Article

Not peer-reviewed version

Hierarchical Analysis of Miombo Woodland Spatial Dynamics in Lualaba Province (DR Congo), 1990-2024: Integrating Remote Sensing and Landscape Ecology Techniques

Yannick Useni Sikuzani , Médard Mpanda Mukenza * , John Kikuni Tchowa , Delphin Kabamb Kanyimb , François Malaisse , Jan Bogaert *

Posted Date: 2 September 2024

doi: 10.20944/preprints202409.0072.v1

Keywords: Deforestation; Biodiversity conservation; Anthropogenic pressures; Remote sensing; Landscape analysis; Protected areas

Article

Hierarchical Analysis of *Miombo* Woodland Spatial Dynamics in Lualaba Province (DR Congo), 1990–2024: Integrating Remote Sensing and Landscape Ecology Techniques

Yannick Useni Sikuzani [1], Médard Mpanda Mukenza [2,*], John Kikuni Tchowa [3], Delphin Kabamb Kanyimb [4], François Malaisse [5] and Jan Bogaert [5,*]

[1] Unité Ecologie, Restauration Ecologique et Paysage, Faculté des Sciences Agronomiques, Université de Lubumbashi, Lubumbashi P.O. Box 1825, Democratic Republic of the Congo; sikuzaniu@unilu.ac.cd
[2] Département de Gestion des Ressources Naturelles Renouvelables, Faculté des Sciences Agronomiques, Université Technologique Katumba Mwanke, Lubumbashi P.O. Box 74, Democratic Republic of the Congo; mpandamedard@gmail.com
[3] Département de Phytotechnie, Faculté des Sciences Agronomiques, Université de Kolwezi, Kolwezi, RD Congo; kikunitchowajohnw@gmail.com
[4] Ecole Régionale Postuniversitaire d'Aménagement et de Gestion Intégrés des Forêts et Territoires Tropicaux, Kinshasa P.O. Box 15373, Democratic Republic of the Congo; delphinkabamb@gmail.com
[5] Unité Biodiversité et Paysage, Gembloux Agro-Bio Tech, Université de Liège, 5030 Gembloux, Belgium; malaisse1234@gmail.com (F.M.) ; j.bogaert@uliege.be (J.B.)
* Correspondence: mpandamedard@gmail.com (M.M.M.); j.bogaert@uliege.be (J.B.)

Abstract: Lualaba Province, located in the southeastern Democratic Republic of the Congo, consists of five territories with varied dominant land uses: agriculture (Dilolo, Kapanga, and Musumba in the west) and mining (Mutshatsha and Lubudi in the east). The province also includes protected areas with significant governance challenges. The unique miombo woodlands of Lualaba are threatened by deforestation, posing risks to biodiversity and local livelihoods that depend on these woodlands for agriculture and forestry. To quantify the spatio-temporal dynamics of Lualaba's landscape, we utilized Landsat images from 1990 to 2024, supported by a Random Forest Classifier. Landscape metrics were calculated at multiple hierarchical levels: province, territory, and protected areas. Our provincial-level analysis revealed a pronounced deforestation trend, with miombo woodland cover declining from 62,90 % to less than 25 % over the 34-year period. This trend was characterized by the fragmentation and dissection of woodland patches and a decline in remaining woodland fragments, due to their ongoing replacement by savannas, agriculture, and urbanization. The average distance between miombo woodland patches increased significantly, indicating heightened fragmentation and spatial isolation. Agricultural areas such as Sandoa and Kapanga were particularly vulnerable to deforestation. On the other hand, the miombo forest cover in the mining areas is still representative, with over 30% of the landscape covered. Notably, the reduction in woodland cover within protected areas was substantial, with significant losses observed across both agricultural and mining territories. The loss of miombo woodland cover in Lualaba and its territories was accompanied by an increase in landscape patch diversity, as indicated by the Shannon diversity index, suggesting a shift to more heterogeneous landscapes. These findings underscore a complex deforestation pattern, highlighting the intense local impact on miombo woodland cover loss. Urgent action is needed to implement land conservation policies, promote sustainable agricultural practices, strengthen miombo woodland regulation enforcement, and actively support protected areas. Involvement from both local and international stakeholders is imperative to preserve the ecological richness and functionality of Lualaba Province's miombo woodland ecosystems.

Keywords: deforestation; biodiversity conservation; anthropogenic pressures; remote sensing; landscape analysis; protected areas

1. Introduction

Forests ecosystems, covering a third of the Earth, vary according to climate, terrain, soil, and human activities [1]. They provide crucial services and goods such as timber, medicines, and non-timber forest products essential for human well-being [2,3]. Based on their floristic composition, structure, and geographic location, forests can be classified into temperate forests, boreal forests, mangroves, mountain forests, humid tropical forests, and dry tropical forests [4]. Each forest types exhibits unique characteristics in terms of biodiversity, productivity, and resilience to environmental changes. Among these forest types, dry tropical forests are adapted to prolonged dry seasons, evolving over time in response to climate and human activities [5]. Despite threats, they are essential for local communities, providing habitats, resources, water regulation, and soil fertility [6]. They hold cultural value for local peoples and promote ecotourism, thus supporting local economies [7].

Dry tropical forests cover approximately one-sixth of the Earth's surface and half of Africa [8]. These ecosystems are among the most threatened, primarily due to human activities [9]. Among these ecosystems, miombo woodlands, predominant in Southern Africa, are characterized by the prevalence of species belonging to the genera Brachystegia, Julbernardia, and Isoberlinia of the Caesalpionioideae subfamily [10]. They cover an area of 2 million km², encompassing parts of Angola, the Democratic Republic of the Congo (DR Congo), Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe [11]. This ecoregion is recognized as an important center of endemism, hosting over 8,500 plant species, with more than 4,000 being endemic [12]. These ecosystems play a vital role in maintaining biodiversity and supporting the livelihoods of local populations [13].

If the miombo woodland covered nearly 23% of the total forest area in the DRC in 2000 [14], it represented 95.2% of the total forest cover in the Katanga region that same year [15]. Over the period from 2000 to 2010, the Katanga region experienced a loss of approximately 350,900 ha due to the expansion of mining and subsistence activities (agriculture, collection of non-timber forest products, charcoal production among other), supported by demographic explosion and rapid urbanization [16–18]. In Katanga region, the Lualaba province exemplifies the decline of the miombo woodland [19]. For decades, Lualaba has been closely linked to mining, which has marked its history. The discovery of valuable mineral resources attracted a significant workforce, leading to the rapid expansion of mining settlements within the miombo woodland [20]. After the political independence of the DRC in 1960, these settlements experienced rapid spatial expansion without adequate planning, severely affecting the surrounding forests [21]. Subsequently, the increasing demand of land for agriculture led to massive deforestation in surrounding rural areas, triggering a cycle of environmental degradation [18,22]. The energy crisis, particularly the energy deficit associated with the rapid expansion of settlements, also played a crucial role in this accelerated deforestation. Indeed, the widespread use of charcoal as an energy source in urban areas intensified pressure on already fragile forest resources [23]. This situation has endangered the biodiversity of the region, affected not only forests but also protected areas.

Among these protected areas, Potapov et al. [14] findings revealed that the highest forest cover loss was observed within hunting reserves close to Kolwezi, where forest cover loss within several protected areas was close to 5% between 2000-2010. Indeed, most protected areas are small and are trapped within a landscape dominated by agricultural or mining zones [24]. Consequently, due to land saturation at the periphery, these protected areas are constantly degrading under pressure from local populations, whose interests are generally not considered in management systems [19]. Finally, the creation of the Lualaba Province in 2015 exacerbated these challenges since persistent population growth continues to exert immense anthropogenic pressure on the remaining forest resources [18].

Monitoring deforestation in the Lualaba Province is of crucial importance as it allows for the identification of deforestation pattern, understanding its evolution over time [25], and anticipating

 doi:10.20944/preprints202409.0072.v1

potential future issues. With precise data, policymakers can take appropriate measures for the conservation and sustainable environmental management of forest ecosystems [26]. In this context, remote sensing provides extensive coverage, ideal for tracking deforestation on a large scale in a province. It also provides frequent data for continuous monitoring [27–30]. Concurrently, applying landscape ecology analysis tools complements this by understanding the ecological processes underlying spatio-temporal changes in landscapes, aiding in locating at-risk areas [31–33]. Hierarchical analysis of landscape dynamics, combining remote sensing and landscape ecology, is essential from the provincial to local scale. It enables a nuanced understanding of spatial heterogeneity, ecological processes, and anthropogenic impacts across scales. This approach supports precise, scale-appropriate interventions in landscape management, conservation planning, and sustainable development, ensuring more effective ecological and socio-economic outcomes.

The general objective is to quantify the multiscale spatio-temporal dynamics of forest ecosystems within the Lualaba Province. We hypothesize that multiscale analysis of Landsat images combined with a fine-scale landscape analysis approach will reveal significant trends in the spatial dynamics of landscapes in the Lualaba Province between 1990 and 2023. We expect to observe an increase in deforested and fragmented areas, as well as alteration of the spatial pattern and connectivity of forest *miombo* woodland over time, notably at the fine scale, due to the impact of human activities (mining, urbanization and agriculture).

2. Materials and Methods

2.1. Study Area

The Lualaba Province (7°38′14,80″-11°44′20,82″ South et 21°44′43,19- 27°11′16,11″ East) in the southeastern part of the DRC, covering 121,309 km², constitutes 5.2% of the national territory (Figure 1). It exhibits a diverse climate, featuring a warm temperate climate in the eastern sector (Mutshatsha and Lubudi territories) and a more humid tropical climate in the western areas (Kapanga, Dilolo, and Sandoa) [20]. The province experiences distinct rainy and dry seasons, spanning approximately five months from April to May. Its annual rainfall is around 1600 mm for the northwest, compared to nearly 1200 mm for the eastern part of the Province. The average annual temperature hovers around 25°C [20,22]. The primary vegetation in the Lualaba Province encompass dry dense forests, edaphic dense forests, woodland, savannas, and aquatic environments [15,20]. The region's soils are notably diverse [34], with the prevalence of Ferralsols, Acrisols, and Arenosols. Named after the Congo River, the Lualaba Province is characterized by plateaus, with various rivers like Lufupa, Kalule, Lulua, Luao, Lubilanshi, Luashi, Dikulwe, Musonoi, and Mumonwezi playing pivotal roles in local life and the economy. Recent data suggests a population of 4.3 million inhabitants (2021), with an average household size of 6.1 and life expectancy at 58.2 years. In the Lualaba province, the poverty rate stands at 83%, while the unemployment rate is 85%. Additionally, the annual population growth rate is close to 4% [35]. The province's mining sector, including both industrial and artisanal mining, has flourished, fostering formal and informal activities like general trade, subsistence agriculture, and informal commerce [36]. As for the employment sector breakdown, agriculture accounts for a substantial 71.4%. Regarding access to modern healthcare services, only 15.4% of the population has such access, and the electrification rate remains extremely low at just 1% [35]. The province is composed of 5 territories, within which are located protected areas (Table 1).

Table 1. Brief description of each territory in the province of Lualaba (DRC), its surface area, the economic activities of the population and the protected area.

Territory	Area (km²)	Population	Description
Lubudi	18939	387000	Economic activities include mining (artisanal and industrial), agriculture, and trade. The region is home to the rural municipality of Fungurume and the historic city of Bunkeya. Additionally, the

 doi:10.20944/preprints202409.0072.v1

			territory encompasses the Hunting Domain of Mulumbu (993.56 km²), and it is electrified with some paved roads.
Mutshatsha	18859	1268500	Mining, agriculture, and commerce are key activities in this area, which includes the city of Kolwezi, the capital of the Province. The territory is home to the Hunting Domain and Reserve of Basse Kando (479.18 km²), as well as the Tshangalele Reserve (523.52 km²). The territory is electrified and has some paved roads.
Sandoa	25337	765400	Agriculture and commerce thrive in this area. The territory, which lacks electricity and paved roads, is home to the Lunda-Tshokwe Hunting Domain (2345.27 km²) and the Mwene-Kay Reserve (531.33 km²).
Kapanga	25509	1255600	Agriculture and commerce flourish in the territory, which is without electricity and paved roads. It is home to the Tshikamba Hunting Domain (4857.21 km²).
Dilolo	25648	623,500	Agriculture and commerce are prominent in this area, which includes the city of Kasaji. The territory, lacking electricity and paved roads, is home to the Mwene Musoma Hunting Domain (1303.99 km²).

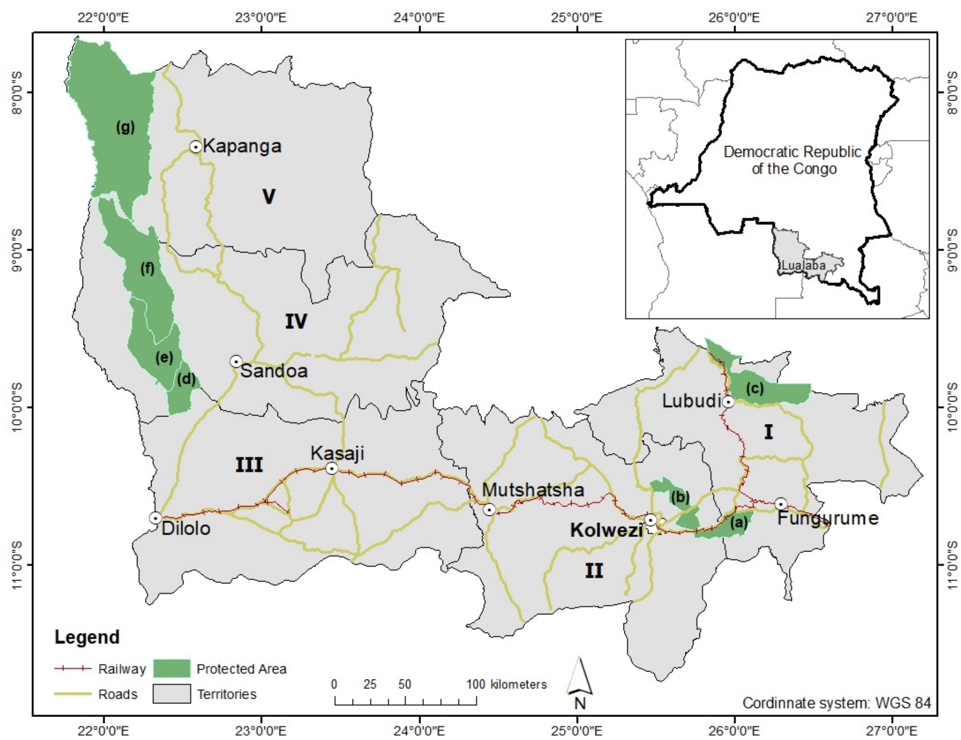

Figure 1. Geographical map of the Lualaba Province in the DRC, detailing its five territories: key agricultural zones (IV) Sandoa, (V) Kapanga, and (III) Dilolo, and major mining areas (I) Lubudi and (II) Mutshatsha. The map also identifies seven protected areas within Lualaba Province: (a) Basse Kando Hunting Domain (BKHD), (b) Lac Tshangalele Hunting Domain (LTHD), (c) Mulumbu Hunting Domain (MHD), (f) Alunda and Tutshokwe Hunting Reserve (ATHR), (d) Mwene Kay Hunting Domain (MKHD), (e) Mwene Musoma Hunting Domain (MMHD), and (g) Tshikamba Hunting Reserve (THR).

2.2. Data

Landsat images with a 30-meter spatial resolution, covering the period from 1990 to 2024, were used to map and quantify forest cover loss in Lualaba Province. The analysis, divided into intervals

 doi:10.20944/preprints202409.0072.v1

(1990-1995, 1995-2001, 2001-2006, 2006-2010, 2010-2015, 2015-2020, and 2020-2024), highlights long-term trends and changes in landscape dynamics. The year 1990 marked the start of a political crisis, leading to looting and infrastructure destruction. The years 1995 and 2001 framed the Congo wars, causing significant population displacement to Lualaba. In 2006, The general elections in the DRC could have negatively impacted landscape dynamics by intensifying land disputes, accelerating deforestation, and disrupting conservation efforts due to political instability. The post-global economic crisis (2010) led to mine closures and uncertainty before the 2011 elections. In 2015, institutions were established in Kolwezi to govern the new Lualaba Province, and in 2020, there was a political regime change. The year 2024 provided a snapshot of the most recent landscape conditions. The selected Landsat images, captured during the dry season (June and July) to minimize cloud cover, were chosen for clear visibility and precise land cover interpretation. These images, representing surface reflectance data from Level 2 Collection 2 Tier 1 datasets, were selected based on availability, quality (cloud-free, no streaks), and the study's objectives [37]. Images from 1990, 1995, 2001, and 2006 were sourced from the Landsat 5 Thematic Mapper (TM) sensor, those from 2010 from the Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and those from 2015 and 2024 from the Landsat 8 Operational Land Imager (OLI).

2.3. Classifications

The Landsat images were georeferenced to the UTM Zone 35S coordinate system, using the WGS-84 reference ellipsoid, appropriate for the study area, and underwent extensive preprocessing. Radiometric calibration was initially applied to correct sensor biases and account for atmospheric effects, ensuring temporal consistency in readings [38,39]. Subsequently, geometric calibration addressed distortions caused by satellite movements, ensuring accurate pixel representation of the Earth's surface [40]. Atmospheric correction was then performed to eliminate effects such as haze and scattering, enhancing surface reflectance analysis [41]. Additional radiometric preprocessing was conducted (for images from 2010 onward) to correct the spatial discontinuity that occurred in May 2003 following the Landsat 7 Scan Line Corrector (SLC) failure, which resulted in the loss of approximately 22% of data in each image scene. To mitigate this limitation, a "gap mask" technique was applied [42], effectively recovering missing data and ensuring the reliability and accuracy of subsequent analyses.

For improved analysis, a false-color composite was carefully created by combining mid-infrared, near-infrared, and red bands, allowing for clearer differentiation of vegetation types [43]. Land cover units were identified and codified for each scene, and Regions of Interest (ROI) were defined on the images based on field knowledge and GPS points (accuracy of 3 meters, model 64st). These ROIs were strategically selected to avoid transitional areas, minimizing pixel mixing and enhancing result accuracy. These ROIs were then used to build a training model for the Random Forest classifier under Google Earth Engine (GEE) [44,45]. This method, which relies on multiple decision trees [45], allowed for the classification of five land cover types, each represented by 200 ROIs. The land cover categories include "forest," encompassing dominant miombo patches, dense dry forest, and gallery forest; "savanna," characterized by low tree density and predominance of herbaceous cover; "agriculture," covering harvested, abandoned, or areas occupied by annual and off-season crops; "built-up areas and bare soil," including bare lands and residential areas with minimal vegetation; and finally, "other land cover types" such as water bodies and unclassified areas. The extensive archives of remote sensing data and GEE's powerful cloud computing resources ensured consistency and standardization of data collection procedures across different regions and datasets [44].

To evaluate the classification accuracy, were calculated using a sample of ground truth points, randomly collected within each land cover class between 1990 and 2024 [46]. The samples were stratified into 9 categories: 5 stable strata (forest, savanna, agriculture, built-up areas, and bare soil) and 4 change strata (forest loss, savanna gain, agriculture gain, built-up area and bare soil gain). Sample sizes were determined using Cochran's method, with 1,000 points per period (1990-1995, 1995-2001, 2001-2006, 2006-2010, 2010-2015, 2015-2020, and 2020-2024) [47]. QGIS version 3.26.1 was used to calculate the error matrix and measure accuracies: Overall Accuracy (OA), Producer's

Accuracy (PA), and User's Accuracy (UA). The F1 score was also computed [48], which integrates PA and UA, providing a single accuracy measure for classification. It was deemed more significant than the kappa coefficient and OA [49,50]. Finally, land cover maps were produced using ArcGIS version 10.8.

2.4. Quantifying Spatio-Temporal Pattern Changes in Forest Ecosystems

A range of landscape metrics were computed using Fragstats software version 4.2 (Developed by McGarigal, Amherst, MA, USA) to assess the influence of human activities on landscape structure and spatial patterns across three distinct scales: Province, territory, and designated protected areas. The calculation of class area, representing the proportional extent of specific land cover types within the landscape, served to identify the landscape matrix [51,52]. Edge density, indicating the total length of edge segments per hectare, was used to gauge landscape complexity. Higher edge density points to a more complex land cover type with distinct boundaries, while lower edge density suggests smoother boundaries [53]. The number of patches played a crucial role in assessing landscape fragmentation, where a higher count indicated fragmentation and dispersed distribution [54]. Further insights into spatial dispersion were gained through the average Euclidean distance to the nearest neighbor, measuring the average distance between patches and their closest neighbors. Additionally, the largest patch index, reflecting the size of the largest patch within a land cover type, was considered. A higher index value indicates that a particular land cover type forms larger, more connected patches, beneficial for species needing extensive habitats or connectivity between patches for movement, migration, and genetic exchange [55]. The deforestation rate, derived from changes in forest class area, provided insights into the intensity of human impacts on forest ecosystems [56]. The Shannon index, commonly used to assess the spatial arrangement of patches, was also computed. A Shannon value close to zero indicates a highly uniform distribution of patches, while a value closer to 1 indicates a more dispersed distribution [53].

A decision tree approach was employed to identify the ecological processes driving observed spatio-temporal dynamics [57]. From a diachronic analysis, reductions in patch number and class area signify attrition, while an increase in class area alongside a decrease in patch number indicates aggregation. Unchanged patch numbers with increased class area suggest enlargement, whereas simultaneous growth in both metrics indicates the creation of new patches. Dissection is characterized by decreased class area and increased patch number, often due to linear disruptions with minimal area loss. Conversely, fragmentation involves an increase in patch number accompanied by significant class area loss. Perforation occurs when reductions in class area lead to an increased total perimeter, while patch shrinkage occurs when the total perimeter remains constant. A consistent total perimeter with unchanging patch number and class area signals a shift, while changes in the total perimeter suggest deformation. To distinguish between fragmentation and dissection, the ratio of class area at different time points was analyzed. A ratio exceeding 0.75 indicated dominance of dissection, whereas a ratio equal to or below 0.75 indicated prevalent fragmentation [58].

3. Results

3.1. Classification Accuracy and Mapping

The Overall Accuracy (OA) of the supervised classifications of Landsat images using the Random Forest (RF) classifier exceeds 90% for each analyzed period, demonstrating the reliability in distinguishing various land cover categories (Table 1). User's Accuracy (UA) and Producer's Accuracy (PA), ranging from 90% to 100%, attest to the high quality of the classifications, with minimal errors in class identification. The high F1 score values for both UA and PA further confirm the excellent performance of the RF classifier.

 doi:10.20944/preprints202409.0072.v1

Table 1. Evaluation of the accuracy of land cover change maps from 1990 to 2024, based on the supervised classification of Landsat images using the Random Forest classifier. FR: Forest; SV: Savanna; AG: Agriculture; BBS: Built-up & Bare Soil; OT: Other Land Cover; UA: User's Accuracy; PA: Producer's Accuracy. The change in the "OT" category was not assessed due to its relative stability throughout all periods. The F1 score is calculated as the harmonic mean of the UA and PA.

1990-1995	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**BBS Gain**
PA [%]	99.00	94.42	98.99	98.00	100	96.04	98.04	97.98	95.06
UA [%]	99.01	100	98.00	97.09	98.97	99.00	99.01	98.98	100
F1 [%]	99.00	97.13	98.49	97.54	99.48	97.50	98.52	98.48	97.47
Overall accuracy [%]	95.60								
1995-2001	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**OT Gain**
PA [%]	93.58	100	98.05	100	100	100	95.88	100	100
UA [%]	97.14	100	99.01	99.03	96.08	96.3	89.42	99.03	96.08
F1 [%]	95.33	100.00	98.53	99.51	98.00	98.12	92.54	99.51	98.00
Overall accuracy [%]	98.40								
2001-2006	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**OT Gain**
PA [%]	97.02	100	96.04	98.04	97.98	95.06	100	98.9796	93.578
UA [%]	99.02	98.97	99	99.01	98.98	100	99.0196	96.0396	97.1429
F1 [%]	98.01	99.48	97.50	98.52	98.48	97.47	99.51	97.49	95.33
Overall accuracy [%]	96.61								
2006-2010	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**OT Gain**
PA [%]	98.06	99.03	100	98.04	100	100	99.03	97.8	97.35
UA [%]	98.54	100	99	100	98.02	100	100	100	99.1
F1 [%]	98.30	99.51	99.50	99.01	99.00	100.00	99.51	98.89	98.22
Overall accuracy [%]	98.30								
2010-2015	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**OT Gain**
PA [%]	98	96	98.11	98.1	100	100	98.04	97.98	97.06
UA [%]	97.09	98.06	99.05	99.04	98.99	95.1	99.01	98.98	100
F1 [%]	97.54	97.02	98.58	98.57	99.49	97.49	98.52	98.48	98.51
Overall accuracy [%]	98.91								
2015-2020	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**OT Gain**
PA [%]	99.09	100	98.97	93.58	100	98.05	100	98.06	93.58
UA [%]	100	99.02	96.04	97.14	100	99.01	97.06	98.06	97.14
F1 [%]	99.54	99.51	97.48	95.33	100.00	98.53	98.51	98.06	95.33
Overall accuracy [%]	97.51								
2020-2024	**FR**	**SV**	**AG**	**BBS**	**OT**	**FR Loss**	**SV Gain**	**AG Gain**	**OT Gain**
PA [%]	100	98.04	100	100	100	100	100	100	98.08
UA [%]	100	100	98.02	100	98.02	100	100	99.06	98.08
F1 [%]	100.00	99.01	99.00	100.00	99.00	100.00	100.00	99.53	98.08
Overall accuracy [%]	98.45								

The visual analysis of land cover maps (Figure 2) reveals a gradual and ongoing regression of forested areas in the Lualaba province. This forest decline is particularly pronounced along a west-east gradient, where previously forested areas are progressively being replaced by anthropogenic land cover classes, especially savannas, whose expansion is both rapid and striking. This phenomenon highlights the increasing pressures exerted by human activities on natural ecosystems. Nevertheless, despite this widespread trend of deforestation, forest fragments persist in the southeastern part of the province, indicating the resilience of certain forested areas in the face of anthropogenic expansion.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 September 2024 doi:10.20944/preprints202409.0072.v1

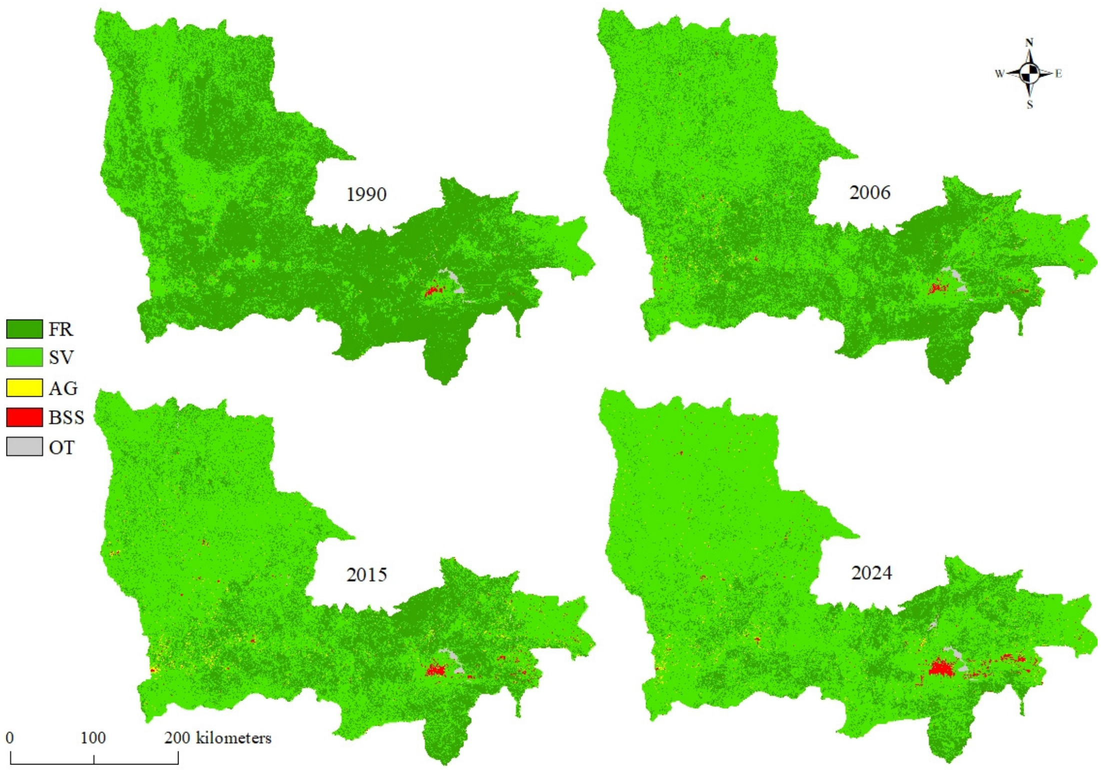

Figure 2. Spatial mapping of land cover dynamics in the Lualaba province landscape from 1990 to 2024, utilizing supervised classification of Landsat images with the Random Forest classifier. The land cover classes are denoted as follows: FR (Forest), SV (Savanna), AG (Agriculture), BBS (Built-up & Bare Soil), and Other land cover. Intermediate dates not displayed on this map did not exhibit significant perceptible changes in the landscape.

3.2. Landscape Composition Dynamics

3.2.1. Composition Dynamics in Lualaba Province and Its Territories

The multi-scale landscape analysis from 1990 to 2024 reveals significant dynamics across the five territories of Lualaba province (Figure 3). Overall, forest cover has notably decreased, dropping from 62.90% in 1990 to 24.59% in 2024, with an average annual deforestation rate of -1.2 at the provincial level (A). Simultaneously, savannas have expanded considerably, increasing from 36.47% to 75.97%, while agricultural land and built-up areas have slightly risen to 1.78% and 1.09%, respectively. Similar trends are observed in Lubudi territory (B), where forest cover has significantly decreased from 85.11% to 32.05%, accompanied by an expansion of savannas from 14.66% to 63.69%. Agricultural lands and built-up areas have also modestly increased. In Mutshatsha territory (C), deforestation is even more pronounced, with forest cover declining from 84.52% to 32.81%. During the same period, savannas expanded from 13.75% to 65.00%, and agricultural lands and built-up areas saw a slight increase. In Dilolo territory (D), forest cover has decreased from 71.14% to 27.17%, while savannas have continued their expansion, reaching 69.68% in 2024. Agricultural lands increased to 2.76%, while built-up areas remain limited. Additionally, in Sandoa territory (E), forest cover has significantly declined from 52.56% to 12.80%, with a concomitant increase in savannas from 47.11% to 85.19%. Agricultural lands and built-up areas have shown little change, reaching 1.38% and 0.56%, respectively. Finally, in Kapanga territory (F), forest cover has drastically decreased from 49.66% to 5.57%, while savannas have experienced substantial expansion, reaching 92.55% in 2024. In this territory, agricultural lands and built-up areas occupy less space in 2024.

Moreover, the global analysis of landscape diversity indices in Lualaba province indicates generally stable diversity with notable variations (Figure 4). From 1990 to 1995, diversity is homogeneous and high. However, from 2001 onwards, some territories exhibit a temporary increase, but diversity decreases in several areas from 2015, particularly in Kapanga. By 2024, diversity is low in Kapanga but stable in other territories, reflecting changes in landscape management and environmental conditions.

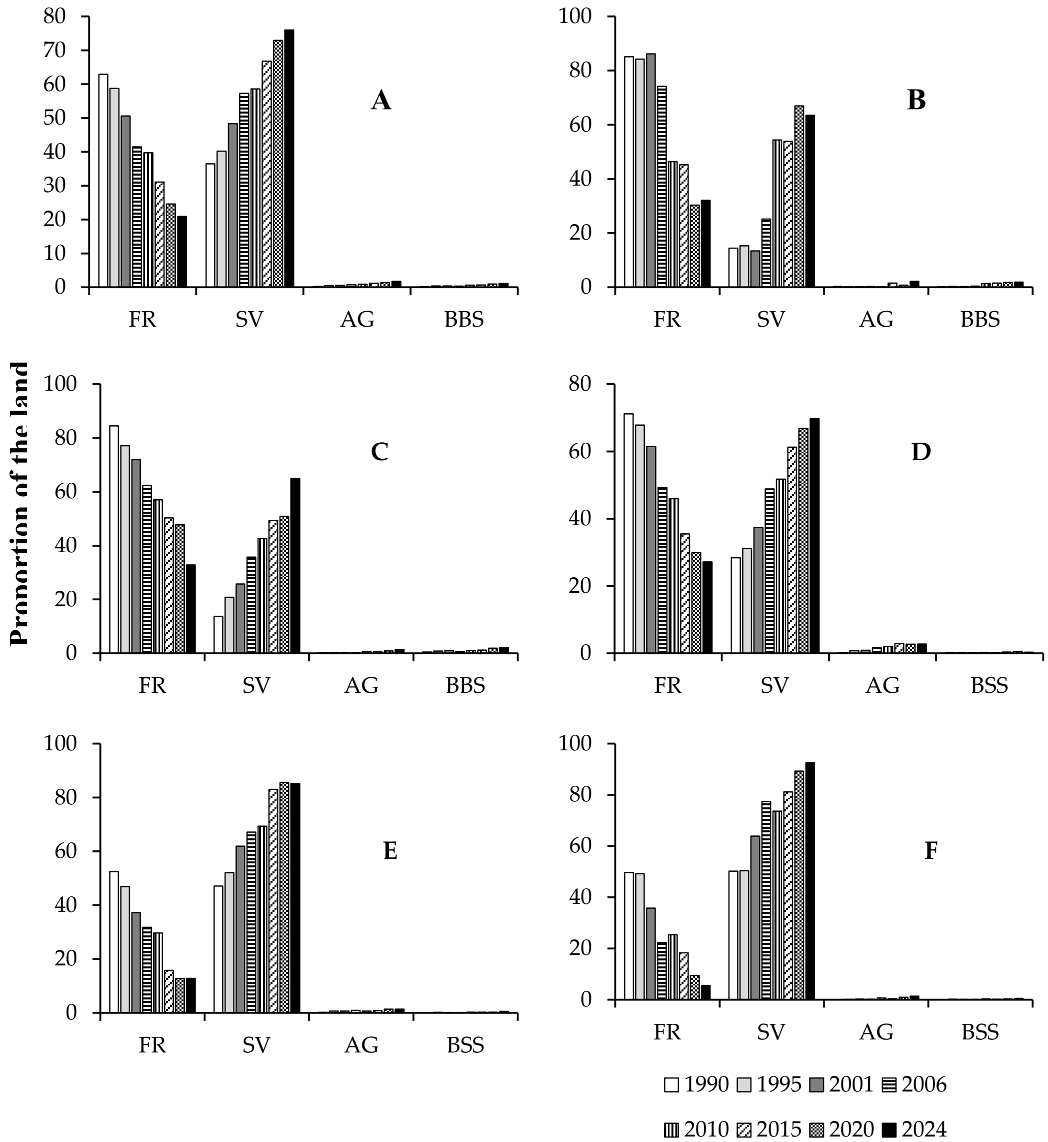

Figure 3. Landscape composition evolution in Lualaba province (A) (DRC) and their territories: (B) Lubudi, (C) Mutshatsha, (D) Dilolo, (E) Sandoa et (F) Kapanga from 1990 to 2024. FR (Forest), SV (Savanna), AG (Agriculture), and BBS (Built-up & Bare Soil). The total landscape proportion in Lualaba province ant for each territory does not sum to 100 % as other land cover classes were excluded from the analyses due to their relatively stable nature.

 doi:10.20944/preprints202409.0072.v1

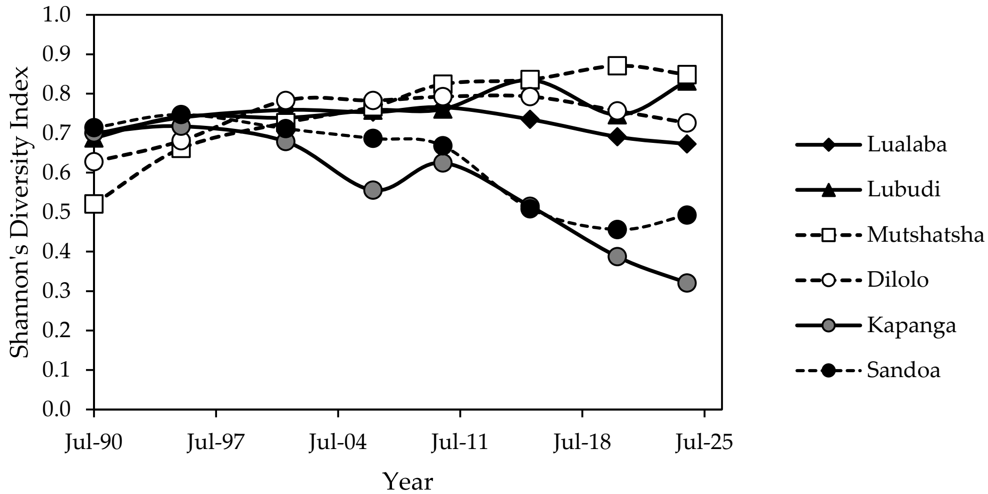

Figure 4. Dynamics of landscape diversity in Lualaba province (DRC) and its territories (Lubudi, Mutshatsha, Dilolo, Kapanga and Sandoa). The overall landscape of Lualaba province has remained relatively stable between 1990 and 2024, though with notable variations during this period.

3.2.2. Dynamics of Land Cover Composition within Protected Areas in Lualaba Province

The analysis of land use data within the seven protected areas of Lualaba province from 1990 to 2024 highlights concerning deforestation and significant conversion of forests into savannas (Figure 5). The Basse Kando Hunting Domain (A) saw its forest cover drop from 78.51% in 1990 to just 4.35% in 2024. This loss was particularly pronounced after 2010, with a parallel increase in savannas from 20.87% to 78.27%. Simultaneously, built-up areas and bare soils expanded, reaching 15.11% in 2024. Similarly, the Lac Tshangalele Hunting Domain (B) experienced a significant reduction in forests, decreasing from 39.07% in 1990 to 2.18% in 2024. This decline accelerated after 2006, while savannas more than doubled, covering 57.11%. The growth of built-up areas reflects an intensification of human activities. Furthermore, the Mulumbu Hunting Domain (C) saw its forest cover decrease by nearly 50%, from 62.78% in 1990 to 13.09% in 2024. This reduction was particularly marked between 2010 and 2020, with savannas expanding to cover 85.99%, becoming the dominant land cover. Similarly, the Alunda and Tutshokwe Hunting Reserve (D) recorded a significant decline in forest cover, dropping from 51.64% in 1990 to 7.12% in 2024. Savannas nearly doubled, representing 91.46% in 2024, illustrating a massive forest conversion. The Mwene Kay Hunting Domain (E) also suffered a major loss in forest cover, decreasing from 64.86% in 1990 to 15.89% in 2024. This reduction was accompanied by an increase in savannas, which covered 82.73% of the area in 2024. Similarly, the Mwene Musoma Hunting Domain (F) recorded a notable reduction in its forests, from 48.74% in 1990 to 9.26% in 2024. Savannas nearly doubled, reaching 90.28%, indicating a significant loss of forest biodiversity. Finally, the Tshikamba Hunting Reserve (G) shows a similar trend, with forest cover declining from 38.44% in 1990 to 7.53% in 2024. Savannas increased to 90.59%, while built-up areas and bare soils experienced slight expansion.

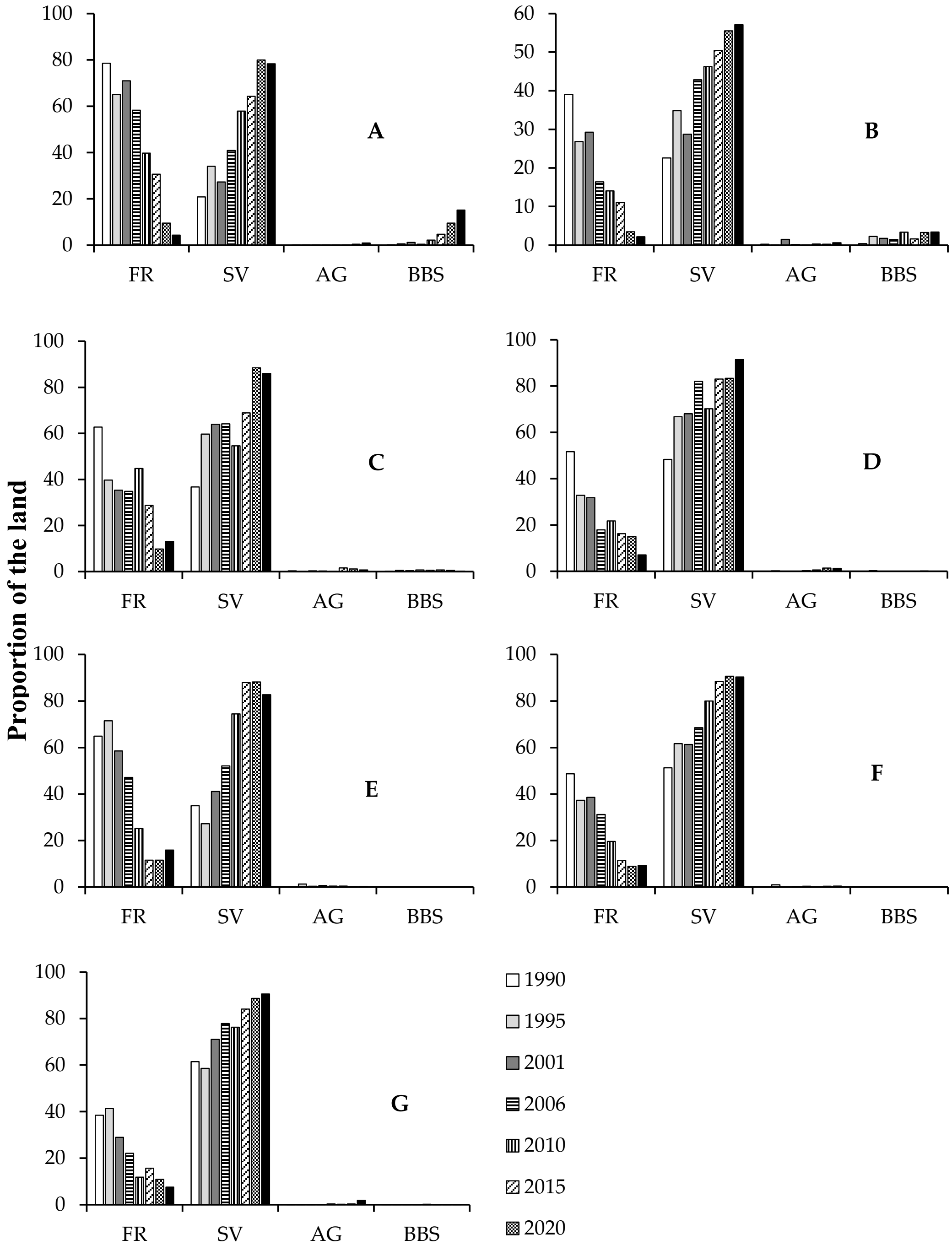

Figure 5. Landscape composition evolution in Protected areas in Lualaba province from 1990 to 2024: The Basse Kando Hunting Domain (A); the Lac Tshangalele Hunting Domain (B); the Mulumbu Hunting Domain (C); the Alunda and Tutshokwe Hunting Reserve (D); The Mwene Kay Hunting Domain (E); the Mwene Musoma Hunting Domain (F); the Tshikamba Hunting Reserve (G). FR (Forest), SV (Savanna), AG (Agriculture) and BBS (Built-up & Bare Soil). The total landscape proportion for each Protected area does not sum to 100 % as other land cover classes were excluded from the analyses due to their relatively stable nature.

The analysis of landscape diversity within Lualaba's protected areas reveals distinct trends (Figure 6). The Basse Kando Hunting Domain (BKHD) and the Mulumbu Hunting Domain (MHD) show an increase in landscape diversity. Conversely, the Alunda and Tutshokwe Hunting Reserve

(ATHR), the Mwene Musoma Hunting Domain (MMHD), and the Mwene Kay Hunting Domain (MKHD) exhibit a significant reduction in diversity, indicating landscape degradation or conversion. The Lac Tshangalele Hunting Domain (LTHD) maintains high and stable diversity, while the Tshikamba Hunting Reserve (THR) shows declines and fluctuations, indicating potential management challenges for habitats. These results underscore the significant variations in landscape management and condition within the protected areas.

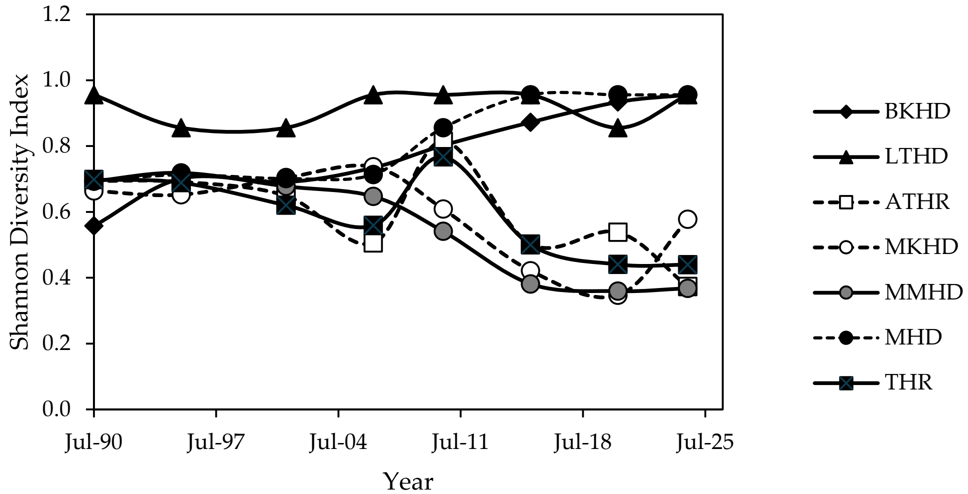

Figure 6. Dynamics of landscape diversity in the protected areas of Lualaba Province between 1990 and 2024. The protected areas have experienced variations in landscape homogeneity and heterogeneity over this period. Basse Kando Hunting Domain (BKHD), Lac Tshangalele Hunting Domain (LTHD), Mulumbu Hunting Domain (MHD), Alunda and Tutshokwe Hunting Reserve (ATHR), Mwene Kay Hunting Domain (MKHD), Mwene Musoma Hunting Domain (MMHD), and Tshikamba Hunting Reserve (THR).

3.4. Analysis of the Spatial Pattern Dynamics

Applying the decision tree model of Bogaert et al. [57] (Figure 7, Panels A & B), our analysis reveals that, except for Lubudi and Mutshatsha, the forest in the Lualaba Province experienced an attrition process from 1990 to 1995, characterized by a decrease in class area (CA) followed by a reduction in the number of patches (PN). Lubudi and Mutshatsha, on the other hand, underwent dissection (ratio 0.95>0.75) due to a decline in CA coupled with an increase in PN. From 1995 to 2001, forest attrition continued in Lualaba province, while dissection (ratio 0.87>0.75) was observed in Mutshatsha, Dilolo, and Sandoa. Concurrently, Kapanga faced fragmentation (ratio 0.72<0.75) due to reduced CA and increased PN, whereas Lubudi territory experienced aggregation, with a decrease in PN followed by an increase in CA. Between 2001 and 2006, dissection (ratio 0.84>0.75) prevailed across Lualaba province, except in Kapanga, where fragmentation (ratio 0.62<0.75) occurred because of increased PN and decreased CA. During 2006-2010, dissection (ratio 0.90>0.75) persisted in Lualaba, Mutshatsha, Dilolo, and Sandoa, while Lubudi was marked by fragmentation (ratio 0.62<0.75) and Kapanga by aggregation.

From 2010 to 2015, attrition impacted forest land cover in the entire province, as well as in Lubudi, Sandoa, and Kapanga, linked to decreases in both CA and PN. In Dilolo and Mutshatsha, dissection (ratio 0.82>0.75) was observed, driven by increased PN and decreased CA. Between 2015 and 2020, suppression was identified in Lualaba and Dilolo, while Lubudi and Kapanga experienced fragmentation (ratio 0.59<0.75), and Mutshatsha faced dissection due to decreased CA and increased PN. Finally, from 2020 to 2024, suppression affected Lualaba and Kapanga, Mutshatsha experienced fragmentation (ratio 0.68<0.75), and Dilolo underwent dissection (ratio 0.90>0.75), with Lubudi and Sandoa showing aggregation due to slight increases in CA followed by reductions in PN.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 September 2024 doi:10.20944/preprints202409.0072.v1

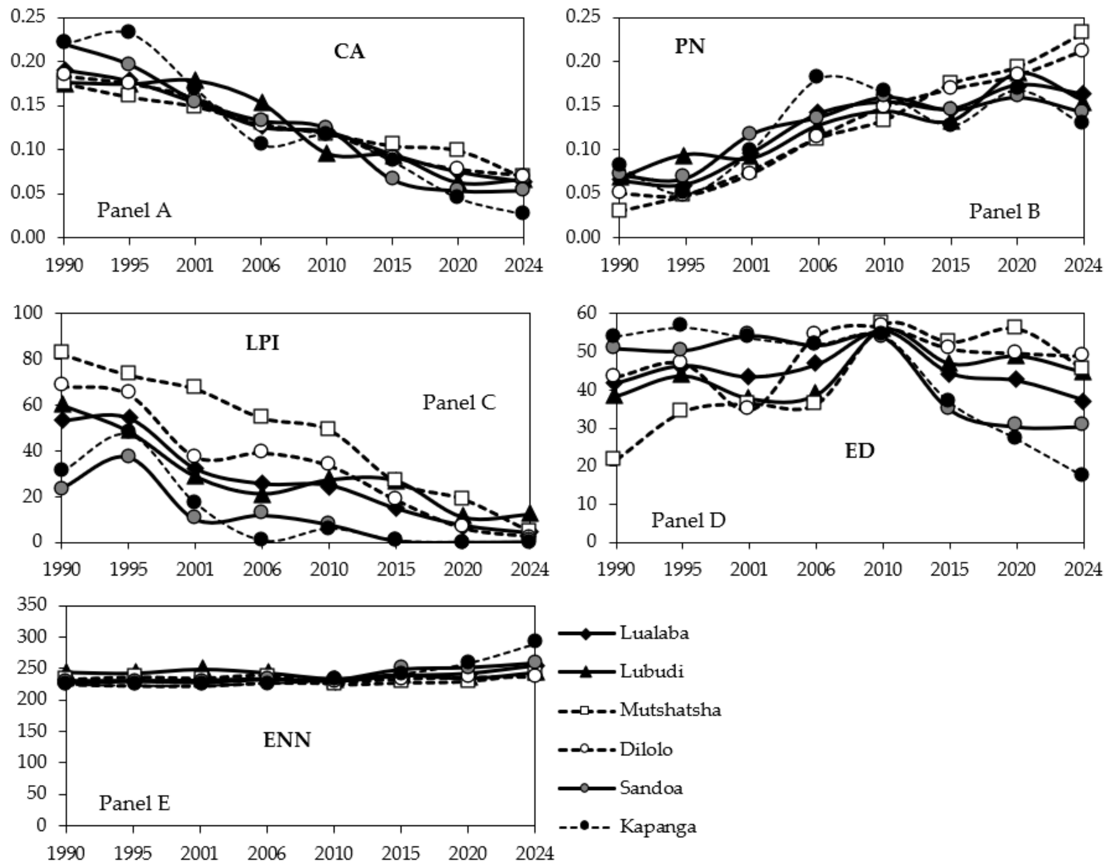

Figure 7. Dynamics of Forest Spatial Patterns (1990-2024). Panel A displays the class area (CA, in km²) of forests, with absolute values calculated by dividing the total forest area for each year by the sum of forest areas across all studied years. Panel B illustrates the patch number (PN, also in absolute values) of forest patches across the landscapes of Lualaba Province and its territories from 1990 to 2024. The variations in CA and PN during this period enabled the identification of spatial transformation processes, which were analyzed using the decision tree algorithm developed by Bogaert et al. [57]. Panel C shows the evolution of the Largest Patch Index (LPI, in %), which indicates the proportion of the landscape occupied by the largest forest patch. Panel D depicts Edge Density (ED, in m/ha), reflecting the amount of edge habitat in relation to forest area. Finally, Panel E presents the Mean Euclidean Nearest-Neighbor Distance (ENN, in meters), which measures the average distance between the nearest neighboring patches, providing insights into forest connectivity.

Between 1990 and 2024, the Lualaba Province and its territories witnessed a dramatic decline in forest cover, with the largest patch of forest plummeting from 53.1% in 1990 to just 3.98% in 2024 (Figure 7, Panel C), highlighting massive and concerning deforestation. Territories like Lubudi and Mutshatsha exhibited similar trends, with significant declines noted especially after 2001. Dilolo, Sandoa, and Kapanga have nearly lost all their forests, reaching the value of the largest patch near-zero by 2024, indicating rapid and alarming degradation. In parallel, edge density (ED) in the province exhibited fluctuations (Figure 7, Panel D). Overall, ED showed a general trend of reduced forest degradation, peaking at 55.51 in 2010. Lubudi saw an initial increase in ED up to 2010 (55.95), followed by a slight decrease, reflecting initial fragmentation followed by stabilization. Mutshatsh*a*'s ED rose significantly from 21.80 in 1990 to 55.90 in 2020, then slightly declined, indicating substantial mid-period fragmentation. Dilolo followed a similar trend, with an increase until 2010 (56.50) and a slight decrease thereafter. Sandoa exhibited high and stable ED until 2010, then a marked decrease, signifying reduced degradation. Kapanga experienced a continuous decline in ED from 54.07 in 1990 to 17.42 in 2024, suggesting progressive loss of degradation.

 doi:10.20944/preprints202409.0072.v1

Additionally, the average distance between forest fragments increased from 230.53 meters in 1990 to 254.47 meters in 2024, reflecting growing forest fragmentation at the provincial level (Figure 7, Panel E). Lubud*i*'s distance remained relatively stable, from 244.72 meters in 1990 to 244.17 meters in 2024, indicating consistent fragmentation. In Mutshatsha, the average distance rose from 232.21 meters in 1990 to 242.18 meters in 2024, signaling increased fragmentation. Dilol*o*'s distance slightly increased from 225.03 meters in 1990 to 237.57 meters in 2024, showing moderate fragmentation. Sandoa experienced a notable distance increase, from 226.57 meters in 1990 to 258.56 meters in 2024. Kapanga saw a significant rise from 224.12 meters in 1990 to 289.88 meters in 2024, illustrating heightened fragmentation with larger gaps between forest fragments.

Furthermore, our results reveal a complex evolution of spatial forest transformation processes within protected areas in the Lualaba Province from 1990 to 2024 (Figure 8, Panels A & B). Between 1990 and 1995, forests in the MKHD and THR experienced an aggregation process, characterized by an increase in CA followed by a decrease in PN. Conversely, other protected areas showed an increase in PN and a decrease in CA, indicating a shift to dissection for ATHR and MMHD (ratio 0.79 > 0.75) and fragmentation (ratio 0.59 < 0.75) for BKHD, LTHD, and MHD. In the subsequent period, from 1995 to 2001, a notable change occurred in THR, where forests underwent fragmentation (ratio 0.69 < 0.75), driven by a decrease in CA combined with an increase in PN. Concurrently, forests in LTHD, MHD, and MKHD experienced dissection (ratio 0.79 > 0.75), while ATHR, BKHD, and MMHD observed the creation of forest patches, marked by a simultaneous increase in CA and PN.

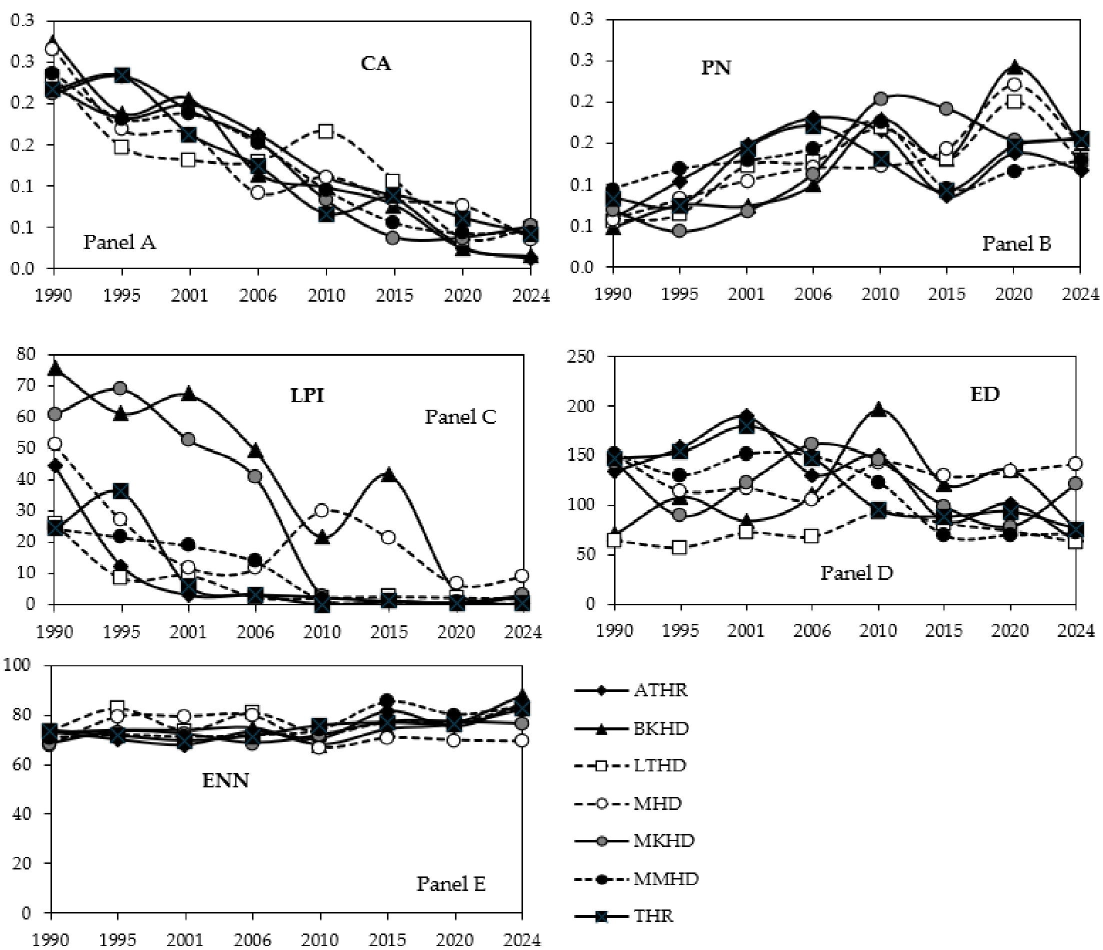

Figure 8. Dynamics of Forest Spatial Patterns (1990-2024). Panel A displays the class area (CA, in km²) of forests, with absolute values calculated by dividing the total forest area for each year by the sum of forest areas across all studied years. Panel B illustrates the patch number (PN, also in ab-solute

 doi:10.20944/preprints202409.0072.v1

values) of forest patches across the landscapes of Lualaba Province and its territories from 1990 to 2024. The variations in CA and PN during this period enabled the identification of spatial transformation processes, which were analyzed using the decision tree algorithm developed by Bogaert et al. [57]. Panel C shows the evolution of the Largest Patch Index (LPI, in %), which indicates the proportion of the landscape occupied by the largest forest patch. Panel D depicts Edge Density (ED, in m/ha), reflecting the amount of edge habitat in relation to forest area. Finally, Panel E presents the Mean Euclidean Nearest-Neighbor Distance (ENN, in meters), which measures the average distance between the nearest neighboring patches, providing insights into forest connectivity. Basse Kando Hunting Domain (BKHD), Lac Tshangalele Hunting Domain (LTHD), Mulumbu Hunting Domain (MHD), Alunda and Tutshokwe Hunting Reserve (ATHR), Mwene Kay Hunting Domain (MKHD), Mwene Musoma Hunting Domain (MMHD), and Tshikamba Hunting Reserve (THR).

From 2001 to 2006, dissection dominated across all studied protected areas (ratio 0.83 > 0.75), except for BKHD and MHD, which experienced fragmentation (ratio 0.56 < 0.75). These transformations resulted from an increase in PN followed by a decrease in CA, a recurrent pattern continuing to shape forest ecosystems. The period from 2006 to 2010 introduced a creation of the forest's patches in LTHD and MHD, due to a concurrent increase in CA and PN. Simultaneously, attrition was observed in ATHR and THR, marked by decreases in both CA and PN. However, MKHD and MMHD were characterized by fragmentation (ratio 0.58 < 0.75), while BKHD showed a dissection process (ratio 0.85 > 0.75), both characterized by an increase in PN. Between 2010 and 2015 in THR, forest aggregation was observed resulted from a decrease in PN followed by an increase in CA. whereas other protected areas (ATHR, BKHD, LTHD, MHD, MKHD & MMHD) experienced attrition of forest patches resulted from an increase in PN and CA, enhancing the diversity of forest dynamics. Between 2015 and 2020, fragmentation (ratio 0.30 < 0.75) was noted in ATHR, BKHD, THR, and LTHD due to increased PN and decreased CA. Meanwhile, MHD and MMHD experienced dissection of forest patches (ratio 0.84 > 0.75), and MKHD underwent attrition resulted from an increase in PN followed by a decrease in CA, illustrating the complexity of spatial interactions in these zones. Finally, from 2020 to 2024, attrition of forest patches dominated in ATHR, BKHD, and MHD, while THR faced fragmentation (ratio 0.30 < 0.75) since resulted from an increase in PN followed by a decrease in CA. MKHD and MMHD saw a spatial creation process, and LTHD experienced aggregation, concluding this analysis of forest transformations with an illustration of varied and dynamic spatial trends in protected areas.

From 1990 to 2024, large forest patches within protected areas drastically diminished, with the largest patches index dropping to nearly zero in ATHR, BKHD, MMHD, and THR, with less pronounced declines in MKHD and LTHD (Figure 8, Panel C). MHD showed a slight recovery after 2010 but remains at very low levels. Concurrently, the high Edge Density (ED) reflects increased forest fragmentation over time. Despite initially high ED values, both ATHR and MMHD experienced a decrease in ED, whereas BKHD exhibited a significant rise until 2010, followed by a slight decline. LTHD, on the other hand, maintained relatively stable ED with a slight upward trend (Figure 8, Panel D). MHD and MKHD showed fluctuations but generally followed an increasing trend in ED, while THR displayed a continuous rise, indicating ongoing fragmentation. This pattern is further supported by the Mean Euclidean Nearest-Neighbor Distance (ENN) between forest patches, which was relatively consistent in 1990 but progressively increased in subsequent years (Figure 8, Panel E). By 2024, ATHR and LTHD showed the greatest distances between forest patches, signaling increased fragmentation, while BKHD, MKHD, and THR also exhibited notable increases. These trends underscore the intensifying fragmentation of forests, emphasizing the urgent need for conservation measures to protect and restore remaining forest habitats.

4. Discussion

4.1. Methodology

This study utilized multiscale analysis with Landsat images and various landscape metrics—such as class area, patch number, and edge density—to gain insights into deforestation dynamics

[59]. Employing multiple metrics is crucial for a comprehensive understanding of deforestation, as a single metric alone is insufficient due to the complex nature of deforestation involving numerous factors [60,61]. The study incorporated a decision tree to analyze and interpret these metrics, helping differentiate between anthropogenic and natural land cover transformations and linking observed changes to their causes. To address the temporal sensitivity of spatial transformation processes, the study refined the temporal resolution to 5 to 6 years [57,62,63].

Although Landsat images have a 30-meter resolution, they are effective for regional-scale analysis, offering valuable insights into land cover trends and changes over time [14,64]. Landsat's capacity to detect vegetation changes at this scale allows for mapping and quantifying the impacts of human activities on forest ecosystems, which is vital for management and conservation [65]. Additionally, the free access to Landsat data makes it a valuable tool for monitoring landscape dynamics, particularly in areas with limited surveillance resources [66,67].

The study focused on key land cover classes such as agriculture, urbanization, savannas, and forests to understand landscape transformation dynamics and their impact on deforestation. However, combining grassland and wooded savannas, which represent distinct ecosystems, may have limitations. Despite this, merging these categories was justified for capturing general deforestation trends at a regional scale, while acknowledging the potential for finer-scale analyses in future studies. Moreover, the literature indicates that these two land uses are generally of anthropogenic origin, with their significance in the landscape increasing alongside human activities [20,68].

4.2. Anthropogenic Pressures and Extent of the Hierarchical Changes in the Spatio-Temporal Pattern of Deforestation in Lualaba Province

Our results indicate significant expansion of savannas, agricultural fields, and urban areas in Lualaba Province, driven by abundant natural resources like fertile soils and mineral-rich deposits, including copper and cobalt [36]. These resources have attracted investments in agriculture and mining, leading to the growth of these sectors [18,69]. Similar patterns were observed in southern central Angola [70]. Additionally, improved road networks have facilitated access to rural areas, further promoting agriculture and mining [14] and stimulating urbanization by enabling rural populations to migrate to urban centers for employment and services [18]. In Mekelle, Ethiopia, a favorable investment climate has similarly driven rural-to-urban migration, increasing demand for urban land [71]. The growing national and international demand for rosewood and mining products has fueled expansion in these sectors [69,72,73].

The need to expand agricultural land to meet rising food demands has led to the conversion of forests into maize and cassava fields, as observed in the Katangense copperbelt [18,74]. Both large- and small-scale mining operations have also contributed to deforestation for mining infrastructure and extraction [14]. Unplanned urban expansion has converted forest lands into residential, commercial, and industrial zones, leading to habitat fragmentation and loss. In the Lubumbashi plain, Cabala et al. [68] reported the conversion of 177.5 km² of forest to bare soil and settlements between 2005 and 2011. Economic challenges have forced populations to build makeshift housing in forest-adjacent areas with limited infrastructure, often prioritizing immediate survival over resource sustainability.

Our results show that the extent of deforestation is linked to the socio-economic and political context of the province. The period of socio-political instability in the DRC (1990-2001) was marked by several factors that had a significant impact on agriculture, urbanization, and consequently reduced the extent of deforestation [66]. Indeed, political instability created an environment of insecurity and farmers faced challenges accessing land, agricultural inputs, and markets, leading in disorganization of agricultural production systems. Barima et al. [75] found that there was minimal growth in cocoa cultivation during a period of political turmoil in Ivory Coast, leading to a reduced rate of deforestation. Additionally, limited investments in urban infrastructure due to precarious political situations slowed down the development of urban areas in the Lualaba province, echoing the results found by Useni et al. [76] in the city of Lubumbashi. Basic services such as electricity were inadequate, discouraging new populations from settling in urban centers [77]. Regarding deforestation, political instability limited economic activities such as large-scale logging, consequently foreign investments in this sector decreased [78], confirming the findings at the national level, which showed that the deforestation rate halved when comparing the period of political crisis (0,08% from 1990-2000) and the post-crisis period (0.16 from 2000-2010) [79].

However, the liberalization of the mining sector in 2002 has generally led to an increase in large-scale mining operations, particularly for minerals like copper and cobalt. The rise in the quantity and size of mining sites has caused fragmentation of vegetation in the Lualaba province [19]. But, a trend in the decrease of deforestation extent was observed during the period following the global financial crisis (2008). Indeed, a reduction in mining activity was linked to a decrease in demand for forest lands for mining infrastructures, potentially leading to a decline in the deforestation rate. Globally, during the financial crisis period, deforestation rates in Asia, Africa, and Europe decreased by 83 %., 43 %, and 22 %, respectively [80]. Additionally, the establishment of the new province in 2015 increased the deforestation rate, particularly due to the infrastructural development, urbanization, and expansion of economic activities that added additional pressure on forest resources [18]. In a new province where the majority of the population is poor and access to electricity is low, the exploitation of forest resources for charcoal production has become an excellent refuge sector [77]. It's also worth noting that charcoal is an essential energy source for cooking and heating [81], and therefore its constant demand by households in the province's main urban areas ensures a certain economic stability for producers [68]. Yet, the carbonization yield remains low in the region [82].

Our findings revealed that deforestation occurs through the fragmentation of forest patches, confirming the results of previous studies [16,18]. Indeed, forests ecosystems are generally fragmented into smaller patches by roads and infrastructure development, expanding agricultural areas, and urban zones [83]. This fragmentation can lead to a simplification of the shapes of residual fragments as intact areas of natural forests become increasingly scarce [84]. As anthropogenic pressure intensifies while forest resources are becoming scarce [85], the remnant forest patches subsequently disappear, as found in the Lufira Biosphere Lufira [24]. Conversely, savanna patches merge into the landscape due to factors such as extensive agricultural practices, charcoal production and bushfires [17]. Indeed, agricultural activities whether preceded by charcoal production or not and bushfires can gradually transform forest areas into savannas [86,87]. The exploitation of forest resources for charcoal production can lead to the conversion of forests into savannas due to intensive tree cutting for charcoal, resulting in reduced forest cover [88]. The expansion of agricultural fields typically involves creating new patches rather than enlarging existing ones due to increasing land demand. As soil fertility declines, farmers shift to new plots, continually creating cultivated areas and exerting ongoing pressure on forest resources [89]. The ongoing decline in tree abundance facilitates light penetration, promoting the growth of herbaceous species [90]. This often leads to the formation of savannas, explaining their increasing presence in the landscapes of Lualaba Province. Malaisse [20] supports this trend, noting that savannas are anthropogenic in the region, expanding in tandem with landscape disturbance levels.

In the context of uncontrolled urbanization, acquiring new land often proves simpler and more cost-effective than densifying existing urban areas. Densification typically necessitates complex land regularization processes and substantial infrastructure investments, making it a less attractive option for rapid urban expansion [91]. This phenomenon is especially prevalent in regions with minimal urban development, such as the DR Congo. In these areas, urban growth is frequently concentrated around mining sites, where construction on bare soil is relatively straightforward [21]. However, this practice can exacerbate human exposure to environmental hazards, including trace metals, which are commonly present in the soils around mining operations [92]. Consequently, uncontrolled urban expansion not only contributes to inefficient land use but also poses significant health risks to the population.

Deforestation is generally more severe in areas practicing shifting cultivation compared to mining regions. Shifting cultivation, or slash-and-burn agriculture, is a traditional practice in DR Congo involving the periodic cutting and burning of forest plots for crop cultivation, leading to

 doi:10.20944/preprints202409.0072.v1

temporary and recurrent deforestation [93,94]. This can result in land degradation and pressure on protected areas due to inadequate monitoring [24,67,95]. Agricultural areas are more accessible and less regulated than mining zones, which are managed with stricter environmental controls and regulations [69]. Consequently, agricultural lands are more prone to deforestation driven by local economic interests [96]. Despite their protected status, forest cover in these areas declines due to poor management, demographic pressure, and illegal activities [95]. Corruption and enforcement challenges exacerbate this issue. Studies in the DR Congo, Zambia, Ghana, and Burkina Faso confirm that agriculture is a leading cause of deforestation [97–99].

Deforestation rates in this study significantly exceed the national average of 0.4% per year. The rate in Lualaba province is higher due to intensified logging, agricultural and mining expansion, illegal activities, and weak forest governance. Despite national conservation efforts, local factors contribute to higher deforestation in provinces like Lualaba. Deforestation varies with spatial scale: protected areas face intense pressure from subsistence agriculture, artisanal mining, and fuelwood collection, compounded by outdated monitoring resources [100]. This situation mirrors issues in Kasenga [101], Butembo [102], and Zambia [103], leading to severe deforestation in areas like the Lufira Biosphere Reserve [24]. At larger scales, commercial agriculture and mining drive deforestation, though conservation measures at provincial or national levels can mitigate these effects [19,104,105].

The results indicate that, regardless of the scale of analysis, the density of forest edges increases, including the average distance between neighboring patches, alongside a decrease in the size of the largest forest patch. This trend is primarily driven by habitat fragmentation, often resulting from urban expansion, agriculture, and mining activities [54,55]. As new edges are created, the number and density of forest fragments increase, while the size of continuous forest areas decreases. On one hand, forest fragmentation can enhance habitat diversity by creating various microenvironments along the edges. But generally, it has significant negative effects: the loss of continuous habitat can threaten biodiversity by isolating species populations and disrupting migration corridors [84]. Additionally, edges may be more susceptible to disturbances such as storms and invasions by exotic species [106]. The consequences of this fragmentation include a reduction in the resilience of forest ecosystems to climate and environmental changes. Furthermore, the decline in large forest patches limits the ability of ecosystems to provide essential services such as climate regulation, biodiversity conservation, and carbon storage [55,84].

4.3. Implications for the Conservation of Landscape and Forest Ecosystems in Lualaba

Agriculture-oriented territories are highly susceptible to deforestation, even in protected areas. To address this, policies must promote sustainable land management, including reforestation and ecosystem restoration with indigenous species, as well as financial incentives for sustainable agriculture. Efforts to increase carbon stocks through forest restoration could potentially restore 700 million hectares globally in the next 50 years [107]. For instance, the agroforestry project near Lubumbashi has successfully planted 350 hectares of degraded land with *Acacia auriculiformis* [108]. Local governments should establish buffer zones around protected areas to curb agricultural expansion while encouraging environmentally friendly farming practices. Integrated territorial planning is crucial to prevent inappropriate land conversion for urban or agricultural use. This requires collaboration among local authorities, farmers, urban planners, and ecologists to create balanced development strategies.

Collaborative management between state wildlife agencies and NGOs can attract investment and enhance protected area performance [109]. Additionally, agricultural reserves with regulated and sustainable practices can help mitigate deforestation from intensive agriculture. These reserves must be managed collaboratively, addressing limitations of current land allocation models controlled solely by local customary authorities [73].

For extremely poor populations, adopting sustainable agricultural practices is crucial. Techniques such as agroforestry, crop rotation, and water conservation can enhance productivity and minimize deforestation. For instance, on the Batéké plateau in Kinshasa, 8000 hectares of *Acacia*

 doi:10.20944/preprints202409.0072.v1

auriculiformis plantations produce 8000 to 12,000 tons of charcoal annually, along with 10,000 tons of cassava, 1200 tons of maize, and 6 tons of honey [110]. Improving agricultural practices through the use of adapted seeds, integrated pest management, and crop diversification can reduce forest pressure and support ecosystem preservation. For example, using improved maize varieties and recycled human waste in Lubumbashi has enhanced crop growth and nutrition, leading to higher maize yields compared to inorganic fertilizers. Creating corridors with native species, like the Ambositra-Vondrozo Corridor in Madagascar, can also improve ecological connectivity. This corridor, spanning 200 km and covering 1,352 km^2, links two major national parks, Ranomafana and Andringitra, facilitating species movement and genetic flow between forest patches [111].

Local communities must be actively engaged in natural resource conservation to combat deforestation effectively. The lack of local involvement in forest conservation efforts has been a major factor in deforestation in the Lubumbashi region [85]. In contrast, strong community participation has facilitated forest regeneration in Burundi's Bururi region [112]. To promote sustainable practices, awareness programs, environmental education, and capacity-building initiatives are essential [113]. Although governance challenges can complicate these efforts, partnerships with international organizations and NGOs can provide necessary financial and technical support [114,115]. Media campaigns and targeted educational programs can further raise environmental awareness [116].

Strengthening environmental legislation and ensuring rigorous enforcement of regulations are crucial for protecting sensitive forest areas and curbing unsustainable activities [117]. This includes enhancing monitoring within protected areas, implementing strict access and land use measures, and imposing penalties for illegal deforestation. For example, in the Forest Reserve of Bururi, forest area increased due to restrictions on human activities, reduced agricultural disruptions, and more forest rangers [112]. Addressing poor governance and corruption requires robust transparency and accountability mechanisms to ensure effective monitoring and management within protected areas [118,119].

5. Conclusion

Our study utilized a methodological approach that integrated remote sensing techniques with landscape analysis methods. This allowed us to confirm a notable increase in deforested and fragmented areas within the Lualaba province. These changes were attributed to the expansion of anthropogenic activities such as mining, urbanization, and agriculture, which have significantly altered the structure and connectivity of forest ecosystems over time. The findings from our study clearly demonstrated that deforestation, characterized by the fragmentation of forest patches followed by attrition, is primarily influenced by the expansion of savannas, agricultural practices, and urban development. Of particular concern is the vulnerability of agricultural territories to this phenomenon, even including their designated protected areas which were found to be impacted as well. Despite the valuable insights gained, our study did encounter limitations. These included the spatial resolution of remote sensing data and the lack of socio-economic surveys, which could have provided a more comprehensive understanding of long-term trends, and the intricate nature of human-environment interactions, which adds complexity to the analysis. Despite, our results unveiled a complex pattern of deforestation, with a significant impact observed at the local scale. This emphasizes the critical need for immediate actions to preserve the remaining forest ecosystems in the Lualaba region through the implementation of land conservation policies, adoption of sustainable agricultural practices, and the enforcement of stricter forest regulations. Collaborative actions are necessary to safeguard the ecological richness and functionality of the forest ecosystems within the Lualaba province for future generations.

Author Contributions: Y.U.S.: conceptualisation, methodology and writing—original draft preparation; M.M.M.: methodology, writing—original draft preparation and data curation; J.K.T, D.K.K & F.M.: writing—review and editing; J.B.: supervision, writing—original draft and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by Academy for Research and Higher Education, Commission for Development Cooperation (Belgium).

Data Availability Statement: The authors confirm that all data supporting the findings of this study are available within the article.

Acknowledgments: The authors would like to thank the development research project "Capacity building for the sustainable management of the miombo clear forest through the assessment of the environmental impact of charcoal production and the improvement of forest resource management practices (CHARLU)" and the administrative services of the border cities studied for the facilities provided.

Conflicts of Interest: The authors have no conflicts of interest to declare. All co-authors have reviewed and approved the contents of the manuscript, and there are no financial interests to report. We confirm that the submission represents original work and is not currently under review by any other publication.

References

1. Malhi, Y.; Meir, P.; Brown, S. Forests, Carbon and Global Climate. *Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci*. **2002**, *360*, 1567-1591. https://doi.org/10.1098/rsta.2002.1020.
2. Mori, A.S.; Lertzman, K.P.; Gustafsson, L. Biodiversity and Ecosystem Services in Forest Ecosystems: A Research Agenda for Applied Forest Ecology. *J. Appl. Ecol*. **2017**, *54*, 12-27. https://doi.org/10.1111/1365-2664.12669.
3. Mulumbati, M.C.; Godoy Jara, M.; Baboy Longanza, L.; Bogaert, J.; Werbrouck, S.; Sikuzani, Y.U.; Mazinga Kwey, M. In Vitro Regeneration Protocol for Securidaca longepedunculata Fresen., a Threatened Medicinal Plant within the Region of Lubumbashi (Democratic Republic of the Congo). Conservation **2023**, *3*, 411-425. https://doi.org/10.3390/conservation3030028.
4. Osman, K.T. Forest Types and Their Associated Soils. In Forest Soils: Properties and Management; Osman, K.T., Ed.; Springer: Dordrecht, Netherlands, **2013**; pp. 123-155.
5. Dirzo, R. Seasonally Dry Tropical Forests: Ecology and Conservation; Island Press: Washington, DC, USA, **2011**. https://doi.org/10.5822/978-1-61091-021-7
6. Peña-Claros, M.; Poorter, L.; Alarcón, A.; Blate, G.; Choque, U.; Fredericksen, T.S.; Toledo, M. Soil Effects on Forest Structure and Diversity in a Moist and a Dry Tropical Forest. Biotropica **2012**, *44*, 276-283. https://doi.org/10.1111/j.1744-7429.2011.00813.x.
7. Colfer, C.J.P.; Elias, M.; Jamnadass, R. Women and Men in Tropical Dry Forests: A Preliminary Review. Int. For. Rev. **2015**, *17*, 70-90. DOI: 10.1505/146554815815834877.
8. Miles, L.; Newton, A.C.; DeFries, R.S.; Ravilious, C.; May, I.; Blyth, S.; Gordon, J.E. A Global Overview of the Conservation Status of Tropical Dry Forests. J. Biogeogr. **2006**, *33*, 491-505. https://doi.org/10.1111/j.1365-2699.2005.01424.x.
9. Blackie, R.; Baldauf, C.; Gautier, D.; Gumbo, D.; Kassa, H.; Parthasarathy, N.; Sunderland, T. Tropical Dry Forests: The State of Global Knowledge and Recommendations for Future Research; Cifor: Bogor, Indonesia, **2014**,41p. https://doi.org/10.17528/cifor/004408.
10. Jew, E.K.; Dougill, A.J.; Sallu, S.M.; O'Connell, J.; Benton, T.G. Miombo Woodland under Threat: Consequences for Tree Diversity and Carbon Storage. For. Ecol. Manag. **2016**, *361*, 144-153. https://doi.org/10.1016/j.foreco.2015.11.011.
11. Syampungani, S.; Chirwa, P.W.; Akinnifesi, F.K.; Sileshi, G.; Ajayi, O.C. The Miombo Woodlands at the Cross Roads: Potential Threats, Sustainable Livelihoods, Policy Gaps and Challenges. In Proceedings of the Natural Resources Forum, Oxford, UK, *Blackwell Publishing Ltd.* **2009**,*33*, pp. 150-159. https://doi.org/10.1111/j.1477-8947.2009.01218.x.
12. Chidumayo, E.N. Changes in Miombo Woodland Structure under Different Land Tenure and Use Systems in Central Zambia. *J. Biogeogr*. **2002**, *29*, 1619-1626. https://doi.org/10.1046/j.1365-2699.2002.00794.x.
13. Ribeiro, N.S.; Matos, C.N.; Moura, I.R.; Washington-Allen, R.A.; Ribeiro, A.I. Monitoring Vegetation Dynamics and Carbon Stock Density in Miombo Woodlands. *Carbon Balance Manag*. **2013**, *8*, 1-9. https://doi.org/10.1186/1750-0680-8-11.
14. Potapov, P.V.; Turubanova, S.A.; Hansen, M.C.; Adusei, B.; Broich, M.; Altstt, A.; Mane, L.; Justice, C.O. Quantifying forest cover loss in Democratic Republic of the Congo, 2000–2010, with Landsat ETM+data. Remote Sens. *Environ.* **2012**, *122*, 106–116.
15. Kabulu Djibu, J.P.; Bamba, I.; Munyemba Kankumbi, F.; Defourny, P.; Vancutsem, C.; Nyembwe, N.S.; Bogaert, J. Analyse de la structure spatiale des forêts au Katanga. Annales de la Faculté des Sciences Agronomiques de l'Université de Lubumbashi **2008**, 1.
16. Cabala, K.S.; Useni, S.Y.; Sambieni, K.R.; Bogaert, J.; Munyemba, K.F. Dynamique des écosystèmes forestiers de l'Arc CuprifèreKatangais en République Démocratique du Congo. Causes, Transformations spatiales et ampleur. *Tropicultura* **2017**, *35*, 192–202.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 September 2024 doi:10.20944/preprints202409.0072.v1

17. Useni, S.Y.; Malaisse, F.; Kaleba, S.C.; Kankumbi, F.M.; Bogaert, J. Le rayon de déforestation autour de la ville de Lubumbashi (Haut-Katanga, RD Congo): Synthèse. *Tropicultura* **2017**, *35*, 215–221.
18. Khoji, M.K.; N'Tambwe, N.D.-D.; Malaisse, F.; Waselin, S.; Sambiéni, K.R.; Cabala, K.S.; Munyemba, K.F.; Bastin, J.-F.; Bogaert, J.; Useni, S.Y. Quantification and Simulation of Landscape Anthropization around the Mining Agglomerations of SoutheasternKatanga (DR Congo) between 1979 and 2090. *Land* **2022**, *11*, 850. https://doi.org/10.3390/land11060850.
19. Dupin, L.; Nkono, C.; Burlet, C.; Muhashi, F.; Vanbrabant, Y. Land cover fragmentation using multi-temporal remote sensing on major mine sites in Southern Katanga (Democratic Republic of Congo). Adv. *Remote Sens*. **2013**, *2*, 127-139. http://dx.doi.org/10.4236/ars.2013.22017.
20. Malaisse, F. How to Live and Survive in Zambezian Open Forest (Miombo Ecoregion); Les presses agronomiques de Gembloux: Gembloux, Belgium, **2010**.
21. Chai, B.; Seto, K.C. Conceptualizing and Characterizing Micro-Urbanization: A New Perspective Applied to Africa. Landsc. Urban Plan. 2019, 190, 103595. https://doi.org/10.1016/j.landurbplan.2019.103595.
22. Useni, Y.S.; Malaisse, F.; Yona, J.M.; Mwamba, T.M.; Bogaert, J. Diversity, use and management of household-located fruit trees in two rapidly developing towns in Southeastern DR Congo. *Urban For. Urban Green*. **2021**, *63*, 127220.
23. Gnassou, L. The End of the Commodities Super-Cycle and its Implications for the Democratic Republic of Congo in Crisis. Afr. Policy J. 2016, 12, 77. Available online: https://apj.hkspublications.org/wp-content/uploads/sites/13/2017/03/APJ-2016.pdf. (accessed on 24 March 2024).
24. Useni, S.Y.; Muteya, H.K.; Bogaert, J. Miombo woodland, an ecosystem at risk of disappearance in the Lufira Biosphere Reserve (Upper Katanga, DR Congo)? A 39-years analysis based on Landsat images. *Glob. Ecol. Conserv*. **2020**, *24*, e01333.
25. Lele, N.; Joshi, P.K. Analyzing Deforestation Rates, Spatial Forest Cover Changes and Identifying Critical Areas of Forest Cover Changes in North-East India during 1972–1999. Environ. Monit. *Assess.* **2009**, *156*, 159-170.
26. Hein, L.; Van Ierland, E. Efficient and Sustainable Management of Complex Forest Ecosystems. *Ecol. Model*. **2006**, *190*, 351-366. https://doi.org/10.1016/j.ecolmodel.2005.04.029.
27. Achard, F.; DeFries, R.; Eva, H.; Hansen, M.; Mayaux, P.; Stibig, H.J. Pan-Tropical Monitoring of Deforestation. *Environ. Res. Lett*. **2007**, *2*, 045022. https://doi.org/10.1088/1748-9326/2/4/045022.
28. Achard, F.; Stibig, H.J.; Eva, H.D.; Lindquist, E.J.; Bouvet, A.; Arino, O.; Mayaux, P. Estimating Tropical Deforestation from Earth Observation Data. Carbon Manag. **2010**, *1*, 271-287. https://doi.org/10.4155/cmt.10.30.
29. Tucker, C.J.; Townshend, J.R. Strategies for Monitoring Tropical Deforestation Using Satellite Data. *Int. J. Remote Sens*. **2000**, *21*, 1461-1471. https://doi.org/10.1080/014311600210263.
30. De Sy, V.; Herold, M.; Achard, F.; Asner, G.P.; Held, A.; Kellndorfer, J.; Verbesselt, J. Synergies of multiple remote sensing data sources for REDD+ monitoring. Curr. Opin. *Environ. Sustain*. **2012**, *4*, 696-706. https://doi.org/10.1016/j.cosust.2012.09.013.
31. Frohn, R.C. Remote sensing for landscape ecology: New metric indicators for monitoring, modeling, and assessment of ecosystems. In CRC Press, **2018**; pp. 1-350.
32. Imbernon, J.; Branthomme, A. Characterization of landscape patterns of deforestation in tropical rain forests. Int. J. Remote Sens. 2001, 22, 1753-1765. DOI: 10.1080/014311601300176033.
33. Crowley, M.A.; Cardille, J.A. Remote sensing's recent and future contributions to landscape ecology. Curr. Landsc. Ecol. Rep. 2020, 5, 45-57. DOI: 10.1007/s40823-020-00054-9.
34. Van Engelen, V.W.P.; Verdoodt, A.; Dijkshoorn, K.; Van Ranst, E. Soil and Terrain Data Base of Central African; SOTERCAF, Version 1.0; FAO: Rome, Italy, **2006**; 22p.
35. INS (Institut National de la Statistique). Anuaire Statistique RDC 2022; Ministère National du Plan: Kinshasa, Democratic Republic of the Congo, **2022**; 433p.
36. Katz-Lavigne, S. Artisanal copper mining and conflict at the intersection of property rights and corporate strategies in the Democratic Republic of Congo. *Extract. Ind. Soc.* **2019**, *6*, 399-406. https://doi.org/10.1016/j.exis.2018.12.001.
37. Roy, D.P.; Wulder, M.A.; Loveland, T.R.; Woodcock, C.E.; Allen, R.G.; Anderson, M.C.; Zhu, Z. Landsat-8: Science and product vision for terrestrial global change research. Remote Sens. Environ. **2014**, *145*, 154-172. https://doi.org/10.1016/j.rse.2014.02.001.
38. Chander, G.; Markham, B.L.; Helder, D.L. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sens. Environ*. **2009**, *113*, 893-903. https://doi.org/10.1016/j.rse.2009.01.007.
39. Choate, M.J.; Rengarajan, R.; Storey, J.C.; Lubke, M. Geometric calibration updates to Landsat 7 ETM+ instrument for Landsat Collection 2 products. Remote Sens. 2021, 13, 1638. https://doi.org/10.3390/rs13091638.
40. Storey, J.; Choate, M.; Lee, K. Landsat 8 operational land imager on-orbit geometric calibration and performance. Remote Sens. 2014, 6, 11127-11152. https://doi.org/10.3390/rs61111127.

41. Vermote, E.; Justice, C.; Claverie, M.; Franch, B. Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sens. Environ*. **2016**, *185*, 46-56. https://doi.org/10.1016/j.rse.2016.04.008.
42. Chen, J.; Zhu, X.; Vogelmann, J.E.; Gao, F.; Jin, S. A simple and effective method for filling gaps in Landsat ETM+ SLC-off images. *Remote Sens. Environ*. **2011**, *115*, 1053-1064. https://doi.org/10.1016/j.rse.2010.12.010.
43. Zoran, M.A.; Zoran, L.F.V.; Dida, A.I. Forest vegetation dynamics and its response to climate changes. In Remote Sensing for Agriculture, Ecosystems, and Hydrology XVIII; SPIE: Bellingham, WA, USA, **2016**,*9998*, pp. 598-608. DOI : 10.1117/12.2241374.
44. Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D.; Moore, R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 2017, 202, 18-27. https://doi.org/10.1016/j.rse.2017.06.031.
45. Chaudhary, A.; Kolhe, S.; Kamal, R. An improved random forest classifier for multi-class classification. Inf. Process. Agric. 2016, 3(4), 215-222. https://doi.org/10.1016/j.inpa.2016.08.002.
46. Olofsson, P.; Foody, G.M.; Herold, M.; Stehman, S.V.; Woodcock, C.E.; Wulder, M.A. Good practices for estimating area and assessing accuracy of land change. *Remote Sens. Environ*. **2014**, *148*, 42–57.
47. Cochran, W.G. Sampling Techniques; John Wiley and Sons: New York, NY, USA, 1977.
48. Schuster, C.; Schmidt, T.; Conrad, C.; Kleinschmit, B.; Forster, M. Grassland habitat mapping by intra-annual time series analysis—Comparison of RapidEye and TerraSAR-X satellite data. *Int. J. Appl. Earth Obs. Geoinf*. **2015**, *34*, 25-34. https://doi.org/10.1016/j.jag.2014.06.004.
49. Strahler, A.H.; Boschetti, L.; Foody, G.M.; Friedl, M.A.; Hansen, M.C.; Herold, M.; Mayaux, P.; Morisette, J.T.; Woodcock, C.E. Global Land Cover Validation: Recommendations for Evaluation and Accuracy Assessment of Global Land Cover Maps; European Commission: Luxembourg, **2006**.
50. Olofsson, P.; Foody, G.M.; Stehman, S.V.; Woodcock, C.E. Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sens. Environ. 2013, 129, 122-131. https://doi.org/10.1016/j.rse.2012.10.031.
51. Zhang, J.; Qu, M.; Wang, C.; Zhao, J.; Cao, Y. Quantifying landscape pattern and ecosystem service value changes: A case study at the county level in the Chinese Loess Plateau. *Glob. Ecol. Conserv*. **2020**, *23*, e01110. https://doi.org/10.1016/j.gecco.2020.e01110.
52. Wang, H.; Zhang, M.; Wang, C.; Wang, K.; Wang, C.; Li, Y.; Zhou, Y. Spatial and temporal changes of landscape patterns and their effects on ecosystem services in the Huaihe River Basin, China. *Land* **2022**, *11*, 513. https://doi.org/10.3390/land11040513.
53. McGarigal, K. FRAGSTATS Help; University of Massachusetts: Amherst, MA, USA, **2015**; 182p.
54. Fahrig, L. Habitat fragmentation: A long and tangled tale. *Glob. Ecol. Biogeogr*. **2019**, *28*, 33–41. https://doi.org/10.1111/geb.12839.
55. Haddad, N.M.; Brudvig, L.A.; Clobert, J.; Davies, K.F.; Gonzalez, A.; Holt, R.D.; Townshend, J.R. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci. Adv.* **2015**, *1*, e1500052. https://doi.org/10.1126/sciadv.1500052.
56. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Townshend, J.R. High-resolution global maps of 21st-century forest cover change. Science 2013, 342(6160), 850-853. https://doi.org/10.1126/science.1244693.
57. Bogaert, J.; Ceulemans, R.; Salvador-Van, E.D. Decision tree algorithm for detection of spatial processes in landscape transformation. Environ. Manag. **2004**, *33*, 62–7.
58. de Haulleville, T.; Rakotondrasoa, O.L.; Rakoto Ratsimba, H.; Bastin, J.F.; Brostaux, Y.; Verheggen, F.J.; Rajoelison, G.L.; Malaisse, F.; Poncelet, M.; Haubruge, É.; et al. Fourteen years of anthropization dynamics in the Uapaca bojeri Baill. Forest of Madagascar. Landsc. Ecol. Eng. **2018**, *14*, 135–146.
59. Wang, J.; Yang, X. A hierarchical approach to forest landscape pattern characterization. *Environ. Manag*. **2012**, *49*, 64–81. https://doi.org/10.1007/s00267-011-9762-9.
60. Lausch, A.; Herzog, F. Applicability of landscape metrics for the monitoring of landscape change: Issues of scale, resolution and interpretability. *Ecol. Indic.* **2002**, *2*, 3-15. https://doi.org/10.1016/S1470-160X(02)00053-5.
61. Bogaert, J.; Vranken, I.; André, M. Anthropogenic effects in landscapes: Historical context and spatial pattern. In Biocultural Landscapes: Diversity, Functions and Values; Springer: Dordrecht, Netherlands, **2014**; pp. 89-112.
62. TV, R.; Setturu, B.; Chandran, S. Geospatial analysis of forest fragmentation in Uttara Kannada District, India. *Forest Ecosyst*. **2016**, *3*, 1-15.
63. Martinez Pardo, J.; Saura, S.; Insaurralde, A.; Di Bitetti, M.S.; Paviolo, A.; De Angelo, C. Much more than forest loss: Four decades of habitat connectivity decline for Atlantic Forest jaguars. *Landscape Ecol*. **2023**, *38*, 41-57. https://doi.org/10.1007/s10980-022-01557-y.
64. Stellmes, M.; Udelhoven, T.; Röder, A.; Sonnenschein, R.; Hill, J. Dryland observation at local and regional scale—Comparison of Landsat TM/ETM+ and NOAA AVHRR time series. *Remote Sens. Environ*. **2010**, *114*, 2111-2125. https://doi.org/10.1016/j.rse.2010.04.016.

65. Vogelmann, J.E.; Gallant, A.L.; Shi, H.; Zhu, Z. Perspectives on monitoring gradual change across the continuity of Landsat sensors using time-series data. *Remote Sens. Environ*. **2016**, *185*, 258-270. https://doi.org/10.1016/j.rse.2016.02.060.
66. Gorsevski, V.; Kasischke, E.; Dempewolf, J.; Loboda, T.; Grossmann, F. Analysis of the impacts of armed conflict on the Eastern Afromontane forest region on the South Sudan—Uganda border using multitemporal Landsat imagery. *Remote Sens. Environ*. **2012**, *118*, 10-20. https://doi.org/10.1016/j.rse.2011.10.023.
67. Koy, J.K.; Wardell, D.A.; Mikwa, J.F.; Kabuanga, J.M.; Monga Ngonga, A.M.; Oszwald, J.; Doumenge, C. Dynamics of deforestation in the Yangambi biosphere reserve (Democratic Republic of Congo): Spatial and temporal variability in the last 30 years. *Bois For. Trop.* **2019**, *341*, 15-28.
68. Khoji, M.H.; Nghonda, D.-d.N.; Kalenda, F.M.; Strammer, H.; Kankumbi, F.M.; Malaisse, F.; Bastin, J.-F.; Sikuzani, Y.U.; Bogaert, J. Mapping and Quantification of Miombo Deforestation in the Lubumbashi Charcoal Production Basin (DR Congo): Spatial Extent and Changes between 1990 and 2022. *Land* **2023**, *12*, 1852. https://doi.org/10.3390/land12101852.
69. Mwitwa, J.; German, L.; Muimba-Kankolongo, A.; Puntodewo, A. Governance and sustainability challenges in landscapes shaped by mining: Mining-forestry linkages and impacts in the Copper Belt of Zambia and the DR Congo. Forest Policy Econ. 2012, 25, 19-30. https://doi.org/10.1016/j.forpol.2012.08.001.
70. Schneibel, A.; Stellmes, M.; Röder, A.; Frantz, D.; Kowalski, B.; Haß, E.; Hill, J. Assessment of spatio-temporal changes of smallholder cultivation patterns in the Angolan Miombo belt using segmentation of Landsat time series. Remote Sens. Environ. 2017, 195, 118-129. https://doi.org/10.1016/j.rse.2017.04.012.
71. Fenta, A.A.; Yasuda, H.; Haregeweyn, N.; Belay, A.S.; Hadush, Z.; Gebremedhin, M.A.; Mekonnen, G. The dynamics of urban expansion and land use/land cover changes using remote sensing and spatial metrics: The case of Mekelle City of northern Ethiopia. Int. J. *Remote Sens.* **2017**, *38*, 4107-4129. https://doi.org/10.1080/01431161.2017.1317936.
72. Molinario, G.; Hansen, M.; Potapov, P.; Tyukavina, A.; Stehman, S. Contextualizing landscape-scale forest cover loss in the Democratic Republic of Congo (DRC) between 2000 and 2015. *Land* **2020**, *9*, 23. https://doi.org/10.3390/land9010023.
73. Mpanda, M.M.; Muteya, H.K.; Nghonda, D.-D.N.; Sambiéni, K.R.; Malaisse, F.; Kaleba, S.C.; Bogaert, J.; Sikuzani, Y.U. Uncontrolled Exploitation of Pterocarpus tinctorius Welw. and Associated Landscape Dynamics in the Kasenga Territory: Case of the Rural Area of Kasomeno (DR Congo). *Land* **2022**, *11*, 1541. https://doi.org/10.3390/land11091541.
74. Molinario, G.; Hansen, M.C.; Potapov, P.V. Forest cover dynamics of shifting cultivation in the Democratic Republic of Congo: A remote sensing-based assessment for 2000–2010. *Environ. Res. Lett.* **2015**, *10*, 094009. https://doi.org/10.1088/1748-9326/10/9/094009.
75. Barima, Y.S.S.; Kouakou, A.T.M.; Bamba, I.; Sangne, Y.C.; Godron, M.; Andrieu, J.; Bogaert, J. Cocoa crops are destroying the forest reserves of the classified forest of Haut-Sassandra (Ivory Coast). *Global Ecol. Conserv*. **2016**,*8*, 85-98. https://doi.org/10.1016/j.gecco.2016.08.009.
76. Useni, Y.S.; André, M.; Mahy, G.; Kaleba, S.C.; Malaisse, F.; Kankumbi, F.M.; Bogaert, J. Interprétation paysagère du processus d'urbanisation à Lubumbashi: Dynamique de la structure spatiale et suivi des indicateurs écologiques entre 2002 et 2008. In Anthropisation des Paysages Katangais; Presses Agronomiques de Gembloux: Gembloux, Belgium, **2018**; 281p.
77. Trefon, T.; Hendriks, T.; Kabuyaya, N.; Ngoy, B. L'économie politique de la filière du charbon de bois à Kinshasa et à Lubumbashi: Appui stratégique à la politique de reconstruction post-conflit en RDC. IOB, GIZ, University of Antwerp, **2010**.
78. Alemagi, D.; Nukpezah, D. Assessing the performance of large-scale logging companies in countries of the Congo Basin. Environ. Nat. Resour. Res. 2012, 2, 38. https://doi.org/10.5539/enrr.v2n2p38.
79. Ernst, C.; Mayaux, P.; Verhegghen, A.; Bodart, C.; Christophe, M.; Defourny, P. National forest cover change in Congo Basin: deforestation, reforestation, degradation and regeneration for the years 1990, 2000 and 2005. Glob. Chang. Biol. 2013, 19, 1173-1187. https://doi.org/10.1111/gcb.12092.
80. Antonarakis, A.S.; Pacca, L.; Antoniades, A. The effect of financial crises on deforestation: A global and regional panel data analysis. Sustainability Sci. 2022, 17, 1037-1057. https://doi.org/10.1007/s11625-021-01086-8.
81. Kabulu, D.J.-P.; Vranken, I.; Bastin, J.-F.; Malaisse, F.; Nyembwe, N.S.; Useni, S.Y.; Ngongo, L.M.; Bogaert, J. Approvisionnement En Charbon de Bois Des Ménages Lushois: Quantités, Alternatives et Conséquences. In Anthropisation des Paysages Katangais; Bogaert, J., Colinet, G., Mahy, G., Eds.; Presses Universitaires de Liège: Liège, Belgium, **2018**; pp. 297–311.
82. Mukendi, N.K.; Muteya, H.K.; Nghonda, D.D.N.T.; Berti, F.; Useni Sikuzani, Y.; Ndjibu, L.N.; Bogaert, J. Quantification and Determinants of Carbonization Yield in the Rural Zone of Lubumbashi, DR Congo: Implications for Sustainable Charcoal Production. *Forests* **2024**, *15*, 554.https://doi.org/10.3390/f15030554.
83. Bogaert, J.; Bamba, I.; Koffi, K.J.; Sibomana, S.; Djibu, J.P.K.; Champluvier, D.; Visser, M.N. Fragmentation of forest landscapes in Central Africa: causes, consequences and management. In Patterns and Processes in

Forest Landscapes: Multiple Use and Sustainable Management; Lafortezza, R., Chen, J., Sanesi, G., Crow, T.R., Eds.; Springer: Dordrecht, Netherlands, 2008; pp. 67-87. https://doi.org/10.1007/978-1-4020-8504-8_5.
84. Fischer, R.; Taubert, F.; Müller, M.S.; Groeneveld, J.; Lehmann, S.; Wiegand, T.; Huth, A. Accelerated forest fragmentation leads to critical increase in tropical forest edge area. Sci. Adv. 2021, 7, eabg7012. https://doi.org/10.1126/sciadv.abg7012.
85. N'tambwe Nghonda, D.-D.; Muteya, H.K.; Kashiki, B.K.W.N.; Sambiéni, K.R.; Malaisse, F.; Sikuzani, Y.U.; Kalenga, W.M.; Bogaert, J. Towards an Inclusive Approach to Forest Management: Highlight of the Perception and Participation of Local Communities in the Management of miombo Woodlands around Lubumbashi (Haut-Katanga, D.R. Congo). *Forests* **2023**, *14*, 687. https://doi.org/10.3390/f14040687.
86. Useni, S.Y.; Mpanda Mukenza, M.; Khoji Muteya, H.; Cirezi Cizungu, N.; Malaisse, F.; Bogaert, J. Vegetation Fires in the Lubumbashi Charcoal Production Basin (The Democratic Republic of the Congo): Drivers, Extent and Spatiotemporal Dynamics. *Land* **2023**, *12*, 2171. https://doi.org/10.3390/land12122171.
87. Useni Sikuzani, Y.; Khoji Muteya, H.; Langunu, S.; Gerardy, A.; Bogaert, J. Amplification of anthropogenic pressure heavily hampers natural ecosystems regeneration within the savanization halo around Lubumbashi city (Democratic Republic of Congo). *Int. J. Environ. Sci. Nat. Resour*. **2019**.
88. Mama, A.; Bamba, I.; Sinsin, B.; Bogaert, J.; De Cannière, C. Déforestation, savanisation et développement agricole des paysages de savanes-forêts dans la zone soudano-guinéenne du Bénin. *Bois For. Trop.* **2014**, *322*, 66-75. DOI: 10.19182/bft2014.322.a31237.
89. Mama, A.; Sinsin, B.; De Cannière, C.; Bogaert, J. Anthropisation et dynamique des paysages en zone soudanienne au nord du Bénin. *Tropicultura* **2013**, *31*. pp. 78–88.
90. Rakotondrasoa, O.L.; Malaisse, F.; Rajoelison, G.; Gaye, J.; Razafimanantsoa, T.M.; Rabearisoa, M.; Bogaert, J. Identification des indicateurs de dégradation de la forêt de tapia (Uapaca bojeri) par une analyse sylvicole. *Tropicultura* **2013**, *31*, 31-41.
91. Useni Sikuzani, Y.; Boisson, S.; Cabala Kaleba, S.; Nkuku Khonde, C.; Malaisse, F.; Halleux, J.M.; Munyemba Kankumbi, F. Dynamique de l'occupation du sol autour des sites miniers le long du gradient urbain-rural de la ville de Lubumbashi, RD Congo. Biotechnol. *Agron. Soc. Environ*. **2020**, *24*, 1-12.
92. Banza, C.L.N.; Nawrot, T.S.; Haufroid, V.; Decrée, S.; De Putter, T.; Smolders, E.; Nemery, B. High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. *Environ. Res*. **2009**, *109*, 745-752. https://doi.org/10.1016/j.envres.2009.04.012.
93. Tanzito, G.; Ibanda, P.A.; Talaguma, R.; Lusanga, N.M. Slash-and-burn agriculture, the major cropping system in the region of Faradje in Democratic Republic of Congo: Ecological and socio-economic consequences. J. Dev. Agric. Econ. 2020, 12, 25-36. DOI: 10.5897/JDAE2019.1140.
94. Montfort, F.; Nourtier, M.; Grinand, C.; Maneau, S.; Mercier, C.; Roelens, J.B.; Blanc, L. Regeneration capacities of woody species biodiversity and soil properties in Miombo woodland after slash-and-burn agriculture in Mozambique. *For. Ecol. Manage*. **2012**, *274*, 142-154. https://doi.org/10.1016/j.foreco.2021.119039.
95. Useni, S.Y.; Mpanda, M.M.; Malaisse, F.; Kaseya, P.K.; Bogaert, J. The Spatiotemporal Changing Dynamics of Miombo Deforestation and Illegal Human Activities for Forest Fire in Kundelungu National Park, Democratic Republic of the Congo. Fire **2023**, *6*,174. https://doi.org/10.3390/fire6050174.
96. Vermeulen, C.; Dubiez, É.; Proces, P.; Diowo, M.; Yamba, Y.; Mutambwe, S.; Doucet, J.L. Enjeux fonciers, exploitation des ressources naturelles et Forêts des Communautés Locales en périphérie de Kinshasa, RDC. *Biotechnologie, Agronomie, Société et Environnement* **2011**, *15*, 651-661.
97. Phiri, D.; Mwitwa, J.; Ng'andwe, P.; Kanja, K.; Munyaka, J.; Chileshe, F.; Kwenye, J.M. Agricultural expansion into forest reserves in Zambia: A remote sensing approach. Geocarto International **2023**, *38*, 2213203. DOI: 10.1080/10106049.2023.2213203.
98. Dimobe, K.; Ouédraogo, A.; Soma, S.; Goetze, D.; Porembski, S.; Thiombiano, A. Identification of driving factors of land degradation and deforestation in the Wildlife Reserve of Bontioli (Burkina Faso, West Africa). *Global Ecology and Conservation* **2015**, *4*, 559–571. https://doi.org/10.1016/j.gecco.2015.10.006.
99. Acheampong, E.O.; Macgregor, C.J.; Sloan, S.; Sayer, J. Deforestation is driven by agricultural expansion in Ghana's forest reserves. In Proceedings of the 2019 Conference on Tropical Deforestation, Accra, Ghana, 15–17 October **2019**.
100. Chitonge, H.; Mfune, O. The Urban Land Question in Africa: The Case of Urban Land Conflicts in the City of Lusaka, 100 Years after Its Founding. *Habitat Int.* **2015**, *48*, 209-218. https://doi.org/10.1016/j.habitatint.2015.03.012.
101. Useni Sikuzani, Y.; Kipili Mwenya, I.; Khoji Muteya, H.; Malaisse, F.; Cabala Kaleba, S.; Bogaert, J. Anthropogenic Pressures and Spatio-Temporal Dynamics of Forest Ecosystems in the Rural and Border Municipality of Kasenga (DRC). *Landsc. Ecol. Eng.* **2024**, *20*, 195-212. https://doi.org/10.1007/s11355-023-00589-z.
102. Kasereka, K.K.; Mweru, J.P. Gouvernance environnementale de la ville de Butembo par les services publics urbains (Nord-Kivu, République Démocratique du Congo). *Tropicultura* **2018**, *36*, 578–592.

103. Kaswamila, A.L.; Songorwa, A.N. Participatory Land-Use Planning and Conservation in Northern Tanzania Rangelands. Afr. J. Ecol. 2009, 47, 128-134. https://doi.org/10.1111/j.1365-2028.2008.01059.x.
104. Butsic, V.; Baumann, M.; Shortland, A.; Walker, S.; Kuemmerle, T. Conservation and conflict in the Democratic Republic of Congo: The impacts of warfare, mining, and protected areas on deforestation. Biological Conservation 2015, 191, 266–273. https://doi.org/10.1016/j.biocon.2015.06.037.
105. Majambu, E.; Tsayem Demaze, M.; Sufo-Kankeu, R.; Sonwa, D.J.; Ongolo, S. The effects of policy discourse on the governance of deforestation and forest degradation reduction in the Democratic Republic of Congo (DRC). *Environmental Policy and Governance* 2023, *34*, 307-320. https://doi.org/10.1002/eet.2077.
106. Meyer, S.E.; Callaham, M.A.; Stewart, J.E.; Warren, S.D. Invasive Species Response to Natural and Anthropogenic Disturbance. Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector **2021**, 85-110. https://doi.org/10.1007/978-3-030-45367-1_5.
107. Stanturf, J.A. Restoration of boreal and temperate forests. CRC Press: Boca Raton, FL, USA, **2004**; pp. 154–196.
108. Boldrini, S. Guide technique. Plantation agroforestière d'Acacia auriculiformis dans le Haut-Katanga. Master's Thesis, University of Lubumbashi, Lubumbashi, Democratic Republic of the Congo, **2017**.
109. Lindsey, P.; Baghai, M.; Bigurube, G.; Cunliffe, S.; Dickman, A.; Fitzgerald, K.; Robson, A. Attracting Investment for Africa's Protected Areas by Creating Enabling Environments for Collaborative Management Partnerships. Biological Conservation 2021, 255, 108979. https://doi.org/10.1016/j.biocon.2021.108979.
110. Bisiaux, F.; Peltier, R.; Muliele, J.C. Plantations industrielles et agroforesterie au service des populations des plateaux Batéké, Mampu, en République Démocratique du Congo. Bois Forêts Trop. 2009, 301, 21–32.
111. Ramiadantsoa, T.; Ovaskainen, O.; Rybicki, J.; Hanski, I. Large-scale habitat corridors for biodiversity conservation: A forest corridor in Madagascar. PLoS One 2015, 10(7), e0132126. https://doi.org/10.1371/journal.pone.0132126.
112. Havyarimana, F.; Masharabu, T.; Kouao, J.K.; Bamba, I.; Nduwarugira, D.; Bigendako, M.J.; De Canniere, C. La dynamique spatiale de la forêt située dans la réserve naturelle forestière de Bururi au Burundi. *Tropicultura* **2017**, *35*, 158–172.
113. Zikargae, M.H.; Woldearegay, A.G.; Skjerdal, T. Empowering rural society through non-formal environmental education: An empirical study of environment and forest development community projects in Ethiopia. *Heliyon* **2022**, *8*, *e09127*. https://doi.org/10.1016/j.heliyon.2022.e09127.
114. Bare, M.; Kauffman, C.; Miller, D.C. Assessing the impact of international conservation aid on deforestation in sub-Saharan Africa. *Environmental Research Letters* **2015**, *10*, 125010. https://doi.org/10.1088/1748-9326/10/12/125010.
115. Khoji, M. H. ; Mokuba, H. K. ; Sambieni, K. R. ; Sikuzani, Y. U. ; Moyene, A. B. & Bogaert, J. Évaluation de la dynamique spatiale des forêts primaires au sein du Parc national de la Salonga sud (RD Congo) à partir des images satellites Landsat et des données relevées in situ. *VertigO-la revue électronique en sciences de l'environnement* **2024**, *24*.
116. Mapira, J. Zimbabwe's Environmental Education Programme and its implications for sustainable development. Doctoral Dissertation, Stellenbosch University, Stellenbosch, South Africa, **2014**.
117. Galabuzi, C.; Eilu, G.; Nabanoga, G.N.; Turyahabwe, N.; Mulugo, L.; Kakudidi, E.; Sibelet, N. Has the evolution process of forestry policies in Uganda promoted deforestation? *International Forestry Review* **2015**, *17*, 298–310. DOI: 10.1505/146554815815982657.
118. Khoji, M.H. ; Mpanda, M. M., Mwenya, I. K. ; Malaisse, F. ; Mukendi, N. K. ; Bastin, J. F. ; Bogaert, J. & Useni, S. Y. Protected area creation and its limited effect on deforestation: Insights from the Kiziba-Baluba Hunting Domain (DR Congo). *Trees, Forests and People* **2024**, *18*, 100654. https://doi.org/10.1016/j.tfp.2024.100654.
119. Klein, B.; Mullard, S.; Ahamadi, K.; Mara, P.; Mena, J.; Nourdine, S.; Maraina, A.V. (Re) Interpreting corruption in local environments: Disputed definitions, contested conservation, and power plays in Northern Madagascar. *Political Geography* **2023**, *107*, 102973. https://doi.org/10.1016/j.polgeo.2023.102973.