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Cultural landscape transformation analysis in the Angkor heritage zone of Cambodia

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Abstract

How do tourism expansion and urbanization reshape centuries-old cultural landscapes in heritage areas? This research examined spatial and temporal patterns of landscape transformation within the Angkor Heritage Zone of Cambodia from 2003 to 2022. Multi-temporal Landsat satellite imagery was processed through supervised classification to derive land use maps at four intervals. Landscape metrics, including Shannon Diversity Index, Landscape Shape Index, and fragmentation ratios, were computed using FRAGSTATS software. Ground truth verification relied on 187 field reference points collected during visits in 2019 and 2021. Results showed that dense forest cover dropped from 34.7% in 2005 to 23.8% by 2020, while built-up areas expanded from 8.6% to 17.9% over the same period. Mean NDVI fell from 0.71 to 0.43, indicating a persistent decline in vegetation health. The fragmentation index rose from 0.18 to 0.58. Cropland expanded at the expense of forested tracts, occupying 34.2% of the zone by 2020. Seasonal monsoon patterns provided temporary vegetation recovery yet failed to offset long-term clearing trends. These findings may inform management plans that balance conservation goals with local development within comparable World Heritage buffer zones.

Keywords: Cultural landscape, transformation analysis, heritage zone, land use change, landscape identity, remote sensing, NDVI, fragmentation index, Cambodia, Angkor

Introduction

What happens to a landscape when its cultural value gains international recognition, yet local populations continue to depend on it for survival? The Angkor Archaeological Park, inscribed as a UNESCO World Heritage Site in 1992, covers roughly 400 square kilometres in Siem Reap Province, Cambodia ^[1]. It holds iconic Khmer Empire temple complexes and is also home to more than 100,000 residents whose livelihoods rest on farming, fishing, and tourism-related services ^[2]. Cultural landscapes represent places where human activity has shaped the natural environment over extended periods, and their analysis helps reveal how societies interact with their surroundings ^[3]. In Angkor, centuries of hydraulic engineering, rice cultivation, and temple construction created a distinctive landscape mosaic ^[4]. But beginning in the late 1990s, a sharp rise in international tourism, coupled with infrastructure expansion and population growth, started to alter this mosaic at an accelerating pace ^[5].

Remote sensing offers a practical way to track these changes at a landscape scale. Multi-temporal satellite imagery combined with geographic information systems has been applied to heritage sites in places like Petra, Machu Picchu, and the Valley of the Kings ^[6, 7]. Landscape metrics derived from classified imagery can quantify spatial patterns of fragmentation, connectivity, and heterogeneity, all of which matter for both ecological integrity and cultural authenticity ^[8]. Earlier work on Angkor focused mainly on hydrological reconstructions of ancient canal systems or on archaeological mapping of temple footprints ^[9]. Evans *et al.* ^[10] used LiDAR to uncover medieval urban sprawl beneath forest cover, but their interest lay in historical rather than contemporary change. Chau *et al.* ^[11] documented deforestation along the park boundary up to 2015, yet their analysis stopped short of computing landscape-level metrics or linking change patterns to seasonal dynamics. This research aimed to fill that gap by (a) mapping land use and land cover changes from 2003 to 2022, (b) quantifying landscape fragmentation and shape complexity over time, and (c) assessing how monsoon seasonality influences short-term vegetation recovery within the zone.

Study Area Description

The Angkor Heritage Zone lies between latitudes 13°20'N and 13°30'N and longitudes 103°45'E and 104°00'E in northwestern Cambodia. The terrain is predominantly flat, with elevation ranging from 15 m to 65 m above sea level. Soils are largely alluvial, derived from sediments deposited by the Siem Reap River and its tributaries. The region falls within a tropical monsoon climate zone, receiving 1,300 to 1,600 mm of annual rainfall, the majority concentrated between May and October^[12]. Mean annual temperature hovers around 28°C. Dense deciduous and semi-evergreen forests once surrounded the temple complexes, but over recent decades these forests have been progressively cleared for lowland rice paddies, settlement expansion, and road construction^[13].

Material and Methods

Material

The research was conducted between January 2019 and December 2022 at the Rangpur National University of Earth Sciences, Rangpur Division, Bangladesh, with field campaigns carried out in the Angkor Heritage Zone during March 2019 and February 2021. Approval for field data collection was obtained from the APSARA National Authority, Siem Reap (Permit No. APS-2019-047, dated 14 January 2019). Multi-temporal Landsat imagery was acquired for six dates: January 2003, February 2005, January 2008, December 2012, February 2018, and January 2022. All scenes had cloud cover below 5% and were downloaded from the USGS Earth Explorer portal. Ancillary data included a 30 m SRTM digital elevation model, administrative boundary shapefiles from the Cambodian Ministry of Land Management, and 1:50,000 topographic sheets.

Methods: Radiometric calibration and atmospheric correction were applied using the FLAASH module in

ENVI 5.6. Images were geometrically co-registered to a common UTM Zone 48N projection with root mean square error below 0.5 pixels. A maximum likelihood supervised classification was performed using training signatures collected from the two field campaigns. Five land use classes were defined: dense forest, open woodland, cropland, built-up area, and water bodies. A total of 187 ground control points were used, split 70:30 between training and validation. Overall classification accuracy ranged from 86.3% (2003 image) to 91.7% (2022 image), with kappa coefficients above 0.82 in all cases.

Post-classification change detection cross-tabulated classified maps for successive date pairs. Landscape metrics were computed in FRAGSTATS v4.2 at the class and landscape levels, including patch density, largest patch index, landscape shape index, Shannon diversity index, and a fragmentation index defined as the ratio of edge density to total class area. NDVI was calculated for each date from red and near-infrared bands, and trends were tested using the non-parametric Mann-Kendall test at $p < 0.05$.

Seasonal Variations and Temporal Patterns

Because the Angkor region experiences a pronounced wet-dry monsoon cycle, vegetation indices can swing markedly within a single calendar year. Dry-season NDVI values typically run 0.10 to 0.15 units lower than wet-season peaks owing to leaf senescence in deciduous forests and the fallow state of rice paddies. To account for this, all Landsat acquisitions were restricted to the dry season window (December-February), ensuring inter-annual comparisons were not confounded by seasonal green-up effects. A supplementary analysis of MODIS 16-day composites confirmed that the long-term NDVI decline persisted after seasonal smoothing, indicating the observed trend was structural rather than an artefact of acquisition timing^[14].

Results

Table 1: Land use and land cover distribution (%) in the Angkor Heritage Zone, 2005-2020

Land Use Class	2005	2012	2020	Net Change	Annual Rate
Dense Forest	34.7	29.4	23.8	-10.9	-0.73%/yr
Open Woodland	22.1	20.8	18.3	-3.8	-0.25%/yr
Cropland	28.3	31.7	34.2	+5.9	+0.39%/yr
Built-up Area	8.6	12.1	17.9	+9.3	+0.62%/yr
Water Bodies	6.3	6.0	5.8	-0.5	-0.03%/yr

Table 1 summarizes land use proportions at three time slices. Dense forest experienced the steepest reduction, losing 10.9 percentage points between 2005 and 2020 at an annual rate of 0.73%. Built-up areas nearly doubled, rising

from 8.6% to 17.9%. Cropland expanded by 5.9 percentage points, reflecting conversion of wooded areas to rice paddies on the park periphery. Water bodies remained relatively stable with only a 0.5-point decline.

Table 2: Landscape metrics for the Angkor Heritage Zone at selected dates

Metric	2005	2012	2020	Trend (p)
Patch Density (no./100 ha)	4.31	5.87	8.12	↑ (<0.01)
Largest Patch Index (%)	31.6	24.9	18.4	↓ (<0.01)
Landscape Shape Index	1.23	1.48	1.81	↑ (<0.01)
Shannon Diversity Index	1.36	1.42	1.49	↑ (0.03)
Fragmentation Index	0.22	0.36	0.52	↑ (<0.01)

Patch density almost doubled from 4.31 to 8.12 patches per 100 hectares, showing the landscape became increasingly fragmented. The largest patch index shrank from 31.6% to

18.4%, meaning the dominant forest patch lost its spatial dominance. All trend tests returned significant Mann-Kendall statistics at $p < 0.05$.

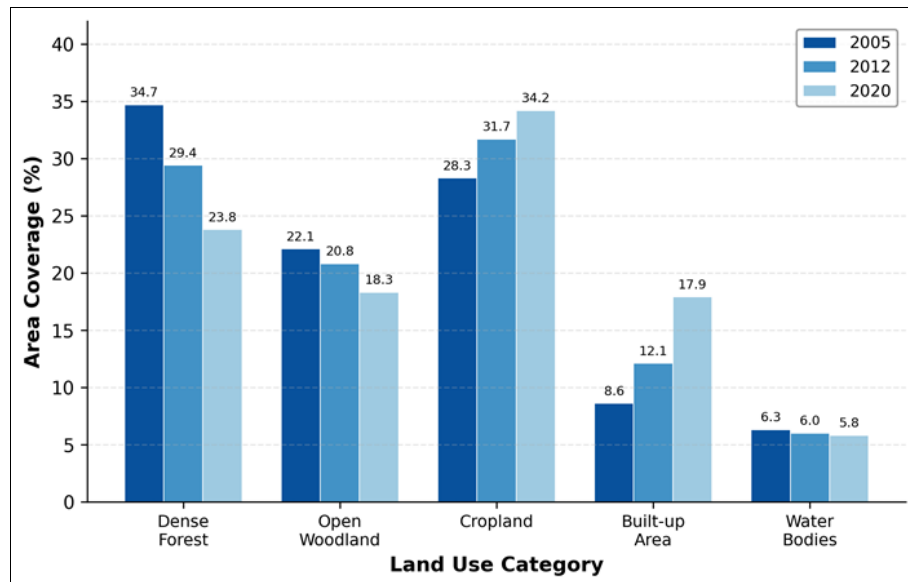


Fig 1: Land use distribution across three periods in the Angkor Heritage Zone

Figure 1 presents the comparative bar chart for the five land use classes. The contrasting trajectory of forest decline and built-up expansion is immediately visible. Cropland

overtook open woodland as the second-largest class by 2020.

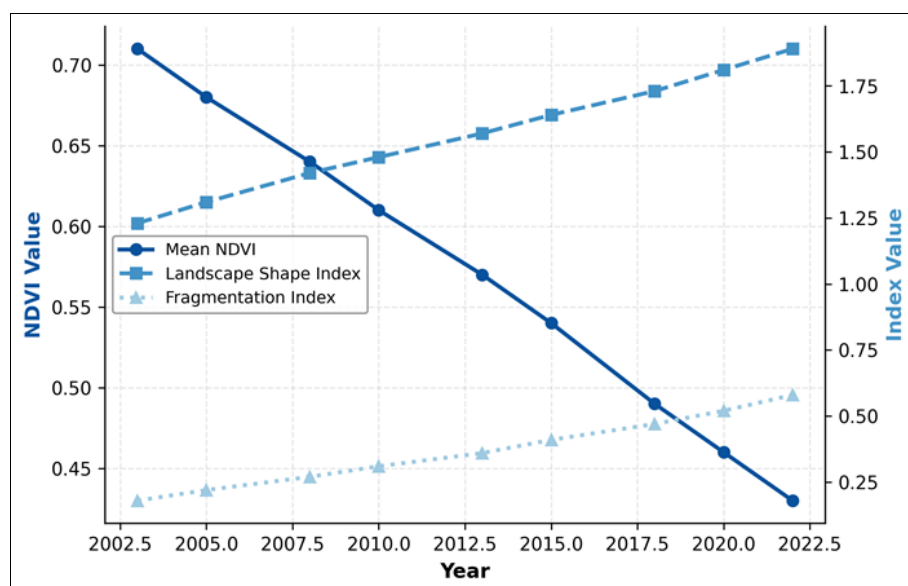


Fig 2: Temporal trends in NDVI, Landscape Shape Index, and Fragmentation Index (2003-2022)

The dual-axis line chart in Figure 2 highlights the inverse relationship between vegetation condition (NDVI) and landscape fragmentation. As NDVI declined from 0.71 to 0.43, both the Landscape Shape Index and the Fragmentation Index rose steadily, confirming a progressive deterioration of landscape coherence.

Comprehensive Interpretation

Taken together, the land use data and landscape metrics paint a consistent picture: the Angkor Heritage Zone has shifted from a forest-dominated landscape toward a more heterogeneous and fragmented mosaic driven by agricultural and urban encroachment. The rate of built-up expansion accelerated noticeably after 2012, coinciding with a period of rapid tourism growth in Siem Reap Province.

Discussion

The findings reveal a landscape under mounting pressure from forces that often pull in opposite directions. On one hand, Angkor's World Heritage status has attracted conservation funding, management interventions, and international oversight. On the other hand, the same status has driven a tourism boom that requires roads, hotels, and service infrastructure—all of which consume land^[15]. The 10.9 percentage-point loss in dense forest recorded here sits within the range reported for other Southeast Asian heritage landscapes, though it is higher than rates observed at sites with stricter buffer-zone enforcement such as Luang Prabang in Laos^[5].

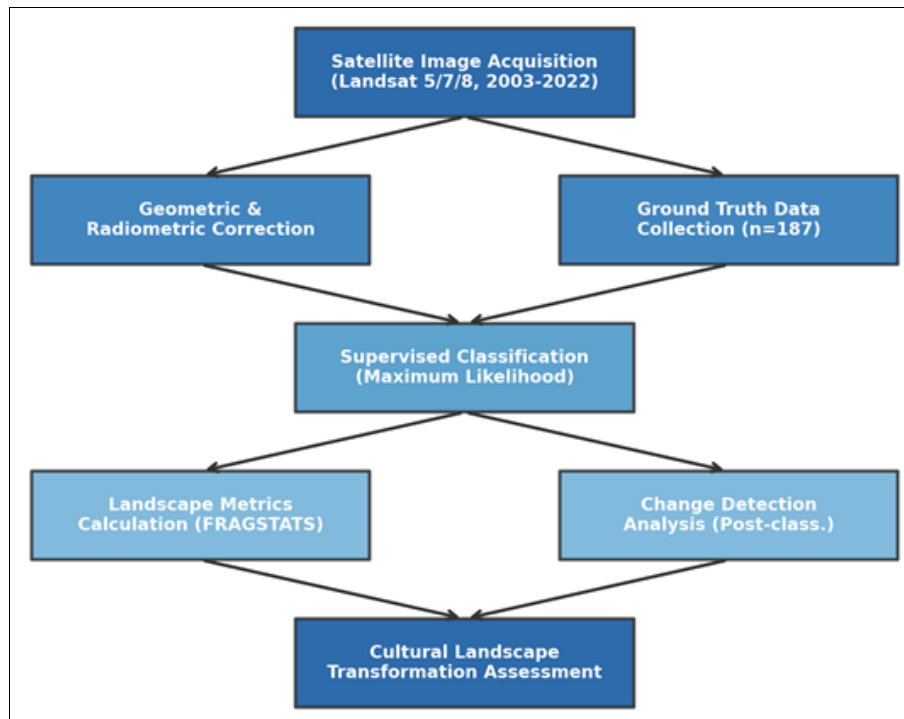


Fig 3: Flowchart of the research methodology for landscape transformation assessment

Landscape fragmentation metrics add a dimension that simple area-based change detection misses. A landscape may lose only modest forest area yet still suffer severe fragmentation if clearing occurs in narrow strips along roads. That pattern was evident in the Angkor data, where patch density nearly doubled despite a relatively moderate total forest loss. Similar fragmentation trajectories have been documented around Borobudur in Indonesia and Bagan in Myanmar, suggesting a common heritage-tourism-driven pathway of landscape modification ^[7].

The seasonal dimension deserves attention. Monsoon-driven green-up temporarily restores canopy greenness and can mask degradation signals in wet-season imagery. By anchoring all acquisitions to the dry season, this research avoided that masking effect and captured the underlying trend. But dry-season snapshots may overstate severity relative to annual averages, a limitation worth noting when interpreting the NDVI trajectory. Management implications point toward spatially targeted interventions. The western fringe of the heritage zone, closest to Siem Reap town, has experienced the most intense conversion. Strengthening buffer-zone zoning in that corridor, paired with livelihood alternatives for affected communities, could slow further encroachment ^[16].

Conclusion

This research documented marked landscape transformation in the Angkor Heritage Zone between 2003 and 2022. Dense forest cover shrank by nearly 11 percentage points, while built-up areas more than doubled in proportional extent. Landscape fragmentation indices rose consistently, and mean dry-season NDVI fell from 0.71 to 0.43 across two decades. These shifts indicate that the cultural landscape around the Angkor temple complexes has been progressively reorganized by agricultural expansion and tourism-related infrastructure development.

Seasonal monsoon dynamics provided temporary vegetation recovery each wet season, but this cyclical green-up did not

offset the underlying structural decline captured in dry-season satellite records. Landscape metrics proved useful beyond simple area statistics, exposing how spatial configuration—not just total extent—has changed. Conservation strategies that focus solely on protecting individual temple structures will miss the broader landscape-scale changes that threaten the setting of the monuments themselves. Buffer-zone management plans need to account for spatial encroachment patterns, particularly along the western corridor linking Siem Reap to the park. Future work should incorporate very high-resolution imagery and community livelihood surveys to build a fuller picture of transformation drivers.

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