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Ecological integrity of forest landscapes in the Kisangani region (DRC) using spatial analysis of edge effect exposure and magnitude of edge influence

Julien Bwazani Balandi[1,2*], Jean-Pierre Pitchou Meniko To Hulu[3], Kouagou Raoul Sambieni[1,2], Yannick Useni Sikuzani[4], Jean-François Bastin[2], Léon Iyongo Waya Mongo[5], Joël Mobunda Tiko[1,3] and Jan Bogaert[2]

*Correspondence:
Julien Bwazani Balandi
j.bwazani@eraift-rdc.org
[1]Ecole Régionale Postuniversitaire d'Aménagement Et de Gestion Intégrés Des Forêts Et Territoires Tropicaux, P.O. Box 15373, Kinshasa, Democratic Republic of the Congo
[2]Unité Biodiversité Et Paysage, Gembloux Agro-Bio Tech, Université de Liège, 4000 Liège, Belgium
[3]Institut Facultaire Des Sciences Agronomiques de Yangambi, P.O. Box 1232, Kisangani, Democratic Republic of the Congo
[4]Unité Ecologie, Restauration Ecologique Et Paysage, Faculté Des Sciences Agronomiques, Université de Lubumbashi, P.O. Box 1825, Lubumbashi, Democratic Republic of the Congo
[5]Faculté de Gestion Des Ressources Naturelles Renouvelables, Université de Kisangani, B.P. 2012, Kisangani, Democratic Republic of the Congo

Abstract
Assessing long-term forest fragmentation is essential for understanding the ecological integrity of tropical landscapes. This study investigates historical trends in forest loss, patch configuration, and edge-related disturbances across four forest landscapes near Kisangani, Democratic Republic of the Congo: Masako, Mbiye, Yoko, and Yangambi, using satellite imagery from 1986 to 2024. Landscape metrics, including Relative Forest Area Change and Largest Patch Index (LPI), were used to characterize both compositional and configurational changes. Interior-to-edge (I/E) ratios, interior and edge areas, and edge-affected percentages were computed across four buffer distances (50–200 m) to assess edge influence, while patch area was analyzed in relation to edge-induced Land Surface Temperature (LST) variation. Finds reveal accelerating fragmentation in the peri-urban landscapes of Masako and Mbiye, especially after 2016. Both landscapes lost over 80% of forest cover between 1986 and 2024, with sharp LPI declines, near-complete disappearance of interior forests, and I/E ratios approaching zero. By contrast, Yangambi retained over 90% of its initial cover and Yoko over 60%, with higher LPI and limited edge exposure, indicating more stable spatial patterns. Edge-related thermal effects showed a significant inverse relationship between patch size and LST in Yangambi and Yoko, suggesting larger patches mitigate edge warming. In Masako and Mbiye, low R^2 values reflected advanced fragmentation and diminished thermal buffering capacity. These results highlight major ecological risks, including biodiversity loss and ecosystem service decline. Landscape-specific strategies are recommended: restoration, reconnection of remnant patches, agroforestry integration, and community resource management. For relatively intact landscapes, legal reinforcement, spatial monitoring, and environmental education are proposed to prevent further degradation.

Keywords Forest fragmentation, Ecological integrity, Edge effect exposure, Remote sensing, Kisangani

1 Introduction

Tropical forest landscapes are essential for maintaining biodiversity, regulating microclimatic and ecological processes, and providing key ecosystem services [1, 2]. These functions are increasingly critical in regions exposed to accelerating anthropogenic pressures [2, 3]. Tropical forests also constitute a cornerstone of nature-based climate solutions, which are estimated to provide more than 30% of the cost-effective mitigation needed to keep global temperature rise below the 2 °C threshold of the Paris Agreement [4]. Yet these forests continue to experience widespread degradation [5, 6]. Over recent decades, agricultural expansion, logging, and urban growth have reshaped forested regions, intensifying fragmentation and habitat degradation at multiple scales [7, 8]. According to Hansen et al. [9], between 2000 and 2012, tropical forests were the only climatic region showing a statistically significant increasing trend in forest loss, with the annual rate of forest loss increasing by approximately 2,101 km^2 per year. In Central Africa, tropical forests experienced an estimated decline exceeding 8.2% between 2010 and 2019 [10], contributing to the increased fragmentation and isolation of remaining forest patches [11, 12].

Forest fragmentation is widely recognized as a primary indicator of landscape degradation [3]. One of its most pervasive outcomes is the expansion of forest edges, transitional zones between interior habitats and adjacent disturbed environments [13–15]. These zones are prone to abrupt microclimatic shifts, altered species composition, and reduced ecological functioning, which ultimately compromise forest integrity [16–18]. Consequently, edge effects have become a central focus in tropical landscape ecology, given their substantial influence on biodiversity patterns, habitat quality, and ecological interactions [19].

Research across tropical regions has extensively documented how edge effects modify species diversity, habitat affinity, and animal mobility [13–15, 17, 20]. Spatial metrics have also emerged as critical tools for quantifying forest vulnerability to fragmentation, enabling the assessment of interior versus edge-affected forest and helping identify priority areas for conservation [21–23]. Complementary modeling approaches have further demonstrated the importance of preserving interior forest patches to maintain ecological processes and structural resilience [24, 25]. These insights highlight the need to combine spatial metrics and ecological indicators to better evaluate the integrity of fragmented forest landscapes.

Despite the growing body of research on this topic, there are still limited spatially explicit assessments of fragmentation and edge influence in the Congo Basin, one of the least documented major tropical forest regions, despite its global importance. This knowledge gap is evident throughout the region, including in the Kisangani area of the Democratic Republic of the Congo (DRC), where forest landscapes experience increasing pressure from agricultural expansion, growing informal settlements, and the development of peri-urban infrastructure [7, 26]. In such rapidly changing environments, it is essential to characterize both the structural dimensions of fragmentation (e.g., forest loss, patch isolation) and the functional implications of edge exposure for forest integrity. Metrics capable of quantifying edge-affected forest, when coupled with ecological indicators such as Land Surface Temperature (LST), provide a robust framework for identifying microclimatic degradation and detecting vulnerable forest habitats. Integrating these spatial and environmental perspectives is crucial for evidence-based conservation planning, as it enables the identification of priority areas for intervention, monitoring of degradation trajectories, and formulation of adaptive management strategies tailored to the socio-ecological contexts of Central African forests.

This study addresses these gaps through a spatio-temporal analysis of four forest landscapes, Yangambi, Yoko, Masako, and Mbiye, representing distinct conservation contexts within the Kisangani region. Their strategic locations, varying distances from the urban center, and differing levels of disturbance provide a relevant gradient for understanding how fragmentation processes evolve under different socio-ecological pressures. A particular focus is placed on assessing the temporal expansion of edge-affected forest using multiple ecological edge distances and on examining how patch size influences microclimatic disturbance as inferred from LST, a recognized indicator of canopy degradation and surface thermal alteration [27–29]. In fragmented landscapes, reduced vegetation density and increased exposure to solar radiation near edges often result in elevated surface temperatures, which likely indicate increased microclimatic stress that may affect plant physiology and soil moisture retention. Such microclimatic changes could potentially influence species composition, disrupt ecological interactions such as pollination, and reduce the overall resilience of forest ecosystems to climatic variability. Moreover, LST can be reliably derived from satellite observations at high spatial and temporal resolutions, enabling the detection of fine-scale thermal variations across heterogeneous forest mosaics. By linking spatial fragmentation patterns with an ecological stress indicator, this approach offers a robust framework for assessing forest integrity. These analyses further highlight how fragmentation influences both the spatial configuration and ecological functioning of tropical forests within rapidly transforming peri-urban landscapes.

Therefore, we hypothesize that forest fragmentation has increased across all four landscapes, resulting in a measurable decline in forest area and configuration, as evidenced by negative trajectories in Relative Forest Area Change and reductions in the Largest Patch Index (LPI). We further expect that the proportion of edge-affected forest has expanded over time, especially at broader ecological distance thresholds where microclimatic disturbances are more pronounced. Finally, we anticipate that smaller forest patches exhibit stronger LST-based thermal anomalies due to their greater exposure and reduced buffering capacity. Together, these analyses contribute a spatially explicit understanding of fragmentation patterns and edge influence in the Kisangani region, supporting evidence-based conservation planning in Central African forest ecosystems.

2 Materials and methods

2.1 Study areas

The study area includes four forest landscapes surrounding Kisangani in northeastern DRC (Fig. 1). These landscapes span a gradient from peri-urban forests to large protected areas. The Masako Forest Reserve, located about 15 km northeast of Kisangani, covers 2,105 ha and represents a peri-urban forest under increasing human pressure [13, 14]. The Mbiye Forest Reserve, a 38-km^2 island southeast of the city, is similarly exposed to local anthropogenic activities [30]. The Yoko Forest Reserve, situated 32 km southeast of Kisangani, extends over 70 km^2 and lies at an average elevation of 450 m [31]. Further west, the Yangambi Biosphere Reserve covers 273,955 ha across the Isangi and Banalia territories and includes the N'Gazi Reserve and the INERA concession, both incorporated since its UNESCO recognition in 1977 [32]. As part of the MAB Program,

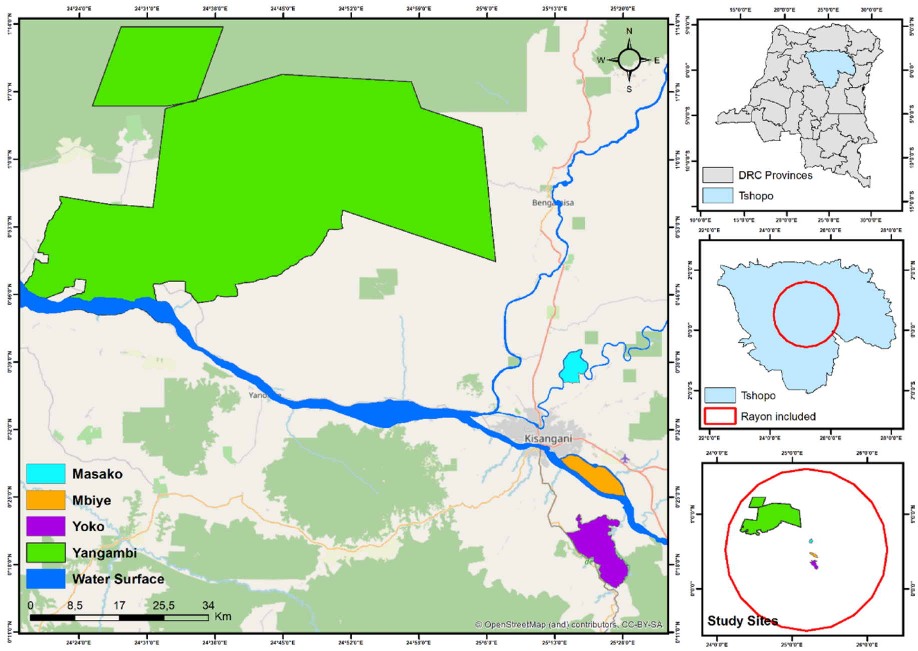

Fig. 1 The geographical location of the four forest landscapes studied near Kisangani, Democratic Republic of the Congo: Masako, Mbiye, Yoko, and Yangambi

Table 1 Characteristics of the geodata used

Satellite images	Months filtered	Years	Spatial resolution
Landsat images (MSS–TM)	15 Dec–28 Feb	1986–1991–1996	30 m
Landsat images (ETM +)	15 Dec–28 Feb	2001–2006–2011	30 m
Landsat images (OLI)	15 Dec–28 Feb	2016–2021–2024	30 m
Hansen global change map	–	2000–2024	30 m
GPS data	August–March	2022–2023	–

Yangambi constitutes a key site for ecological research and forest conservation in Central Africa [33].

2.2 Data and preprocessing

The analysis of ecological integrity by quantifying forest areas impacted by edge effects in the four protected reserves was conducted using Landsat satellite imagery from TM (1986, 1991, 1996), ETM + (2001, 2006, 2011), and OLI-TIRS (2016, 2021, 2024), all with a spatial resolution of 30 m. Consequently, satellite images with less than 10% cloud cover were selected, allowing for a multi-temporal assessment over 38 years. While the temporal resolution generally follows a five-year interval, slight variations occur for the most recent observations (2021 and 2024). These satellite data were supplemented by GPS field surveys, which provided detailed on-the-ground information (Table 1).

To reduce atmospheric and radiometric inconsistencies among Landsat sensors [34], surface reflectance (SR) imagery was used. Landsat 4–7 SR data were processed with LEDAPS, and Landsat 8–9 data with LaSRC [35, 36], ensuring consistent radiometric and spectral quality for reliable image comparisons [36]. All images were georeferenced to WGS 84, resampled to 30 m resolution, and reprojected to UTM Zone 35 North.

To enhance the differentiation of land cover types, false-color composites were generated for each date using the mid-infrared (MIR), near-infrared (NIR), and red (R) spectral bands. These composites improve the visual interpretation of vegetation and anthropogenic features. For the supervised classification, training samples were collected for three main land cover categories: (1) Human Altered Landscape, encompassing all anthropogenic features such as built-up areas, bare soil, agricultural fields, and herbaceous cover; (2) Old-Growth Vegetation, corresponding to mature forest stands characterized by closed canopies and minimal human disturbance; and (3) Water Surface, including the Congo and Tshopo. Although relatively simple, this three-class scheme has limitations, as it does not distinguish among different types of anthropogenic land cover or vegetation stages. Nevertheless, it was deliberately chosen to maintain temporal and spatial consistency, as these classes can be reliably identified across all study landscapes. Importantly, this approach aligns with the study objective: aggregating all human-modified areas enables consistent delineation of forest edges, enabling robust assessment of the proportion of mature forest exposed to edge effects over time.

2.3 Classification and accuracy assessment

The supervised classification was carried out using the Random Forest algorithm [7, 37]. To ensure reliable accuracy and consistent performance, the number of decision trees was set to 100 for all image classifications. This algorithm is particularly effective due to its use of multiple decision trees, which independently evaluate the training samples and assign them to the most appropriate land cover classes, thereby improving classification accuracy [26, 38]. For the calibration of land cover classifications, a minimum of 100 points per class was collected for each of the three land cover categories. These training points were selected based on visual interpretation of false-color composites generated from the mid-infrared (MIR), near-infrared (NIR), and red (R) spectral bands, and supported by high-resolution imagery from Google Earth. To assess the accuracy of land cover classifications for earlier years, independent validation samples were derived from Google Earth historical imagery. In the Kisangani study area, high-spatial-resolution archival imagery was available years 2011, 2016, and 2021, allowing year-specific validation samples to be collected for each corresponding Landsat epoch. For earlier dates (2006, 2001, 1996, 1991, and 1986), although Google Earth imagery was available for the study region, its spatial resolution was relatively coarser. Consequently, validation samples for these periods were derived from land cover features exhibiting clear spatial patterns and long-term temporal stability (e.g., persistent forest patches and stable non-forest areas), ensuring consistency across the time series. All validation samples were selected independently from the training data to avoid bias in the accuracy assessment. Given the geographical proximity of the Masako and Mbiye reserves, a single combined area was defined for the land cover classification. For subsequent spatial analyses, however, the classified maps were subdivided, and each reserve was analysed separately.

During field missions conducted in March 2023, a total of 642 GPX control points were collected across the four study landscapes, depending on site accessibility, and used to validate the 2024 reference classification. These points were allocated to the three land cover classes as follows: 33% to built-up areas and bare soil, 27% to agricultural land and grasslands, and 20% to degraded or secondary forest, all grouped into the human-altered landscape class; the remaining 20% corresponded to mature forest (old-growth vegetation).

Two separate subsets were used for analysis: 310 points for validating the 2024 reference classification, and 232 points for comparing the locally produced land cover classifications with the global tree cover dataset developed by Hansen et al.[9]. To support this comparison, land cover classes were harmonized into two broad categories: (1) non-forest and (2) Forest. In Hansen's dataset, we defined a forest pixel as any pixel with 50% or more forest cover, indicating a dominant presence of forest [7]. Therefore, any forest pixel that experienced a decrease in canopy cover below 50% between 2000 and 2024 was considered to have transitioned to non-forest. Conversely, pixels that reached or exceeded 50% canopy cover during the same period were classified as forest. A contingency table was generated to compare the local classification results with the global dataset provided by Hansen, discriminating between forest and non-forest classes. This matrix was then used to compute users' accuracy, producers' accuracy, and overall accuracy, as defined by Eqs. (1) and (3) in Olofsson et al.[39].

2.4 Fragmentation and ecological integrity

To assess the spatial patterns and temporal dynamics of forest fragmentation across the four landscapes surrounding Kisangani (Masako, Mbiye, Yoko, and Yangambi), a set of complementary landscape metrics was computed. The Relative Forest Area Change (RFAC) (Eq. 1) was used to quantify compositional changes in total forest cover over time, providing a baseline for comparing forest loss trajectories across different anthropogenic contexts. The Largest Patch Index (LPI) (Eq. 2) captured shifts in the spatial dominance and cohesion of the largest remaining forest patch, serving as an indicator of landscape connectivity and configuration.

To better understand the spatial consequences of fragmentation, we computed the total area of interior forest, defined as forest located beyond the influence of the ecological edge effect, and the total area of edge-affected forest, which is more exposed to external disturbances. From these values, the Interior-to-Edge Ratio (I/E), defined as the area beyond a specified edge buffer distance relative to the total patch area [22, 24], was derived. This provides insight into habitat quality and susceptibility to edge effects. The analysis was conducted using vector data and multiple buffer distances (50 m, 100 m, 150 m, 200 m) to account for varying sensitivities to ecological edges. These distances were selected based on previous studies in tropical forests, capturing both short- and medium-range microclimatic and ecological effects. Using multiple thresholds enables a robust assessment of edge influence on forest patches of varying sizes and exposure levels. In addition, the percentage of forest area influenced by edge effects was calculated to enable standardized comparisons of edge exposure across landscapes and time periods. These metrics are used due to their effectiveness in quantifying the spatial configuration, extent, and degree of isolation of forest patches, which are critical indicators of habitat integrity and landscape connectivity [22, 24, 40, 41]. These metrics provide a robust analytical framework for characterizing both the spatial pattern of fragmentation and the degree to which forests remain functionally intact under ongoing anthropogenic pressure.

To ensure comparability across sites and landscape metrics, a linear regression approach was applied to assess temporal trends in forest structural indices over the study period. This approach was selected to provide a consistent and interpretable framework for comparing trajectories among the four study sites, which are characterized by distinct ecological contexts and levels of anthropogenic pressure.

$$\boldsymbol{RFAC} = \frac{a_f}{a_i} \tag{1}$$

where $RFAC$ is the Relative Forest Area Change, $\boldsymbol{a_f}$ refers to the forest area of a given landscape at the final time point (Year 2), and $\boldsymbol{a_i}$ represents the forest area of a given landscape at the initial time point (Year 1). RFAC values greater than 1 indicate a net gain in forest area over the observed period, suggesting reforestation or natural regeneration, while RFAC values less than 1 indicate a net loss in forest area, reflecting deforestation or degradation. RFAC equal to 1 indicates that the forest area has remained stable over time. This index provides a straightforward yet robust method for quantifying long-term changes in forest extent. It enables direct comparison of forest dynamics across multiple landscapes, regardless of their initial forest cover, spatial scale, or socio-ecological context.

$$\mathbf{LPI} = \frac{max_{j=1}^{n}(a_{ij})}{A} \times (100) \tag{2}$$

where: a_{ij} = Area (m^2) of patch *ij*; A = Total landscape area (m^2).

2.5 LST retrieval, patch area, and edge-effect magnitude

To evaluate the influence of forest patch area on edge-effect magnitude, land surface temperature (LST) was used as a biophysical indicator of thermal stress for the year 2024, representing current thermal edge conditions in the Masako, Mbiye, Yoko, and Yangambi landscapes. LST was estimated from harmonized Sentinel-2 data. Two biophysical predictors were derived: (i) the Normalized Difference Vegetation Index (NDVI), calculated from bands B4 and B8, and (ii) broadband surface albedo, calculated from bands B2, B3, B4, B8, B11, and B12 using specific weighting coefficients from Bonafoni et al.[42]. The broadband surface albedo α is estimated by integration of narrowband reflectances across the SW spectrum, as (Eq. 3)[42]:

$$\alpha = \sum_{B=1}^{N} \rho_B . w_B \tag{3}$$

where ρ_B is the surface reflectance for a specific band B of MSI, and w_B is the weighting coefficient [42].

An empirical linear regression model was then calibrated to link LST to Sentinel-2 NDVI and albedo (Eq. 4), as adapted from Eq. 7 of Naserri et al. [43].

$$LST = a_0 + a_1 * NDVI + a_2 * Albedo \tag{4}$$

where a_0, a_1, and a_2 are regression coefficients.

To ensure a region-specific calibration, Landsat 8 LST was used as the reference target variable, while the Sentinel-2 imagery used to compute NDVI and albedo was resampled to 30 m to match the Landsat LST pixel resolution. This resampling ensured that each Sentinel-2-derived pixel corresponded directly to a Landsat LST pixel for regression analysis. This approach was chosen because the spectral responses and band-specific albedo coefficients differ between Landsat 8 and Sentinel-2, as highlighted by Liang [44], Smith [45], and Bonafoni [42]. Consequently, the Landsat-based NDVI and albedo coefficients (a_1, a_2) are not directly transferable to Sentinel-2 variables, which are derived from different spectral bands and albedo formulations. The regression coefficients linking LST to NDVI and albedo are therefore sensor-specific, and those derived for the Kisangani region were then applied to estimate LST from Sentinel-2 data. Sentinel-2 was selected as the LST primary source because its spatial resolution (10–20 m) allows the detection of fine-scale thermal heterogeneity within the highly fragmented tropical forest mosaics of the Kisangani landscape. Model performance was assessed using both the root-mean-square error (RMSE) and the coefficient of determination (R^2). LST values for 2024 were then averaged across 21 cloud-free Landsat scenes to reduce atmospheric variability, residual clouds, and seasonal fluctuations, providing a robust representation of patch-level microclimatic conditions for the current year.

To measure the magnitude of edge influence (MEI) on land surface temperature (LST), a framework distinct from structural edge analysis was applied. Specifically, two distance buffers were used for the LST-based MEI. A 20-m buffer was consistently applied across all four landscapes, as this distance captures microclimatic edge effects that occur even in highly fragmented forests such as Masako and Mbiye, where most remaining patches are small and rarely contain interior habitat beyond 50 m. An additional 50-m buffer was applied only to the Yangambi and Yoko landscapes, where larger and more continuous forest blocks still existed in 2024. In these less fragmented forests, edge-related temperature gradients are expected to penetrate further into the forest interior, thereby justifying the use of a larger buffer. Importantly, two distinct edge-distance frameworks were used in this study: multi-distance thresholds (50–200 m) were applied exclusively to structural edge exposure metrics, whereas fixed distances (20 m across all landscapes, and additionally 50 m for Yangambi and Yoko) were used solely for the LST-based Microclimatic Edge Influence (MEI) analysis. Therefore, the MEI was calculated using the formula (Eq. 5) [46, 47]:

$$\boldsymbol{MEI} = \frac{e - i}{e + i} \tag{5}$$

where $\boldsymbol{e}$ represents the value of the parameter (here, LST) measured within the edge zone, and $\boldsymbol{i}$ corresponds to the mean value within the forest interior beyond the edge buffer. This index ranges from – 1 to + 1, with values near zero indicating negligible edge effects and higher values indicating greater thermal contrast between the edge and interior zones. A simple linear regression was then applied to test the effect of patch area on the magnitude of edge influence on LST, allowing for a quantitative assessment of how patch size moderates thermal edge responses across forest landscapes. Given the highly asymmetric distribution of patch area, with many small patches and a few very large ones, patch area is log-transformed prior to regression. The transformation is applied to reduce skewness, limit the disproportionate influence of large patches, stabilize variance, and improve the linearity of the relationship with edge influence (Fig. 2).

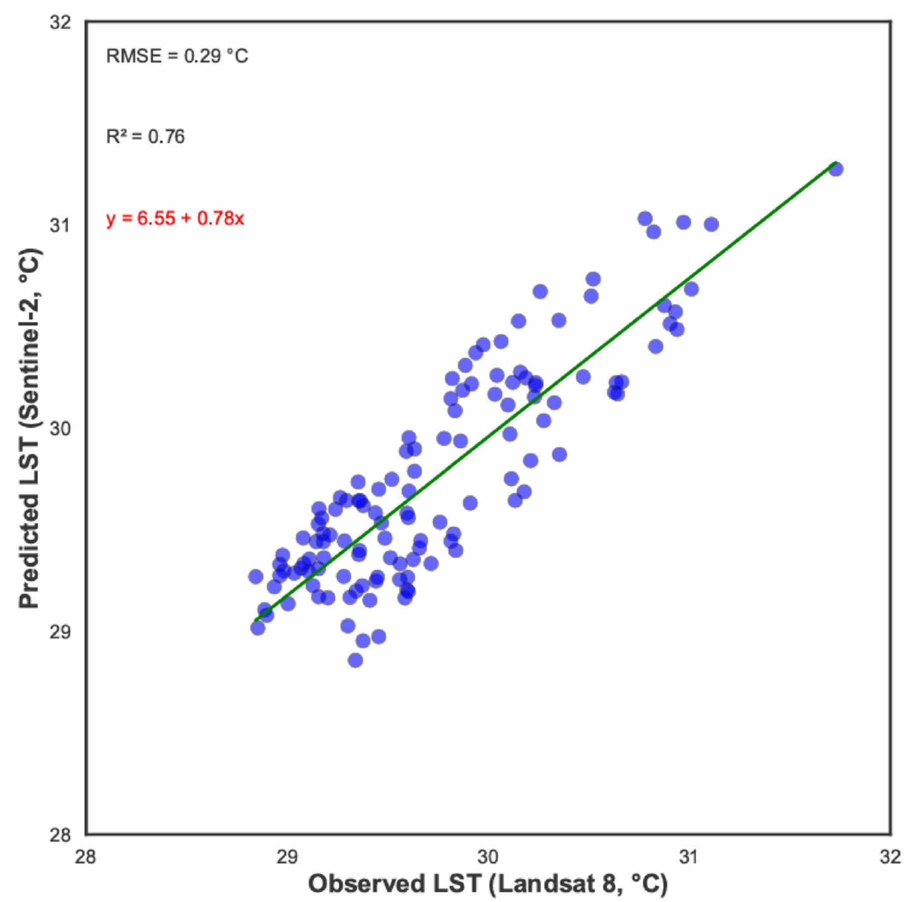

Fig. 2 Validation of Sentinel-2 predicted LST using Landsat 8 observations. Predicted LST from Sentinel-2 is compared with Landsat 8 measurements to evaluate model performance. This scatterplot provides a visual and quantitative assessment of accuracy, highlights potential biases, and confirms the reliability of the recalibrated Sentinel-2 LST for spatial analyses

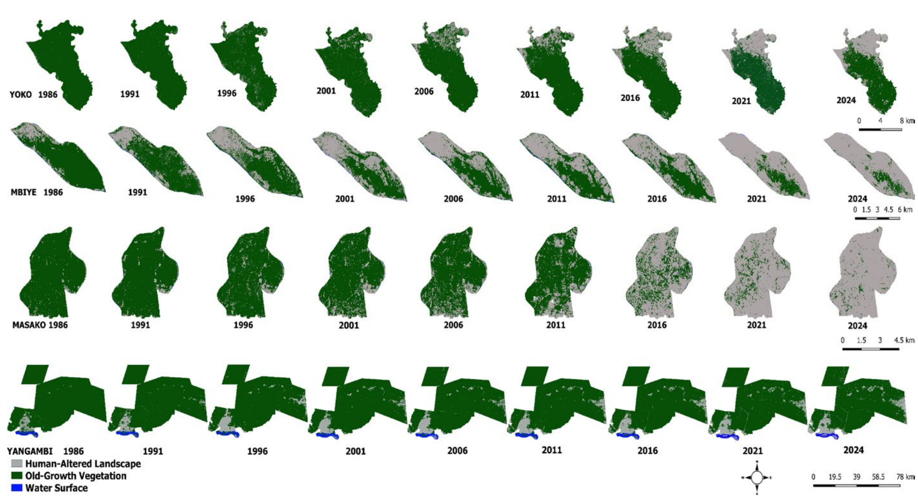

Fig. 3 Changes in forest landscapes in the Kisangani region (1986–2024): progressive decline of old-growth vegetation and expansion of the human-altered landscape

3 Results

3.1 Classification accuracy and Sentinel-2 LST model evaluation

3.2 Multi-temporal mapping of mature forest

The visual interpretation of land cover maps from 1986 to 2024 across the four studied landscapes reveals a general trend of increasing landscape artificialization (Fig. 3). The Yoko Forest Reserve, in particular, demonstrates growing anthropogenic pressure, especially in its Northern section. While the Yangambi Biosphere Reserve still retains large forest patches, significant human disturbance is evident along the Bengamisa road corridor, particularly in the eastern and southwestern zones. In contrast, the Masako and Mbiye Forest Reserves are experiencing near-total disappearance. Since 2016, anthropogenic pressure has intensified around these reserves, which are located near urban areas, leaving only a few scattered forest patches.

3.3 Historical trends of forest landscape fragmentation

As expected, the overall results reveal a consistent trajectory of forest degradation over time, characterized by a significant decline in both the Relative Forest Area Change and the Largest Patch Index (LPI) across all four landscapes (Fig. 4). These two metrics capture distinct but complementary aspects of landscape dynamics: the relative forest area reflects changes in landscape composition, while the LPI captures aspects of landscape configuration, notably the spatial dominance of the largest remaining forest patch. Between 2021 and 2024, Masako and Mbiye experienced a substantial reduction in forest cover, losing over 80% of their initial forest area. This sharp decline in forest composition suggests an accelerated conversion of forest land to other uses, likely driven by intense urban expansion from the city of Kisangani. In parallel, the significant drop in LPI in these landscapes indicates a pronounced fragmentation process, in which formerly dominant forest patches have been progressively disaggregated into smaller, more isolated fragments, leading to a substantial loss of spatial cohesion.

In contrast, Yangambi maintained over 90% of its initial forest area, and Yoko retained more than 60% by 2024, suggesting comparatively higher resilience in both composition and configuration. Despite some decline, these landscapes still preserve larger, more cohesive forest patches, as reflected in their relatively higher LPI values. The

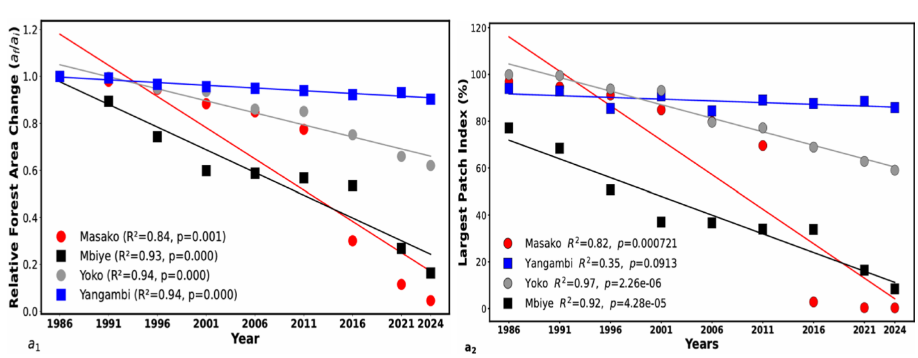

Fig. 4 Changes in relative forest area (**a₁**) and Largest Patch Index (**a₃**) in forest landscapes around the Kisangani region (1986–2024). The relative forest area was calculated as the ratio of the final to the initial forest area, providing a standardized measure of overall forest loss across landscapes. The results show a consistent decline in both the total proportion of forest cover and the dominance of the largest patch over time, reflecting ongoing degradation in both the composition and configuration of forest landscapes. The loss of forest extent and the shrinking of the largest patches indicate increasing fragmentation and reduced spatial cohesion, particularly in Masako and Mbiye

divergent trajectories of the landscapes highlight how socio-economic pressures and land-use dynamics shape both the extent and the spatial configuration of tropical forest ecosystems.

3.4 Temporal changes in forest landscape integrity

Between 1986 and 2024, the Masako Forest Reserve experienced significant losses in its interior forest areas. As a result, from 2016 to 2024, all forest patches, regardless of the edge effect distance considered, were entirely exposed to edge influences. The interior-to-edge (I/E) ratio dropped significantly, approaching zero, while the percentage of edge-affected forest area increased notably over time. This suggests that forest patches are becoming increasingly vulnerable to edge effects. These trends, characterized by more fragmented and edge-dominated patches, were especially noticeable in recent years (2016–2021 and 2024), particularly in the Mbiye Forest Reserve and even more so in the Masako landscape. Since 2016, all remaining forest patches in these two landscapes appear to be entirely influenced by edge effects, regardless of the buffer distance considered. The Yoko Forest also shows alarming indicators of ecological integrity. The area of core forest patches has consistently decreased across all edge effect distances. For an edge effect distance of 200 m, the interior area declined by more than 40 km^2 between 1986 and 2024. As a result, the interior-to-edge (I/E) ratio declined markedly, from 2.0 in 1986 to approximately 0.5 in 2024. In contrast, the Yangambi Biosphere Reserve, located approximately 100 km from the urban center of Kisangani, has remained relatively well-preserved. Although a general reduction in core forest area in favor of edge-dominated zones was observed, the impacts in Yangambi appear to be less severe, likely due to its relative remoteness from urban-induced disturbances (Figs. 5, 6, 7, 8).

3.5 Exploring the influence of patch area on the LST edge effect magnitude

The analysis reveals an inverse relationship between patch size and the magnitude of edge effects on Land Surface Temperature (LST). Across all four landscapes, analyses conducted at a 20 m buffer distance (Fig. 9a1, a2, a3, and a4) show that larger patches are associated with lower edge-related thermal gradients, indicating a mitigation of edge influence as patch area increases. This relationship was also assessed at a 50-m scale for Yangambi and Yoko, where sufficiently large forest remnants remained intact in 2024 (Figs. 9b1 and 9b2), yielding similarly robust and statistically significant results. The reduced thermal contrast in larger patches likely reflects their higher core-to-edge ratios, which protect the forest interior from external climatic stress. These findings underscore the importance of conserving large, compact forest patches for their structural resilience and in mitigating microclimatic disruptions associated with edge exposure.

4 Discussion

4.1 Quantification of forest landscape exposure to edge influence

The exposure of forest landscapes to edge influences was quantified using widely applied indices, including the interior-to-edge ratio (I/E), the area of interior patches, and the area of patches affected by edge effects [21, 24, 48], at various distances (50 m, 100 m, 150 m, and 200 m). These distances were chosen to account for variability in edge-influence penetration across ecological processes and disturbance agents. The extent of edge effects into forest interiors can vary widely depending on the type and intensity

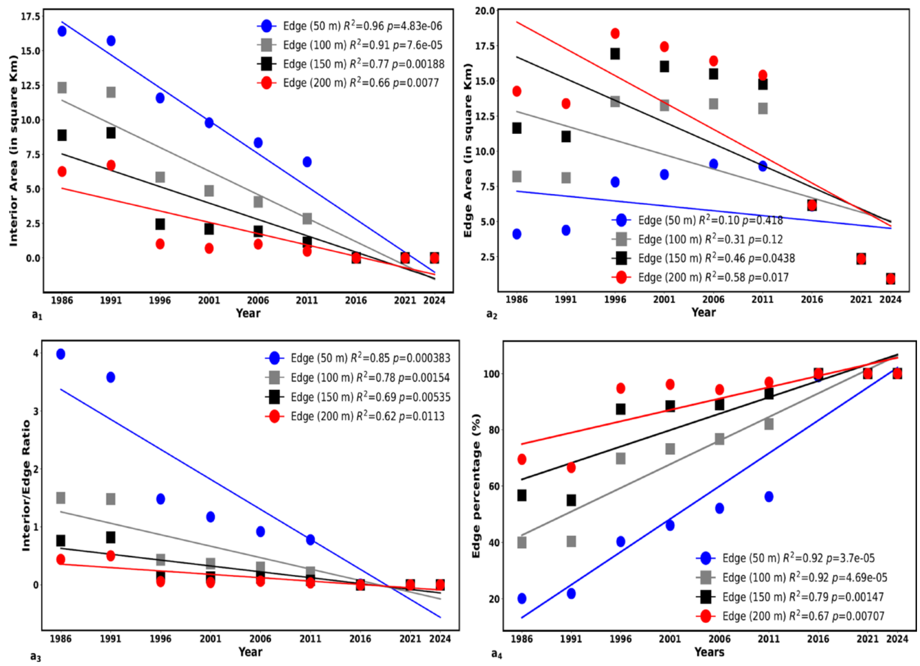

Fig. 5 Changes in interior area (**a_1**), edge patch area (**a_2**), interior-to-edge ratio (**a_3**), and edge percentage (**a_4**) in Masako Forest Reserve (1986–2024). Over time, particularly since 2016, the total edge area has significantly declined. However, this decline does not reflect an improvement in forest integrity, but rather the progressive shrinking of forest patches, which reduces the total area available for both interior and edge zones. As patch sizes decrease, the interior area contracts more rapidly than the edge, leading to a relative increase in edge exposure. This trend is clearly illustrated by the declining interior-to-edge (**I/E**) ratio and the rising edge-area percentage, indicating that the remaining patches are more vulnerable to edge-related ecological processes

of disturbance, as well as the ecological parameters affected. Edge-related changes in microclimate, such as relative humidity, air temperature, and wind speed, often penetrate different distances from the forest edge [22, 47]. For example, in northern Queensland, Australia, edge effects on light intensity have been observed to penetrate up to 50 m into the forest interior [49], while in Czechia, near Prague, edge effects on mean air temperature can reach 100 m inside the forest [50]. These examples illustrate that the depth of edge effects varies across ecosystems and parameters. Previous pantropical analyses indicate that edge effects on forest biomass can extend hundreds of meters, with measurable impacts up to 500 m from the forest edge, highlighting the broad range of possible edge-effect depths in tropical forest landscapes [51]. To account for this inherent variability, we evaluated multiple buffer distances (50, 100, 150, and 200 m) for the structural edge-exposure metrics. This approach allows a comprehensive assessment of edge effects across the Masako, Mbiye, Yoko, and Yangambi forest landscapes, accommodating both highly fragmented patches with limited interior habitat and larger, more continuous forest patches. Therefore, the I/E ratio, a simple yet effective metric, provides a strong estimate of edge influence, a crucial aspect of landscape ecology. It reflects the relative exposure of a habitat to edge effects, which can significantly impact the ecological quality of a patch [22–24].

Although non-parametric approaches may offer a more flexible representation of complex local dynamics, particularly in sites such as Yoko, where weaker and less consistent linear relationships were observed, the present study adopted a linear framework to ensure methodological consistency and comparability across all sites and landscape

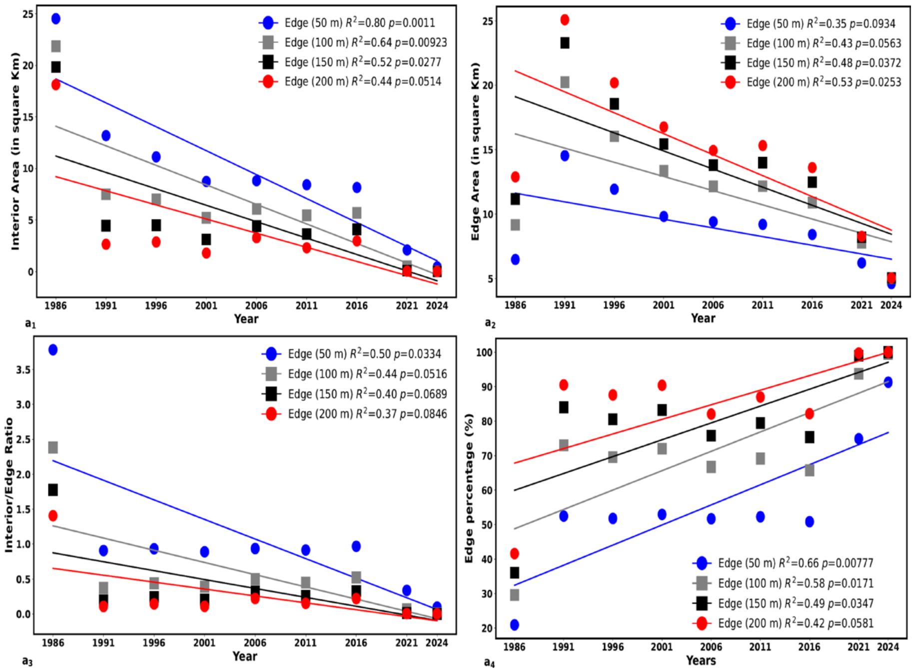

Fig. 6 Changes in interior area (**a$_1$**), edge patch area (**a$_2$**), interior-to-edge ratio (**a$_3$**), and edge percentage (**a$_4$**) in Mbiye Forest Reserve (1986–2024). Since 2016, and assuming an edge effect depth of 200 m, the remaining patches of mature vegetation in the Mbiye Forest Reserve have experienced a near-total loss of interior area. This shift is a direct consequence of continued patch shrinkage, which reduces the spatial extent available for the forest interior. As forest fragments become smaller, interior zones disappear while edge conditions become dominant. This dynamic is reflected in the decline of the interior-to-edge (**I/E**) ratio and the rising edge percentage, underscoring the increasing exposure of remnant patches to edge-related disturbances

metrics. This choice was driven by the need to synthesize long-term temporal trajectories across contrasting ecological contexts in a coherent and interpretable manner, rather than capturing fine-scale nonlinear fluctuations within individual sites.

4.2 Integrity of forest landscapes: substantial fragmentation of Masako and Mbiye

Among the four forest landscapes analyzed, Masako and Mbiye exhibited the most alarming signs of ecological degradation. Unlike Yangambi, where forest integrity remains relatively intact due to several initiatives linking conservation to sustainable development, particularly in line with Sustainable Development Goal 15, which emphasizes the protection, restoration, and sustainable use of terrestrial ecosystems [52], Masako and Mbiye have exhibited critical levels of degradation in recent years. Since 2016, the remaining forest patches in Masako have lost nearly all their interior cores. The interior-to-edge (I/E) ratio steadily approached zero between 2016 and 2024 across all buffer distances considered (50 m, 100 m, 150 m, and 200 m), indicating that almost all remaining forest patches are subject to edge effects. Furthermore, in both Masako and Mbiye, the relationship between patch area and the magnitude of edge influence (MEI) exhibited low R^2 values, indicating that patch size explains only a small proportion of the variation in LST in these areas. This suggests that, in these landscapes, the thermal dynamics of remaining forest fragments are only weakly influenced by patch size, with edge effects prevailing across patches regardless of their area, reflecting a high degree of degradation where true interior forest conditions are largely absent or severely compromised.

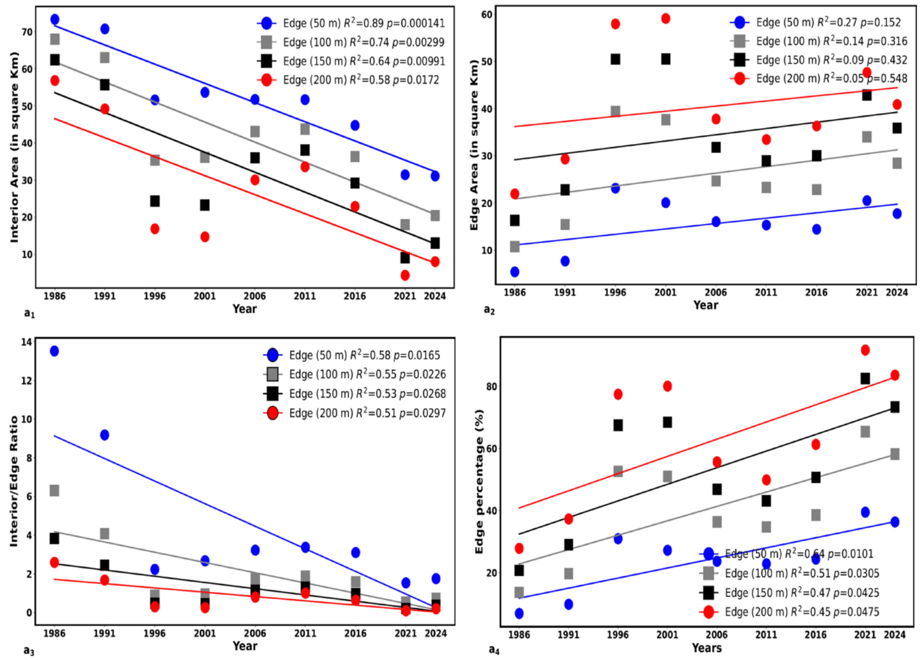

Fig. 7 Changes in interior area (**a_1**), edge patch area (**a_2**), interior-to-edge ratio (**a_3**), and edge percentage (**a_4**) in the Yoko Forest Reserve (1986–2024). For edge effect distances of 100 m, 150 m, and 200 m, the percentage of edge-affected forest area has increased significantly over time, indicating a continuous expansion of zones subjected to edge influences. This trend reflects a progressive contraction of core interior forest habitats, which are crucial for maintaining ecological integrity and mitigating the effects of external disturbances. The decrease in the interior-to-edge (**I/E**) ratio further underscores the growing dominance of edge conditions within the landscape. Such shifts in forest spatial structure may have significant ecological consequences, including altered microclimates, increased vulnerability to invasive species, and changes in species composition

Both landscapes are located near urban areas and face intense anthropogenic pressures, including urban and agricultural expansion, charcoal production, and artisanal logging, with the latter being particularly frequent in Mbiye. Several studies have highlighted the negative impact of these anthropogenic factors on forest landscapes in Central Africa, particularly in contexts where spatial management is poorly regulated. Urban and peri-urban expansion [7, 26], as well as the rural complex, comprising small-scale agriculture, settlements, and road networks [53], are identified as the leading drivers of deforestation and degradation. While several studies [13, 14] have raised concerns in recent years about the impact of fragmentation in the Masako Forest Reserve on animal diversity, the near disappearance of interior forest patches, as observed in this study, may have far-reaching consequences not only for animal and plant biodiversity, thermal regulation as revealed in this study but also for the functioning and resilience of key ecosystem services such as carbon sequestration [54–55] and landscape connectivity.

In contrast, the Yangambi landscape shows a more favorable trajectory. Throughout the study period, it consistently exhibited relatively low levels of edge exposure across all distance thresholds, including the more conservative 200 m buffer. This suggests that a substantial portion of the forest remains protected from edge-related disturbances, thereby preserving the interior forest conditions. These patterns reflect a higher degree of structural and functional integrity, likely sustained by the presence of large, contiguous forest patches and reinforced by multiple, long-standing management efforts. In particular, coordinated initiatives by various research and development entities operating within the Yangambi Biosphere Reserve have played a critical role in promoting

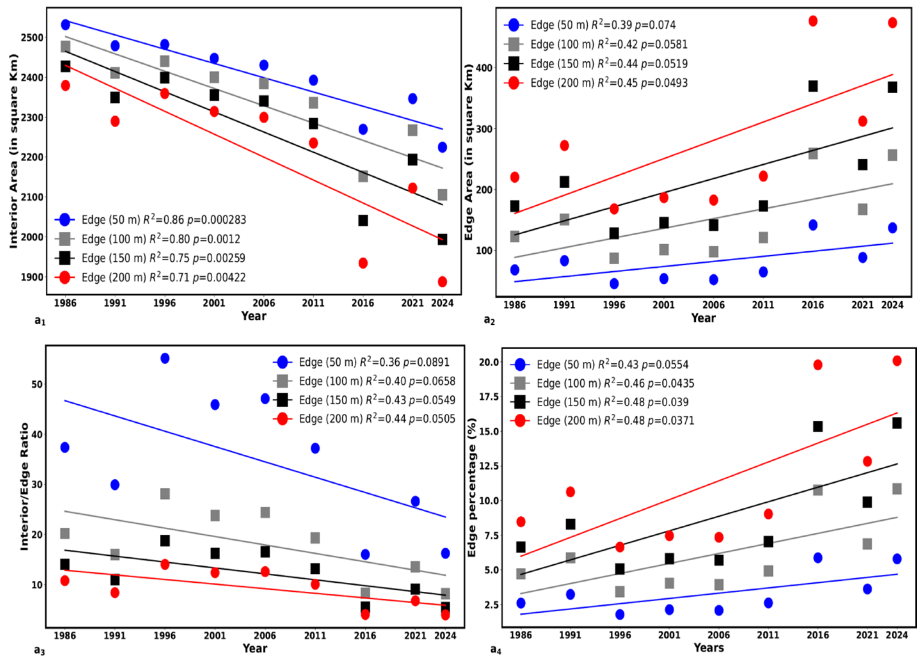

Fig. 8 Changes in interior area (**a$_1$**), edge patch area (**a$_2$**), interior-to-edge ratio (**a$_3$**), and edge percentage (**a$_4$**) in the Yangambi Biosphere Reserve (1986–2024). Although the percentage of edge-affected forest area has increased significantly over time, it remains relatively low compared to other forest landscapes in the Kisangani region. This pattern indicates that Yangambi's forest retains a relatively intact and compact spatial configuration, characterized by large, contiguous patches with well-preserved core interiors. The high interior-to-edge (**I/E**) ratio further reflects limited fragmentation and reduced susceptibility to edge effects, which are critical for maintaining stable microclimates and biodiversity within the reserve

conservation, sustainable land use, and forest restoration. These efforts have contributed to maintaining ecological functionality and distinguishing Yangambi from the more fragmented and vulnerable landscapes of Masako and Mbiye.

The Yoko Forest landscape, despite experiencing anthropogenic expansion in its northern section (Fig. 2), remains relatively well preserved. However, some indicators reveal emerging risks. Notably, the interior-to-edge (I/E) ratio has declined significantly at edge-effect distances of approximately 200 m, indicating an increased vulnerability of interior forest areas to peripheral disturbances. These findings underscore the urgent need for targeted management interventions to maintain ecological function and prevent further degradation.

4.3 Effective and resilient strategies

Based on the observed patterns of forest loss and fragmentation, our results suggest that priority actions could include identifying and protecting remnant forest patches in Masako and Mbiye, which may serve as ecological cores supporting natural regeneration. These core areas could potentially be managed as strictly protected zones to maintain habitat refugia and provide local seed sources for forest recovery. Enhancing ecological connectivity by establishing forest corridors linking isolated patches may help mitigate edge-related microclimatic stress and facilitate species movement, potentially combining natural regeneration with reforestation using native species. Agroforestry systems around these patches and corridors might act as buffers, helping to reduce pressure on remaining forests while also supporting local subsistence needs.

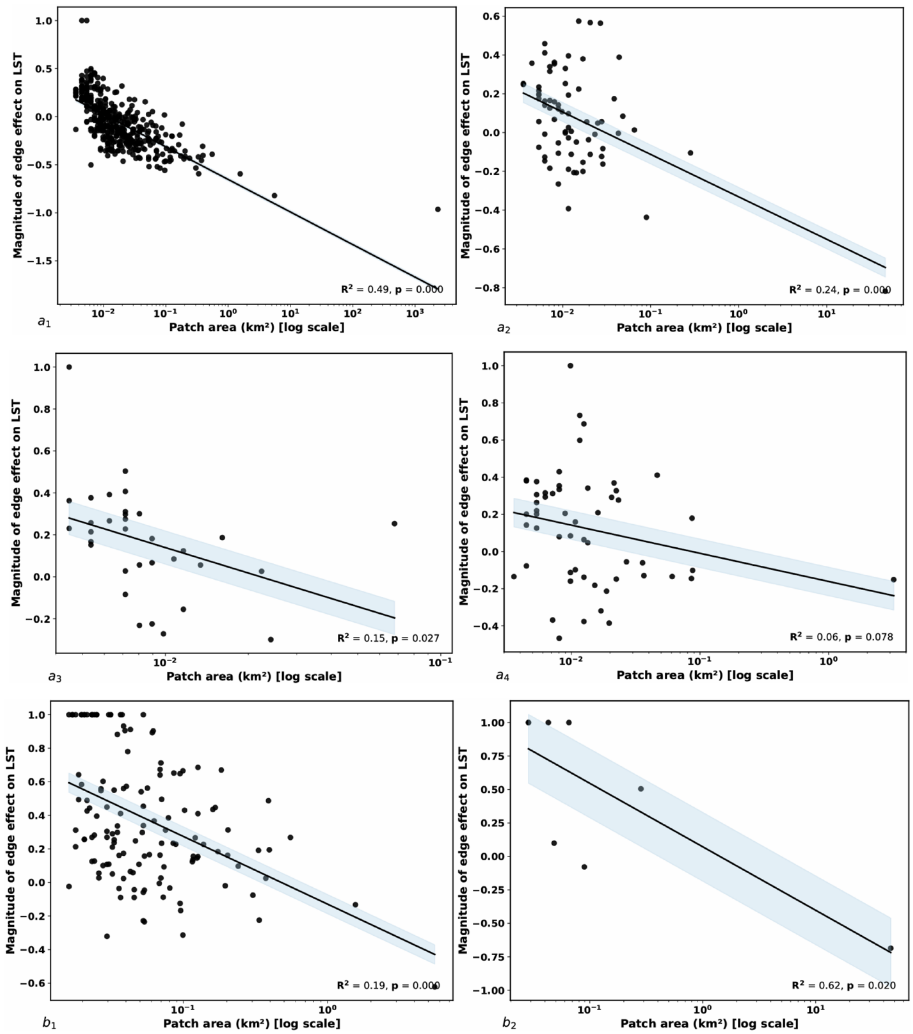

Fig. 9 Variation in edge effect magnitude (LST) as a function of patch size in four protected forest landscapes near Kisangani: Yangambi (**a_1**), Yoko (**a_2**), Masako (**a_3**), and Mbiye (**a_4**) within 20 m of the forest edge; Yangambi (**b_1**) and Yoko (**b_2**) within 50 m. The analysis reveals a negative relationship between patch size and the magnitude of edge effects on Land Surface Temperature. Larger patches exhibit lower magnitudes of edge influence, suggesting a reduced impact of thermal disturbances in more extensive forest remnants. This attenuation likely results from higher core-to-edge ratios, which limit the spatial extent of edge-exposed forest zones

Unregulated wood extraction and charcoal production have contributed to fragmentation, and the results indicate that community-based management strategies could help formalize these practices and reduce ecological impact. Additionally, integrating forest conservation into spatial planning around Kisangani, such as maintaining exclusion zones around remaining forest patches, may help mitigate pressures from urban expansion.

Overall, the results highlight that restoration and management strategies could aim to balance conservation objectives with local land-use needs, with measures directly informed by observed patterns of forest loss, fragmentation, and microclimatic stress.

5 Conclusion

This study examined the historical trends of forest fragmentation and measured the extent of edge-affected forest areas across four Forest landscapes near Kisangani, Democratic Republic of the Congo: Masako, Mbiye, Yoko, and Yangambi. Additionally, it examined the relationship between forest patch size and the magnitude of edge influence, using Land Surface Temperature (LST) as an indicator of edge-related ecological stress. By using satellite data from 1986 to 2024 and applying a suite of spatial landscape metrics, the study quantified changes in both forest composition and spatial configuration.

Spatial metrics revealed significant forest loss and fragmentation in Masako and Mbiye. Between 1986 and 2024, over 80% of the forest area was lost in Masako and Mbiye, while Yangambi retained over 90% of its original forest area, and Yoko preserved more than 60%, indicating relatively higher resilience. Edge-effect metrics confirm that forest patches in Masako and Mbiye are more vulnerable to edge disturbances, with interior forest patches having almost entirely disappeared by 2016 across all edge distances (50, 100, 150, and 200 m). By contrast, Yangambi and Yoko have maintained higher levels of forest cover and larger, more connected patches, reflecting greater resilience to fragmentation. LST analyses showed that smaller, more fragmented patches are more vulnerable to edge-related thermal stress, whereas larger patches mitigate these effects. However, this relationship is weaker in severely degraded landscapes, likely because the remaining forest patches are small and highly isolated, limiting their capacity to influence local thermal conditions.

By integrating structural and thermal indicators, this study provides a robust assessment of forest integrity across the Democratic Republic of the Congo's forested landscapes, at the core of the Congo Basin. The results underscore the importance of protecting remnant forest cores, maintaining landscape connectivity, and accounting for patch-size effects in conservation planning, thereby offering general guidance for landscape-scale management.

Author contributions
J.B.B: Data collection and analysis, wrote the first draft of the article, J.B.B., J.-P.P.M.T.H., K.R.S., Y.U.S., J.-F.B., LIWM and J.B.: Conceptualization, methodology, and formal analysis J.B.B., JMT: were responsible for proofreading the text J.B.: Validation and supervision.

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Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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