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Analysis of Forest Cover in the Tumba-Lediima Nature Reserve (RTL-DRC)

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Abstract: This study analyzes the evolution of forest cover in the Tumba-Lediima Nature Reserve between 2010 and 2022, a period marked by increasing anthropogenic pressures. The main drivers of deforestation identified are agricultural expansion, illegal exploitation of forest resources and urbanization. These activities have led to the fragmentation of critical habitats, putting endemic and threatened species at risk, while also compromising the ecological integrity of the reserve. Furthermore, local communities face diminished livelihoods due to reduced access to natural resources. These dynamics lead to a critical loss of biodiversity, affecting critical habitats and compromising the livelihoods of local communities. Using Landsat 7 and 8 satellite imagery, combined with NDVI calculation and supervised classifications validated by a high Kappa coefficient, this study provides an accurate mapping of land cover change. The results reveal an alarming reduction in primary forest cover, accompanied by an increase in secondary forests and fallow land, suggesting limited potential for regeneration. This pattern underscores the urgent need to address the drivers of deforestation through targeted actions. These trends call for urgent conservation measures, including the targeted regeneration of degraded areas, the strengthening of environmental laws and the integration of local communities in the sustainable management of resources. By proposing concrete strategies in the short, medium and long term, this study offers essential perspectives for preserving the biodiversity and ecological resilience of the reserve. By proposing actionable strategies in the short, medium, and long term, this study provides a roadmap for preserving not only the biodiversity and ecological resilience of the reserve but also offers scalable solutions for similar tropical forest regions facing comparable challenges.

Keywords: Deforestation, Anthropogenic impact, Tropical Forest, Protected area

INTRODUCTION

Forests play a crucial role in producing oxygen, regulating the climate, hosting exceptional biodiversity, and providing vital natural resources. Their deforestation and degradation represent major global challenges, affecting biodiversity, the climate, and local communities (Hisano et al. 2018). In the Democratic Republic of Congo (DRC), forests cover a vast area and are a cornerstone for the livelihoods of local populations. According to the DRC's Forest Code, these ecosystems are home to unique species and significantly influence soils, climate, and water regimes. Despite their importance, a systematic understanding of forest dynamics in many protected areas remains limited.

The Tumba-Lediima Nature Reserve, located in a region marked by increasing human expansion, perfectly illustrates these challenges. In 2018, approximately 55.5% of Congolese lived in rural areas, directly dependent on natural resources (Liu, 2018). Agriculture, infrastructure projects, the use of wood as an energy source, and the illegal exploitation of resources all represent anthropogenic pressures on this reserve (Hourticq et al., 2013). Moreover, recent studies, such as Frayssinhes (2023), Touron-Gardic et al. (2024), and Fesenfeld et al. (2023), highlight the aggravating role of climate change and infrastructure on deforestation rates. These pressures have been extensively studied in other tropical forests, but there is a significant gap in research focusing specifically on protected areas like the Tumba-Lediima Reserve. In particular, there is a lack of integration of advanced geospatial techniques to monitor the long-term dynamics of forest cover in this region.

This research aims to fill this gap by implementing an innovative methodology combining Landsat imagery and Geographic Information Systems (GIS). The use of Landsat data, with its extensive temporal coverage and medium spatial resolution, provides an unprecedented opportunity to study forest changes over a long period (2010–2022). Although prior studies have utilized similar datasets, few have focused on the spatio-temporal dynamics within the Tumba-Lediima Reserve, a region of significant ecological and socio-economic importance. Unlike previous works that primarily target better-studied regions or use limited methodologies, this study employs advanced remote sensing techniques such as Normalized Difference Vegetation Index (NDVI) calculations and supervised classification to produce high-quality, actionable data.

The main research question is: What has been the historical evolution of forest cover in the Tumba-Lediima Nature Reserve, and which areas have been most affected by deforestation? Answering this question is crucial for preserving the unique biological richness of the reserve, which is home to numerous plant and animal species, some of which are endemic or threatened. Furthermore, this study contributes to the growing body of research on tropical forest conservation by focusing on a protected area often overlooked in global deforestation studies.

This study hypothesizes that deforestation has significantly increased in areas under anthropogenic pressure, such as those accessible or near human settlements. By leveraging the combined power of Landsat imagery and GIS, it aims not only to document land cover changes but also to identify the underlying drivers of deforestation. This approach is built upon the works of Ouattara et al. (2021) and Fossati (2024), who demonstrated the value of remote sensing in tropical forest monitoring, while applying these techniques in a novel context and scale.

The originality of this research lies in the integrated use of advanced geospatial methodologies and recent data to address critical conservation gaps. This approach not only fills the void left by previous studies but also provides concrete recommendations for the sustainable management of forest resources. The results will have broader implications for the conservation of tropical forests in similar regions, offering a model for balancing ecological preservation with socio-economic realities.

SITE, MATERIALS & METHODS

Site Description

The Tumba-Lediima Reserve (RTL), created in 2006 by a ministerial decree, covers a vast area of 750,000 hectares, located at the geographical coordinates 1°28'48" S and 17°15'0" E. It encompasses three territories: Inongo (Mai-Ndombe province), Bikoro and Lukolela (Equateur province) in the Democratic Republic of Congo (Figure 1).

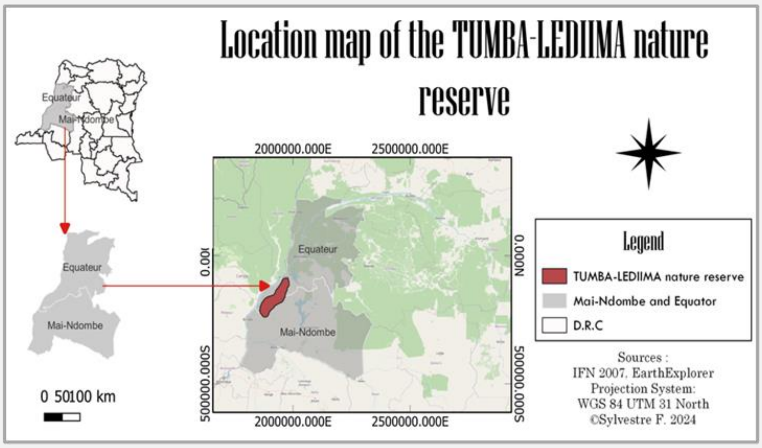

Figure 1. Location map of the TUMBA-LEDIIMA nature reserve.

This site is distinguished by its exceptional biodiversity, home to iconic species such as eastern lowland gorillas, forest elephants and many endemic plant and animal species. In addition to its ecological importance, the reserve plays a vital role for local communities, who depend directly on its natural resources for their livelihoods, including through hunting, fishing and subsistence farming.

The reserve is under heavy threat from human activities such as deforestation, poaching and illegal hunting, exacerbated by increasing pressure from agricultural expansion and infrastructure. The geographical position of the reserve, located in a region where socio-economic dynamics lead to high deforestation, makes it an ideal terrain to study the impacts of human activities on tropical rainforests.

The specificity of the Tumba-Lediima Reserve also lies in its transitional situation between still intact primary forests and degraded areas in regeneration, offering a unique opportunity to understand the processes of deforestation and regeneration. This feature allows for better documentation of changes in land use and for the development of conservation strategies applicable to other similar tropical regions. As a representative microcosm of global pressures on tropical forests, RTL provides an ideal framework to study the complex dynamics between conservation, human development and sustainability.

Materials

The assessment of the evolution of vegetation cover in the Tumba-Lediima Nature Reserve (RTL) is based on the use of three main categories of data: satellite images and field surveys. The choice of the periods studied (2010 and 2022) is based on the availability of satellite images and the years during which developments were carried out. However, the availability of images poses a major challenge due to the geographical location of the reserve at the equator, near the Atlantic coast. This geographical position has a negative impact on optical satellite sensors, resulting in a constant presence of clouds on the images.

To produce the land cover map, we used sets of images from the Landsat-7 and Landsat-8 satellites. The choice of these two satellites is justified by the period covered by this study. Since the first survey was in 2010 and the Landsat-8 satellite was launched into orbit on February 11, 2013, we had to use the images from the Landsat-7 satellite for years prior to 2013. The study area is delimited by the path and row 181061 coordinates. The processing of these images was carried out using the Envi 5.3 and Terrset software. The spatial analysis and the production of land cover maps were carried out using QGIS. In addition, a Garmin GPS was used to take a few points in the field.

Methods

The main method of this research was observation, supplemented by a few other approaches, as mentioned below:

Extracting the study area

The study area, corresponding to the Tumba-Lediima Nature Reserve, was delineated using vector files (shapefile). This extraction allowed for an exclusive focus on the region of interest, as shown in Figure 2.

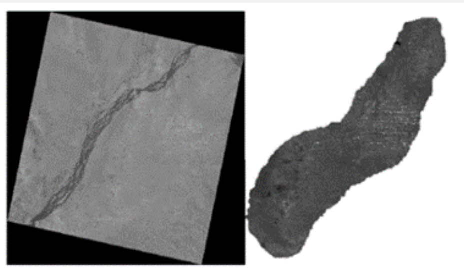

Figure 2. Procedure for extracting the study area.

Radiometric correction has been applied to satellite images to improve their quality and facilitate interpretation (Tabopda et al., 2010). This step converted the raw numerical values into calibrated data to better reflect the actual characteristics of the Earth's surface (Chander et al., 2009). QGIS was used to correct visual defects, especially for the 2010 images where cloud cover issues were present.

Landsat data 7 and 8 were chosen because of their availability over the study period (2010-2022) and their relevance for long-term monitoring of forest ecosystems. Although equatorial regions such as the DRC pose challenges, including persistent cloud cover, these satellites offer sufficient temporal and spectral resolution to document changes in land use. The use of Landsat 7 for periods prior to 2013 and Landsat 8 for subsequent data ensured consistency in the analyses, while minimizing biases caused by local climatic conditions.

Normalized Difference Vegetation Index (NDVI)

The NDVI index was used to assess vegetation cover. This index, calculated according to the formula below (Avotins et al. 2020):

$$NDVI = \frac{(Band\ 5 - Band\ 4)}{(Band\ 5 + Band\ 4)} \quad (1)$$

It measures the density and health of vegetation. The calculations were carried out on QGIS, making it possible to distinguish areas of dense vegetation from bare soil or built-up areas. This process has been simplified to ensure better understanding without compromising the accuracy of the results.

Colour composition and classification

After extracting the study area, performing the radiometric calibration, and calculating the NDVI, artificial color combinations were created by associating Band 5 (mid-infrared) with the red channel, Band 4 (near-infrared) with the green channel, and Band 3 (red) with the blue channel.

The method aims to improve the perception of vegetation, as the variation in humidity is particularly visible with this configuration. Some authors, notably Chatelain (1996) and Girard (1999), have emphasized the importance of these bands. Band 5 is used to characterize the different types of vegetation (Chatelain, 1996). The near infrared (band 4) is used to establish the typology of vegetation, making it possible, for example, to distinguish bare soils, agriculture, etc. (Girard, 1999). Band 3 is related to the chlorophyll absorption wavelength (Chatelain, 1996).

A supervised classification was carried out to identify the different land cover classes (primary forest, secondary forest, bare and built-up soils, fallow land). The method relied on learning zones defined from pixel coloration, with algorithms included in the TerrSet software. Classification validation was performed via a confusion matrix and a Kappa coefficient, which measure the overall accuracy of the classifications. The Kappa coefficients obtained (greater than 0.8) indicate a very satisfactory agreement between the classified maps and the field data.

Sampling and validation procedures

The samples for each land cover class were selected according to their spectral separability. These learning areas were validated by field surveys, carried out using Garmin GPS. These surveys confirmed the representativeness of the satellite data, thus guaranteeing a reliable analysis. Particular attention has been paid to areas with high population density and close to infrastructure, where human impacts are most pronounced.

General Classification Approach

After acquiring the images, an interpretation process is conducted to stratify land use. The samples selected for each class are assessed based on their separability. A confusion matrix is used to evaluate the classification accuracy.

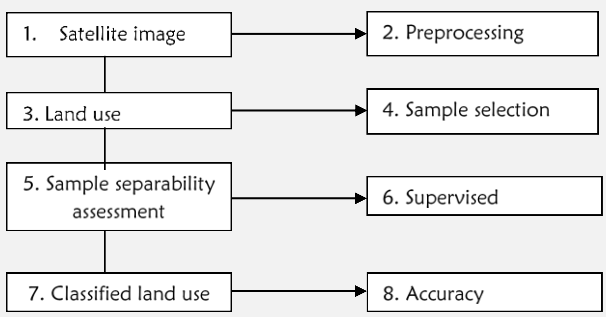

Figure 3. Diagram of the General Classification Approach.

Calculation of the deforestation rate

It is necessary to find the rate of deforestation in the area between the two dates. Thus, it should be noted that there are several formulas for calculating the rate of deforestation. The deforestation rate was calculated using the following formula:

$$\text{Deforestation rate} = \frac{\text{Initial forest area} - \text{final forest area}}{\text{Initial forest area}} \times 100 \quad (2)$$

with the initial forest area represents the area of forest at the beginning of the reporting period and final forest area represents the area of forest at the end of the reporting period.

This method made it possible to assess the extent of forest loss between 2010 and 2022. The rates obtained were classified according to the thresholds defined by Catalan et al. (1991), ranging from low (< 0.5%) to maximum (> 3%), thus providing a clear understanding of the deforestation dynamics within an area.

Table 1. Deforestation Qualifications

Annual deforestation rates in %	Qualification
< 0.5	Low
0.5-1.5	Medium
1.5-3.0	High
>3.0	Highest

Workflow Diagram of Methodology

Figure 4 shows the workflow of the methodology for this study, starting with the extraction of the study area and ending with the calculation of the deforestation rate.

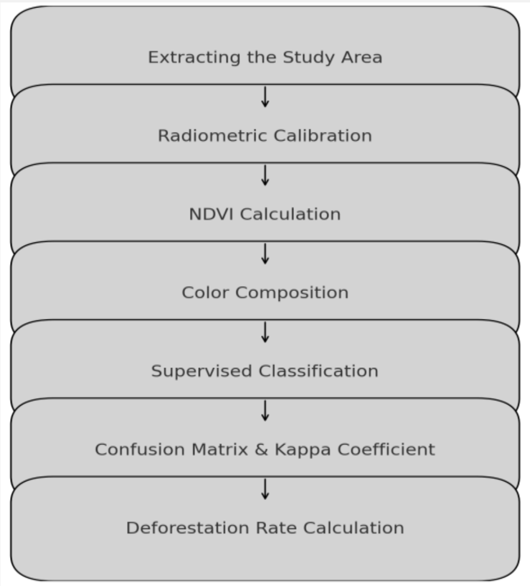

Figure 4. Workflow Diagram of Methodology.

Supervised classification algorithms play a central role in the identification of land cover classes. Among them is the Random Forest, a robust algorithm that combines multiple decision trees to assign a class to each pixel, based on majority votes. This model is particularly suitable for noisy and large data, such as that from satellites. Another frequently used algorithm is the Support Vector Machines (SVM), which is based on the creation of an optimal hyperplane to separate the different classes in a multidimensional space. These algorithms require well-defined learning zones, selected on satellite images according to their representativeness for each class (primary forest, secondary forest, etc.). These areas are used to train the models that then generalize the classification to all pixels in the image, producing detailed maps of land cover types.

The confusion matrix is a crucial tool for validating the results of classification algorithms. It compares the classes assigned by the model to the actual data collected in the field, providing a measure of accuracy for each class. The Kappa coefficient is then calculated to assess the overall reliability of the classification, considering the expected concordances due to chance. A Kappa value greater than 0.8

indicates excellent algorithm performance. These tools make it possible to measure the quality of the algorithms used, such as the Random Forest and the SVM, and to ensure that the results accurately reflect the realities on the ground.

RESULTS

NDVI of the study site

The Normalized Difference Vegetation Index (NDVI) values for the 2022 scene range between 0.4 and 0.03, indicating a moderate to high density of vegetation. NDVI is a widely used index for measuring and monitoring plant growth, vegetation cover, and biomass production from satellite data. The observed values in the positive range (0 to 1) confirm the presence of healthy vegetation. Specifically, higher NDVI values (closer to 1) typically represent dense vegetation such as forests or croplands, while lower values (closer to 0) can indicate sparse vegetation or bare soil. The results suggest a heterogeneous landscape with patches of dense vegetation, possibly including areas of primary forest, secondary forest, and agricultural land.

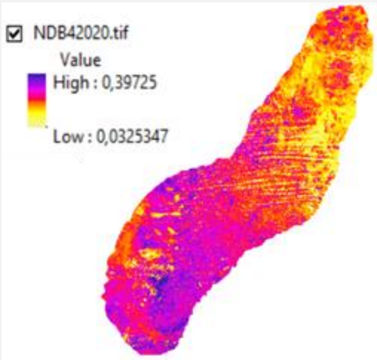

Figure 5. NDVI of the Tumba-Lediima scene.

Moderate to high NDVI values in 2022 show that the Tumba-Lediima Nature Reserve maintains substantial vegetation cover, despite increasing anthropogenic pressures. The areas with the highest NDVI values are likely to correspond to relatively intact primary forests, which support unique biodiversity and represent critical habitats for local species. These areas remain untouched by the most destructive human activities, such as illegal logging and agricultural expansion, but require enhanced protection to prevent future degradation.

In contrast, areas with lower NDVI reveal significant impacts of human activities, including slash-and-burn agriculture and land conversion to non-forest uses. These areas of secondary forest or agricultural land show altered vegetation, highlighting the need for targeted interventions. Sustainable management practices, such as reforestation and the introduction of agroforestry, could help restore these areas and strengthen the ecological resilience of the reserve. This heterogeneity of NDVI values reflects the varying impacts of anthropogenic pressures in the different parts of the reserve. Identifying areas with low NDVI as priorities for reforestation and the adoption of sustainable practices will reduce the effects of human activities on forest cover.

Confusion Matrices

Confusion matrices were generated post-classification to evaluate the accuracy of the classification models for the years 2010 (Table 2) and 2022 (Table 3). These matrices compare the predicted land cover classes with actual field data to determine the precision of the classifications.

The confounding matrices were used to assess the performance of the classifications for the years 2010 and 2022. In 2010, primary forests (FP) and fallow (J) had the highest accuracy rates, reaching 91.56% and 87.9%, respectively. In 2022, although the accuracy of primary forests decreased to 78%, secondary forests (SFs) and follow maintained high levels of accuracy, with values of 75% and 76%, respectively. These results demonstrate a reliable correspondence between classifications and field data, but also reveal significant transitions in land cover, influenced by increasing anthropogenic pressures.

The bare soil and built-up area (SB) class showed lower accuracy, likely due to the spectral similarity between these two canopy types, which complicates their differentiation. To improve the distinction between these classes, the integration of high-resolution data or the use of radar observations could be considered.

Table 2. Matrices of Confusion (2010)

Classes	SB	FP	FS	J
SB	66	0	0,95	4,1
FP	12,05	91,56	19,02	0
FS	11,19	8,27	63,86	8
J	10,76	0,17	16,17	87,9
Total	100	100	100	100

Kappa coefficients: K=0,9188

Table 3. Matrices of Confusion (2022)

Classes	SB	FP	FS	J
SB	68	0	0,9	7
FP	13	78	10	0
FS	8,1	10	75	17
J	9,9	3	9	76
Total	100	100	100	100

Kappa coefficients: K=0,8688

The Kappa coefficients, calculated at 0.9188 in 2010 and 0.8688 in 2022, confirm the strong agreement between classified data and field observations. Values greater than 0.8, such as those obtained, generally reflect the excellent reliability of the classification models. These high rates validate the accuracy of the classifications and underline the robustness of the methods used. The decrease in the Kappa coefficient between 2010 and 2022 reflects the challenges posed by changing land cover dynamics, requiring potential improvements in models and data sources to maintain optimal performance.

Land Use Map

The 2010 and 2022 land cover maps of the Tumba-Lediima Reserve (Figure 6) provide a visual representation of the spatial distribution and proportions of four land cover classes: bare and built-up land (SB), primary forest (PF), secondary forest (FS) and fallow land (J). These maps reveal significant changes in land use over the study period, highlighting a decrease in forest cover and an increase in urban and agricultural areas.

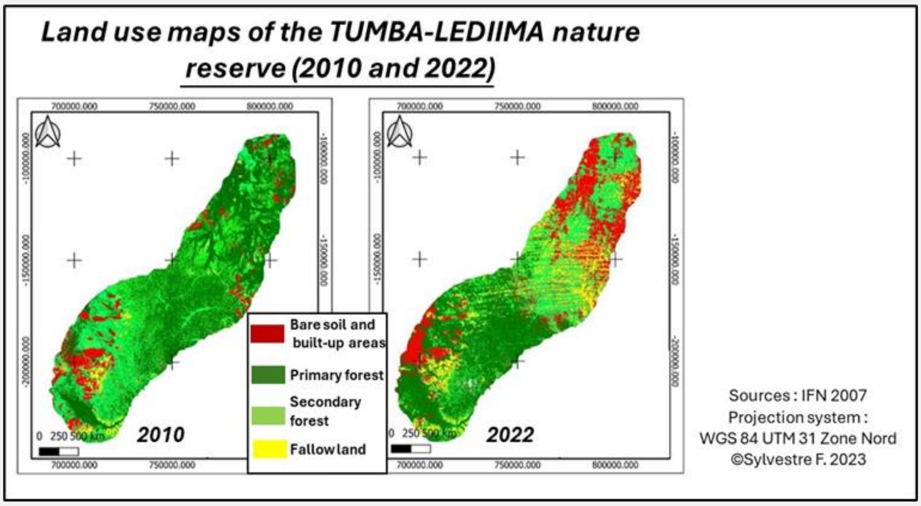

Figure 1. Land use mapping in the Tumba-Lediima reserve between 2010 and 2022.

They show a 13.7% decrease in the area of primary forests between 2010 and 2022, accompanied by an increase in secondary forests (+4.9%), bare and built-up land (+4.6%), and fallow land (+4.2%). These transitions suggest several key dynamics:

Loss of primary forests: Primary forests are shrinking mainly in the northern part of the reserve, where agricultural expansion, illegal logging and urbanization are under increasing pressure. This trend is alarming because it directly affects biodiversity and critical ecosystem services.

Increase in secondary forests: This increase reflects natural regeneration processes or the degradation of primary forests into secondary forests. Although these areas are often seen as opportunities for ecological restoration, they do not compensate for the loss of biodiversity associated with primary forests.

Expansion of summer fallow and bare land: The increase in summer fallow (+4.2%) could indicate longer agricultural cycles or temporarily abandoned areas. These lands, although in transition, could represent opportunities for reforestation or agroforestry programs.

Land cover dynamics as a percentage of classes

Figure 7 display the percentage changes in land cover classes between 2010 and 2022.

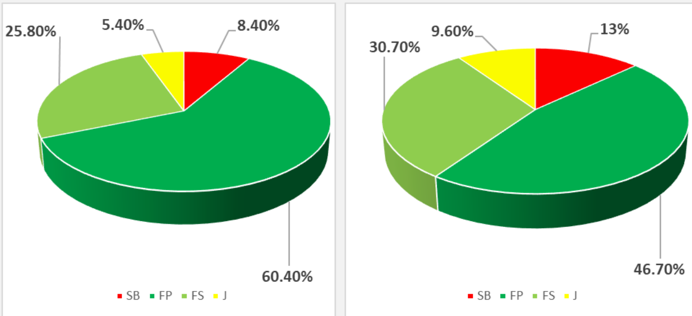

Figure 2. Evolution of the surface area of land cover classes between 2010 and 2022.

Table 4. Changes in Land Cover Classes from 2010 to 2022

Land Cover Class	2010 (%)	2022 (%)	Change (%)
Primary Forest (FP)	60.4	46.7	-13.7
Bare and Built Land (SB)	8.4	13.0	+4.6
Secondary Forest (FS)	25.8	30.7	+4.9
Fallow Land (J)	5.4	9.6	+4.2

Percentage analysis in Table 4 shows a 13.7% decrease in primary forest area, reflecting a significant loss of mature forest cover. Conversely, the areas of bare and built-up land (SB), secondary forest (SF) and fallow land (J) have increased, indicating a shift towards urbanization and more intensive agricultural practices. In the northern part of the reserve, vegetation cover has decreased due to agricultural expansion and illegal logging, corroborated by local accounts of conflict between residents and managers of the reserve. The high population density in this region, mainly devoted to agriculture and firewood production, further exacerbates deforestation pressures.

This significant reduction in primary forest cover is alarming as it not only indicates a loss of biodiversity, but also highlights the potential for increased carbon emissions due to deforestation. Increased secondary forest cover may suggest areas for regrowth or reforestation efforts, although these are often less diverse and mature than primary forests. The increase in bare and built-up land indicates urban sprawl and infrastructure development, further fragmenting the forest landscape. The observed increase in fallow could indicate changes in agricultural practices, perhaps towards more sustainable forms of land use or reflecting areas left to regenerate naturally after cultivation.

These findings are consistent with previous studies conducted in other tropical regions. For example, Simeon et al. (2024) documented similar trends near urban areas in the Kinshasa and Lubumbashi regions, where anthropogenic pressures, such as agricultural expansion and demand for firewood, accelerate deforestation. Similarly, Ahrends et al. (2010) in Tanzania and Fonge et al., (2019) in Cameroon observed similar dynamics, where proximity to urban areas contributes to the gradual encroachment on tropical forests.

Local observations in the Tumba-Lediima Reserve corroborate these global trends. The high population density in adjacent areas leads to increased exploitation of forest resources to meet food and energy needs. These findings underscore the urgency of strengthening conservation efforts and integrating sustainable agricultural practices to limit impacts on forest cover.

The transition matrix of the Tumba-Lediima Reserve

Table 5 presents the transition matrix of the Tumba-Lediima reserve, with the legend SB (Bare and built soil), FP (Primary Forest), FS (Secondary Forest) and J (Fallow).

Table 5. Transition matrix from 2010 to 2022

	SB	FP	FS	J	Total
SB	2,1	0,0	7,5	3,4	13,0
FP	0,5	46,2	0,0	0,0	46,7
FS	2,8	7,9	18	2,0	30,7
J	3,0	6,3	0,3	0,0	9,6
Total	8,4	60,4	25,8	5,4	100

The transition matrix of the Tumba-Lediima Reserve highlights major changes in land cover types between 2010 and 2022. Primary forest (PF) has declined significantly from 60.4% to 46.7%, representing a substantial loss of mature forest cover. This transition is mainly due to the shift from primary forest areas to secondary forests (7.9%) and bare and built-up land (0.5%). These results illustrate not only the increasing anthropogenic pressures, but also the fragility of these critical ecosystems in the face of agricultural expansion, urbanization and illegal logging.

Secondary forests (SFs) increased from 25.8% to 30.7%, which may reflect natural regeneration processes or degradation of primary forests. This dynamic can be interpreted as a potential for ecological recovery, but it is essential to note that secondary forests often offer lower biodiversity and ecosystem services than primary forests. This change highlights the need for management policies that promote the conservation of primary forests while supporting the sustainable regeneration of secondary areas.

The category of bare and built soil (SB) has seen a significant increase from 8.4% to 13%. This clearly reflects the impact of urban sprawl and infrastructure, which further fragment forest landscapes. An increase in fallow (J), from 5.4% to 9.6%, suggests a change in agricultural practices, where some land may have been temporarily abandoned or left for natural regeneration. This could indicate a shift towards more sustainable land use or a transition to other uses.

DISCUSSION

Detailed analysis of the transition matrix and its implications

The transition matrix between 2010 and 2022 shows that 7.9% of primary forests (PF) were converted to secondary forests, 0.5% to bare and built-up land, and 6.3% to fallow. These transitions illustrate a complex interplay of ecosystem degradation and opportunities for natural regeneration. The PF → SF transition reflects moderate anthropogenic pressures, such as selective logging, which gradually degrades primary forest ecosystems without causing complete loss. However, this transition remains a concern, as it is accompanied by a loss of biodiversity and a decrease in ecosystem services, including carbon sequestration (Chazdon et al., 2009).

The conversion of primary forests to bare and built-up land (+4.6%) highlights the direct impact of urbanization and infrastructure development on critical ecosystems. For instance, road construction facilitates access to forest areas, amplifying illegal resource extraction (Stauffer et al., 2017). While the increase in fallow land (+4.2%) and secondary forests (+4.9%) suggests some potential for natural regeneration, these ecosystems remain less ecologically efficient than primary forests (Poorter et al., 2016). These dynamics underscore the need for conservation and restoration policies aimed at promoting reforestation and directed regeneration of degraded areas.

Correlation between human activities and deforestation

Anthropogenic pressures, such as agricultural expansion and urbanization, appear to be major drivers of the observed transitions. The sharp increase in bare and built-up land is directly linked to population growth and the rising demand for agricultural land and infrastructure. Roads and human settlements exacerbate forest fragmentation, enabling illegal logging and uncontrolled agricultural expansion.

This finding aligns with Laurance et al. (2014), who argue that reducing the distance between forests and human settlements accelerates deforestation. To mitigate these impacts, regional policies should include the establishment of buffer zones around primary forests and the promotion of sustainable agricultural practices. Creating ecological corridors to connect fragmented forests could also enhance ecosystem resilience to these pressures.

Comparisons with previous studies

The dynamics observed in the Tumba-Lediima Reserve reflect similar trends in other tropical regions. Simeon et al. (2024) and Muteya et al. (2022) demonstrated that proximity to urban areas is a key driver of deforestation due to increased agricultural and energy demands.

Likewise, in Tanzania (Ahrends et al., 2010) and Cameroon (Fonge et al., 2019), road infrastructure and human settlements have significantly increased forest landscape fragmentation. These comparisons highlight the need for global solutions to combat deforestation while accounting for local specificities.

Regional context and trends

In the provinces of Mai-Ndombe and Equateur, canopy alterations are particularly pronounced along roads and streams, which facilitate forest access. The construction of road infrastructure often attracts migrant populations, leading to land-use changes (Stauffer et al., 2017).

This trend is consistent with Arroyo-Rodríguez et al. (2017), who showed that limited accessibility reduces human pressures on forests. Our findings align with these dynamics, as the transition matrix demonstrates a significant conversion of primary forests into bare and built-up land or fallow.

Methodology and reliability of results

The use of Landsat 7 and 8 imageries, coupled with advanced supervised classification techniques, produced reliable results, as evidenced by the high Kappa coefficients (0.9188 in 2010 and 0.8688 in 2022). However, to improve differentiation of complex classes such as bare and built-up land, integrating high-resolution satellite data, such as those provided by Sentinel-2, would be valuable (Chen et al., 2021).

CONCLUSION

This study highlighted the strategic role of remote sensing and GIS in the management and preservation of the natural resources of the Tumba-Lediima Reserve. Analysis of land cover change between 2010 and 2022 revealed significant transitions, including an alarming reduction in primary forests in favour of secondary forests, bare and built-up land, and fallow. These dynamics illustrate the increasing pressures exerted by human activities, such as agricultural expansion and urbanization, on the critical ecosystems of the reserve.

The results of this research highlight the need for an integrated, multisectoral approach to curb deforestation and promote sustainable land management. In this regard, the following recommendations are made:

- Strengthening environmental policies and laws by:
  - Establishing legal measures to limit illegal logging, regulate agricultural expansion and protect areas of high ecological value.
  - Establish buffer zones and ecological corridors: Develop a zoning plan that identifies and protects key habitats while connecting fragmented ecosystems. These measures would help maintain biodiversity and improve the resilience of landscapes to anthropogenic pressures.
- Raising awareness and engaging local communities in:
  - Educational programmes with the organisation of awareness campaigns focusing on the ecological and socio-economic importance of forests. These programmes should include training on agroforestry, sustainable agricultural practices and alternative livelihoods.
  - Partnering with communities, involving local people in deforestation monitoring, restoration initiatives and natural resource management. This could include the creation of community management committees to ensure their long-term commitment.
- Promoting sustainable land management by:
  - Prioritizing the restoration of degraded areas, including bare land and fallow, through direct or natural reforestation initiatives.
  - Integrating agroforestry with agricultural systems combining forest production and conservation, which can reduce pressure on primary forests while supporting local food security.
- Improvement of local and technical capacities with:

- Remote sensing and GIS training to strengthen the skills of local actors in the use of modern technologies to monitor land cover change and assess the impact of environmental policies.
- Real-time monitoring by setting up a remote sensing-based tracking system to quickly detect changes and enable immediate interventions.

▪ For international collaboration and support:
  - Seek the support of international organizations to provide sustainable funding and conservation expertise.
  - Foster exchanges with other tropical regions facing similar challenges to adapt best practices.

This study demonstrates that GIS and remote sensing can be deployed on a larger scale to monitor land cover transitions and identify critical areas requiring intervention. In other tropical regions, these tools can be used to:

▪ Detect illegal activities, such as logging or poaching, using real-time satellite imagery.
▪ Evaluate the effectiveness of conservation initiatives and adjust strategies accordingly.
▪ Map ecological corridors to connect habitat fragments and promote ecological connectivity.

Finally, this study provides a solid foundation to guide conservation efforts in Tumba-Lediima and beyond. The combination of wise management, community engagement and the use of modern technology will preserve this reserve for future generations. By acting now, decision-makers can limit ecological losses and ensure a sustainable future for the region's critical ecosystems.

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