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Original Article

Assessing the Trends and Dynamics of Landscape Pattern Change in the Trang An Mixed World Heritage Site, Ninh Binh Province

Pham Van Manh[1], Nguyen Thi Thu Hang[1], Do Thi Nhung[1], Tran Ngoc Tuong[1], Le Trung Hieu[1], Nguyen Thi Diem My[2,*]

[1]*VNU University of Science, VNU Vietnam National University, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam*
[2]*Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH University of Krakow, Mickiewicza 30, 30-059 Krakow, Poland*

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Abstract: The Trang An Landscape Complex, Vietnam's first mixed heritage site and Southeast Asia's, currently faces these challenges. This study applies spatiotemporal analysis to clarify the ongoing conflict between conserving natural and cultural landscapes and urbanizing heritage areas. The methodology involves classifying LULC over twenty years from 2004 to 2024 using Landsat satellite images, analyzing landscape fragmentation with metrics such as Area metrics (LM1), Density metrics (LM2), Shape metrics (LM3), and Connectivity metrics (LM4), and assessing the impacts of socioeconomic development on the Outstanding Universal Value (OUV). The LULC classification achieved overall accuracies of 85.93% to 87.96%, with Kappa coefficients ranging from 0.83 to 0.86. The results show that the core zone has maintained large patches and ecological integrity, while the buffer zone faces increasing fragmentation pressure, undermining landscape protection efforts and increasing the risk of pattern disruption. Furthermore, the results reveal distinct spatiotemporal trends in landscape dynamics, characterized by increasing patch density, shape complexity, and fragmentation intensity in the buffer zone, accompanied by a gradual decline in landscape connectivity over time. By explicitly linking long-term landscape pattern dynamics with heritage zoning, this study provides empirical evidence to support adaptive conservation and spatial planning strategies for mixed World Heritage sites under rapid urbanization. This comprehensive framework offers an effective decision-support tool for planning and guiding sustainable urban development at World Heritage sites amid ongoing urbanization challenges.

Keywords: Remote sensing, Landscape pattern, Urbanization, World Heritage conservation, Trang An Landscape Complex.

* Corresponding author.
E-mail address: diemmybn24@gmail.com

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1. Introduction

Rapid global urbanization has increased the conflict between heritage conservation and land-use change in key areas [1]. Vietnam is also directly affected, as many heritage sites face increasing pressure from urban development [2]. Although the country has only a small number of UNESCO-recognized World Heritage sites, each one holds unique symbolic value that reflects its cultural and historical identity, as well as its distinctive natural landscape ecosystems. Consequently, changes driven by urbanization can significantly affect their integrity and value. In the context of rapid socio-economic growth in the early 21st century, protecting and enhancing the value of cultural heritage has become a crucial priority to prevent deterioration and support sustainability for future generations [3, 4]. Infrastructure development, urban expansion, and tourism, while benefiting communities, have also caused notable changes in the landscape and ecosystems of heritage sites [2]. Core zones, buffer zones, and protected areas with favourable terrain and infrastructure have become hotspots for development. This has placed considerable pressure on sensitive landscape patterns [5, 6]. These challenges highlight the urgent need for integrated conservation planning and non-structural management measures.

The lack of effective control over infrastructure development and tourism growth has caused spatiotemporal landscape fragmentation, weakening ecological connectivity within World Heritage sites [7]. Disruptions in ecological connectivity limit species movement and reduce the regulatory functions of the regional ecosystem [8]. As a result, the Outstanding Universal Value (OUV) of these sites is negatively impacted, reducing their integrity and long-term conservation potential. This situation highlights the urgent need for a systematic evaluation framework to identify and analyze the links between land-use changes and OUV conservation at World Heritage sites [9, 10]. In this context, land-use change assessment tools and models are seen as effective methods for monitoring and predicting landscape dynamics [11, 12]. However, integrating landscape metrics with land-use/land-cover (LULC) data could offer a more comprehensive assessment of how LULC changes influence ecological structure and function, but this integration remains limited and underexplored.

Applying landscape metrics helps quantify fragmentation, spatial pattern complexity [13, 14] and the decline in ecological connectivity [15, 16] all of which are vital factors impacting the integrity of heritage sites. The Trang An Landscape Complex, recognized as Vietnam's first mixed World Heritage site, represents a typical case of the tension between conservation and development. Recent decades have witnessed a substantial decline in agricultural land, most notably rice fields and natural forests, accompanied by the progressive conversion of buffer zones into new forms of land use. At the same time, unauthorized construction activities such as residential developments, hotels, homestays, restaurants, and tourism-related transport infrastructure have expanded into both the core and buffer zones. These changes fundamentally alter natural landscape patterns and diminish the distinctiveness of indigenous architectural features, posing a serious threat to the integrity of this mixed-heritage site.

Many studies focus on static land-cover mapping or short-term assessments. However, attention to the long-term spatio-temporal dynamics of landscape patterns and their differential behaviour between core and buffer zones remains limited. Furthermore, integrated quantitative frameworks linking landscape model indicators to socio-economic development pressures in mixed cultural-natural heritage sites are still inadequate. To address these gaps, this study proposes an integrated analytical framework that combines multi-temporal remote sensing data with landscape model indicators directly linked to the spatio-socio-economic context, enabling a systematic assessment of landscape dynamics in the Trang An Landscape Complex over twenty years. This approach allows for a differential assessment of landscape change processes in the core and

buffer zones, providing new quantitative insights to support heritage conservation and spatial planning under urbanization pressures aimed at conserving heritage values.

2. Materials and Methods

2.1. Study area

The Trang An Landscape Complex is located in the southern part of the Red River Delta, within the administrative boundaries of Ninh Binh Province, approximately 90 km south of Hanoi. Most of the site is within three nationally designated protected areas: the Hoa Lu ancient capital cultural and historical relics site, the Trang An-Tam Coc-Bich Dong scenic landscape, and the Hoa Lu special use forest [17]. Trang An is surrounded by a buffer zone of over 6,226 hectares, mainly within Truong Yen and Ninh Hai communes (Hoa Lu city). This area constitutes a special protection zone for the landscape complex and is fully integrated into the Trang An tourism area plan. The buffer zone spans 6,026 hectares, primarily consisting of wetlands and paddy fields, situated between 20°13′ and 20°15′ north latitude and 105°53′ and 105°56′ east longitude (Figure 1).

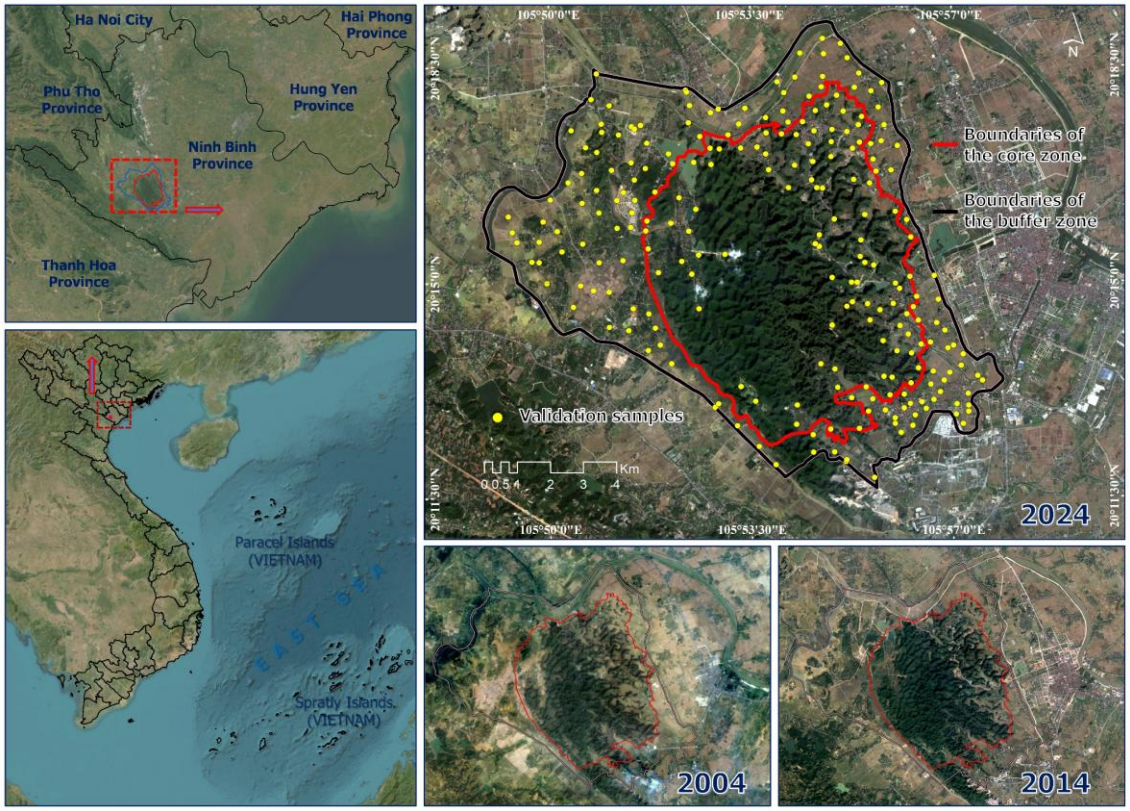


Figure 1. Location of the study area and spatial distribution of validation samples in the Trang An Landscape Complex, Ninh Binh Province. The lower-left panel shows the location of the study area in northern Vietnam; the upper-left panel provides a more detailed view of its location within Ninh Binh Province; the upper-right panel presents the detailed study area in 2024, including the boundaries of the core and buffer zones and the distribution of validation samples; and the lower-right panels show the corresponding study area in 2004 and 2014, respectively.

The study area occupies a geographically significant location, serving as a transitional zone between the Red River Delta plain and the Trang An - Tam Diep karst mountain systems.

This geological transition produces a diverse landscape that harmoniously integrates limestone mountains, valleys, subterranean waterways, caves, plains, and wetlands, with geomorphic features rarely found elsewhere in Vietnam. Trang An Landscape Complex not only has exceptional scenic and cultural value but also plays a key role in the socioeconomic growth and sustainable preservation of both cultural and natural resources in Ninh Binh Province. This area blends stunning natural beauty with profound cultural and spiritual importance, which deeply influences local life. In 2014, the World Heritage Committee of the United Nations Educational, Scientific and Cultural Organization (UNESCO) officially recognised the Trang An Landscape Complex, Ninh Binh Province, on the World Heritage List as Vietnam's and Southeast Asia's first mixed cultural and natural heritage site. As a result, the primary land-use categories examined in this study include:

Table 1. Land-cover and land-use types used in the Trang An Landscape Complex

Type	Abbreviation	Description
Water surface	WS	Lakes, streams, canals, and artificial water bodies display a variety of shapes, often irregular. Ponds are also classified under land-cover/land-use.
Low-density build-up	LDB	Human settlements are sparsely spread across the suburban outskirts, marked by low-rise villas scattered across large lots, interwoven with orchards and green spaces.
Agricultural land	ARGL	Land used for farming, including areas for seasonal crops like wet rice paddies and farmland left idle during land preparation, is characterized by sparse vegetation or scattered plant patches.
Forest and shrubs	FRS	Natural forests, plantation forests, forest restoration zones, or conservation areas.
Other land cover	OL	Areas where vegetation covers less than one-third of the total surface have mostly exposed land, which is barren with a thin soil layer, sandy or rocky substrate, or other soil types.
High-density build-up	HDB	Includes all artificial surface covers such as high-density residential areas, commercial zones, industrial regions, and transportation infrastructure, all characterized by clearly organized spatial patterns.

2.2. Datasets

An integrated approach, based on a methodology framework that combines remote sensing and landscape intensity index groups, was applied to determine land-use and land-cover changes and their impact on landscape patterns in the Trang An Landscape Complex, a UNESCO World Heritage site, over 20 years from 2004 to 2024. The process is described in detail using the methodology framework below (Figure 2).

2.2.1. Input Data and Multi-temporal Landsat Images Preprocessing

Satellite imagery from the Landsat series was obtained from the United States Geological Survey (USGS) EarthExplorer database (http://earthexplore.usgs.gov) with less than 3% cloud cover to ensure quality. The remote sensing scenes correspond to three acquisition dates: December 23, 2004 (Landsat-5), December 18, 2014 (Landsat-8), and November 30, 2024 (Landsat-9). Image preprocessing involved atmospheric and topographic correction using the ATCOR module within the CATALYST Professional software package (https://catalyst.earth/solutions/catalyst-professional), thereby removing the effects of solar radiation and atmospheric conditions on the surface reflectance [18]. Subsequently, all scenes were geometrically corrected and reprojected to the Universal Transverse Mercator (UTM) coordinate system, Zone 48N, based on the WGS-84 datum. To support

detailed analysis of land-use change within the study area, spatial resolution was increased using the University of New Brunswick (UNB) pan-sharpening technique. This method combines high-resolution panchromatic imagery with lower-resolution multispectral bands to produce composite scenes at a 15 m spatial resolution [4, 19, 20], thereby improving feature delineation and increasing the accuracy of spatiotemporal change detection.

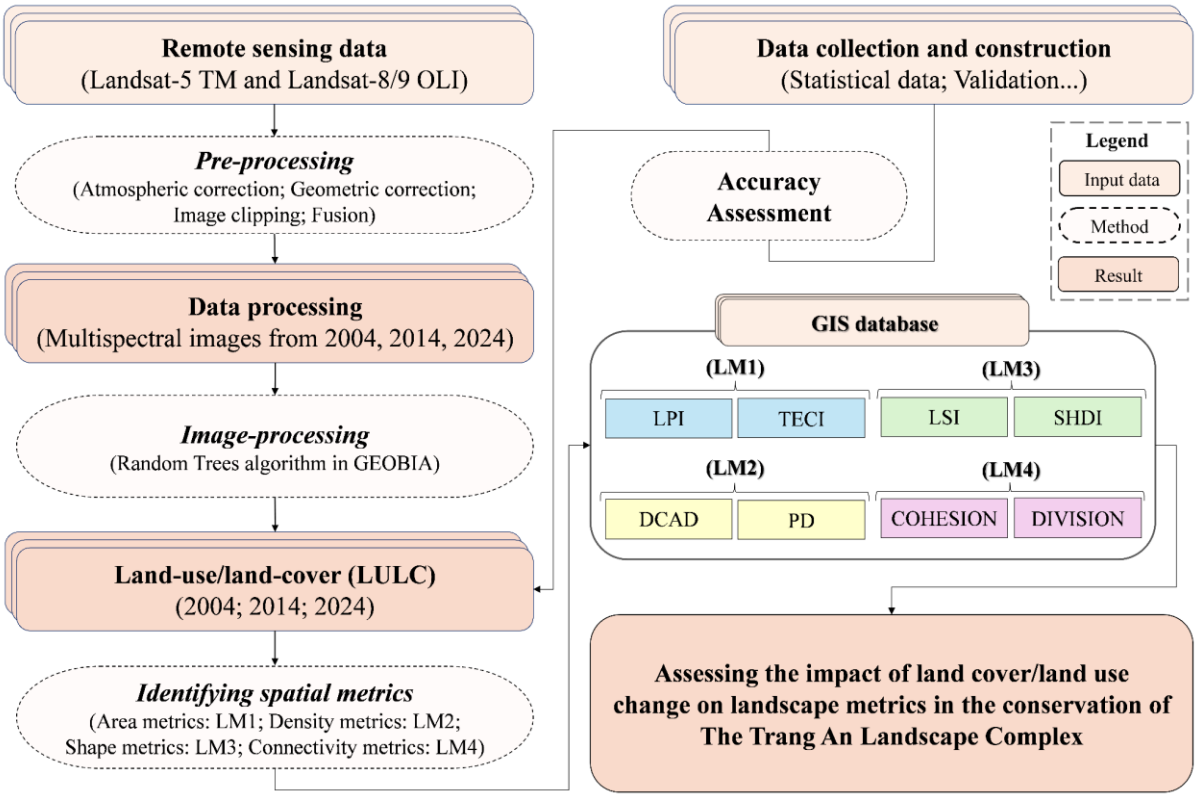


Figure 2. Flowchart of the process for assessing land-use cover change and its impact on landscape fragmentation in the Trang An Landscape Complex - UNESCO World Heritage Site.

2.2.2. Image Processing and Geographic Object-based Image Analysis Random Trees Classification

Digital image classification aims to generalize data by distinguishing objects and outlining land-use/land-cover (LULC) boundaries based on spectral homogeneity. The classification results are subsequently converted into geospatial data within a GIS environment [21]. To support reliable interpretation of remote sensing imagery and LULC analysis in Trang An Landscape Complex, field surveys were conducted at representative sites across the core and buffer zones. Sampling locations were selected to ensure: i) Representativeness of the main land-use and land-cover types, ii) Spatial dispersion throughout the study area; and iii) inclusion of both relatively undisturbed forest areas and areas affected by residential activities. This field-based dataset served as ground truth for both training the classification model and assessing the accuracy of the LULC results.

In this research, an object-based image analysis classification approach was adopted to overcome the limitations of pixel-based methods by integrating geometric, structural, and spatial relationship features, thereby improving the accuracy of object detection and recognition [4].

This approach is effective not only for high-spatial-resolution satellite imagery but also for medium-resolution data, as it flexibly combines multiple classification algorithms. It uses larger training sample sets by segmenting spectrally similar pixel groups based on shape, compactness, and scale. As a result, this method also supports an accurate spatiotemporal assessment of LULC change with high precision [2]. The classification process follows these steps:

Image segmentation: The scale, shape, and compactness parameters (15, 0.80, and 0.65, respectively) were selected based on multiple iterative tests with different settings. Segmentation used the Blue, Green, Red, and Near-Infrared spectral bands to enhance classification results.

Training and validation process: This stage was conducted to develop the LULC classification rule set. The initial step was to analyse the spectral and spatial features of LULC objects in the imagery, which is essential for establishing classification thresholds for each category. Each image object included attributes such as spectral-band values, brightness, shape, geographic location, texture, area, and distance to the image boundaries. Establishing the LULC classification rules requires a thorough understanding of each band's spectral behaviour, the reflectance properties of target features, detailed knowledge of the study area, and the relationships among various LULC types. For the research area, LULC categories were divided into six main classes: HDB, LDB, FRS, AGRL, WS, and OL.

Classification: The object-based classification framework combines multiple algorithms, including Decision Trees (DT), K-Nearest Neighbors (K-NN), Random Trees (RT), and Support Vector Machines (SVM), to facilitate the LULC classification process. Previous performance assessments have indicated that RT surpasses other machine-learning methods, mainly when used with medium and high-resolution satellite imagery [22, 23]. In digital image classification, the Random Trees (RT) algorithm, often known as Random Forest (RF) when expanded into an ensemble of decision trees, is a machine-learning approach based on decision-tree theory. This method constructs a collection of independent classification trees, each trained on a bootstrap sample of the original dataset and a randomly chosen subset of input variables. At each node, a binary split is selected to maximize the purity of LULC classes within the resulting branches. The final classification results from majority voting across all trees in the forest. By combining numerous trees, the model gains greater stability and reduces the risk of overfitting compared to a single decision tree. The performance of the algorithm depends on hyperparameters such as the number of trees, the maximum depth of each tree, and the number of features considered at each split. RT is particularly effective for remote sensing image classification due to its robustness against noise and its ability to handle complex class boundaries accurately. In this study, RT was used to classify LULC objects within the Trang An Landscape Complex.

Accuracy assessment: The land-cover/land-use (LULC) classification results were refined through manual inspection to ensure precise delineation of each object. An accuracy assessment was performed on the final class layers after integrating the various LULC object categories. This assessment employed independent field survey samples as reference (ground truth) data. A confusion matrix was used to compare LULC classification results with the reference samples. Overall accuracy and the Kappa coefficient were calculated to quantify classification reliability. The accuracy evaluation for the 2024 LULC utilized ground truth data collected from 25 to 28 December 2024. A total of 238 reference locations were included: 66 agricultural land (AGRL), 20 forest and shrubs (FRS), 56 high-density built-up (HDB), 64 low-density built-up (LDB), 25 water surfaces (WS), and 7 other land cover (OL). For 2004 and 2014, the LULC accuracy assessment relied on analysis of actual data from historical land-use maps. A 70:30 ratio for training and

validation data was applied to improve the precision of the LULC categorization.

2.2.3. Analysis of Land-use/land-cover Change Using Landscape Metrics

The process of evaluating land-use changes for landscape conservation in Trang An was carried out using multi-temporal remote-sensing image analysis. An image from an initial baseline date was chosen as a reference point, and land-cover/land-use (LULC) layers from later time points were analyzed to identify and measure changes in each land use category. This assessment not only identifies trends in temporal change but also provides a basis for quantitatively analyzing the spatial structure of LULC features, thereby supporting scientific and effective management and conservation of the heritage landscape. In the study, landscape metrics were used to describe the spatial characteristics and variability of landscape pattern samples within the Trang An Landscape Complex, which were classified into four main groups [13]. *Area metrics (LM1):* These reflect the size, total area, and spatial layout of landscape patches, which are crucial for maintaining ecological stability. *Density metrics (LM2):* These indicate the influence of spatial structure on organism movement and material flows within the ecosystem, aiding in identifying ecological corridors or barriers. *Shape metrics (LM3):* These evaluate how spatial morphology impacts species expansion, contraction, and movement, affecting habitat quality and biodiversity levels. *Connectivity metrics (LM4):* These represent the potential to maintain ecological flows and the level of functional connectivity among habitat patches, helping identify priority areas for protection to preserve the environmental integrity of the heritage site (Table 2). These metric groups were calculated using Fragstats 4.3, with input data processed within a GIS environment.

Table 2. System of landscape metric groups used in the study

Landscape metrics	Name	The ecological significance of landscape metrics
Area metrics (LM1)		
LPI	Largest Patch Index	LPI represents the dominance of a specific land-cover and land-use type within a landscape by showing the area of the largest patch as a percentage of the total landscape. LPI helps identify dominant species and evaluate biodiversity levels, while also serving as an indicator of landscape fragmentation and patchiness. Changes in LPI over time reveal human impacts on spatial structure and trends in land-use change.
TECI	Total Edge Contrast Index	TECI measures how different neighboring patches are in a landscape. TECI affects critical ecological processes like dispersal, isolation, and species survival. High TECI values show that patch boundaries act as barriers, limiting organism movement and resource use in landscape ecology.
Density metrics (LM2)		
DCAD	Disjunct Core Area Density	DCAD measures the level of fragmentation in core areas of a landscape. It is a key indicator of habitat loss and is crucial for assessing habitat fragmentation and promoting biodiversity conservation.
PD	Patch Density	PD indicates the level of landscape fragmentation. Higher PD values suggest that the landscape consists of smaller patches, which can impact ecological processes such as migration, dispersal, and habitat persistence within the heritage area.
Shape metrics (LM3)		

LSI	Landscape Shape Index	LSI measures how isolated patches are within a landscape. As LSI increases, landscape patterns become more complex, which causes patches to become more separated, less connected, and reduces ecological cohesion.
SHDI	Shannon's Diversity Index	SHDI measures the heterogeneity and diversity of landscape patterns, susceptible to uneven distributions among individual patch types. SHDI reflects the diversity present in land-use changes.
Connectivity metrics (LM4)		
DIVISION	Landscape Division Index	DIVISION measures the level of fragmentation or aggregation in a landscape, describing spatial complexity by breaking down landscape pattern types into distinct, separate patches. This process affects system connectivity and ecological function.
COHESION	Patch Cohesion Index	COHESION measures the level of spatial connectedness among patches, affected by the distance between patches and how they are arranged. High COHESION values show strong links among larger, closely spaced habitat patches, helping to preserve the ecological integrity of the landscape mosaic.

3. Results and Discussion

3.1. Results of Land-use/land-cover Classification in the Trang An Landscape Complex

The Random Trees machine-learning algorithm was applied within an object-based classification framework to Landsat imagery for 2004, 2014, and 2024 (Figure 3). Following post-classification processing, including merging small patches and refining class boundaries, classification accuracy was evaluated using independent validation datasets. The overall accuracy (OA) was 86% (2004), 87% (2014), and 88% (2024), with corresponding Kappa coefficients of 0.83, 0.85, and 0.86. These values meet the standard accuracy thresholds for satellite-based land-use/land-cover classification (OA $\geq$ 85% and Kappa $\geq$ 0.75). The classification results for all three time periods are considered highly reliable, ensuring consistency and suitability for subsequent analyses in the study (Table 3).

The period from 2004 to 2024 witnessed significant shifts in LULC structure within the Trang An Landscape Complex, reflecting rapid urban expansion and land-use conversion (Table 4). Notably, water surface (WS) increased slightly from 974.7 ha to 1,190.8 ha, indicating the expansion of reservoirs and irrigation systems that could promote ecotourism. Low-density built-up (LDB) grew quickly from 940.1 ha to 3,066.8 ha (over 226%). In comparison, high-density built-up (HDB) rose significantly from 0.6 ha to 117.7 ha, indicating rapid growth of residential areas and transportation infrastructure in both the core and buffer zones of the heritage site. Meanwhile, agricultural land (AGRL) declined significantly from 4,444.7 ha to 3,152.3 ha, underscoring the conversion of farmland to built-up land, which could threaten the cultural and ecological values tied to traditional local farming. Alarmingly, forest and shrubs (FRS), essential for maintaining the natural landscape and biodiversity of the heritage area, decreased steadily from 5,613.4 ha to 4,425.3 ha. The other land cover (OL) category also fluctuated, showing an initial increase followed by a slight decrease. These changes highlight a pronounced shift from agricultural and forest lands toward land uses that support urban development and livelihood changes. This trend poses a significant challenge to conserving OUV of research area, necessitating adjustments in land-management policies, spatial planning, and stronger measures to protect the cultural-natural landscape as social and economic dynamics continue to evolve and develop.

Table 3. LULC classification confusion matrix for the study area

LULC 2004	AGRL	FRS	HDB	LDB	WS	OL	∑	User's (%)
AGRL	18	0	1	1	0	0	20	90
FRS	1	5	0	0	0	0	6	83
HDB	1	0	13	2	1	0	17	76
LDB	2	0	1	16	0	0	19	84
WS	0	0	0	0	8	0	8	100
OL	0	0	0	0	0	2	2	100
∑	22	5	15	19	9	2	72	-
Producer's (%)	82	100	87	84	89	100	-	-
Overall Accuracy (OA)								86%
Kappa Statistic (Kappa)								0.83
LULC 2014	AGRL	FRS	HDB	LDB	WS	OL	∑	User's (%)
AGRL	18	0	1	1	0	0	20	90
FRS	1	5	0	0	0	0	6	83
HDB	0	1	13	2	1	0	17	76
LDB	1	1	1	16	0	0	19	84
WS	0	0	0	0	8	0	8	100
OL	0	0	0	0	0	2	2	100
∑	20	7	15	19	9	2	72	-
Producer's (%)	90	71	87	84	89	100	-	-
Overall Accuracy (OA)								87%
Kappa Statistic (Kappa)								0.85
LULC 2024	AGRL	FRS	HDB	LDB	WS	OL	∑	User's (%)
AGRL	18	1	0	1	0	0	20	90
FRS	1	5	0	0	0	0	6	83
HDB	1	0	14	1	1	0	17	82
LDB	1	0	1	17	0	0	19	89
WS	1	0	0	0	7	0	8	88
OL	0	0	0	0	0	2	2	100
∑	22	6	15	19	8	2	72	-
Producer's (%)	82	83	93	89	88	100	-	-
Overall Accuracy (OA)								88%
Kappa Statistic (Kappa)								0.86

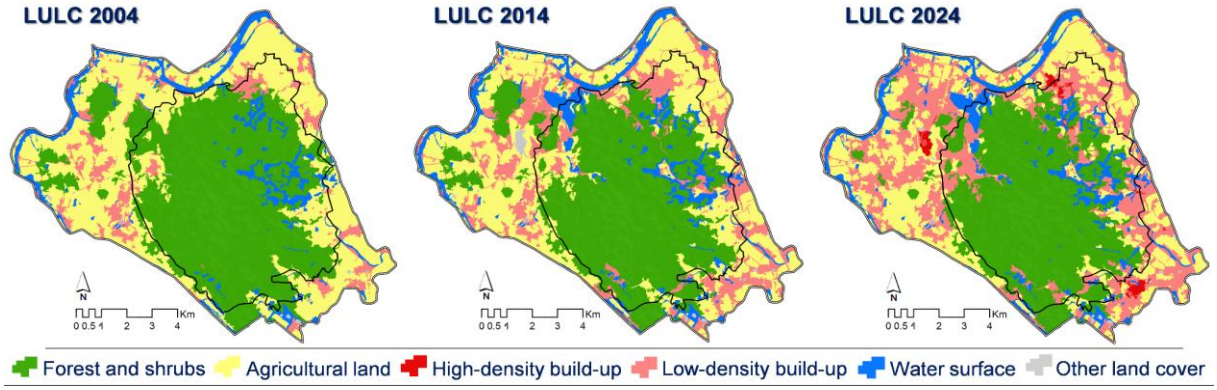


Figure 3. Land-use/land-cover classification results for Trang An in the period of 2004-2024.

Table 4. LULC type areas within the Trang An Landscape Complex (2004–2024)

Unit: ha	The period from 2004 to 2024		
LULC category	2004	2014	2024
Water surface (WS)	974.7	1,179.4	1,190.8
Low-density built-up (LDB)	940.1	1,927.7	3,066.8
Agricultural land (AGRL)	4,444.7	3,969.1	3,152.3
Forest and shrubland (FRS)	5,613.4	4,844.5	4,425.3
Other land cover (OL)	34.8	85.5	55.4
High-density built-up (HDB)	0.6	2.2	117.7

3.2. Trend Analysis of Landscape Pattern Changes Related to Land Use in the Trang An Landscape Complex from 2004 to 2024

The analysis of landscape metrics for the Trang An Landscape Complex during the period 2004 - 2024 was conducted at two scales: landscape-level and class-level metrics. The corresponding spatial data are shown in Table 5. Based on these results, several key characteristics emerge, indicating significant changes in the landscape structure of the study area over the period given. These features are explained in detail below to highlight the trends and extent of the changes across various landscape types.

Table 5. Calculated spatial metrics for 2004, 2014, and 2024

Metric Group		LM1		LM2		LM3		LM4	
Class-level metrics		LPI	TECI	DCAD	PD	LSI	SHDI	COHESION	DIVISION
2004	WS	1.138	73.315	0.707	0.707	44.865	-	98.331	1.000
	LDB	2.455	54.824	2.138	0.905	64.088	-	98.941	0.999
	ARGL	15.721	54.889	0.426	0.426	45.042	-	99.804	0.957
	FRS	8.150	55.855	0.086	0.086	15.898	-	99.688	0.992
	OL	0.088	71.871	0.645	0.645	35.088	-	93.972	1.000
	HDB	0.305	94.108	0.036	0.036	7.376	-	98.340	1.000
Landscape-level metrics		1.721	82.777	3.014	2.805	42.546	1.200	99.598	0.948
2014	WS	1.087	72.397	0.776	0.776	46.428	-	98.291	1.000
	LDB	6.025	56.508	2.260	0.779	69.932	-	99.457	0.995
	ARGL	9.933	54.966	0.758	0.758	52.208	-	99.586	0.985
	FRS	6.464	55.038	0.100	0.100	15.854	-	99.621	0.995
	OL	0.157	70.547	0.757	0.757	40.959	-	95.671	1.000
	HDB	1.003	84.386	0.103	0.103	15.173	-	98.756	1.000
Landscape-level metrics		9.933	58.730	4.754	3.272	50.228	1.319	99.439	0.975
2024	WS	1.562	71.670	0.792	0.792	46.458	-	98.263	1.000
	LDB	8.070	58.273	2.379	0.702	71.535	-	99.597	0.991
	ARGL	6.776	54.818	1.014	1.013	53.630	-	99.400	0.991
	FRS	5.415	54.219	0.108	0.107	16.739	-	99.591	0.996
	OL	1.501	68.035	0.741	0.741	40.453	-	95.988	1.000
	HDB	1.774	85.289	0.176	0.176	23.224	-	99.011	1.000
Landscape-level metrics		8.070	55.750	5.208	3.531	52.898	1.382	99.423	0.977

Area Metrics (LM1): The decline of agricultural land (AGRL) over the study period is evident in the marked decrease in the Largest Patch Index (LPI), which dropped from 15.721 in 2004 to 6.776 in 2024. This trend indicates increasing fragmentation of cultivated areas and a shift of farmland to other land-use types. In contrast, both low-density built-up (LDB) and high-density built-up (HDB) exhibited substantial gains in spatial dominance.

Specifically, the LPI of LDB increased from 2.455 in 2004 to 8.070 in 2024, while that of HDB rose from 0.305 to 1.774 over the same period. These shifts highlight rapid urban expansion that not only enlarges built-up areas but also intensifies their spatial clustering. Figure 4 shows the spatiotemporal changes of the LM1 suite throughout the Trang An Landscape Complex, displaying both the prominence of large landscape patches and the precise boundaries between land-use types. In the core zone, the size and edge configuration of major patches remained relatively stable throughout 2004-2024. By contrast, sharp reductions in LPI were observed in the western–northwestern and northeastern buffer zones, where large patches were fragmented into smaller, more isolated units. This fragmentation is strongly associated with the growth of tourism infrastructure, which has disrupted the traditional agricultural mosaic and weakened ecological connectivity. The Total Edge Contrast Index (TECI) decreased from 82.777 in 2004 to 55.750 in 2024, indicating increasing spatial homogenization of land use and a more simplified landscape with reduced ecological functional diversity. However, urbanized categories such as HDB retained high TECI values, underscoring strong ecological contrasts between built-up areas and adjacent landscapes. Within the core zone, TECI showed an upward trend, particularly along boundaries with the buffer zone. This suggests that large natural patches at the periphery are beginning to fragment due to infrastructure development, thereby increasing the density of interfaces between natural and human-modified features. Taken together, the contrasting spatial patterns of LPI and TECI underscore the inherent tension between conservation and development. While the core zone has demonstrated resilience in maintaining large landscape patches and ecological integrity, the buffer zone is increasingly subjected to fragmentation pressures, reducing its capacity to protect primary landscape patches and heightening the risk of ecological disconnection.

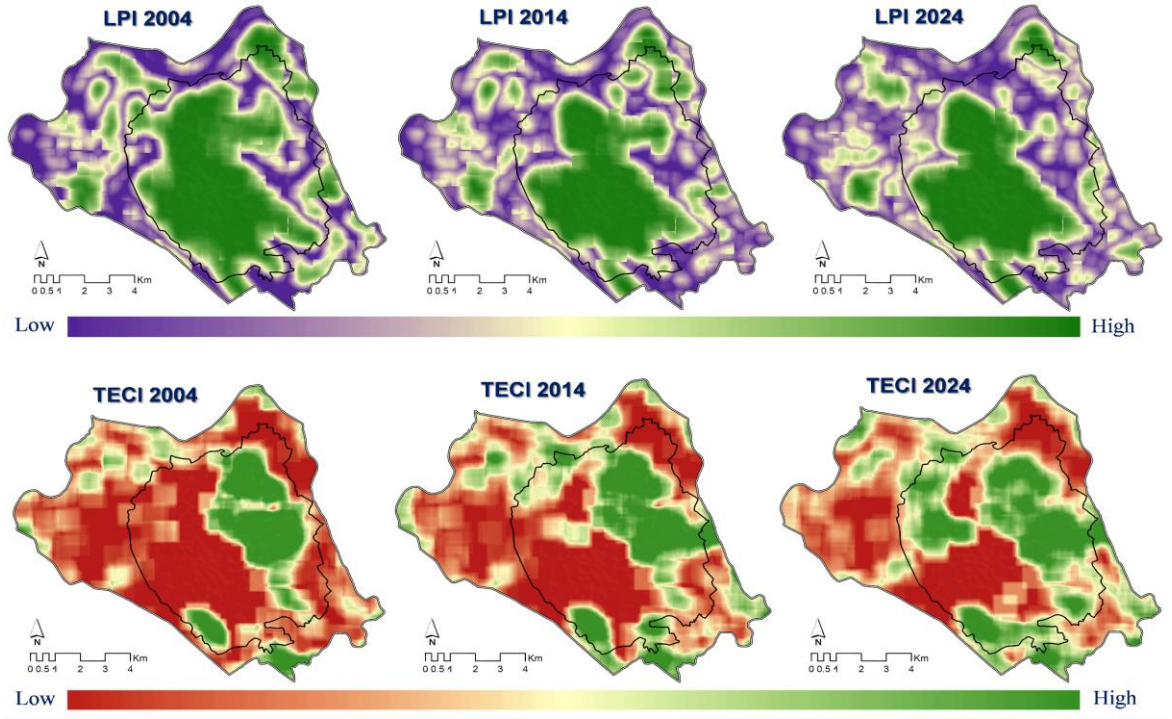


Figure 4. Spatiotemporal changes in LM1 within Trang An from 2004 to 2024.

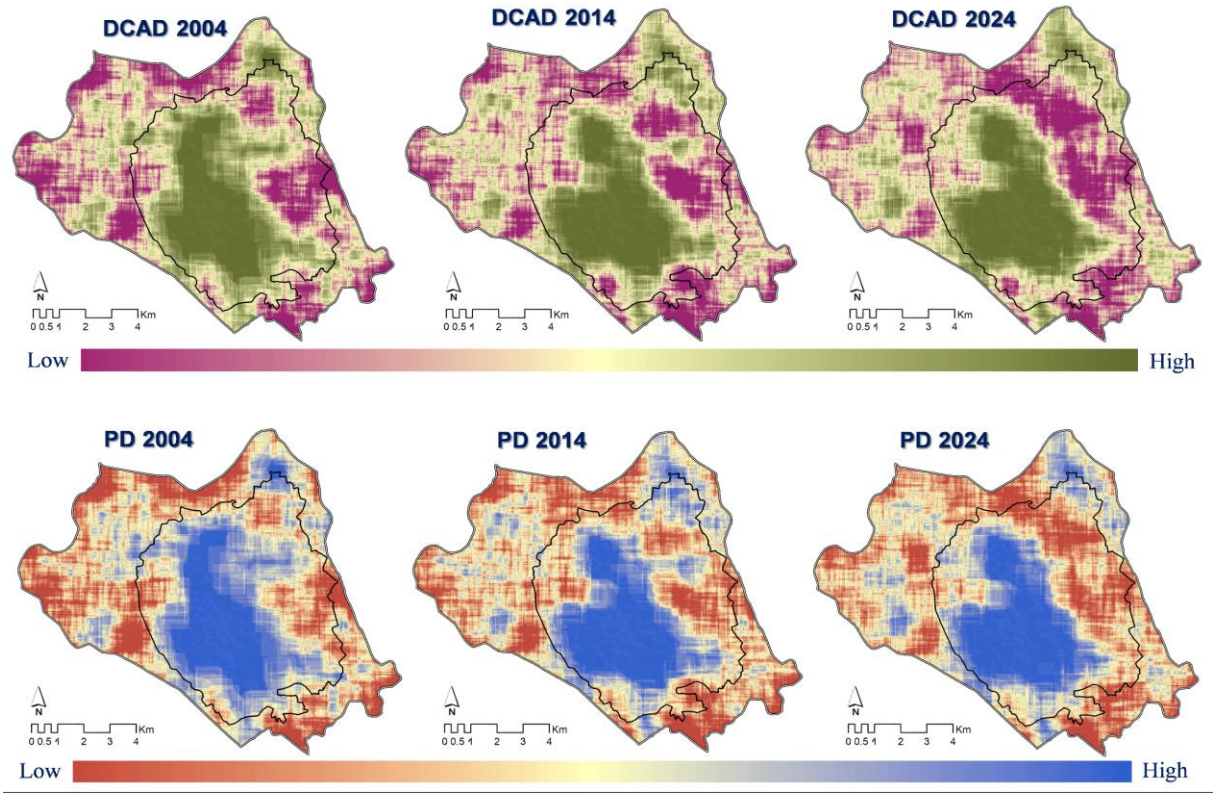


Figure 5. Spatiotemporal changes in LM2 within Trang An from 2004 to 2024.

Density metrics (LM2): These metrics evaluate the level of landscape fragmentation and the density of patch distribution in land use change. Within this group, the Disjunct Core Area Density (DCAD) measure reflects the spatial density of fragmented or isolated core areas. The DCAD value increased slightly over the 2004-2024 period, rising from 3.014 to 5.208. This stability indicates that the core zone of the Trang An Landscape Complex maintained a consistent DCAD throughout the study, demonstrating that the main landscape patches have preserved spatial continuity with minimal fragmentation (Figure 5). In contrast, around the heritage buffer zone, the spatial distribution of the degree of core area division (DCAD) shows a steady upward trend, indicating an increase in small, isolated core fragments. This growth is mainly driven by converting agricultural land and forest/shrubland into dispersed land uses that support community-based tourism and local infrastructure. Between 2004 and 2024, patch density (PD) in the Trang An Landscape Complex increased slightly, from 2.805 to 3.531. Inside the heritage core, PD remained steady and focused on larger patches. However, near the buffer zone, it showed a slight spatial increase, signalling the emergence and spread of small, disconnected landscape units. These changes mainly result from the expansion of built-up areas and the growth of household-scale tourism facilities. The simultaneous fluctuations in PD and DCAD within the LM2 category highlight increasing spatial fragmentation in buffer areas: previously connected patches break into smaller pieces, weakening their functional links and creating a patchwork landscape where natural and human-made elements intertwine. As a result, these buffer zones are becoming high-impact areas where landscape patterns are continually reshaped by land-use change.

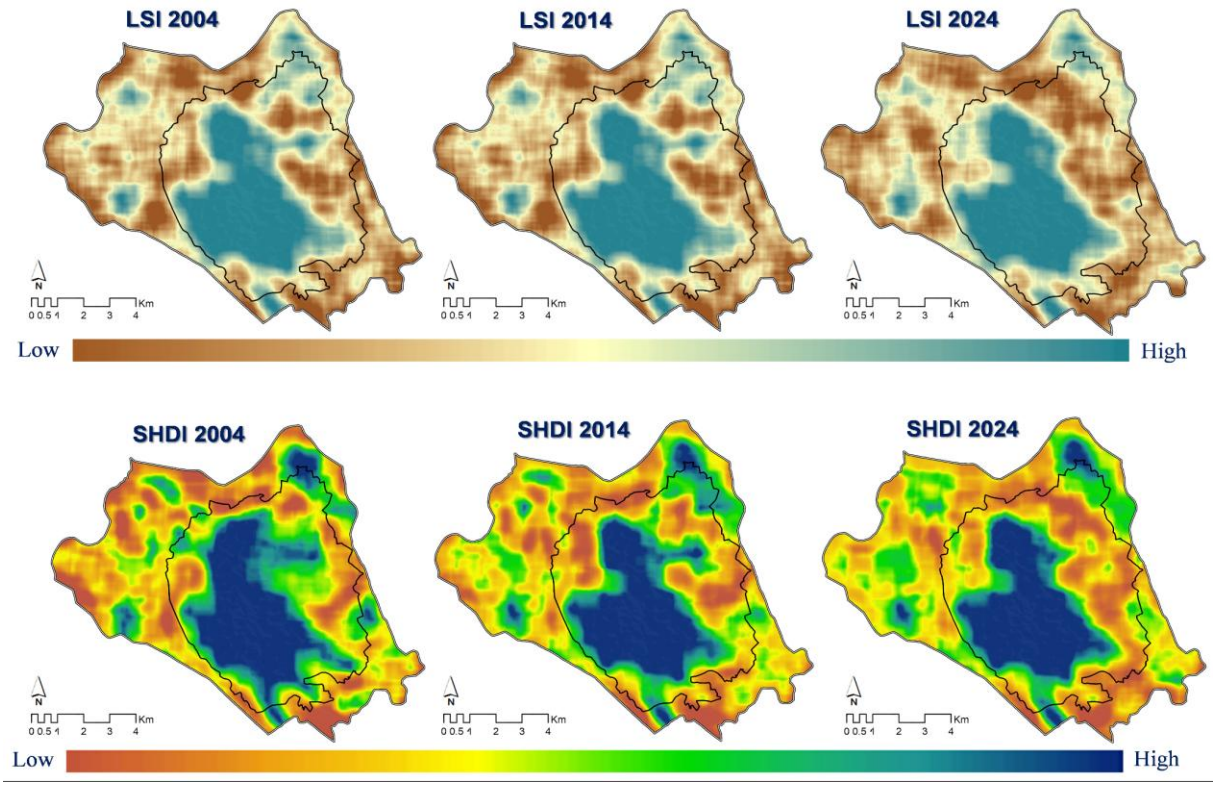


Figure 6. Spatiotemporal changes in LM3 within Trang An from 2004 to 2024.

Shape metrics (LM3): Figure 6 illustrates how landscape shape and diversity vary across the study area, using the Landscape Shape Index (LSI) and Shannon's Diversity Index (SHDI). The LSI steadily increases from 42.546 in 2004 to 52.898 in 2024, indicating the growing spatial complexity of the landscape. The SHDI also rises from 1.200 in 2004 to 1.382 in 2024, reflecting an increase in land-use types and a more balanced distribution among them within the Trang An Landscape Complex. In the core zone, the LSI remains low and stable throughout the study period, showing simple landforms and continuous natural patches. This stability suggests minimal fragmentation and the preservation of intact patch structures despite land-use pressures. Conversely, in the buffer zones surrounding the heritage site, the LSI gradually increases over time. This trend indicates ongoing disruption of patch continuity at the boundaries, leading to more intricate patch shapes and structures. The intermixing of small land parcels has created jagged, heterogeneous patch edges, disturbing the natural blocks' morphological integrity. Meanwhile, the SHDI in the buffer zones also increases significantly, mainly due to the appearance and expansion of human land uses, including high- and low-density built-up areas (HDB and LDB), alongside forest and agricultural land. The simultaneous rise in both LSI and SHDI indicates a systematic spatial reshaping of form and composition within the buffer zones. These changes reveal a dynamic transition driven by development pressures that disturb Trang An's stable landscape and pose major challenges for heritage conservation and sustainable management.

Connectivity metrics (LM4): Figure 7 shows the spatial and temporal distribution of LM4, illustrating how landscape patches connect or become separated over time due to land use changes. The Patch Cohesion Index (COHESION) indicates how effectively patches

are linked across space. A slight decline in COHESION was observed in the Trang An Landscape Complex, with the index falling from 99.598 in 2004 to 99.423 in 2024. Despite this decrease, the consistently high values suggest that overall landscape connectivity remained largely intact under increasing land-use pressures. This slight decline may reflect increasing landscape fragmentation associated with the expansion of built-up land, tourism infrastructure, and residential areas. Greater separation among patches can reduce their capacity to maintain biological connectivity and habitat functions. Conversely, the Landscape Division Index (DIVISION) increases from 0.948 in 2004 to 0.977 in 2024, reflecting a gradual intensification of landscape fragmentation, particularly in areas experiencing active land-use conversion. This fragmentation hampers species movement and the flow of materials and energy within the ecosystem, thereby lowering overall landscape resilience. The increase in DIVISION and decrease in COHESION reflect spatial changes associated with intensified land-use activities in the buffer zone. The buffer zone, where land-use conversion is most intense, becomes a dynamic frontier of fragmentation. Consequently, functional boundaries shift, and the overall spatial layout of the Trang An becomes more complex, creating significant challenges for conservation and ecological management.

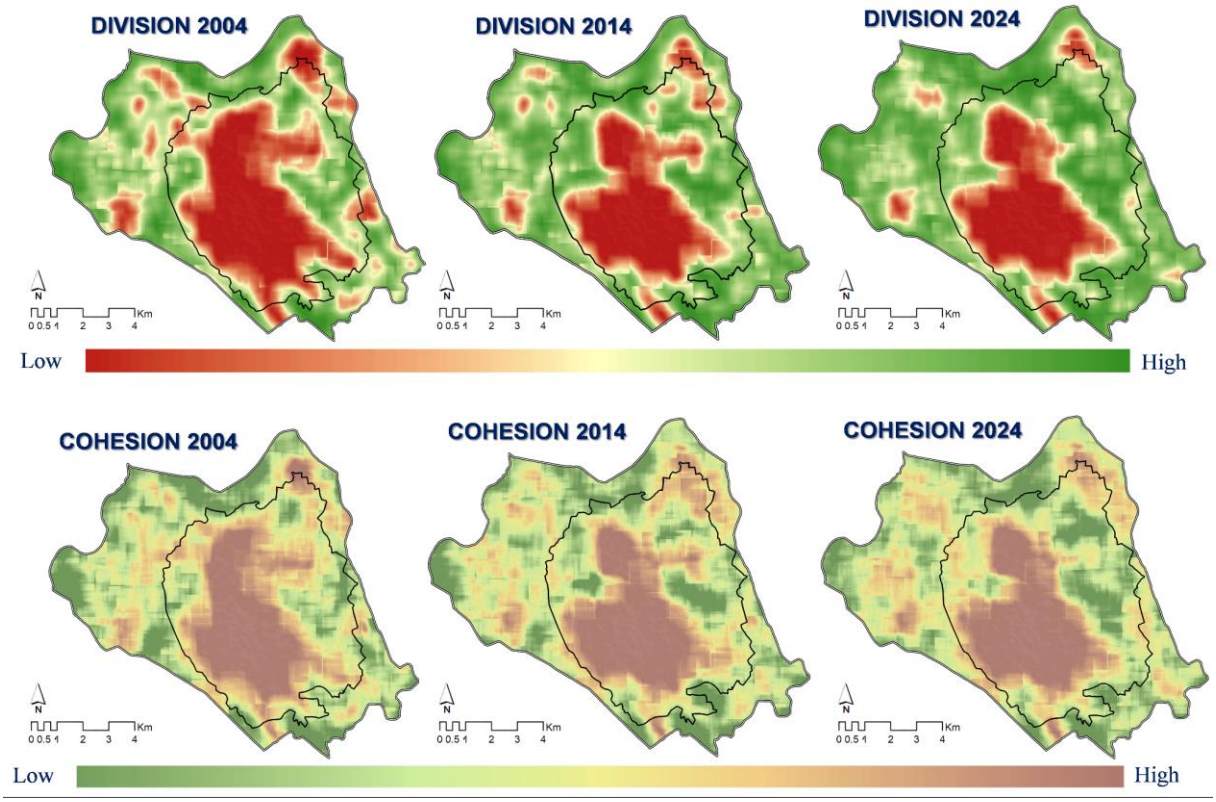


Figure 7. Spatiotemporal changes in LM4 within Trang An from 2004 to 2024.

These landscape patterns not only show how ecosystems are arranged in space but also support the functions of the mixed World Heritage site. Looking at how landscape patterns change over time and space helps us understand the processes behind landscape development and the factors that influence it [25, 26]. In the Trang An Landscape Complex, landscape patterns are

very sensitive and easily affected by external disturbances. Their limited resilience makes them especially vulnerable to unsustainable development activities. Research indicates that areas with high fragmentation mainly appear in the western, northwestern, and northeastern parts of the buffer zone, where construction land density is high. Conversely, the core zone has less fragmentation, showing relative stability in its landscape structure. This is consistent with findings from studies in the Complex of Hue Monuments and Nui Chua World Biosphere Reserve [2, 13]. The increase in human activities, especially the expansion of construction land, is identified as the primary cause of landscape fragmentation. In this context, the buffer zone serves both as an essential protective layer for the World Heritage site and as a region for local socioeconomic growth. However, without proper management, activities in the buffer zone could jeopardize the landscape's integrity and the Outstanding Universal Value (OUV) of the World Heritage site. To achieve heritage preservation and sustainable development goals, future research should focus on analyzing landscape structures, identifying key nodes and bottlenecks in the ecological network, and strengthening environmental security systems. Maintaining ecological connectivity throughout the landscape is crucial for protecting the ecosystem's structure and function within the heritage site.

4. Conclusions

The analysis of land-use/land-cover (LULC) changes in the Trang An Landscape Complex from 2004 to 2024 reveals rapid urbanization that has significantly transformed the region's spatial structure. Agricultural land decreased from 4,444.7 hectares to 3,152.3 hectares, and forest and shrubland declined from 5,613.4 hectares to 4,425.3 hectares. Meanwhile, low-density built-up areas increased by over 226 percent, and high-density built-up areas expanded from 0.6 hectares to 117.7 hectares. Object-based classification using the Random Forest algorithm achieved an overall accuracy of 85.93–87.96 percent and Kappa coefficients of 0.83-0.86, providing a reliable foundation for subsequent landscape-metric analyses. Results from the landscape metrics group (LM1, LM2, LM3, LM4) show that the core zone has maintained large patches, high cohesion, and stable morphological diversity. In contrast, the buffer zone experiences increasing fragmentation: the Largest Patch Index (LPI) and Patch Cohesion Index (COHESION) have declined, while Patch Density (PD), Disjunct Core Area Density (DCAD), Landscape Shape Index (LSI), Shannon's Diversity Index (SHDI), and Landscape Division Index (DIVISION) have all increased. Based on these findings, sustainable planning and management should prioritize the protection of ecological cores through adaptive zoning and the establishment of ecological corridors. Development in buffer zones must be carefully regulated, with strategies focusing on optimizing landscape patterns and enhancing vegetative cover adjacent to the core area. Further research into the socio-ecological functions of the buffer zone is essential to balance heritage conservation with local community development needs. Integrating the Sustainable Development Goals (SDGs) will support a balanced model of high-quality growth that safeguards ecological integrity, promotes sustainable tourism and local community livelihoods. Finally, differentiated governance structures for core and buffer zones should be implemented, with conservation prioritized as the foundation for long-term sustainable development and for protecting the Outstanding Universal Value (OUV) of the Trang An Landscape Complex.

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