2,*} and Zhiming Zhang¹¹ School of Ecology and Environment, Yunnan University, Kunming 650500, China² Department of Plant Resources, Ministry of Forests and Environment, Kathmandu 44600, Nepal* Correspondence: mr.madan.khadka@gmail.com**How To Cite:** Khadka, M.K.; Zhang, Z. Assessing Long-Term Forest Fragmentation and Land Use/Land Cover (LULC) Dynamics along the Proposed China-Nepal Railway Corridor. *Regional Ecology and Management* 2026, 1(1), 6.

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Abstract: Forest fragmentation and Land Use/Land Cover (LULC) change are major drivers of biodiversity loss and ecosystem degradation, particularly in landscapes undergoing infrastructure expansion. This study evaluates long-term LULC dynamics and forest structural fragmentation within the proposed China-Nepal railway corridor across the districts of Rasuwa, Nuwakot, and Kathmandu from 1990 to 2020. LULC classification identified eight major categories: forest, shrubland, grassland, agricultural area, barren area, water body, snow/glacier, and built-up area. A transition matrix approach was applied to quantify class conversions, while forest fragmentation patterns were assessed using spatial metrics, including edge, core, and perforated forest components. Results indicate that forest cover declined between 1990 and 2000, followed by partial recovery through 2020. Despite this recovery, fragmentation metrics reveal an increase in edge and perforated forest areas and fluctuations in core forest extent, suggesting structural reconfiguration of forest landscapes. Substantial forest persistence was observed alongside measurable transitions to agricultural and built-up land uses, highlighting dynamic landscape change rather than continuous forest loss. By integrating multi-decadal LULC transition analysis with spatial fragmentation assessment, this study establishes a structural baseline for the railway corridor prior to major infrastructure implementation. The findings provide spatially explicit evidence to support future environmental monitoring and informed landscape planning in ecologically sensitive Himalayan regions.

Keywords: forest fragmentation; Land Use/Land Cover (LULC); Landscape Fragmentation Tool (LFT); MSPA; GIS; remote sensing; corridor

1. Introduction

Forest fragmentation is a major ecological process affecting forested landscape worldwide and is driven by both natural and anthropogenic factors [1,2]. It refers to the subdivision of large, contiguous forest areas into smaller and increasingly isolated patches due to Land Use/Land Cover (LULC) changes such as deforestation, agricultural expansion and infrastructure development [3]. Fragmentation alters forest structure and spatial configuration, influencing biodiversity patterns, habitat quality and ecological processes [4]. These structural changes reduce interior habitat, intensify edge effects, and increase exposure to invasive species, and microclimatic fluctuations [5,6]. Beyond biodiversity impacts, fragmentation affects ecosystem services including carbon storage, water regulation, and climate stability [7]. As a result, understanding long-term fragmentation dynamics is essential for landscape-level conservation planning and sustainable land management.



Globally, forest fragmentation is closely linked to (LULC) transitions associated with transportation infrastructure, agricultural intensification, and urban expansion [8,9]. Linear infrastructure such as roads and railways creates structural discontinuities within forest landscapes, altering connectivity and facilitating secondary land-use changes [10,11]. These developments may increase accessibility, intensify resource extraction, and modify habitat connectivity [6,12]. Infrastructure expansion is therefore increasingly recognized as an important landscape-scale driver of fragmentation, particularly in ecologically sensitive regions [13,14]. While numerous studies have documented road-related fragmentation, fewer studies have systematically evaluated structural fragmentation patterns in the context of large-scale railway corridors, especially prior to construction [15].

In the Hindu Kush-Himalaya (HKH) region, including Nepal, forest landscapes are shaped by complex interactions among topography, demographic change, land-use practices, and infrastructure expansion [16]. Rapid development of transportation and hydropower projects has intensified land-cover transitions in ecologically sensitive areas [17]. Regions such as Langtang and Shivapuri Nagarjun National Parks represent biodiversity-rich mountain ecosystems where structural fragmentation can have significant ecological implications. The proposed China-Nepal railway corridor, extending from Rasuwagadhi to Kathmandu, intersects forested landscapes within this mountainous terrain [18,19]. Given the ecological sensitivity of the corridor, understanding historical forest cover and structural dynamics provides a critical baseline for evaluating future landscape changes.

Although forest fragmentation has been widely studied, integrated multi-decadal assessments combining LULC transition analysis with structural fragmentation metrics within a transboundary mountain infrastructure corridor remain limited in Nepal. This study addresses this gap by analyzing LULC changes and forest fragmentation patterns from 1990 to 2020 within the proposed China-Nepal railway corridor landscape. Rather than attributing observed changes to railway construction, the study establishes a long-term spatial baseline prior to infrastructure implementation. The research is guided by the following questions:

- (1) How have LULC patterns changed within the corridor landscape between 1990 and 2020?
- (2) What structural forest fragmentation patterns are observed over this period using complementary metrics?
- (3) How have core, edge, and perforated forest components evolved across decades?

Analysis (MSPA), this study provides a spatially explicit evaluation of long-term forest structural dynamics in a high-altitude infrastructure corridor context.

2. Materials and Methods

2.1. Study Area

The study area includes three districts within Bagmati Province, Nepal: Rasuwa (27°55'–28°25' N, 85°00'–85°50' E), Nuwakot (27°45'–28°20' N, 85°00'–85°45' E), and Kathmandu (27°27'–27°49' N, 85°10'–85°32' E) (Figure 1).

These districts fall along the alignment of the proposed China-Nepal railway corridor, extending approximately 72 km from Rasuwagadhi to Kathmandu. The corridor-scale study boundary was defined based on district-level administrative units intersecting the proposed railway alignment, providing a regional landscape context rather than a narrow construction footprint. This approach allows long-term assessment of forest structural dynamics within the broader infrastructure influence zone. Elevation across the study area ranges from approximately 354 m to 7191 m above sea level, reflecting diverse physiographic zones including mid-hills, high mountains, and Himalayan regions [20]. Climate varies from subtropical to temperate, with mean annual temperatures between 10 °C and 20 °C and annual precipitation ranging from 667 mm to 3092 mm, primarily during the monsoon season [21]. The region includes ecologically significant areas such as Langtang National Park and Shivapuri Nagarjun National Park. The objective of selecting this region was to evaluate long-term forest cover and structural fragmentation patterns within a proposed international infrastructure corridor prior to railway construction, thereby establishing a multi-decadal ecological baseline.

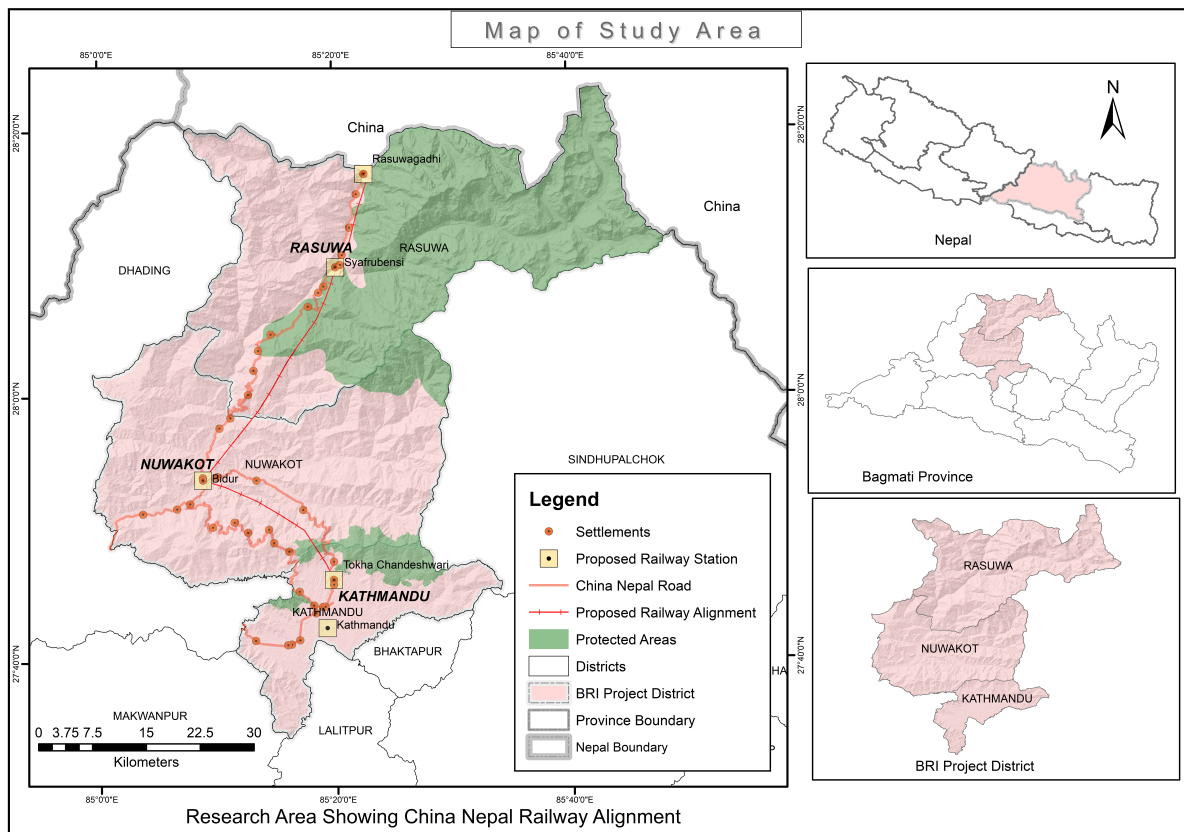


Figure 1. Map of study area.

2.2. Data Sources and Preprocessing

2.2.1. Land Use/Land Cover Data

Land Use/Land Cover (LULC) maps for 1990, 2000, 2010, and 2020 were obtained from the International Centre for Integrated Mountain Development (ICIMOD) and the Forest Research and Training Centre [22]. These datasets were produced under the National Land Cover Monitoring System (NLCMS) using Landsat time-series imagery and machine-learning classification approaches within the Google Earth Engine platform. All LULC datasets were provided at 30 m spatial resolution and harmonized under a consistent classification scheme across years. The ICIMOD/FRTC products are nationally validated datasets developed using standardized methodologies. As this study utilized officially released classification outputs, independent reclassification accuracy assessment was beyond the scope of the present analysis. Eight LULC classes: forest, shrubland, grassland, agricultural area, barren area, water body, snow/glacier, and built-up area were analyzed.

2.2.2 Preprocessing and Binary Classification

All LULC rasters were projected to WGS 1984 UTM Zone 45N and aligned to a common spatial extent prior to analysis. To conduct fragmentation analysis, LULC maps were reclassified into binary categories: forest and non-forest. Forest pixels were assigned a value of 2, and non-forest pixels were assigned a value of 1. The numeric coding (forest = 2; non-forest = 1) was applied solely for computational compatibility with the Landscape Fragmentation Tool (LFT) and GuidosToolbox; the coding scheme does not influence analytical interpretation. Binary forest/non-forest classification was adopted because both LFT and MSPA require two-class inputs. Although this approach simplifies heterogeneous forest types, it is widely used in structural fragmentation analysis where spatial configuration, rather than compositional diversity, is the focus [23–26].

2.3. LULC Transition Analysis

Land-use transitions were quantified using the Tabulate Area tool in ArcMap 10.8, which cross-classified LULC rasters between time periods to produce a transition matrix. The complete transition matrices (expressed in km²) are reported and results were visualized using Sankey diagrams generated in R 4.5.2 to illustrate conversions

among Land Use/Land Cover (LULC) classes across periods. Flow magnitudes in Sankey diagrams correspond directly to reported transition matrix values.

2.4. Forest Fragmentation Analysis

Forest fragmentation was analyzed using the Landscape Fragmentation Tool (LFT v2.0). LFT classifies forests into four primary fragmentation types: patch, edge, perforated, and core. The core category was further subdivided into small core, medium core, and large core based on the size of the forest tract. For this study, an edge width of 100 m was selected. The 100 m edge width was selected based on prior ecological studies indicating its suitability for general fragmentation assessment [23]. Sensitivity testing of alternative edge distances was not performed and represents a potential area for future research. Fragmentation maps were generated for 1990, 2000, 2010, and 2020, and class areas were calculated in km².

2.5. Morphological Spatial Pattern Analysis (MSPA)

To validate structural fragmentation patterns derived from LFT, Morphological Spatial Pattern Analysis (MSPA) was conducted using GuidosToolbox [24]. was conducted following the methodology of [27]. Binary forest-nonforest rasters (30 m resolution) were processed using an edge width of 3 pixels (~90 m), corresponding to the 100 m boundary distance applied in LFT. MSPA classifies forest into seven morphological categories including core, edge, islet, perforation, bridge, loop, and branch.

LFT quantifies fragmentation based on edge-distance classification, whereas MSPA evaluates morphological connectivity components. The combined application of these complementary frameworks strengthens structural validation of observed fragmentation dynamics. Comparative analysis of LFT and MSPA outputs was performed to evaluate consistency in fragmentation trends across decades.

This study focuses on spatial pattern assessment and temporal trend analysis rather than hypothesis-driven statistical testing. The analysis provides a multi-decadal baseline of forest structural dynamics within the proposed infrastructure corridor prior to railway construction, rather than modeling direct railway-induced impacts.

3. Results

3.1. Land Use/Land Cover Change (1990–2020)

Land Use/Land Cover (LULC) maps for 1990, 2000, 2010, and 2020 were analyzed using ICIMOD/FRTC datasets at 30 m spatial resolution. Eight classes were evaluated: forest, shrubland, grassland, agricultural area, barren area, water body, snow/glacier, and built-up area (Figure 2)

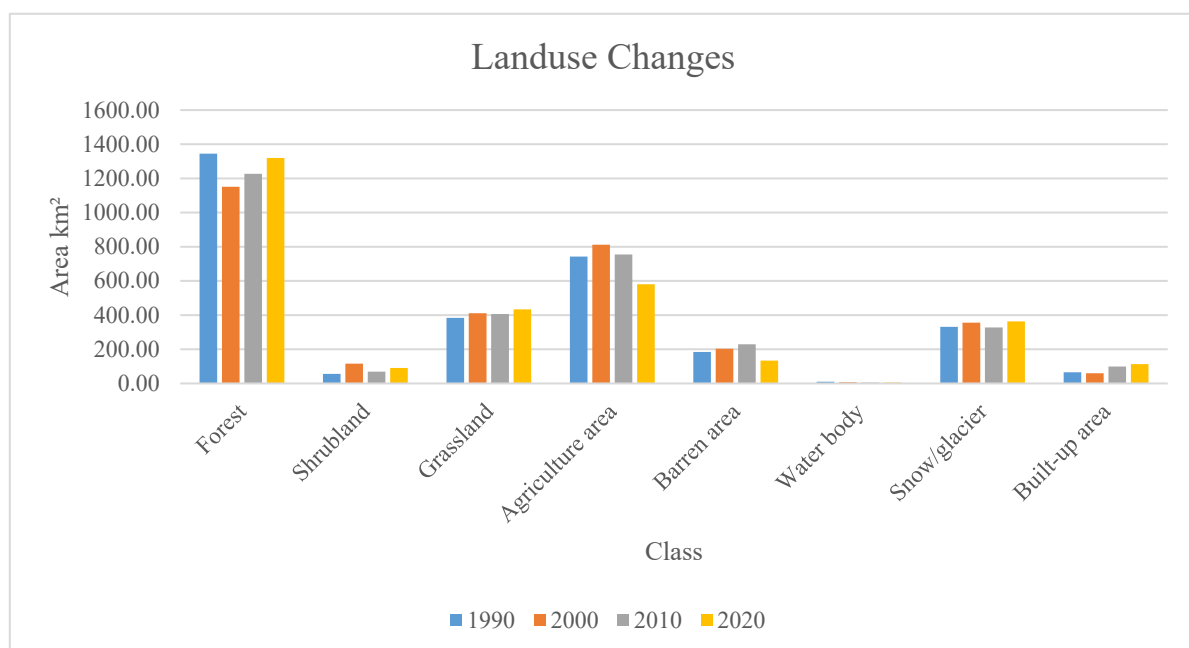


Figure 2. Land Use/Land Cover (LULC) changes area in km² from 1990 to 2020.

Total forest cover declined from 1344.60 km² in 1990 to 1151.37 km² in 2000 representing a net decrease of 193 km². Forest area subsequently increased to 1227.14 km² in 2010 and further to 1319.42 km² in 2020. Despite partial recovery after 2000, the 2020 forest extent remained slightly lower than the 1990 baseline (Table 1).

Table 1. Land Use/Land Cover (LULC) area in km² of 1990, 2000, 2010 and 2020.

| Class | 1990 | 2000 | 2010 | 2020 |
|------------------|---------|---------|---------|---------|
| Forest | 1344.60 | 1151.37 | 1227.14 | 1319.42 |
| Shrubland | 56.42 | 116.27 | 68.88 | 90.63 |
| Grassland | 383.46 | 410.90 | 406.72 | 434.01 |
| Agriculture area | 742.82 | 811.72 | 754.88 | 580.38 |
| Barren area | 184.11 | 202.95 | 229.06 | 133.94 |
| Water body | 10.18 | 7.56 | 5.68 | 5.84 |
| Snow/glacier | 331.59 | 355.65 | 327.88 | 362.97 |
| Built-up area | 64.97 | 59.74 | 99.21 | 113.37 |

Agricultural land and built-up areas exhibited gradual increases over the study period, while shrubland and grassland showed moderate inter-decadal fluctuations. Water bodies and snow/glacier classes remained relatively stable in overall extent.

Overall, the LULC maps indicate dynamic land-cover transitions between 1990 and 2020, with forest decline during the 1990–2000 period followed by partial recovery during 2000–2020 (Figure 3).

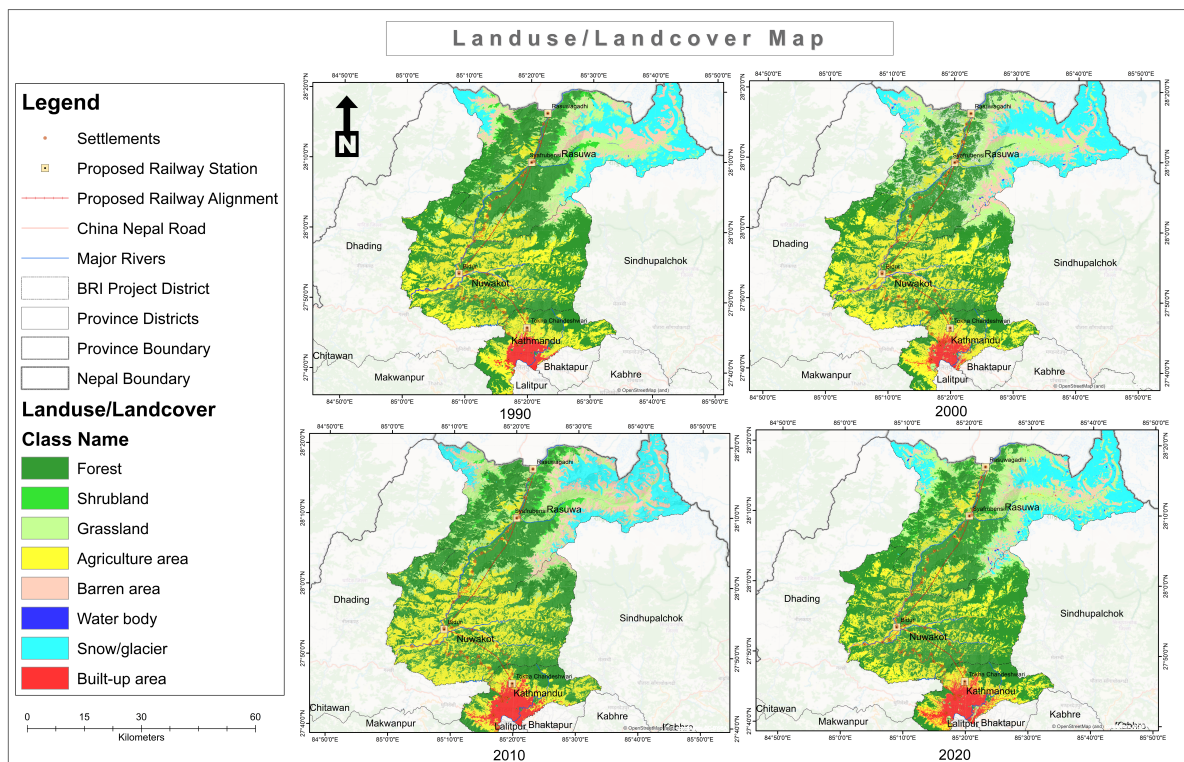


Figure 3. Land Use/Land Cover (LULC) Map of 1990, 2000, 2010 and 2020.

3.2. Land Use/Land Cover (LULC) Transition Analysis

Land Use/Land Cover (LULC) change between 1990 and 2020 was quantified through raster cross-classification using the Tabulate Area tool in ArcMap 10.8 to construct a land transition matrix. Forest persistence between 1990 and 2020 accounted for 1147.74 km². Approximately 67.91 km² of forest converted to agricultural land, while 4.63 km² transitioned to built-up areas. Agricultural land showed strong persistence (468.56 km²) but also significant conversion to forest (179.09 km²) and built-up areas (48.94 km²). Snow/glacier demonstrated high stability (270.94 km²), with limited inter-class conversion (Table 2).

Table 2. Land Use/Land Cover transition matrix from 1990 (rows) to 2020 (columns), expressed in km².

| 1990\2020 | Forest | Shrubland | Grassland | Agriculture Area | Barren Area | Water Body | Snow/Glacier | Built-Up Area |
|------------------|---------|-----------|-----------|------------------|-------------|------------|--------------|---------------|
| Forest | 1147.74 | 59.66 | 61.47 | 67.91 | 0.70 | 0.14 | 0.84 | 4.63 |
| Shrubland | 8.44 | 7.07 | 35.80 | 2.80 | 1.13 | 0.02 | 0.89 | 0.10 |
| Grassland | 16.01 | 10.25 | 199.19 | 50.19 | 49.07 | 1.46 | 54.99 | 1.93 |
| Agriculture area | 179.09 | 15.28 | 29.41 | 468.56 | 0.38 | 0.90 | 0.01 | 48.94 |
| Barren area | 0.05 | 0.15 | 78.63 | 0.52 | 60.80 | 0.34 | 42.43 | 0.94 |
| Water body | 0.83 | 0.37 | 3.48 | 2.72 | 0.39 | 1.57 | 0.01 | 0.78 |
| Snow/glacier | 0.01 | 0.04 | 32.89 | 0.01 | 24.44 | 1.50 | 270.94 | 0.02 |
| Built-up area | 0.07 | 0.03 | 3.30 | 2.51 | 0.02 | 0.02 | 0.00 | 58.96 |

Transitions were visualized using Sankey diagrams to illustrate conversions among major LULC categories (Figure 4). Forest exhibited both persistence and conversion to agricultural land and barren land across decades. Agricultural land demonstrated measurable transitions to built-up areas, particularly during the 2000–2020 period. Shrubland and grassland showed moderate bidirectional transitions with forest and agricultural classes. Water bodies and snow/glacier classes remained comparatively stable, with minimal inter-class conversion.

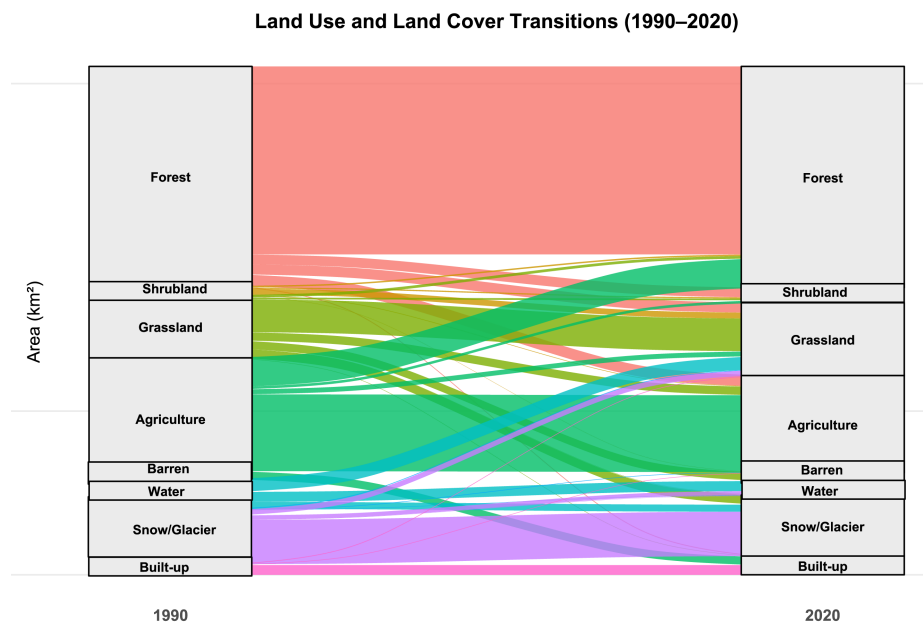


Figure 4. Sankey diagram depicting Land Use/Land Cover (LULC) Transitions between 1990 and 2020 along the China-Nepal railway corridor. Flow widths represent conversion areas expressed in km².

3.3. Forest Fragmentation LFT Analysis

Forest fragmentation patterns were assessed using LFT, which classifies forest into core, perforated, edge, and patch categories. Core forests larger than 500 acres accounted for 1089.70 km², 1012.00 km², 1063.05 km², and 1037.72 km² in 1990, 2000, 2010, and 2020 respectively. Patch forest area measured 101.68 km² (1990), 74.38 km² (2000), 85.78 km² (2010), and 83.51 km² (2020) Patch forest combined with edge forests totaled 437.09 km², 423.03 km², 404.56 km², and 444.51 km² of the total area Patch forest area measured 101.68 km² (1990), 74.38 km² (2000), 85.78 km² (2010), and 83.51 km² (2020) While the perforated area has expanded from 167.88 km² in 1990 to 245.71 km² in 2020 (Table 3).

Table 3. Forest fragmentation area in km² using LFT tools.

| Types | 1990 | 2000 | 2010 | 2020 |
|----------------------|---------|---------|---------|---------|
| patch | 101.68 | 74.38 | 85.78 | 83.52 |
| edge | 335.41 | 348.64 | 318.77 | 361.00 |
| perforated | 167.88 | 154.40 | 152.16 | 245.72 |
| core (<250 acres) | 67.27 | 68.16 | 63.11 | 55.09 |
| core (250–500 acres) | 22.95 | 21.98 | 20.29 | 13.16 |
| core (>500 acres) | 1089.70 | 1012.00 | 1063.05 | 1037.72 |

Overall, core forest area showed fluctuation rather than continuous decline, decreasing between 1990 and 2000, partially recovering by 2010, and slightly declining again by 2020. The LFT results indicate progressive internal fragmentation characterized by increasing perforation and edge dynamics over time (Figure 5).

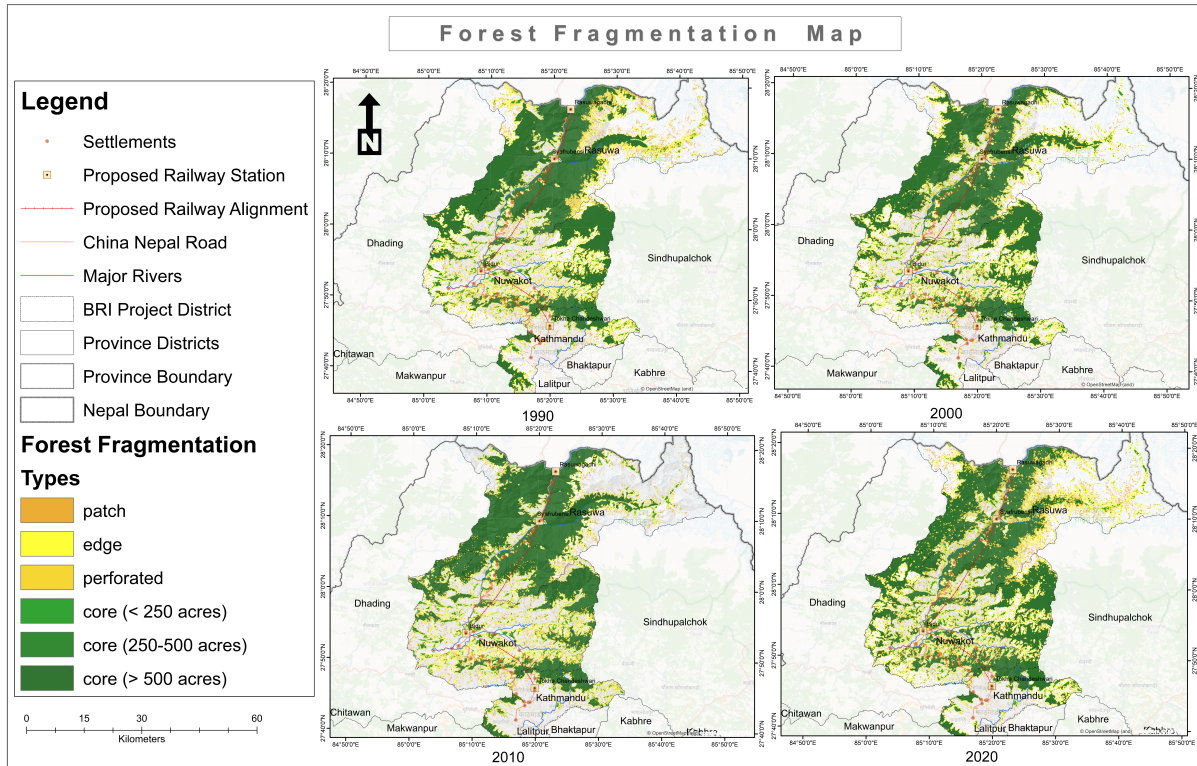


Figure 5. Forest fragmentation 1990, 2000, 2010 and 2020 using LFT tools.

3.4. Morphological Spatial Pattern Analysis (MSPA)

MSPA classified forest structure into seven morphological components including core, edge, islet, perforation, bridge, loop and branch classes (Figure 6).

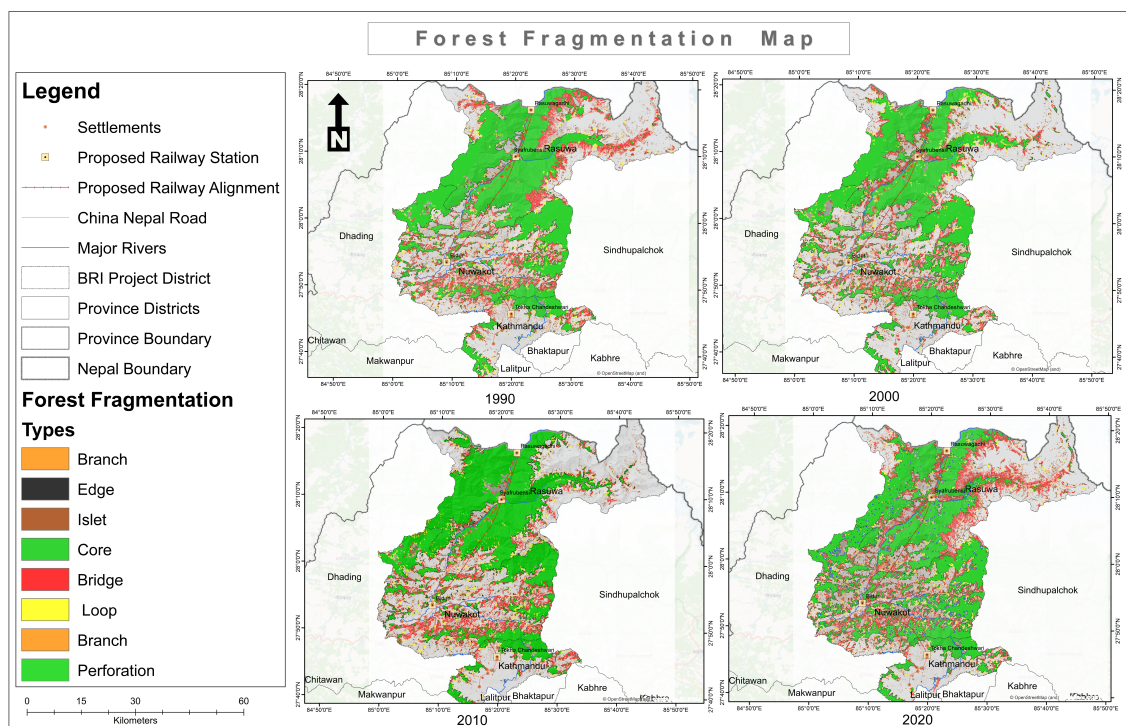


Figure 6. Forest fragmentation 1990, 2000, 2010 and 2020 using MSPA tools.

Core forest area decreased from 1147.20 km² in 1990 to 1062.97 km² in 2020. Edge area increased from 131.03 km² to 165.41 km², while perforation increased from 19.98 km² to 47.00 km² during the same period. Bridge (connectivity) elements increased from 269.82 km² in 1990 to 296.98 km² in 2020. However, branch metrics also increased, suggesting increasing structural dissection of forest patches. (Table 4) suggesting ongoing persistence of forest corridors, although rising branch metrics reveal growing dissection of habitat patches. Overall, MSPA trends verify LFT findings, indicating long-term structural reconfiguration characterized by increased perforation and edge expansion within the forest matrix.

Table 4. Forest fragmentation area in km² using MSPA tools.

| Types | 1990 | 2000 | 2010 | 2020 |
|-------------|---------|---------|---------|---------|
| Core | 1147.20 | 1065.27 | 1113.26 | 1062.97 |
| Edge | 131.03 | 161.50 | 125.86 | 165.41 |
| Islet | 77.95 | 62.45 | 72.45 | 61.75 |
| Branch | 65.80 | 77.68 | 60.78 | 77.70 |
| Loop | 72.65 | 270.71 | 85.52 | 482.99 |
| Bridge | 269.82 | 200.26 | 212.47 | 296.98 |
| Perforation | 19.98 | 30.18 | 31.61 | 47.00 |

4. Discussion

The multi-decadal assessment of land use/land cover (LULC) transitions and forest structural fragmentation between 1990 and 2020 reveals substantial landscape reconfiguration within the proposed China-Nepal railway corridor. The transition matrix indicates strong forest persistence (1147.74 km²), yet measurable conversion to agricultural land (67.91 km²) and built-up areas (4.63 km²). Simultaneously, agricultural land exhibited both persistence (468.56 km²) and conversion to forest (179.09 km²) and built-up areas (48.94 km²), reflecting dynamic bidirectional land transitions. These findings suggest that forest change in the corridor landscape is not characterized by linear decline but by structural reorganization across decades. Similar bidirectional forest-agriculture transitions have been reported in mountain regions undergoing demographic and land-use shifts [16,28–30].

Fragmentation metrics further clarify the structural consequences of these transitions. Although total forest cover partially recovered after 2000, LFT results demonstrate increased perforation from 167.88 km² in 1990 to 245.71 km² in 2020, indicating intensified internal fragmentation. Core forest (>500 acres) fluctuated over time, declining between 1990 and 2000, partially recovering in 2010, and slightly decreasing again by 2020. The increase in perforated and edge forests suggests that forest integrity may be more sensitive to spatial configuration than to net area change. This pattern aligns with previous studies showing that fragmentation often progresses through internal dissection and edge expansion even when total forest extent appears stable [3,6,31,32].

MSPA results corroborate these structural trends. Core forest declined from 1147.20 km² to 1062.97 km², while edge and perforation classes increased over the same period. The growth of bridge elements indicates persistence of structural connectivity, yet rising branch metrics reflect increasing habitat dissection. Such morphological restructuring has important ecological implications, as edge-dominated landscapes are associated with altered microclimatic conditions, increased exposure to disturbance, and reduced suitability for interior-dependent species [5,6]. Fragmentation-driven habitat loss and connectivity reduction can affect biodiversity [33,34], ecosystem services [35], and wildlife movement patterns [2]. In mountain ecosystems, where elevational gradients constrain species dispersal, structural fragmentation may amplify ecological vulnerability [36–38].

Linear infrastructure is widely recognized as a contributor to landscape fragmentation due to its barrier effects and facilitation of secondary land-use change [10,11,14,39,40]. Railways, in particular, can create persistent physical and behavioral barriers to wildlife movement and generate new forest edges [41]. However, the present study does not attribute the observed historical fragmentation trends directly to railway construction, as the proposed China-Nepal railway has not yet been implemented. Rather, the findings establish a multi-decadal structural baseline of forest dynamics within the corridor landscape prior to major infrastructure development [42,43]. This baseline is critical for future comparative assessments and impact evaluation. Where infrastructure expansion is anticipated, mitigation strategies such as wildlife crossings and ecological connectivity planning have been recommended to reduce barrier effects [39–41,44,45].

Despite these findings, several limitations should be acknowledged. First, the analysis relied on ICIMOD/FRTC LULC datasets; independent classification accuracy assessment was beyond the scope of this study. Second, reclassification into binary forest/non-forest categories, while methodologically necessary for LFT and MSPA, simplifies forest heterogeneity and does not account for compositional variation. Third, the study focused on spatial pattern analysis rather than hypothesis-driven statistical testing. Fourth, a fixed 100 m edge

width parameter was applied without sensitivity testing of alternative distances. Finally, the analysis did not incorporate buffer-based or scenario modeling of the proposed railway alignment. Future research integrating higher-resolution imagery, field validation, and infrastructure impact modeling would strengthen causal inference and support corridor-level planning.

5. Conclusions

This study assessed multi-decadal Land Use/Land Cover (LULC) dynamics and forest structural fragmentation within the proposed China-Nepal railway corridor landscape from 1990 to 2020. The results reveal that forest cover experienced an initial decline between 1990 and 2000, followed by partial recovery during 2000–2020. Transition matrix analysis indicates substantial forest persistence (1147.74 km²) alongside measurable conversion to agricultural land (67.91 km²) and built-up areas (4.63 km²). These findings demonstrate that landscape change within the corridor has been characterized by dynamic reorganization rather than continuous forest loss.

Fragmentation analyses provide further insight into structural forest conditions. Although total forest extent partially recovered after 2000, perforated and edge forests increased over the study period, while core forest areas fluctuated. MSPA results similarly indicate declining interior forest components and increasing edge-related structures. These patterns suggest that changes in spatial configuration may be more pronounced than changes in total forest area, with potential implications for habitat integrity and ecological connectivity.

Rather than attributing historical changes directly to railway construction, this study establishes a long-term structural baseline of forest dynamics within the corridor landscape prior to major infrastructure implementation. The integration of LULC transition analysis with complementary fragmentation metrics provides a spatially explicit framework for future monitoring and comparative assessment. Such baseline information is essential for evaluating subsequent landscape transformations and supporting evidence-based corridor planning.

Author Contributions

M.K.K.: conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing original draft, writing review & editing, visualization; Z.Z.: conceptualization, investigation, resources, writing review & editing, supervision. Both authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets generated during this study are available from the corresponding author upon reasonable request and within the framework of cooperation agreements and scientific research projects.

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Conflicts of Interest

The authors declare no conflicts of interest. Given the role as Editorial Board Member, Zhiming Zhang had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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