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Assessment of Spatial Dynamics of Forest Cover in Lomami National Park (DR Congo), 2008–2024: Implications for Conservation and Sustainable Ecosystem Management

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Abstract: Lomami National Park, located in the Democratic Republic of the Congo (DR Congo), is renowned for the integrity of its forest ecosystems, safeguarded by the absence of agricultural activities and limited road access. However, these ecosystems remain under-researched, particularly in terms of forest cover dynamics. This research gap poses a significant challenge to establishing rigorous monitoring systems, which are essential for ensuring the long-term preservation of these valuable ecosystems. This study utilized Google Earth Engine to preprocess Landsat images from 2008, 2016, and 2024, employing techniques such as atmospheric correction and cloud masking. Random Forest classification was applied to analyze land cover changes, using training datasets curated through ground-truthing and region-of-interest selection. The classification accuracy was evaluated using metrics such as overall accuracy, producer's accuracy, and user's accuracy. To assess landscape configuration, metrics such as class area, patch number, largest patch index, disturbance index, aggregation index, and edge density were calculated, distinguishing between the park's core and peripheral zones. Spatial transformation processes were analyzed using a decision tree approach. The results revealed a striking contrast in forest cover stability between Lomami National Park and its surrounding periphery. Within the park, forest cover has been preserved and even showed a modest increase, rising from 92.60% in 2008 to 92.75% in 2024. In contrast, the peripheral zone experienced a significant decline in forest cover, decreasing from 79.32% to 70.48% during the same period. This stability within the park extends beyond maintaining forested areas; it includes preserving and enhancing the spatial structure of forest ecosystems. For example, edge density, a key indicator of forest edge compactness, remained stable in the park, fluctuating between 8 m/ha and 9 m/ha. Conversely, edge density in the peripheral zone exceeded 35 m/ha, indicating that forest edges within the park are considerably more cohesive and intact than those in the surrounding areas. The spatial transformation processes also underscored these contrasting dynamics. In the park, the primary process was the aggregation of primary

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forest patches, reflecting a trend toward continuous and connected forest landscapes. By contrast, the peripheral zone exhibited dissection, indicating fragmentation and the breakdown of forest patches. These findings highlight the park's critical role in maintaining both the extent and structural integrity of forest ecosystems, setting it apart from the more degraded periphery. They underscore the resilience of forest ecosystems in the face of limited anthropogenic pressures and the crucial importance of effective land management and rigorous conservation strategies in addressing the challenges posed by urbanization and rural expansion. Additionally, the results emphasize that well-adapted conservation measures, combined with specific demographic and socio-economic conditions, can play a pivotal role in achieving long-term forest preservation and ecological stability.

Keywords: primary forest; spatial structure; ecosystem conservation; remote sensing/GIS; ecological resilience; land-use planning; protected area

1. Introduction

Tropical forests, covering only ~10% of Earth's surface, harbor ~50% of known species, making them critical reservoirs of terrestrial biodiversity [1]. They provide essential ecosystem services, including carbon sequestration, water regulation, and soil protection, crucial for ecological health and climate stability [2]. Studies, such as those by Ian et al. [3] and Yang et al. [4], emphasize their role in supporting biodiversity, ecosystem stability, and ecological processes like pollination and seed dispersal, which are vital for maintaining ecosystem integrity and combating climate change. Additionally, tropical forests are home to complex interactions between species and ecosystems, fostering essential ecological processes such as pollination and seed dispersal, which are crucial for maintaining the integrity of these environments [5]. These forests also play a key role in reducing the impact of torrential rains by slowing runoff and mitigating soil erosion [2,6]. Additionally, they store substantial amounts of carbon (247 gigatons) while generating a significant portion of the world's annual oxygen (20% to 30%) [7,8]. In Central Africa, these ecosystems provide livelihoods for nearly 60 million people living near or depending on these forests [9–11].

Despite their critical importance, tropical forests are under unsustainable pressures. Deforestation and degradation, primarily from logging, agriculture, and mining, severely threaten tropical forests. Between 2015 and 2020, global forest loss averaged 10 million hectares annually, with tropical forests accounting for over 40% of this loss [12]. The Amazon Basin exemplifies this trend, with deforestation rates rising by 30% from 2018 to 2020, culminating in the clearance of nearly 11,000 square kilometers in 2020 [13]. Africa loses approximately 3.9 million hectares of forest annually, endangering the unique biodiversity and ecosystem services provided by these regions [9,10,13–15]. Unlike other tropical regions where deforestation is often driven by large-scale exploitation projects, in Central Africa, it is primarily caused by small-scale activities such as subsistence agriculture, charcoal production, and fuelwood collection, leading to the loss of nearly 18 million hectares of forest since 2000 [10]. While these practices are driven by immediate economic needs, they compromise resource sustainability and increase the vulnerability of ecosystems to degradation. The significance of understanding land-use changes in tropical forests and their impacts on biodiversity, ecosystem services, and carbon storage has been well documented in the literature [16–18].

In Central Africa, countries are implementing policies to combat deforestation and promote sustainable forest management. The Republic of Congo's national forest strategy aims to sustainably manage 30% of its forests by 2030 through reforestation and community forestry programs. Cameroon's Forestry and Environmental Sector Program enforces strict logging regulations, supports community-based management, and participates in the REDD+ program. Gabon has protected over 10% of its land and, in 2018, became the first African nation to issue carbon credits for forest preservation. Regional initiatives like the Congo Basin Forest Partnership further integrate conservation and economic development goals [12].

The DR Congo aims to protect 17% of its territory through a conservation policy focused on establishing national parks, nature reserves, and wildlife zones. Key protected areas, such as Virunga, Salonga, and Kahuzi-Biega National Parks, are home to endangered species like mountain gorillas, okapis, and forest elephants. In partnership with organizations like WWF, the DR Congo has improved park management, implemented anti-poaching measures, and promoted eco-tourism to support local communities. However, challenges remain, including poaching, illegal logging, and armed conflict, which increase pressure on protected areas. The policy's success depends on stronger enforcement, sustainable funding, and ongoing collaboration with local and international stakeholders [19]. This initiative led to the creation of the Lomami National Park in 2016, covering an impressive area of 8879 km^2, complemented by a buffer zone of 22,000 km^2 [20]. This park consists primarily of lowland tropical moist forests, with emergent islands of edaphic and hydromorphic savanna in its southern part. Located in a region characterized by extremely low population density, this protected area is known for the integrity of its relatively undisturbed forest ecosystems due to the absence of significant agricultural activities, logging, and road inaccessibility [20,21]. However, this assertion is not supported by empirical data. Research gaps in tropical forest studies stem from several factors [1,5,8]. Remote and inaccessible locations make fieldwork logistically challenging and costly. Political instability further hampers long-term research efforts. Moreover, inadequate infrastructure and limited funding for scientific research in these regions restrict data collection on forest cover changes, species composition, and ecosystem services. No detailed studies have yet been conducted to illuminate this essential dimension of forest ecosystem health and resilience.

In the Congo Basin, home to the DR Congo's extensive forests, limited data on forest carbon stocks hampers efforts to quantify the region's contribution to global carbon sequestration [8]. This data deficiency obstructs the effective implementation of REDD+ programs, which depend on accurate carbon measurements for funding and mitigation planning. Without reliable data, assessing the effectiveness of conservation initiatives remains a significant challenge. This situation also restricts access to available funding and the mobilization of initiatives in favor of the park by organizations and policymakers [22]. Furthermore, this data insufficiency makes it difficult to identify threats early, hinders the optimal implementation of preventive measures, and may result in the delayed detection of changes, making corrective interventions more challenging and costly [23]. Finally, it leads to an inefficient allocation of available resources and the implementation of inadequate plans, thus compromising the ability of managers to make informed decisions based on accurate and up-to-date data [24,25]. The spatial and temporal dynamics of primary forest ecosystems within parks in Africa, particularly in Gabon and Cameroon, are well documented. Studies highlight the complexity and stability of these ecosystems in the face of natural and anthropogenic disturbances. However, gaps remain in understanding the specific dynamics of less studied or newly established parks, such as the Lomami National Park. The rationale for conducting a study on deforestation in Lomami National Park lies in the observed research gap in the existing literature. Previous studies have primarily quantified deforestation at the provincial level [26], while investigations focused on Lomami National Park since its establishment have predominantly centered on characterizing its fauna [27–30] or composition, structure, and the sustainability of the use of its forests by local communities in buffer zones [31]. Despite growing recognition of the importance of accurate monitoring methods, including remote sensing, for forest management, detailed studies of forest dynamics in Lomami remain scarce [32]. The absence of detailed quantitative data on forest dynamics in parks like Lomami restricts our ability to effectively assess the impacts of conservation measures and potential threats. Studying and quantifying the forest dynamics of the Lomami National Park will fill this gap by providing essential data on spatial and temporal changes in an unexplored context. Consequently, these studies have largely overlooked the critical analysis of the spatiotemporal dynamics of habitats within the park. By addressing this oversight, this study seeks to analyze deforestation trends and their impacts on habitat integrity to enhance conservation strategies in this critical ecological zone. It combines remote sensing techniques, including satellite imagery and GIS analysis, to monitor forest cover changes over time. Field-based assessments will validate satellite data and provide insights into biodiversity and ecosystem health in key areas, ensuring a comprehensive understanding of deforestation dynamics.

Furthermore, it is also recognized that even ecosystems considered intact can undergo subtle modifications and long-term changes [33]. Monitoring these evolutions is crucial for ensuring biodiversity preservation, assessing human impact, and identifying potential threats before they become critical [34]. To meet these needs, various complementary approaches to data acquisition and analysis, such as remote sensing and landscape ecology, are employed. Remote sensing, particularly through satellite imagery, has been extensively applied to track changes in forest extent, detect deforestation, and assess habitat fragmentation, offering a cost-effective and large-scale alternative to traditional methods [35,36]. Landscape ecology analyzes the spatial structure of landscapes to understand how it influences biodiversity and population dynamics [37,38]. The combination of these approaches, their being less time-consuming and resource-intensive than traditional methods such as forest inventories, weather stations, and environmental sensors, proves particularly effective for monitoring the health of forest ecosystems within protected areas [38–40]. It allows for the design of integrated management strategies aimed at ensuring the long-term preservation of forest biodiversity [41–43].

This study aims to fill a significant gap in understanding the evolution of forest cover in Lomami National Park and its surroundings by conducting a comprehensive spatial analysis of these forest ecosystems dynamics from 2008 to 2024 using Landsat satellite imagery and landscape ecology analysis methods. We hypothesize that due to low population density, geographical isolation, and the absence of agricultural and forestry activities, the forest ecosystems of Lomami National Park have remained relatively intact.

2. Materials and Methods

2.1. Study Area

The study area encompasses the Lomami National Park and its periphery (Figure 1). Located approximately at 2°32′42″ S and 25°42′20″ E, Lomami National Park spans across the Maniema and Tshopo provinces, covering an area of 30,879 km^2. The park is predominantly covered by lowland equatorial rainforest, with hydromorphic savannas localized in its southern part. This forest is rich in floristic biodiversity, hosting species such as *Milicia excelsa* (Welw.) C.C. Berg, *Gilbertiodendron dewevrei* (Linnaeus), *Entandrophragma* spp., *Pycnanthus angolensis* (Linnaeus), and *Musanga cecropioides* (R.Br. ex Tedlie) [20,44]. Despite this diversity, the region remains one of the least botanically explored areas in tropical Africa [45,46]. Previous research in Lomami National Park has faced challenges such as limited species inventory data due to difficult access and political instability. Additionally, studies on flora have been hindered by inadequate funding and a lack of comprehensive baseline data on plant diversity and distribution [20,44,47]. Since 2007, research conducted by the Lukuru Foundation under the TL2 project has revealed notable faunal richness, including 59 species of large mammals and 240 species of birds. A significant discovery was the *Cercopithecus lomamiensis* [47], a newly identified primate species endemic to the forests between the Tshuapa and Lomami rivers [47]. The region's climate is equatorial, with an average annual rainfall of 1600 mm and monthly temperatures ranging between 23 °C and 26 °C. The short dry season occurs from June to July [31]. The soils are ferralitic, composed of sand and clay [44]. Approximately a hundred small hamlets border the park, where local communities primarily engage in subsistence agriculture, hunting, and fishing, mainly within the park's buffer zone [44].

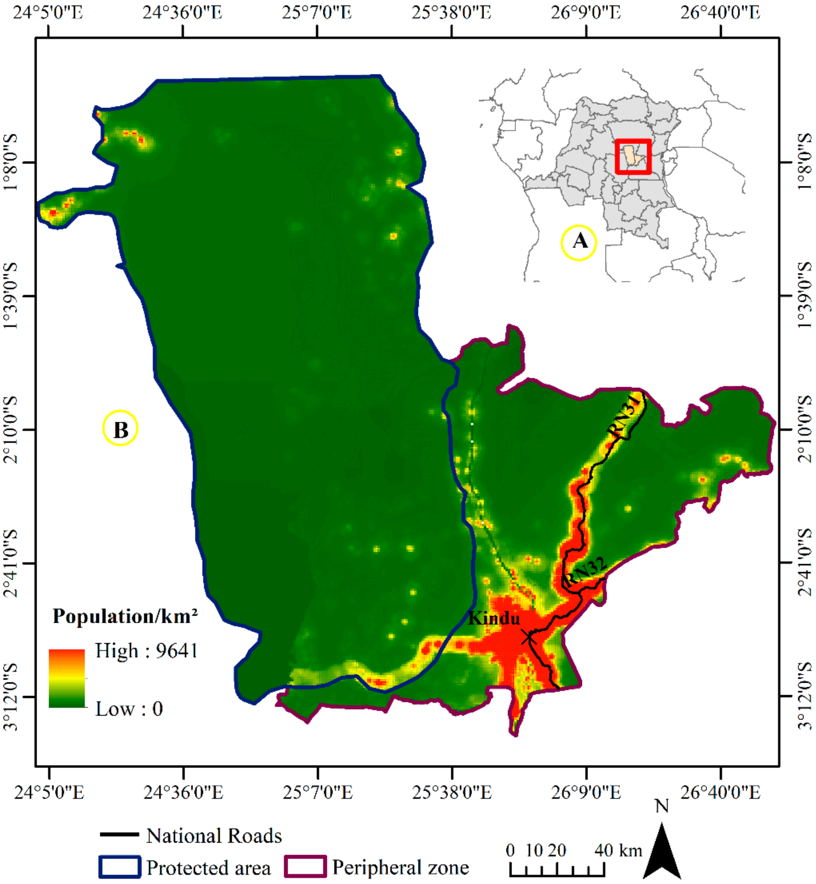

Figure 1. Geographical location of the Lomami National Park (protected area). The park is in the Maniema and Tshopo provinces, in DR Congo (**A**). The park covers a total area of 30,000 km^2 and is attached to a densely populated peripheral zone, including the city of Kindu (**B**). The red box indicates the location of the study area in DR Congo.

2.2. Data

The landscape under study was derived from three satellite images obtained via the geospatial analysis platform Google Earth Engine (GEE), sourced from the USGS/Google site. These images were acquired using Landsat sensors, specifically from 2008 (Enhanced Thematic Mapper Plus sensor), 2016, and 2024 (Operational Land Imager sensor), all with a spatial resolution of 30 m. The choice of these sensors was based on the availability of the images. The images were acquired during the dry season (June–July).

The images were taken during the dry season (June–July) to standardize the spectral response across different vegetation types. This period is crucial because it impacts vegetation phenology, with many plants entering dormancy or experiencing reduced canopy cover, resulting in more stable and distinct spectral signatures. Additionally, lower moisture content in vegetation during this time reduces variability in water-sensitive reflectance bands (e.g., near-infrared), facilitating clearer differentiation between forest, shrubland, and agricultural areas [48,49].

The three Landsat images, captured in 2008, 2016, and 2024, represent three distinct periods: (a) before the park's creation in 2016, (b) during its establishment, and (c) after its creation. This temporal selection enables a comparative analysis of conditions before and after the establishment of Lomami National Park in 2016, offering insights into the environmental changes and impacts resulting from its creation.

The correction and preprocessing of Landsat images were critical steps in ensuring accurate analysis, as variations introduced by calibration methods, atmospheric conditions, and sensor discrepancies could significantly affect the results [50]. The process typically began with geometric correction, which aligned the image to a map projection, removing distortions caused by sensor and Earth movement. Next, radiometric calibration adjusted the image to reflect true radiance values, compensating for sensor-specific biases and ensuring that the data accurately represented surface conditions. Atmospheric correction followed, removing interference caused by factors such as aerosols or water vapor, thus enhancing the accuracy of surface reflectance values [51]. Finally, image enhancement techniques, such as contrast stretching or filtering, were applied to highlight specific features and improve visual interpretation.

Throughout this process, careful attention to calibration methods—whether based on pre-flight radiometric coefficients or on-the-ground field data—was crucial, as variations in these methods could introduce discrepancies in the final results. The FilterMetadata ("CLOUD_COVER", "less_than", 20) filter, based on the image metadata, was used to select images with cloud cover less than 20% [51]. This approach reduced the number of cloud-affected images, thereby enhancing the reliability of the results and the understanding of observed surface variations [52].

For the analysis, Google Earth Engine was utilized for Landsat image preprocessing and land cover classification. Additionally, ArcGIS Pro 3.3 software was employed for map layout design.

2.3. Landsat Images' Classification

Using the preprocessed data, a false-color composite of the Landsat images was created by combining the red (Red), green (Green), and near-infrared (NIR) bands. The NIR and Red bands are crucial for effective vegetation discrimination. Healthy vegetation strongly reflects in the NIR and absorbs in the Red spectrum, making it easily distinguishable from other land cover types. The NIR band is particularly sensitive to chlorophyll content and leaf structure, providing valuable insights into vegetation health and density. The Red band enhances the contrast between vegetated and non-vegetated areas, as non-vegetated surfaces (e.g., water, bare soil, urban areas) reflect less in the Red spectrum. Adding the Green band further improves the composite, enhancing the differentiation of vegetation types and the detection of non-vegetated surfaces [53,54]. Using a GARMIN 64S GPS device (accuracy ±3 m), 500 training zones representing various land cover classes of the Lomami National Park and its peripheral zone were collected. These zones included forests, savannas, and water bodies, as well as mixed urban and agricultural land. The data collection was carried out during a field mission in the park in October 2023. Subsequently, these data were merged into a single, unified collection.

We used selected zones to train the Random Forest (RF) algorithm for land cover classification. The RF algorithm relied only on the three spectral bands from Landsat images (Red, Green, and NIR). RF is a supervised learning model that combines multiple decision trees. Each tree is trained on a random subset of data (bagging) and a random subset of features ("random projections"). For classification tasks, the algorithm aggregates predictions through a majority vote, enhancing accuracy and reducing errors [55,56]. Four land cover classes were identified: forest, savanna, water, and mixed urban–agricultural land (Table 1).

Table 1. Description and illustration of land cover classes and the number of training zones used in analyzing the landscape dynamics of Lomami National Park and its peripheric zone.

Land Cover Class	Description	Illustration	Number of Training Zones (Polygon)
Forest	Natural land cover class representing areas predominantly covered with trees and dense vegetation.		100
Mixed urban and agricultural land	Anthropogenic land cover class consisting of built-up and bare soil, as well as the adjacent agricultural lands.		100
Water	Natural land cover class including water bodies such as rivers and other water masses.		100
Savanna	Anthropic land cover class characterized by grassy vegetation formations with a cover of tall grasses measuring less than 80 cm in height.		100

To assess classification accuracy, we adhered to the best practices outlined by Olofsson et al. [57]. This involved employing unbiased area estimators and estimating uncertainty using reference observations derived from land cover change maps for the periods 2008–2016 and 2016–2024. The samples were stratified based on stable and changing (losses and gains) land cover classes for each period, with sample sizes determined using Cochran's method [58]. This method was selected for its ability to yield statistically valid sample size estimates in stratified sampling, particularly when population variance information is limited. Cochran's method is well suited for heterogeneous populations, ensuring adequate representation of each stratum while minimizing sampling bias.

The sample size was calculated using key factors such as population size, desired confidence level (typically 95%), estimated proportions within each stratum, and the acceptable margin of error. This stratified sampling approach ensured comprehensive and reliable coverage of both stable and dynamic land cover classes, thereby enhancing the accuracy and representativeness of the study results.

Stratification improved estimation accuracy by optimizing spatial coverage and enhancing the statistical representation of various classification categories. Its robustness lies in its ability to control sampling variance and reduce systematic errors while enabling the proportional or optimal allocation of validation points. Using a variance estimator, the total sample size required to achieve the target accuracy was determined. A z-score of 1.96, corresponding to a 95% confidence level, and a 5% margin of error were applied.

The strata included stable categories such as Forest, Water, Savanna, and mixed urban and agricultural land, as well as dynamic categories like forest gain, mixed urban and agricultural land gain, water gain, and savanna loss. These strata were derived by overlaying land cover maps from the periods 2008–2016 and 2016–2024. A total of 1040 points were sampled across these two periods, with proportions allocated based on the relative size of each stratum.

Error matrices were generated using QGIS version 3.26.1 (developed by the global QGIS community, Buenos Aires, Argentina), providing accuracy measures such as user's accuracy (UA), producer's accuracy (PA), confidence interval (CI), and overall accuracy (OA). UA reflects the proportion of pixels correctly classified in a category from the user's perspective, while PA indicates the proportion of pixels belonging to a real category that are correctly represented on the map. CI provides a range around an estimated value, representing uncertainty at a given confidence level, and OA measures the total proportion of correctly classified pixels across all categories, offering a comprehensive performance metric.

It should be noted that the classification validation process for detecting gains and losses followed the methodologies described by Olofsson et al. [57]. This robust approach allows for a precise assessment of both stable and dynamic land cover categories. To ensure that the model is not disproportionately influenced by the more dominant land-use types, a uniform number of training areas was allocated across all land cover classes. This decision was made to provide equal representation of each class in the training data, thereby improving the model's ability to generalize and ensuring a more balanced and accurate classification.

2.4. Assessment of Landscape Dynamics

To analyze the relationships between landscape configuration and ecological processes, it is crucial to quantify landscape structures using landscape metrics [59,60]. Since landscape measurements often exhibit high correlations [61,62], it is important to select diverse metrics to avoid redundancy and achieve a more accurate assessment. Therefore, six metrics were calculated for Lomami National Park and its periphery, enabling a detailed analysis of anthropization levels and the underlying ecological processes (Table 2).

Table 2. Synthesis of computed landscape metrics within the Lomami National Park and its surrounding zone.

Index	Ecological Signification
Class area (CA)	This index measures the total area of all patches within a given land-use class. A high total area in natural zones indicates continuity and integrity of ecosystems, whereas a reduced area suggests fragmentation due to anthropogenic activities [63,64]. An intact landscape will have a high total area for natural classes, reflecting minimally disturbed ecosystems.
Patch number (PN)	This index counts the number of distinct patches or fragments of a class within the landscape. An increase in the number of patches, coupled with a decrease in total area, reveals heightened fragmentation, often resulting from agricultural or urban activities [64]. A high number of patches in a disturbed landscape indicates division into smaller fragments, which reduces habitat connectivity.
Largest patch index (LPI)	It represents the proportion of the area occupied by the largest patch of a class relative to the total area of all patches of that land cover class. A high value indicates low fragmentation, suggesting that the land cover class is relatively continuous [65,66]. This reflects a predominant presence of large patches in a minimally disturbed landscape.
Disturbance index (U)	This ratio between the cumulative area of anthropogenic classes and that of natural classes measures the predominance of anthropogenic pressure in the landscape [67,68]. A value less than 1 indicates dominance of natural classes, while a value greater than 1 reveals a strong anthropogenic influence. This index helps to understand the impact of human activities on the landscape pattern.
Aggregation index (AI)	It measures the degree of aggregation or dispersion of patches within a class. A high index value indicates that the patches are closely grouped and form continuous blocks, whereas a low index value suggests greater dispersion and fragmentation [69]. This index provides insights into habitat continuity and ecological connectivity.
Edge density (ED)	This index quantifies the total length of patch edges per hectare, measuring the roughness of the patches. A high edge density indicates greater complexity of the patches, often associated with increased fragmentation [70]. Edge density provides information on patch structure and the extent of fragmentation.

The validation of the metrics likely involved consulting ecological literature on landscape metrics, where these indicators are commonly employed to assess fragmentation, habitat quality, and human impacts on ecosystems [64]. Previous studies have demonstrated their relevance in similar ecological contexts, thereby justifying their selection for this research [32,35,36]. Additionally, a deforestation rate, derived from changes in the forest class area, provided insight into the intensity of human impacts on forest ecosystems. This rate was calculated using the equation proposed by Puyravaud [71] (Appendix A). The "Landscapemetrics" package in R (version 4.2.3) was used to quantify these landscape aspects [72,73]. The uniform spatial resolution and consistent land cover class morphology ensured that the default settings in the "Landscapemetrics" package were sufficient for accurate analysis, with no need for adjustments. This consistency enabled the precise capture of landscape structure and fragmentation patterns, ensuring robust results.

Furthermore, the decision tree algorithm developed by Bogaert et al. [74] was applied to identify spatial transformation processes in the landscape between two specific dates (Figure 2). This algorithm compares the patch number (PN), class area (CA), and total perimeter of land-use patches to detect changes in landscape configuration. A decrease in PN and CA indicates patch attrition, while an increase in CA suggests patch aggregation. If CA increases while PN remains constant, it signals patch enlargement. Conversely, a simultaneous increase in both CA and PN indicates the creation of new patches, while a decrease in CA with an increase in PN suggests landscape dissection. Fragmentation is characterized by an increase in PN and a significant loss in CA.

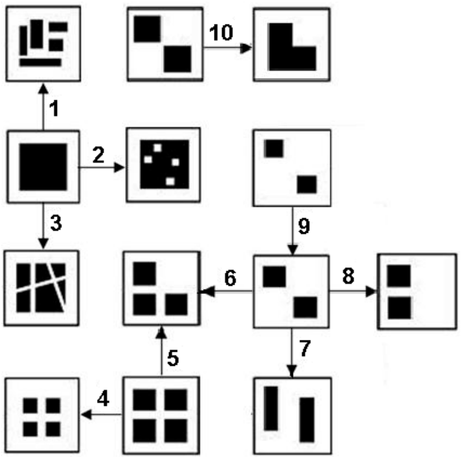

Figure 2. A diagram representing the ten processes of spatial transformation derived from thirteen common types of spatial configurations or geometries in a binary landscape. Adapted from Bogaert et al. [74]. (1) Fragmentation: landscape conversion through the disruption of continuity into five disconnected patches of unequal sizes and shapes; (2) Perforation: transformation by the formation of four holes; (3) Dissection: subdivision of a continuous area by uniformly wide lines of small dimensions; (4) Shrinkage: reduction in patch size; (5) Attrition: disappearance of one of the patches present in the original landscape; (6) Creation: transformation of the landscape by the formation of a new patch, in-creasing the number of patches from two to three; (7) Deformation: transformation characterized by the change in shape of two patches into a rectangular form without a change in area; (8) Shift: translocation of one of the two patches; (9) Enlargement: transformation through the increase in size of both patches; (10) Aggregation: merging of patches.

To differentiate between fragmentation and dissection, a ratio of total areas between the two time points was calculated, with a ratio greater than 0.75 indicating dissection and a ratio of 0.75 or less suggesting fragmentation [75]. A decrease in CA can lead to perforation if the total perimeter increases, or a reduction in patch size if the perimeter remains constant. If both PN and CA are stable, a constant total perimeter suggests displacement, while a variable perimeter indicates deformation.

Displacement, the movement of patches within the landscape, can disrupt ecological processes such as species migration and resource access, contributing to habitat fragmentation. Deformation, which involves changes in patch shape without altering their area, can negatively affect habitat connectivity and ecosystem quality by increasing edge effects [74]. Finally, fragmentation occurs when a landscape is divided into several disconnected patches of unequal sizes and shapes, while perforation involves the creation of gaps within patches. Dissection refers to the subdivision of a continuous area into smaller sections by narrow lines. Shrinkage results in a reduction in patch size, while attrition leads to the disappearance of an existing patch. Creation refers to the formation of new patches, increasing the overall number of patches in the landscape. Deformation alters the shape of patches without changing their area, and shift refers to the relocation of patches within the landscape. Enlargement occurs when patch size increases, while aggregation happens when separate patches merge into a single one. These processes illustrate the dynamic evolution of landscapes through changes in patch configuration, including the number, size, shape, or arrangement of patches (Figure 2).

3. Results

3.1. Classification and Mapping

Table 3 provides a summary of the accuracy results for the supervised classifications of Landsat 7, 8, and 9 images, obtained using the Random Forest classifier for the periods from 2008 to 2024. The classifications exhibited an overall accuracy exceeding 80% for each analyzed period, demonstrating remarkable reliability in differentiating various land cover types (Appendix B). User and producer accuracy values, ranging from 82% to 89%, further attest to the high quality of the results. Additionally, the 95% confidence interval for the stratified area estimates of each land cover class remains below 5% for all studied periods, reinforcing the robustness of the conclusions drawn from this analysis.

Table 3. Summary of indices illustrating the accuracy assessment of Landsat classified images on the Google Earth Engine geospatial analysis platform for the periods 2008–2016 and 2016–2024, following good practices of Olofsson et al. [57]. MUAL: mixed urban and agricultural land.

2008–2016								
	Forest	MUAL	Water	Savanna	Forest Gain	MUAL Gain	Water Gain	Savanna Loss
PA [%]	84.22	84.25	83.22	83.34	83.12	84.23	83.55	85.22
UA [%]	85.25	85.22	83.56	83.46	85.12	83.12	84.38	83.34
95% CI	0.42	0.44	0.47	0.45	0.46	0.46	0.39	0.43
OA	85.33							
2016–2024								
	Forest	MUAL	Water	Savanna	Forest Gain	MUAL Gain	Water Gain	Savanna Loss
PA [%]	84.33	84.55	86.33	84.52	84.22	84.66	84.33	83.44
UA [%]	84.88	83.46	85.56	83.23	84.75	82.23	84.66	88.24
95% CI	0.36	0.41	0.42	0.48	0.38	0.47	0.42	0.46
OA	85.82							

The visual analysis of land cover maps for Lomami National Park and its peripheral zone reveals, on one hand, relative stability in the spatial structure of the protected landscape and, on the other hand, notable transformations in the peripheral zone (Figure 3). Indeed, the stability observed in the protected area is reflected by the absence of significant and perceptible dynamics within different land-use classes between the periods 2008–2016 and 2016–2024. In contrast, the peripheral zone shows centrifugal spatial changes, marked by a regression in forest cover, replaced by mixed urban and agricultural land, mainly around settlements along the Congo River and its tributaries.

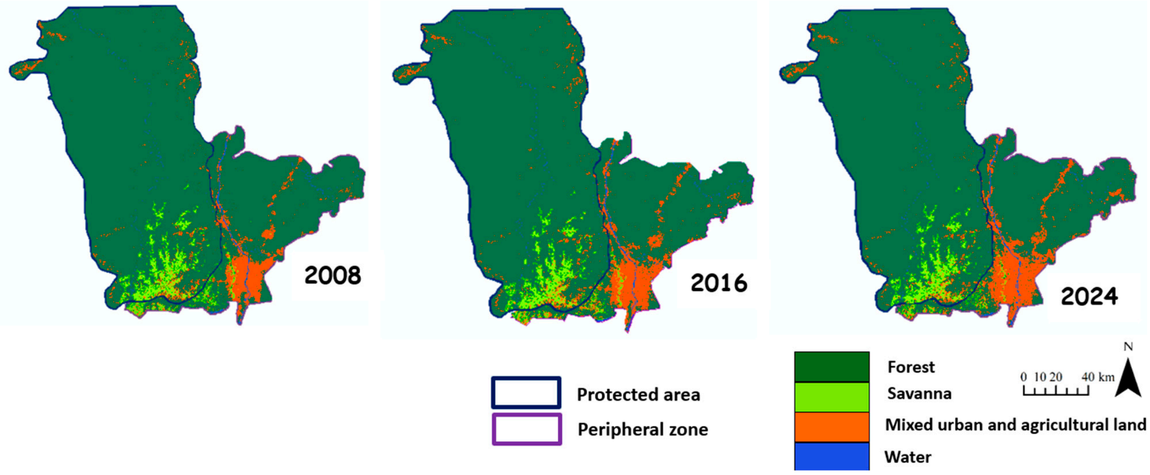

Figure 3. Mapping of land cover changes in Lomami National Park and its peripheral zone between 2008, 2016, and 2024, derived from supervised classifications of Landsat images using the Random Forest algorithm.

3.2. Dynamics of Land Cover Composition in Lomami National Park and Its Periphery Between 2008 and 2024

The evolution of land cover in Lomami National Park reveals a general trend towards landscape stability, with a slight increase in forest cover observed between 2008 and 2024 (Figure 4). This does not necessarily imply the complete absence of change but rather that the overall landscape structure has remained relatively constant, with no significant shifts from one land cover type to another. In contrast, the adjacent peripheral zone has experienced a relative regressive dynamic in its forest ecosystems (the loss of forest cover mainly due to human activity). In 2008, forests covered 92.06% and 79.32% of the areas in the protected zone and the peripheral zone, respectively. By 2016, these proportions had changed, reaching 92.24% for the protected zone, while the peripheral zone saw a decrease to 75.91% due to urbanization, agriculture, and logging. This trend continued until 2024, with forest cover reaching 92.75% in the protected zone, while it reduced to 70.48% in the peripheral zone (Figure 4). There is a general trend of increasing forest cover in the protected zone at the expense of savannas and mixed urban and agricultural land. This expansion of forest cover, replacing savannas, contributes positively to biodiversity conservation by supporting higher species diversity and providing essential ecosystem services.

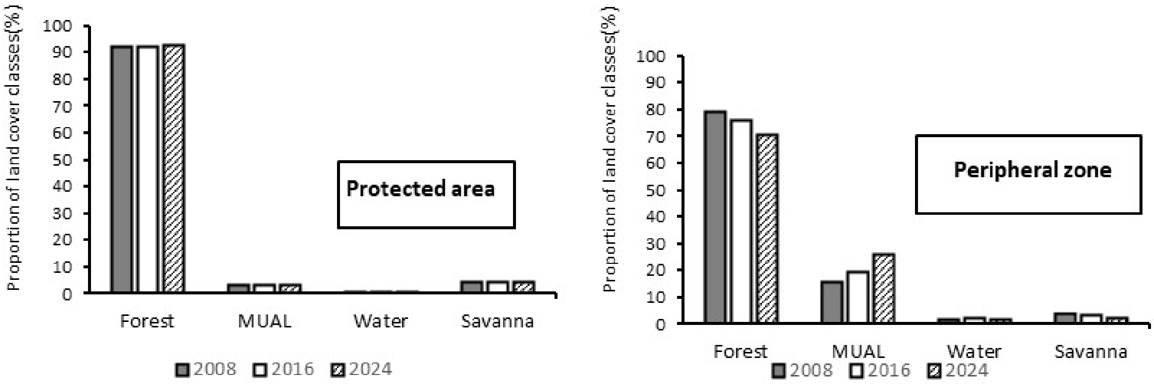

Figure 4. Evolution of the total area of land cover classes in the Lomami National Park and its periphery zone 2008 and 2024. The total areas are 30,879 km^2 for the protected zone and 12,686.05 km^2 for the periphery. MUAL: mixed urban and agricultural land.

Meanwhile, the water class area showed a marginal increase in both the protected and peripheral zones between 2008 and 2016. However, these changes are minimal and may not be statistically significant due to classification errors. The slight increase in water area could reflect a shift toward wetter conditions or changes in hydrological dynamics. These changes may be driven by factors such as increased rainfall, reduced deforestation, changes in agricultural activities, or alterations in water management practices. Although small, this change could have implications for local ecosystems, potentially influencing species distribution, habitat availability, and water quality. For example, increased water in the peripheral zone may enhance biodiversity by expanding aquatic habitats, while in the protected zone, it may indicate the stabilization of natural hydrological processes.

Conversely, savannas experienced a slight regression, with their area decreasing from 4.29% to 4.21% in the protected zone and from 3.60% to 2.97% in the peripheral zone, primarily due to land conversion for agriculture and settlement expansion. The loss of savannas may reduce habitats for species adapted to open ecosystems. While forest expansion supports conservation goals, it is crucial to preserve a mosaic of habitats to maintain the full spectrum of biodiversity, including species that depend on savanna environments.

The dynamics of urbanization and agricultural land use varied, with a slight decrease in the protected zone and an increase in the peripheral zone. However, given the uncertainty associated with these classifications, these observed changes may not be statistically significant. Therefore, while trends are apparent, the extent of change across these land cover types should be interpreted cautiously, considering the classification uncertainty (Figure 4).

The increased urbanization and agricultural expansion in the peripheral zone from 2008 to 2024 indicate intensified human activities that exert pressures such as deforestation, habitat fragmentation, pollution from agricultural runoff, and infrastructure expansion. These threats undermine ecosystem integrity, heighten the risk of encroachment, and challenge the park's conservation objectives (Figure 4).

However, with an annual deforestation rate of 0.03%, which is significantly lower than the national average of 0.40%, these dynamics highlight the effectiveness of conservation efforts within the park. They also underscore the need for continuous monitoring and management, particularly in areas where anthropogenic pressures are on the rise (Figure 4). Conservation strategies include strict law enforcement to prevent illegal logging and poaching, community engagement programs that promote sustainable practices, and targeted reforestation efforts to restore degraded areas. These measures, together with the park's protected status, have been essential in preserving forest cover and minimizing human impact, demonstrating the effectiveness of integrated conservation approaches.

Additionally, the transition matrices presented in Table 4 show a notable consistency in the landscape matrix with few significant conversions between land cover classes for the protected area. In contrast, relatively significant conversions were observed in the periphery zone adjacent to the park. Between 2008 and 2016, only 1.97% of forests in the protected area and 6.13% of those in the periphery zone were converted to other land cover types. Conversely, 2.15% and 2.73% of areas occupied by mixed urban and agricultural land, water bodies, and savannas were reconverted to forests. The main changes include the conversion of 2.08% of mixed urban and agricultural land to forests and 1.80% of forests to mixed urban and agricultural land in the protected area, as well as 5.86% of forests converted to mixed urban and agricultural land in the adjacent zone of the park (Table 4).

Table 4. Transition matrix of land cover classes in Lomami National Park and its peripheral zone between 2008 and 2016 and 2016 and 2024. Rows represent the proportions of land cover classes at the initial date, and columns at the final date, and the bold values indicate the proportions that remained stable. The values in the table are expressed as percentages (%) of the total area of the protected zone (30,879 km^2) and the peripheral zone (12,686.05 km^2). MUAL: mixed urban and agricultural land. Values in boldface referring to the stability proportions.

Protected Area					
	MUAL	**Forest**	**Water**	**Savanna**	**Total 2008**
MUAL	**1.29**	2.08	0.00	0.03	3.40
Forest	1.80	**90.09**	0.02	0.15	92.06
Water	0.00	0.00	**0.25**	0	0.25
Savanna	0.19	0.07	0	**4.03**	4.29
Total 2016	3.28	92.24	0.27	4.21	
	UAC	Forest	Water	Savanna	Total 2016
MUAL	**1.56**	1.46	00.0	0.26	3.28
Forest	1.48	**90.68**	0.01	0.07	92.24
Water	0.00	0.03	**0.24**	00.0	0.27
Savanna	0.06	0.28	0.00	**3.87**	4.21
Total 2024	3.10	92.45	0.25	4.20	

Table 4. *Cont.*

Protected Area					
			Periphery		
	MUAL	**Forest**	**Water**	**Savanna**	**Total 2008**
MUAL	**12.81**	2.44	0.06	0.05	15.36
Forest	5.86	**73.18**	0.08	0.19	79.32
Water	0.01	0.01	**1.70**	00.0	1.71
Savanna	0.59	0.28	0.01	**2.72**	3.6
Total 2016	19.27	75.91	1.85	2.97	
	MUAL	**Forest**	**Water**	**Savanna**	**Total 2016**
MUAL	**17.04**	2.02	0.01	0.20	19.27
Forest	7.97	**67.67**	0.01	0.26	75.91
Water	0.12	0.11	**1.59**	0.03	1.85
Savanna	0.6	0.68	0.01	**1.67**	2.96
Total 2024	25.73	70.48	1.62	2.16	

Between 2016 and 2024, 1.56% of forests in the protected area and 8.24% in the buffer zone were converted to other land cover classes, while 1.77% and 2.81% of areas occupied by mixed urban and agricultural land, water bodies, and savannas were reconverted to forests. Land cover changes were minimal, with low forest losses and gains between 2008 and 2016 and 2016 and 2024 in the protected area. In contrast, forests experienced notable conversions in the periphery zone adjacent to Lomami National Park (Table 4).

The disturbance index measures anthropogenic impacts on the landscape. In this study, the disturbance index values revealed a general trend towards low values (Figure 5), indicating a predominance of natural land cover types. However, an increasing trend was observed in the peripheral zone adjacent to the park. In 2008, the index was 0.08 in the protected zone and 0.23 in the peripheral zone. By 2016, both zones showed values of 0.08 and 0.23, respectively; in 2024, the values increased to 0.75 and 0.38 for the protected and peripheral zones, respectively. The rising disturbance index in the peripheral zone points to growing human activities, such as deforestation and infrastructure development, which contribute to habitat fragmentation and reduce the effectiveness of the buffer zone. These pressures threaten ecological integrity, hinder species movement, and disrupt connectivity between forest areas, isolating populations and limiting their reproduction and dispersal. While the protected zone remains largely unaltered, the increasing anthropization of the peripheral zone highlights a significant trend of natural habitat loss, replaced by human-modified landscapes. This underscores the need for targeted interventions to mitigate these pressures and safeguard the park's ecological functions.

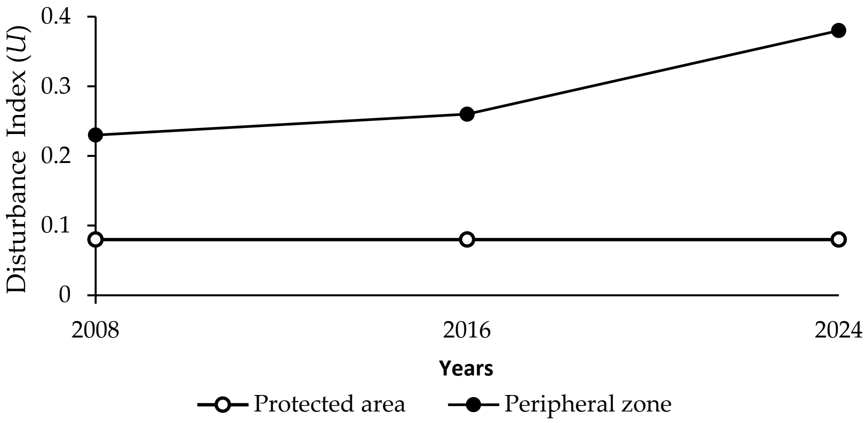

Figure 5. Evolution of the disturbance index in the Lomami National Park and its peripheral zone between 2008 and 2024. Disturbance index quantifies human-induced disturbances, providing insight into anthropogenic pressure.

3.3. Dynamics of Forest Configuration in Lomami National Park and Its Periphery Between 2008 and 2024

In the protected area, the largest patch index (LPI) shows a steady increase from 55.27 in 2008 to 56.58 in 2024 (Table 5). This upward trend indicates enhanced ecological stability as larger forest patches provide more contiguous habitats, supporting greater biodiversity and improving resilience to external disturbances. The decrease in edge density (ED) from 8.62 m/ha in 2008 to 8.57 m/ha in 2024 further supports this trend (Figure 6). Lower edge density is generally associated with reduced edge effects, such as microclimatic fluctuations, invasive species intrusion, and human–wildlife conflict, thereby enhancing the ecological integrity of the forest. Similarly, the consistent increase in the aggregation index (AI) from 98.12% in 2008 to 98.51% in 2024 underscores a trend toward more clustered and consolidated forest patches (Figure 6). A decrease in the aggregation index indicates increased fragmentation, with habitat patches becoming more dispersed and less connected. This loss of connectivity disrupts wildlife movement, limits resource access, and isolates species populations, threatening genetic diversity and long-term viability. Fragmentation also worsens habitat loss, undermining ecosystem stability and conservation efforts.

Table 5. Indices calculated to characterize the spatial configuration of forest in the Lomami National Park and its periphery between 2008, 2016, and 2024. CA: class area (km^2); PN: patch number; LPI: largest patch index (%); ED: edge density (m/ha); AI: aggregation index (%). Class area represents the total area covered by a specific land cover class, reflecting its spatial extent. Patch number represents the total count of distinct patches, indicating landscape heterogeneity. Largest patch index indicates the proportion of the landscape occupied by the largest patch, assessing habitat dominance.

Metrics	**Date**		
	2008	**2016**	**2024**
	Protected area		
CA	28,189.21	28,279.63	28,317.68
PN	17,934	16,546	161,400
LPI	55.27	56.22	56.58
	Periphery		
CA	10,062.11	9629.98	8941.13
PN	30,161	35,274	35,354
LPI	48.10	46.60	46.49
ED	36.65	36.92	38.84
AI	83.99	82.25	81.64

Conversely, in the peripheral zone adjacent to the park, the largest patch index (LPI) has decreased from 48.10 in 2008 to 46.49 in 2024. This decline indicates a fragmentation of large forest patches, potentially threatening the ecological health of these areas by isolating habitats and reducing their ability to support diverse species (Table 5). The increase in edge density (ED) from 36.65 m/ha in 2008 to 38.84 m/ha in 2024 suggests that forest fragmentation is creating more forest edges relative to the total forest area. Higher edge density may exacerbate edge effects, making habitats more vulnerable to degradation, species loss, and the encroachment of non-native species. The consistent decrease in the aggregation index (AI) from 83.99% in 2008 to 81.64% in 2024 further illustrates this fragmentation. Lower spatial aggregation reduces habitat connectivity, disrupting ecological corridors essential for wildlife movement and increasing the likelihood of ecosystem instability (Figure 6).

In summary, while the protected area of Lomami National Park shows positive trends in forest consolidation and ecological health, the surrounding peripheral zone is experiencing increased fragmentation, declining connectivity, and ecological degradation. Smaller, more fragmented forest patches with higher edge density indicate habitat loss, disrupted ecological interactions, and reduced biodiversity. Anthropogenic activities in the peripheral zone could exacerbate these issues by altering microclimates, promoting invasive species, and intensifying human–wildlife conflicts, leading to economic losses and retaliatory actions. These contrasting dynamics underscore the urgent need for targeted conservation strategies to restore connectivity and mitigate fragmentation in the peripheral areas.

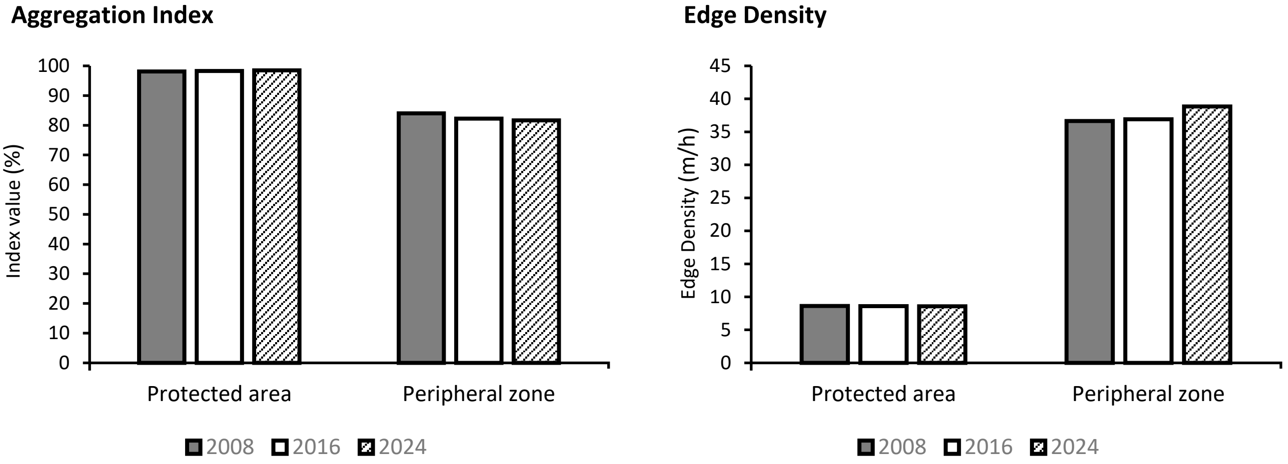

Figure 6. Evolution of aggregation index and edge density in the Lomami National Park and its peripheral zone between 2008 and 2024. Edge density measures the total edge length of patches per unit area, highlighting fragmentation levels. Aggregation index reflects the degree to which similar patches are clumped together, indicating landscape connectivity.

The evaluation of structural dynamics within Lomami National Park, using a decision tree approach [74], identified aggregation as a key spatial transformation process (Table 5 and Figure 7). In contrast, dissection ($tobs = 0.92 > t = 0.75$) was recognized as the primary spatial transformation process in the peripheral zone adjacent to the park. Between 2008 and 2024, the reduction in the number of forest patches, coupled with an increase in class area, indicates a trend toward larger and more consolidated forest areas in the protected zone, enhancing ecological coherence and potentially improving habitat quality. Conversely, in the peripheral zone, the increase in the number of patches, combined with a reduction in class area, suggests habitat degradation, likely due to growing anthropogenic activities, which can lead to biodiversity loss and reduced ecological resilience.

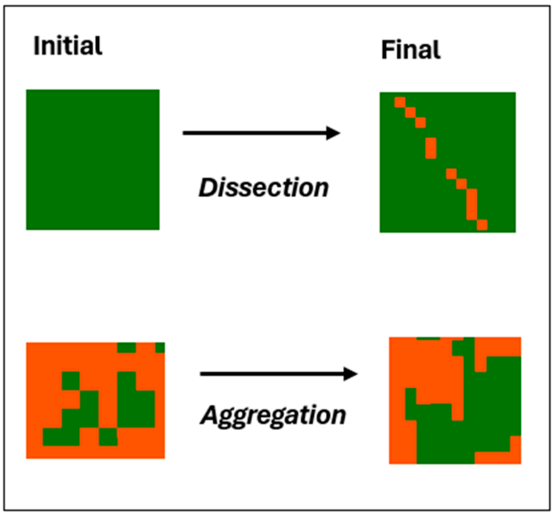

Figure 7. Illustration of the spatial transformation process identified within the Lomami National Park and its surrounding zone.

4. Discussion

4.1. Methodological Approach

Six landscape metrics were employed to evaluate the extent of anthropization in Lomami National Park and its periphery. These indices are pivotal for understanding ecological processes by quantifying landscape complexity, spatial organization, and the interaction between natural and anthropogenic influences across different scales—patches, classes, and entire landscapes [76]. By assessing landscape composition, shape, and configuration, these metrics provide valuable insights into the degree and type of human impact on ecological systems [60,74,77].

The selected indices are effective for detecting structural transformations and understanding how human activities influence landscape morphology. For instance, changes in patch size, shape, and distribution can reflect alterations in habitat connectivity and fragmentation, which are critical for species movement and ecosystem health. The speed of the applied method, in terms of data processing efficiency and frequency of data acquisition, is crucial for adaptive management and conservation strategies [54,74].

The "Classifier" tool within Google Earth Engine (GEE) was used to categorize satellite imagery into distinct land cover classes based on spectral signatures. GEE's integration of temporal satellite data also facilitated the calculation of landscape metrics, such as edge density and patch number, providing a detailed assessment of landscape fragmentation and changes over time. This capability is particularly valuable for ecological studies, where accurate and timely data are essential for understanding dynamics and planning effective conservation efforts [52].

However, challenges such as cloud cover and limited connectivity were encountered in this study. Cloud cover was addressed by applying the "CLOUD_COVER" filter in GEE, selecting images with less than 10% cloud coverage to enhance classification reliability. For areas with limited connectivity, data processing was carried out on cloud platforms, enabling remote access to high-performance computing resources and minimizing delays. These strategies helped maintain classification accuracy by reducing data interference and ensuring consistent access to tools for processing large datasets [40].

The integration of remote sensing and landscape metrics in this study supports ecological health management in Lomami National Park by providing detailed, spatially explicit data on land cover changes and habitat fragmentation. This approach highlighted key trends, such as increasing fragmentation in peripheral zones and stabilizing forest cover within the park, offering valuable insights for targeted conservation strategies and monitoring efforts [32,48].

This study is the first to quantify the evolution of forest cover in Lomami National Park and its peripheral zone using satellite imagery and landscape ecology indices. It provides valuable information on the composition and configuration of the landscape, highlighting an important aspect of the health of this forest ecosystem. Despite the advantages of the chosen imagery, several preprocessing limitations could still impact the results. Atmospheric conditions, such as haze or aerosols, may not be fully corrected, potentially distorting reflectance values and affecting spectral analysis. The spatial resolution of the images might limit the detection of small-scale land cover changes or finer vegetation types, particularly in heterogeneous landscapes. Additionally, the temporal resolution of satellite data may miss short-term variations, such as seasonal changes or rapid deforestation events. Finally, classification accuracy could be compromised by shadowing or mixed pixels, especially in areas with complex topography or dense vegetation, necessitating further post-processing for improved precision [50,51].

4.2. Spatial Dynamics of Lomami National Park and Its Periphery Between 2008 and 2024

Between 2008 and 2024, forest cover in Lomami National Park increased slightly, largely due to the low population density, which limits the demand for agricultural and residential land [78,79]. Additionally, local populations primarily rely on hunting and small-scale subsistence farming rather than large-scale agriculture, which helps to maintain forest preservation at over 90% [80]. The park's remote and challenging access conditions further reduce activities like logging and charcoal production, which are significant factors in forest conservation [81].

The absence of industrial logging and charcoal production can also be attributed to the region's difficult access, making wood harvesting and transportation costly and, thus, discouraging these activities [20,21]. The low local demand for timber, combined with traditional building practices, also supports this preservation. Remote and difficult-to-access areas generally experience less disturbance from logging and urban expansion, which helps to maintain ecological integrity [82,83]. Research indicates that isolated, protected areas tend to have higher rates of biodiversity preservation [81,84–86].

Protective measures initiated before the park's official establishment, and further reinforced by its legal designation, also contribute to the trend of forest preservation [87]. Initiatives by the Lukuru Foundation, including the creation of provincial parks and public awareness efforts, have fostered forest conservation. Similarly, conservation strategies such as park delineation and increased eco-guard numbers have contributed to increased forest cover in other reserves [88]. These proactive measures demonstrate the effectiveness of legal frameworks in forest preservation.

Land governance also plays a crucial role, especially in curbing pressures from agriculture and urban expansion that threaten ecological stability [26]. Clear land-use regulations can help prevent harmful practices leading to deforestation and biodiversity loss, with support from international organizations through funding and capacity-building for sustainable resource management [28]. These organizations support initiatives such as reforestation, sustainable agriculture near the park, and environmental education to improve community engagement [40].

The main land cover changes involve rural areas gradually reverting to forests, although some forest areas transitioned back to non-forest states. This mosaic landscape reflects dynamic interfaces between forests and agricultural areas, where human activities can expand into forests and fallow land can regenerate forest cover [89]. Ecological disturbances, such as fires and selective logging, may initially promote non-forest vegetation, followed by gradual forest recovery [90]. These dynamics underscore the importance of spatial configuration in landscape changes, particularly in low-disturbance areas [54]. The area's disturbance index, under 1, reflects the predominance of natural ecosystems and highlights effective ecological preservation despite some human impact [91]. Furthermore, protected areas like Virunga and Salonga enhance ecosystems by preserving habitats for species such as mountain gorillas and forest elephants while supporting ecological processes like pollination and carbon sequestration. However, anthropogenic pressures in surrounding zones, including logging and agriculture, fragment habitats, reduce biodiversity, and disrupt ecosystems [39,48]. This leads to issues like inbreeding, soil erosion, and disruptions in the water cycle. Effective conservation, therefore, requires targeted strategies beyond park boundaries to balance ecological benefits and mitigate human impact.

The analysis of spatial transformations revealed trends toward forest parcel aggregation within protected areas, contrasting with land fragmentation on the periphery. Lower deforestation rates in the park's periphery, where population density remains low (12 inhabitants/km^2 compared to the national average of 24 inhabitants/km^2), suggest relative ecological stability, paralleling similar conservation outcomes in areas like Salonga

National Park [48]. However, Kindu, the capital of Maniema Province, adds pressure on forest resources, as the local population relies heavily on fuelwood for energy, despite intermittent electricity from the Kalima–Kindu line, which is frequently disrupted by copper cable thefts [92]. The continued use of fuelwood as an energy source threatens forest conservation, as seen in similar scenarios in Burundi [93].

Further complicating conservation, customary land governance often bypasses direct state control, leading to fragmented land regulations that intensify land pressure around the park [94]. This fragmentation contrasts with the park's strict protective laws, which help to maintain or even increase forest cover, demonstrating effective conservation in areas governed by stringent policies [95]. However, unplanned urban expansion in Kindu increases deforestation around the park, with extensive forest clearing to meet construction demands, similar to findings in the Lubumbashi plain [96], Kisangani [97] in DR Congo, and Bujumbura in Burundi [98]. Shifting cultivation also intensifies forest pressure, involving slash-and-burn practices for short-term soil fertility gains [99]. Over time, such areas often transform into grassy savannas, reducing biodiversity [100], as observed in Cameroon's Doume Communal Forest [101]. This transition from forest to savanna-type ecosystems represents a net loss in biodiversity and a gradual ecological degradation process around the park.

Provincial-level data align with this trend, showing a 2.8% forest cover loss in Maniema between 2000 and 2010, highlighting the impact of even low population density on deforestation trends [26]. Differences in land management between the park and its periphery illustrate the challenges of balancing conservation with human needs. In less regulated peripheries, human activities like agriculture and logging persist, while the park's stricter regulations restrict such activities [102,103]. Additionally, the periphery's proximity to the Congo River facilitates access, attracting populations and increasing forest fragmentation due to economic and transportation opportunities [104].

This situation, however, introduces potential threats to Lomami's protected areas. The strong local reliance on hunting resembles cases in areas like Campo-Ma'an National Park in Cameroon, where poaching pressures increased following local conflicts [105]. Similarly, post-conflict areas like Kundelungu National Park in the DR Congo continue to face threats from illegal hunting, challenging forest preservation [40]. Limited infrastructure in parks like Salonga National Park has temporarily stabilized forests, but risks of expansion remain [48].

These pressures could lead to two primary consequences. Human-inhabited areas may face resource scarcity, affecting food security and exacerbating human–wildlife conflicts, as documented near Loango National Park in Gabon [106]. Furthermore, the protected area itself may face gradual ecosystem degradation, as seen in Virunga National Park, where uncontrolled human expansion has damaged natural habitats [107]. Species conservation is also at risk, with apex predators facing declines due to increased human activities, as observed in the former Central African Republic [108].

4.3. Implications for Conservation and Management of Lomami National Park and Its Periphery

The spatial dynamics of Lomami National Park and its surrounding areas between 2008 and 2024 reveal significant land-use changes, particularly the rise in urbanization and agricultural expansion in the peripheral zone, which increased from 15.36% in 2008 to 25.73% in 2024. This trend is most evident in areas surrounding the park, where agricultural activities such as small-scale farming and logging have contributed to habitat fragmentation. The creation of new roads and settlements has further exacerbated edge density and disturbed surrounding ecosystems.

To balance human needs with environmental conservation, several solutions are proposed. These include strengthening community-based conservation programs, such as agroforestry and sustainable farming practices, to reduce pressure on the park's resources. In addition, enhancing law enforcement against illegal logging and undertaking reforestation efforts in degraded areas could mitigate the negative impacts of expansion. Improving land-use planning through the involvement of local communities in decision-making processes and expanding buffer zones around the park could also help to preserve biodiversity while supporting local livelihoods. These measures could foster a more sustainable coexistence between human activities and ecological conservation in the Lomami region.

The observed aggregation of forest patches suggests a positive trend toward enhanced ecosystem connectivity, which facilitates species movement and maintains genetic diversity [109,110]. However, to ensure the long-term sustainability of these forested areas, proactive conservation measures are required. Continuous monitoring using advanced technologies, such as drones and satellite systems, is critical to effectively detect and address threats like agricultural and forestry expansion. Platforms such as Global Forest Watch provide real-time deforestation data, enabling timely and informed interventions [111,112]. In the DR Congo, forest monitoring platforms have successfully identified and mitigated illegal deforestation through coordinated information sharing, highlighting the potential of these technologies to strengthen forest conservation [113,114]. Drones represent a crucial advancement in monitoring efforts, particularly in regions with frequent cloud cover or rugged terrain, which complicates satellite imagery [115,116].

Equipped with high-resolution cameras and thermal imaging capabilities, drones offer precise, real-time visuals, enabling conservationists to detect encroachments, illegal logging, and land-use changes even in dense or remote forests. In Gabon, drones have successfully mapped previously inaccessible areas, providing actionable intelligence for forest management [117,118]. Similarly, in the Amazon, drones have been deployed to monitor vast landscapes, producing detailed imagery that supports ongoing deforestation assessments and rapid responses to threats [119,120]. Unlike traditional methods, drones operate with minimal ecological disturbance, preserving habitat integrity while collecting data [117].

Satellites complement these efforts by offering large-scale, long-term monitoring capabilities. Modern satellite systems equipped with high-resolution sensors, such as those used by NASA's Landsat program or the European Space Agency's Sentinel missions, can detect forest loss, vegetation health, and illegal activities with remarkable accuracy. In conjunction with platforms like Global Forest Watch, satellite data provide an overarching view of deforestation trends, enabling stakeholders to prioritize areas for intervention and conservation planning. These technologies are particularly useful in identifying patterns of agricultural expansion and assessing the cumulative impacts of infrastructure development over time.

Integrating these monitoring tools with the study's practical recommendations could significantly improve conservation outcomes. For instance, drones and satellites could help to establish and enforce buffer zones by providing near-real-time data on land-use changes and encroachments, ensuring these areas remain protected. These technologies could also guide agroforestry projects, ensuring they align with ecosystem stability and sustainable land-use goals. Moreover, data from monitoring technologies can help to identify socio-economic drivers of deforestation, such as population growth and market pressures, allowing for tailored interventions, including sustainable livelihood programs and incentives for conservation-friendly practices.

In addition to technological tools, community engagement remains essential for effective forest conservation. Educational initiatives in Kenya have raised awareness about forest benefits and sustainable agriculture, reducing harmful practices and fostering support for conservation [121,122]. In Ecuador, community participation in managing resources has safeguarded the Amazon rainforest, while agroforestry projects in Tanzania and Bolivia have harmonized local development with forest conservation by improving livelihoods and promoting sustainable land use [123–126]. Monitoring tools can complement these efforts by providing accessible, localized data, empowering communities to take proactive roles in conservation.

Enforcing forestry regulations is also critical. In Indonesia, stricter regulations and penalties have significantly reduced illegal logging [127,128]. Similarly, the enforcement of the forestry code in the DR Congo has curbed illegal deforestation in protected areas, underscoring the importance of strong regulatory frameworks [12,129–131]. Drones and satellites can enhance enforcement by providing irrefutable evidence of illegal activities, enabling authorities to act swiftly and ensure accountability.

The future of protected areas hinges on proactive development management. Salonga National Park in the DR Congo exemplifies successful conservation programs involving local communities to protect biodiversity, an approach adaptable to regions like Maniema, where threats from hunting and agricultural expansion are prevalent [52]. Infrastructure planning is equally vital; unchecked road construction near Virunga National Park has accelerated deforestation and habitat loss due to unplanned urbanization and agriculture. Monitoring technologies can evaluate the environmental impacts of infrastructure projects, supporting comprehensive land-use planning and helping to mitigate risks. Drawing on lessons from the Niokolo-Koba Conservation Corridor in Senegal, which successfully integrates sustainable development with conservation [132], similar approaches can enhance the effectiveness of conservation strategies in DR Congo. Initiatives such as national parks like Virunga and Salonga have demonstrated success in preserving biodiversity and forest cover through measures like anti-poaching, community-based conservation, and REDD+ programs [133,134]. For example, strict enforcement in Virunga has increased mountain gorilla populations, while Salonga has maintained high forest integrity. Additionally, projects like hydroelectric initiatives in Virunga provide alternative livelihoods, reducing reliance on deforestation-driven activities and supporting broader landscape integration [19,44]. However, these efforts often displace activities like logging and farming to park boundaries, causing deforestation in buffer zones (“leakage effect”). Limited benefit-sharing, such as from ecotourism, fosters local resentment, leading to illegal resource use. Addressing these issues requires integrating conservation with community development and sustainable land-use practices for long-term stability [19,44]. In parks like Kahuzi-Biega, stricter enforcement has protected core areas but failed to prevent encroachment for agriculture in surrounding regions. To address these challenges, integrating conservation with community development and sustainable land-use practices around parks is essential for long-term ecological and social stability [135].

5. Conclusions

This study mapped and quantified the landscape dynamics of Lomami National Park and its surrounding areas using Landsat imagery (2008, 2016, and 2024) and landscape ecology analysis tools. The results emphasize the urgent need to update land-use planning and promote sustainable practices in the regions surrounding Lomami National Park. The findings highlight a clear contrast between the stability of the park and the increasing pressures on its surrounding areas. The park itself has demonstrated remarkable resilience, maintaining its forest cover and preserving contiguous forest patches with minimal fragmentation. In contrast, the surrounding peripheral zones are increasingly fragmented due to the expansion of agriculture and urban development. This fragmentation is marked by higher edge density and reduced patch aggregation, reflecting the growing human impact in these areas.

The contrast underscores the park's ability to sustain its ecological structure, while the surrounding landscape faces significant threats that compromise its integrity and biodiversity. These results confirm our hypothesis that factors such as Lomami's geographical isolation, low population density, and limited logging activities contribute to the preservation of its forest structure. However, they also highlight the vulnerability of the surrounding ecosystems, where forest integrity is being compromised by increasing human activity.

The fragmentation of forests in the peripheral zones presents a tangible risk to both biodiversity and long-term ecosystem stability, underscoring the critical need for conservation-focused land-use policies. Effective policy updates should include continuous monitoring using advanced technologies and engage local communities through awareness and education initiatives. Furthermore, conservation efforts would benefit from stricter enforcement of land-use regulations and increased community participation in sustainable practices to support both human and environmental needs.

In light of mounting anthropogenic pressures, these integrated approaches are essential to ensure the continued resilience of Lomami's unique ecosystems. Finally, the study emphasizes the urgent need for protected area policies to address agricultural expansion in peripheral zones. Integrated approaches should prioritize ecosystem protection and community well-being by establishing buffer zones with strict land-use regulations and promoting agroforestry and sustainable farming practices. Policies must address socio-economic drivers such as population growth and market pressures by offering conservation incentives and sustainable livelihood programs. Embedding these strategies in participatory governance can enhance both environmental and social resilience. Effective agricultural management is crucial for preserving Lomami's ecological integrity and ensuring that surrounding landscapes function as sustainable buffers.

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Appendix A

Deforestation rate equation proposed by Puyravaud et al. [71]

$$Td = 1 + \left(\frac{1}{t2 - t1}\right) \ln\left(\frac{A2}{A1}\right) * 100$$

With Td (the annual deforestation rate in percentage); $A1$ (forest area in the initial year in hectares); $A2$ (forest area in the final year in hectares); $t1$ (the initial year of image acquisition); and $t2$ (the final year of image acquisition).

Appendix B

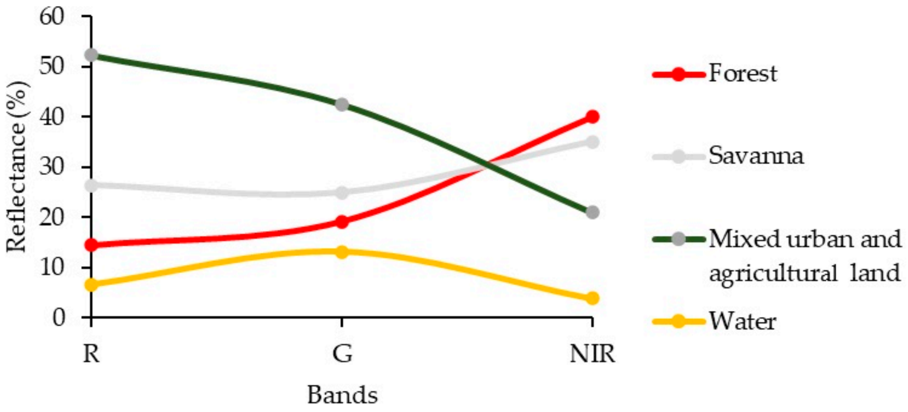

Figure A1. Spectral signature (average of classified Landsat images of 2008, 2016, and 2024) of land cover classes within the Lomami National Park and its surrounding areas across the green, red, and near-infrared spectral bands. R (Red), G (Green) and NIR (near-infrared).

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