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Investigating of Spatial Urban Growth Pattern and Associated Landscape Dynamics in Congolese Mining Cities Bordering Zambia from 1990 to 2023

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Abstract: This study investigates the spatial urban growth patterns of cities along the Democratic Republic of the Congo (DRC) and Zambia border, a region of significant economic importance characterized by cross-border trade. This activity has led to rapid but unplanned urban growth. The objective is to quantify the spatial expansion of Congolese cities (Kipushi, Kasumbalesa, Mokambo, and Sakania) bordering Zambia and to evaluate associated landscape changes. The methodology of this study includes the supervised classification of Landsat images with a spatial resolution of 30 m for the years 1990, 2000, 2010, and 2023. This classification was validated using field data. Subsequently, landscape metrics such as class area, patch number, Shannon diversity index, disturbance index, urban expansion intensity index, largest patch index, and mean Euclidean distance were calculated for each city and each date. The results reveal substantial landscape transformations in the border cities between 1990 and 2023. These changes are primarily driven by rapid urban expansion, particularly pronounced in Kasumbalesa. Between 1990 and 2023, forest cover declined from 70% to less than 15% in Kipushi, from 80% to 10% in Kasumbalesa, from 90% to 30% in Mokambo, and from 80% to 15% in Sakania. This forest cover loss is accompanied by an increase in landscape element diversity, as indicated by the Shannon diversity index, except in Kipushi, suggesting a transition towards more heterogeneous landscapes. In these border cities, landscape dynamics are also characterized by the expansion of agriculture and savannas, highlighted by an increase in the disturbance index. Analysis of spatial pattern changes shows that built-up areas, agriculture, and savannas exhibit trends of patch creation or aggregation, whereas forests are undergoing processes of dissection and patch attrition. Congolese cities bordering Zambia are undergoing substantial spatial changes propelled by intricate interactions between economic, demographic, and infrastructural factors. Our results underscore the need for sustainable development strategies to address urban sprawl through smart growth policies and mixed-use developments, mitigate deforestation via stricter land use regulations and reforestation projects, and enhance cross-border cooperation through joint environmental management and collaborative research initiatives.

Keywords: spatial growth patterns; urban sprawl; deforestation; remote sensing; sustainable development strategies

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1. Introduction

Urbanization is the process of population concentration in urban areas, leading to changes in land use, infrastructure, and socioeconomic structures [1]. It involves rural-to-urban migration, resulting in city growth and the conversion of natural and agricultural landscapes into urban spaces for various purposes [2]. Infrastructure expands to support urban populations, and urban centers become economic hubs, attracting more migrants. Urbanization impacts include environmental changes, social transformations, and economic opportunities and disparities, shaping urban landscapes and regional development trajectories [2].

Global urbanization is a multifaceted process influenced by demographic, economic, and social factors [3]. By 2018, over half of the world's population resided in urban areas, a figure projected to reach 68% by 2050 [4]. Urbanization rates vary globally, with rapid acceleration observed in developing regions such as Africa, fueled by migration and population growth [5]. Though Africa remains predominantly rural, it is expected to undergo significant urbanization by 2050 [5–7], with countries like Nigeria, the Democratic Republic of the Congo (DR Congo), Ethiopia, and Tanzania projected to contribute significantly to this global urban population increase by 2050 [8,9].

Rapid urbanization in Africa induces profound changes in urban landscapes [10] and poses challenges such as housing shortages and strained infrastructure, highlighting the crucial need for effective urban planning and governance [11]. This necessity is particularly acute in small- and medium-sized border cities, which require tailored policies for sustainable development [12]. These cities, often fraught with uncertainties and complexities, have concentrated extreme poverty, especially among those with limited options [13,14]. Located strategically near national borders, they experience rapid population growth due to cross-border activities and economic potential, necessitating careful consideration and strategic interventions [15]. The unplanned expansion of border cities presents significant urban planning challenges that exceed local authorities' capacity, leading to unsustainable urban sprawl that impacts land use, infrastructure, and the environment [16].

In Central-Southern Africa, the Katangese Copperbelt Area (KCA), situated in southeastern DR Congo bordering Zambia, exemplifies this trend. Cities in this area reflect shared histories and cultural exchanges driven by mining activities and trade. Proximity to national borders transforms these cities into dynamic economic hubs fostering cross-border trade and investment [17,18]. Migration, primarily motivated by employment opportunities, significantly contributes to rapid urbanization and demographic growth, intensifying the demand for housing and infrastructure [19,20]. Efficient transport infrastructure crucially supports commercial activities and regional connectivity. This infrastructure includes roads, railways, ports, and airports that facilitate the movement of belongings and people, boosting economic interactions between cities and regions. Meanwhile, industrial policies drive urban expansion by promoting the establishment of industries and economic zones. These policies incentivize investment and job creation, fostering economic growth within urban areas [21,22]. However, these cities face urban planning and governance challenges, leading to rapid, unregulated urbanization resulting in a lack of green spaces and inadequate infrastructure and services [23]. This issue is particularly acute in the DR Congo due to rapid population growth, poor governance, and widespread poverty.

Congolese border cities like Kipushi, Kasumbalesa, Mokambo, and Sakania confront notable challenges concerning urban development and governance, notably housing provision. Mining activities historically shaped Sakania and Kipushi, attracting workers from the city of Lubumbashi (the provincial capital) and beyond post-2002 mining sector liberalization [24,25]. Kipushi developed residential areas for Congolese army personnel, and Kasumbalesa, pivotal for cross-border exchanges, expanded without planning due to recent demographic explosions. Mokambo's growth stems from the road network and a border post, fostering economic opportunities. These agglomerations expand spatially but face largely unplanned, informal urbanization, marked by land use conflicts [26,27]. Social ghettos exacerbate social disparities, and visual landscape degradation leads to biodiversity loss, as evidenced in the city of Lubumbashi, where 3.6 km^2 of green space is lost annually [28]. Yet, urban trees, green belts, and peri-urban forests are essential for sustainable development. These cities are the only urban agglomerations in southern Upper Katanga province with direct terrestrial borders and established crossings with Zambia. Unlike other cities in the province, which interface with Zambia via natural boundaries like Lake Mweru or the

Luapula River, these cities benefit from direct land connections, highlighting their strategic importance in regional trade networks. This fosters intensive economic interactions and demographic flows pivotal to the region's socio-economic fabric. Established border posts enhance their significance as key nodes for cross-border trade, influencing urban growth, infrastructure development, and socio-cultural dynamics. Understanding these dynamics is crucial for effective urban planning, governance, and sustainable development tailored to the unique challenges and opportunities of these border cities.

This study uniquely focuses on the systematic mapping and quantitative assessment of spatial dynamics in Congolese border cities, a topic not extensively explored in the previous literature. Existing studies primarily concentrate on urbanization trends in major African cities such as Lagos and Nairobi [29], overlooking the distinct challenges and dynamics of small- to medium-sized border cities like those in the KCA. Previous research has highlighted urbanization's impacts on large metropolitan areas in Africa, emphasizing issues like infrastructure development and population density [30–32]. However, there is a dearth of comprehensive studies examining the specific spatial dynamics, urban sprawl patterns, and environmental impacts of rapid urbanization in smaller border cities situated within resource-rich but governance-challenged contexts like the KCA. By focusing on these cities, this study aims to fill a critical gap in understanding how cross-border economic activities, demographic shifts, and infrastructural development interact to shape urban landscapes in this unique geopolitical and environmental setting.

Systematic mapping and quantitative assessment of spatial dynamics in Congolese border cities are essential for understanding urban development implications. Remote sensing and landscape ecology techniques offer a robust framework for monitoring spatio-temporal landscape changes [33,34]. Indeed, landscape ecology analyzes the spatial pattern of landscapes, as well as their functioning, qualities, functions, and dynamics in space and time. Additionally, landscape ecology explores landscape structure and ecosystem interactions [35]. The synergy between these approaches fosters a comprehensive understanding of border urbanization and associated landscape dynamics, facilitating evidence-based policies for sustainable growth and resource management [36].

The objective of this study is to conduct an in-depth spatial analysis of border urban dynamics and associated landscape changes between the DR Congo and Zambia from 1990 to 2023. This period allows for identifying long-term trends in urban growth and landscape patterns, including the expansion and consolidation of urban areas. The temporal scope enables the assessment of cumulative impacts on the landscape, such as changes in vegetation cover, habitat fragmentation, and landscape structure. Additionally, the multi-decadal data inform urban planning and policy making by providing insights from historical patterns. The specific objectives are (i) to comprehensively assess landscape composition changes across five land-cover types and (ii) to identify the spatial transformation processes underlying the compositional dynamics observed within each land cover type in the four mining and border cities studied. The hypothesis being tested is that due to rapid population growth and economic opportunities, border towns are experiencing accelerated urban expansion, particularly in medium-sized cities with dynamic economies. This disrupts landscapes by increasing heterogeneity and promotes the expansion of savannas due to forest fragmentation.

2. Materials and Methods

2.1. Study Area: Congolese Cities Bordering Zambia

The cities of Kipushi, Kasumbalesa, Mokambo, and Sakania are strategically located in the southeastern region of the DR Congo (Figure 1), within the KCA [37].

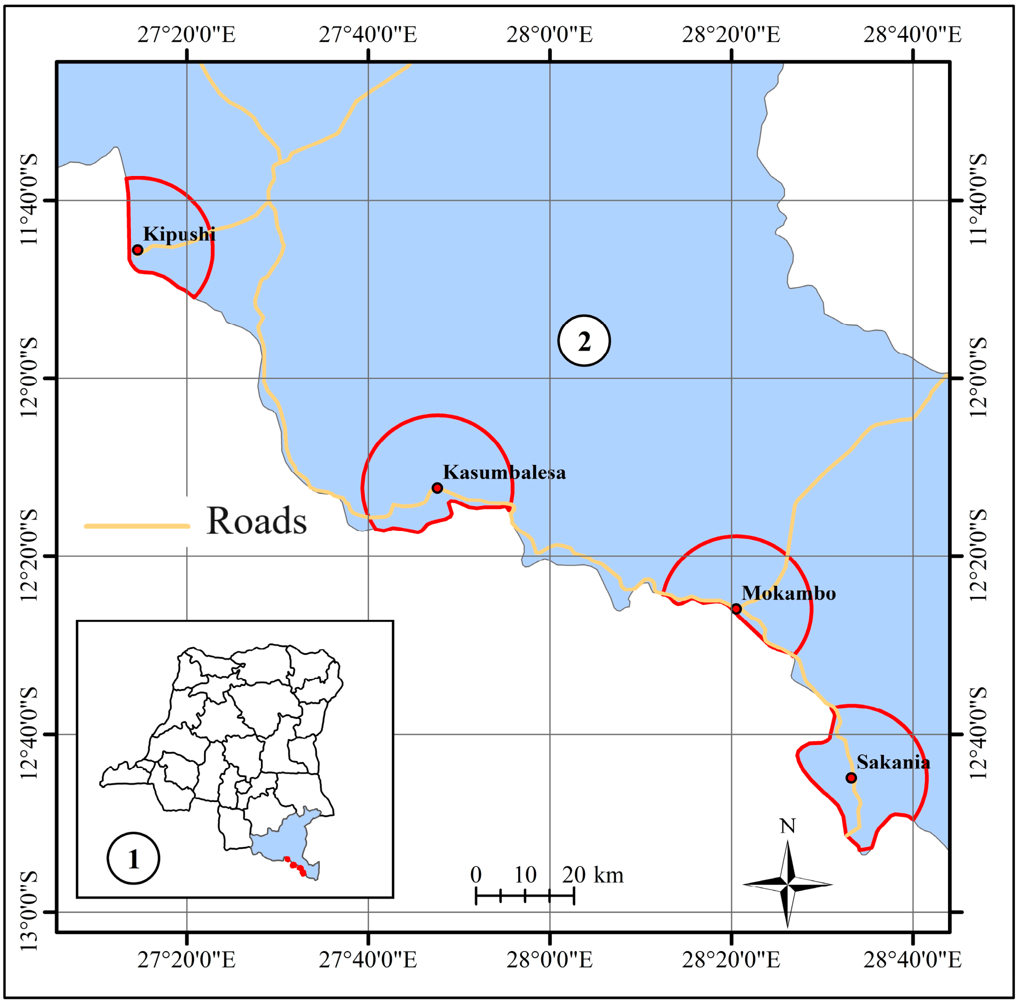

Figure 1. Geographical location of the Congolese cities (2) (red circles) bordering Zambia: Kipushi, Kasumbalesa, Mokambo, and Sakania in the south-eastern region of the Democratic Republic of the Congo (1) (DRC). A geometric center (centroid) was defined for each city. From this center, a 15 km radius was drawn, covering the built-up area and the city's periphery, which were then analyzed. This area corresponds to 307.22 km^2, 534.87 km^2, 424.64 km^2, and 468.60 km^2, respectively, for the cities of Kipushi, Kasumbalesa, Mokambo, and Sakania, respectively. The yellow line corresponds to the roads.

Situated between 10° and 12° S and 26° and 29° E, this region falls under the Cw climate according to the Köppen classification system, characterized by a distinct rainy season from November to March and a dry season from May to September, with transitional months in April and October [38]. The region receives an annual precipitation of approximately 1200 mm and has an average annual temperature of 20 °C [38]. The topography is predominantly flat with scattered hills typical of the Katanga landscape, and the soils are primarily ferralsol-type [39]. Rapid urbanization and human activities have fragmented the original miombo woodland, transitioning it into savannas [40–42]. These cities are experiencing continuous population growth, with estimates of 396,000 in Kipushi (98,000 in 2004), 700,000 in Kasumbalesa (47,000 in 2004), 47,000 in Mokambo (20,000 in 2004), and 55,000 in Sakania in 2022 (8600 in 2004) [43]. Economic activities in this region are diverse, focusing on mining, agriculture, and cross-border trade, particularly significant due to proximity to the Zambian border. Trade between the DR Congo and Zambia is dominated by the exchange of minerals, especially copper and cobalt. The DR Congo mainly exports these minerals to Zambia, and Zambia provides the DR Congo with manufactured and agricultural products, which transit through these border cities. Kasumbalesa serves as a major border city with established customs infrastructure; Mokambo features a dry port and critical road connections; Sakania is influenced by its mining history and industrial potential; and Kipushi is recognized for its mining legacy and ongoing urban revitalization efforts.

2.2. Methodology

2.2.1. Data

Landsat images with a 30 m spatial resolution and less than 5% cloud cover, spanning from 1990 to 2023, were utilized for this study. The selected intervals (1990–2000, 2000–2010, and 2010–2023) enable a decadal analysis, capturing long-term trends and spatial dynamics changes. The Landsat TM, ETM+, and OLI satellite sensors share several common features, including a spatial resolution of approximately 30 m for all spectral bands used [44]. These sensors are employed for environmental monitoring, natural resource management, and studying changes in the Earth's surface through high-quality multispectral images. Introduced with Landsat 4 and 5, the TM sensor captures six spectral bands, including thermal infrared, with a spatial resolution of about 30 m for the visible and infrared bands. Launched with Landsat 7, the ETM+ sensor captures seven spectral bands, including thermal infrared, with a spatial resolution of about 30 m for all bands and an improved thermal resolution of 60 m [45]. Introduced with Landsat 8, the OLI sensors feature nine spectral bands covering a wide spectrum from ultraviolet to thermal infrared, with a spatial resolution of about 30 m for all bands. The OLI provides better radiometric accuracy and improved surface feature discrimination capabilities [46].

The 1990–2000 period was characterized by political turbulence and conflicts in the Eastern region. The 2000–2010 era witnessed mining sector liberalization (2002), the first electoral cycle (2006), subsequent infrastructure modernization, and the global financial crisis (2008). The 2010–2023 period saw additional electoral cycles (2011 and 2018), provincial restructuring (2015), and a change in political regime (2019). The selection of Landsat images specifically during the dry season minimizes cloud cover, ensuring clear visibility for accurate interpretation of landscape features [25]. This approach is crucial for precise mapping and quantification of spatio-temporal landscape changes [47].

2.2.2. Classification

Using the WGS-84 reference ellipsoid, the Landsat images were georeferenced in the UTM Zone 35S coordinate system, which corresponds to the study region [25], and preprocessed. First, radiometric calibration corrects sensor readings to ensure consistency over time and across different sensors. It involves removing sensor biases and accounting for atmospheric effects. Second, geometric calibration ensures that pixels in the image accurately represent locations on the Earth's surface. It corrects for geometric distortions caused by spacecraft movements and sensor orientation. Finally, through atmospheric correction, we removed atmospheric effects such as haze and scattering, allowing for more accurate analysis of surface reflectance [48].

Consecutively, a false color composite of selected Landsat images was meticulously constructed by combining the mid-infrared, near-infrared, and red bands to enhance discrimination among diverse vegetation types [49,50]. For precision and clarity, distinctive land cover units were methodically identified and assigned unique codes across different scenes. To establish a solid foundation for subsequent analyses, Regions of Interest (ROIs), representing training areas, were meticulously delineated for each land cover (Table 1) during the dry season using GPS (64st precision 3 m). The selection of ROIs was guided by sampling polygons, strategically positioned to avoid transition zones, thereby minimizing the impact of the mixel phenomenon and enhancing subsequent analysis accuracy [51,52]. To refine analytical capabilities, these carefully crafted ROIs were utilized to construct a comprehensive model for training the Random Forest classifier under Google Earth Engine. This ensemble approach, incorporating multiple decision trees, provided a robust and adaptable foundation for subsequent land cover classification [53].

Table 1. Description of land cover classes obtained after supervised classification of Landsat images on GEE, based on the Random Forest classifier. ROI: Regions of Interest.

Land Cover	Description	ROI (Polygons)
Forest	Natural land cover, comprising patches of *miombo* woodland, dry dense forest, and gallery forest.	170
Savanna	Generally anthropogenic land cover, characterized by low tree density and predominance of herbaceous cover.	170
Agriculture	The anthropogenic land cover class consists of harvested agricultural lands, abandoned agricultural lands, or lands occupied by annual and off-season crops.	120
Built-up and bare soil	Bare land and residential areas with minimal vegetation, impermeable surfaces, or rarely paved roads.	150
Other land cover	Water and unclassified spaces.	90

The methodology for Landsat image classification, using Google Earth Engine (GEE) and the Random Forest algorithm, represented a rigorous approach implemented to characterize five land cover types: forest, savanna, agriculture, built-up and bare soil, and other land cover (Table 1). GEE is widely used for collecting samples for land cover due to its accessibility to vast remote sensing data archives. It offers powerful cloud-based computing resources for large-scale spatial data analysis and integrates satellite imagery, environmental datasets, and analysis tools. GEE ensures consistency and standardized procedures in data collection across regions and datasets [54].

To evaluate the accuracy of the obtained classifications, we followed the best practices recommendations of Olofsson et al. [55]. An unbiased surface estimators and estimated uncertainty was constructed by collecting a sample of reference observations from change maps between 1990 and 2023. This process relied on truth points collected in each land cover class. Samples were randomly stratified according to a 9-strata map for each period, including 5 stable strata (forest, savanna, agriculture, and built-up and bare soil) and 4 relevant change strata for each period (forest lost, savanna gain, agriculture gain, and built-up and bare soil gain). The sample size was determined using Cochran's method [56], with 800 points sampled for each period (1990–2000, 2000–2010, and 2010–2023). Based on the proportion of each stratum, 250 points were assigned to strata occupying more than 40%, 150 points to strata occupying between 10 and 40%, and 100 points to strata occupying less than or equal to 10%. Subsequently, QGIS software version 3.26.1 (developed by the global QGIS community, Buenos Aires, Argentina) was used to calculate the error matrix, expressed in terms of estimated surface proportions [52]. Measurement accuracies, including overall accuracies and user and producer accuracies, were also automatically generated using the same software. Land cover maps were produced using ArcGIS version 10.8 (developed by ESRI (Environmental Systems Research Institute), Redlands, CA, USA).

2.2.3. Quantifying Urban Landscape Pattern Changes

To quantify human impact on landscape morphology, several metrics have been calculated [57,58]. First, the class area refers to the relative extent of specific land cover types within a defined landscape. This metric helps in understanding the composition of the landscape by identifying the predominant land cover matrix. It provides insights into the dominance or scarcity of certain land cover types and helps in assessing changes in land use over time. Next, the number of patches was crucial in assessing landscape fragmentation. A high number of patches indicates fragmentation and scattered distribution, suggesting significant human impact and disruption of natural habitats. Conversely, a low number of patches suggests infilling or aggregation, which may indicate a more cohesive and less disturbed landscape. The Shannon diversity index was calculated to measure landscape diversity [59]. It considers both the richness (the number of different land cover types) and evenness (the relative abundance of each land cover type) within the landscape, providing a comprehensive view of landscape complexity and diversity. To assess the level of landscape anthropization, the disturbance index was calculated. This index is defined as the ratio between the cumulative area of anthropogenic land cover in the landscape and the forest area [60]. It quantifies the extent of human-induced changes relative to natural land cover types, highlighting the degree of disturbance and potential ecological impact. The urban expansion intensity index (UEII) quantified the rate and magnitude of urban growth within a specified area over time. It provides a comprehensive view of urbanization intensity and its impacts, helping to determine patterns of urban sprawl and its effects on the landscape [61]. The largest patch index (LPI), defined as the ratio between the largest patch area and the class area, provides information on the fragmentation of a land cover following its reduction [59]. A higher LPI indicates that the largest patch dominates the landscape, suggesting less fragmentation, whereas a lower LPI suggests greater fragmentation and distribution of smaller patches. Finally, the average Euclidean distance to the nearest neighbor indicates the average distance between each patch in the landscape and its closest neighboring point. It offers an understanding of spatial pattern dispersion, with greater distances indicating more isolated patches and potential challenges for species movement and ecological connectivity [52]. These metrics were calculated using Fragstats software version 4.2 (developed by McGarigal, Amherst, MA, USA).

Between two dates, changes in patch number and class area indicate distinct spatial transformation processes in landscape dynamics [49,57,62]: decreases in both patch number and class area indicate attrition, whereas an increased class area with a decreased patch number suggests aggregation. Unchanged patch numbers with increased class area signify enlargement, whereas growth in both the class area and patch number reflects the creation of new patches. Dissection is marked by a reduced class area and an increased patch number, often with linear disruptions causing minimal area loss. Fragmentation, on the other hand, involves a patch increase accompanied by a significant class area loss. To differentiate between fragmentation and dissection, the ratio of total areas at different time points was examined, with a ratio above 0.75 indicating dissection dominance and a ratio at or below 0.75 suggesting prevalent fragmentation [63].

3. Results

3.1. Classification Accuracy and Mapping

Table 2 presents the accuracy performance of supervised classifications of Landsat images using the Random Forest classifier for the years 1990, 2000, 2010, and 2023. The overall accuracy exceeds 90% for each analyzed period, underscoring the reliability in distinguishing between different land cover types. The user's and producer's accuracy, ranging from 93% to 100%, further confirm the high quality of the classifications, indicating minimal errors in classifying the various land cover types. Additionally, applying a 95% confidence interval to estimate the stratified area of each land cover class across the different periods reveals a margin of error below 5%. This low uncertainty enhances the credibility of the results, suggesting that the area estimates for each class are reliable and precise.

The visual (Figure 2) analysis reveals the growth of built-up and bare soil is observed in different directions: eastward in the city of Kipushi, northward and southwestward in the city of Kasumbalesa, eastward in the city of Mokambo (C), and westward in the city of Sakania (D). Additionally, an important decrease in forest cover, particularly around the city of Kipushi (A) and the city of Kasumbalesa (B), were observed. Concurrently, savannas are gradually encroaching upon former forested areas around all cities studied, indicating a shift in ecosystem dynamics. There is also a noticeable increase in agricultural lands surrounding all four cities, underscoring the significant impacts of human activities on the landscape. The reduction in forest cover, coupled with the expansion of built-up and bare soil areas, agriculture, and savannas, highlights the extensive footprint of deforestation and urbanization on local landscapes.

Table 2. Evaluation of accuracy and area estimation of land cover change maps from 1990 to 2023 based on supervised classification of Landsat images using the Random Forest classifier and according to Olofsson's methodology in Ref. [55]. FR: forest; SV: savanna; AG: agriculture; BBS: built-up and bare soil; OT: other land cover; UA: user accuracy; PA: producer accuracy; CI: confidence interval. The change in the "OT" land cover was not evaluated due to its relative stability across all studied periods and cities.

1990–2000	FR	SV	AG	BBS	OT	FR Loss	SV Gain	AG Gain	BBS Gain
Accuracy measure									
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
Overall accuracy [%]	97.56								
Stratified estimators of area ± CI [% of total map area]									
Area [%]	18.14	18.23	9.12	9.29	9.20	8.94	8.67	9.65	8.76
95% CI	0.42	0.00	0.35	0.00	0.17	0.17	0.38	0.54	0.30
2000–2010	FR	SV	AG	BBS	OT	FR Loss	SV Gain	AG Gain	BBS Gain
Accuracy measure									
PA [%]	99.00	94.42	98.99	98.00	96.00	98.11	98.10	100.00	100.00
UA [%]	99.01	100.00	98.00	97.09	98.06	99.05	99.04	98.99	95.10
Overall accuracy [%]	97.40								
Stratified estimators of area ± CI [% of total map area]									
Area [%]	19.30	16.95	9.30	9.21	8.66	9.21	9.21	8.94	9.21
95% CI	0.25	0.47	0.30	0.25	0.18	0.25	0.31	0.31	0.31
2010–2023	FR	SV	AG	BBS	OT	FR Loss	SV Gain	AG Gain	BBS Gain
Accuracy measure									
PA [%]	99.00	96.49	100.00	97.02	100.00	96.04	98.04	97.98	95.06
UA [%]	99.02	98.00	95.17	99.02	98.97	99.00	99.01	98.98	100.00
Overall accuracy [%]	96.30								
Stratified estimators of area ± CI [% of total map area]									
Area [%]	18.32	17.96	10.30	9.21	8.66	10.21	9.21	9.94	8.21
95% CI	0.26	0.46	0.33	0.25	0.18	0.27	0.31	0.31	0.31

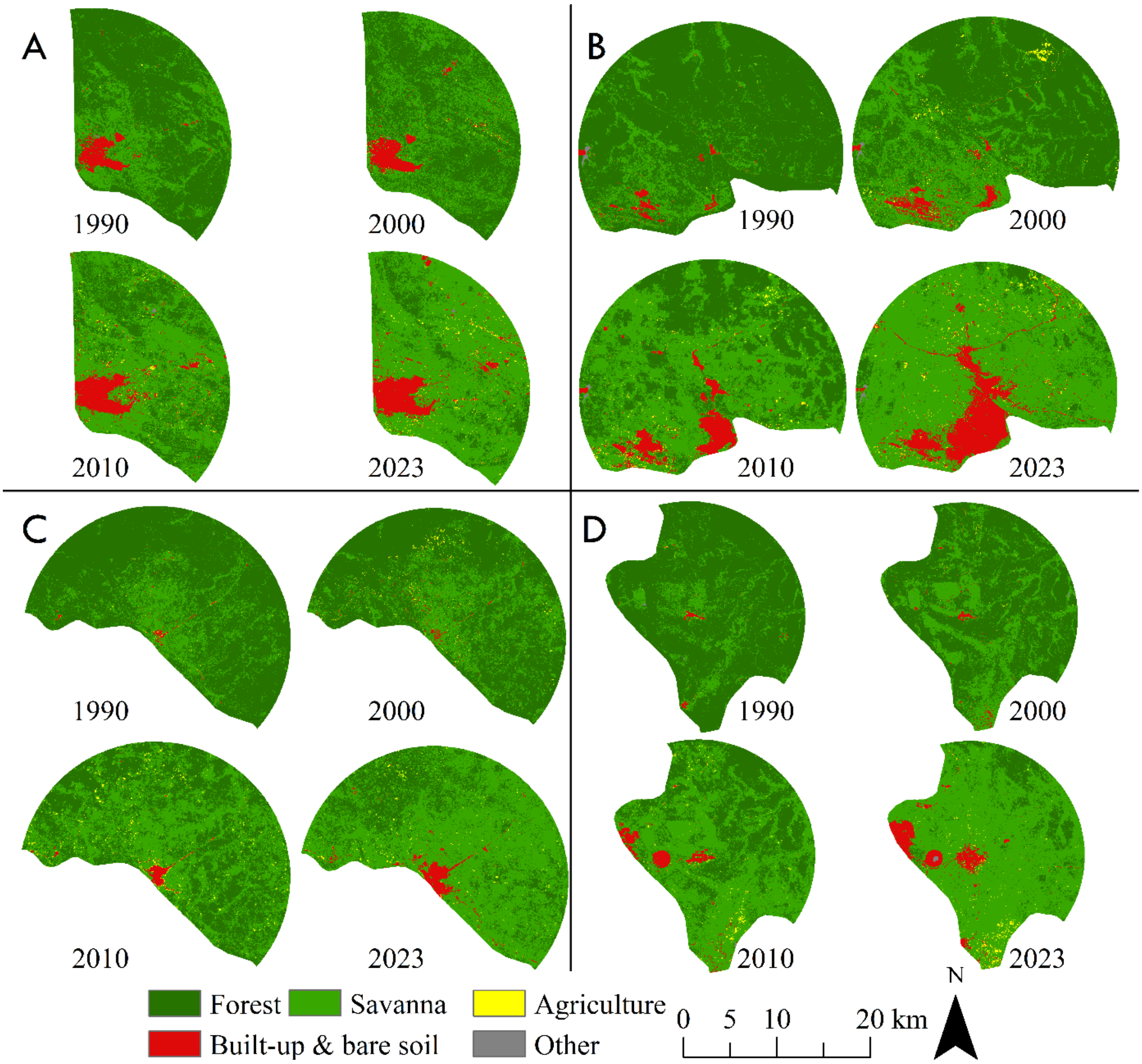

Figure 2. Mapping spatial land cover dynamics in Kipushi (**A**), Kasumbalesa (**B**), Mokambo (**C**), and Sakania (**D**) landscapes from 1990 to 2023 using supervised classification of Landsat images with the Random Forest classifier.

3.2. Landscape Composition Dynamics

Between 1990 and 2023, there was a marked decrease in forest cover surrounding Kipushi, Kasumbalesa, Mokambo, and Sakania. Initially, forests dominated these regions, but by 2023, their extent had drastically diminished, with less than 15% remaining in Kipushi, 10% in Kasumbalesa, 30% in Mokambo, and 15% in Sakania. Conversely, the proportion of savannas multiplied fourfold on average, built-up and bare soil increased eightfold, and the proportion of agriculture surged by a factor of 46 across the four border cities between 1990 and 2023 (in average). These changes signify a significant reshaping of the land cover in the region (Figure 3). Furthermore, an analysisusing the Shannon diversity index indicated shifts in landscape composition, with Kasumbalesa, Mokambo, and Sakania displaying increased diversity between 1990 and 2023, suggesting a transition toward more heterogeneous landscapes. This transformation underscores the diversification of land cover characteristics and types within these border cities (Figure 4).

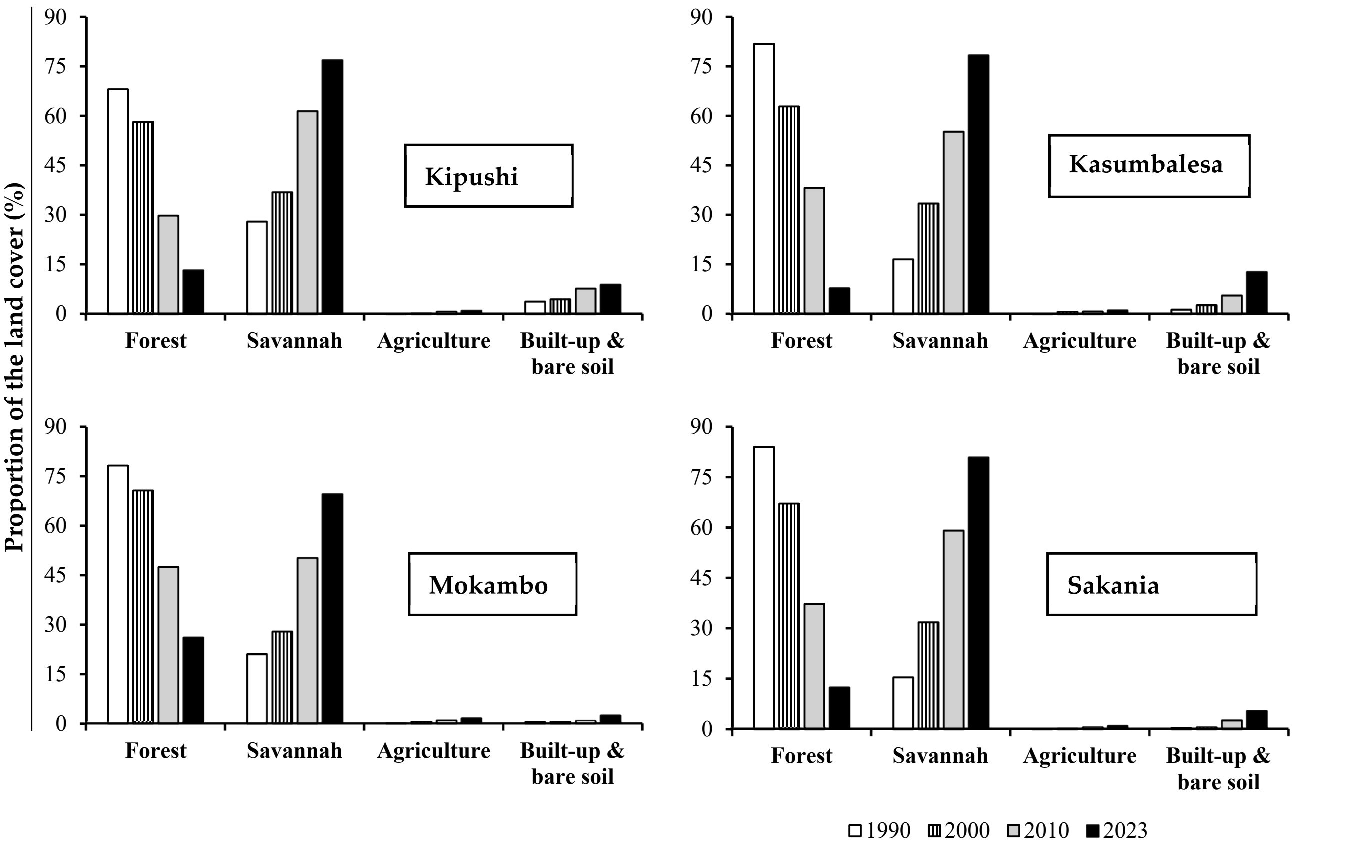

Figure 3. Landscape composition evolution in Congolese Cities (Kipushi, Kasumbalesa, Mokambo, and Sakania) bordering Zambia from 1990 to 2023. The total landscape proportion for each city does not sum to 100%, as other land cover classes were excluded from the analyses due to their relatively stable nature. The dynamics of landscape composition are evidenced by deforestation alongside the expansion of built-up and bare soil, agriculture, and savannas.

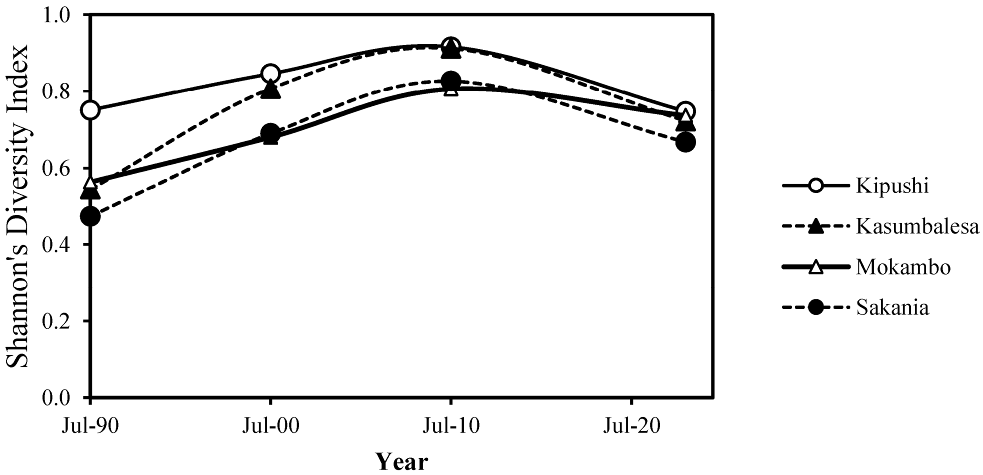

Figure 4. Landscape diversity dynamics of the cities of Kipushi, Kasumbalesa, Mokambo, and Sakania between July-1990 and July-2023. The studied cities are characterized by a transition marked by the shift from a less diversified landscape to a heterogeneous landscape over time.

3.3. Intensity of Urban Expansion, Sprawl, and Associated Landscape Anthropization

During the 1990–2000 decade, the urban expansion intensity index for Kipushi, Kasumbalesa, Mokambo, and Sakania was 0.08, 0.14, 0.02, and 0.03, respectively. These results indicate that Kasumbalesa experienced the most significant urban growth intensity during this period. From 2000 to 2010, there was a substantial increase in the urban expansion intensity index for all border cities studied, with values of 0.32, 0.29, 0.04, and 0.21 for Kipushi, Kasumbalesa, Mokambo, and Sakania, respectively. Compared to the previous decade, Kipushi saw a more pronounced urban expansion intensity during this period. Lastly, from 2010 to 2023, the urbanization intensity index continued to rise, reaching values of 0.54, 0.12, and 0.21 for Kasumbalesa, Mokambo, and Sakania, respectively. For the city of Kipushi, the value decreased fourfold during this period. These results indicate a more important urban expansion intensity in Kasumbalesa, placing it at the forefront in terms of spatial urban growth compared to the other studied cities (Figure 5).

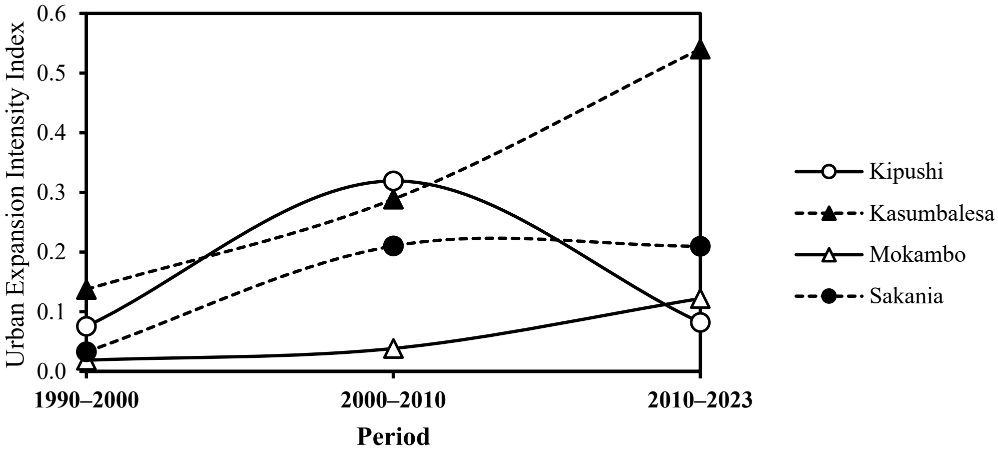

Figure 5. Variation in the urban expansion intensity index between 1990 and 2000, 2000 and 2010, and 2010 and 2023 within the landscapes of the border cities of Kipushi, Kasumbalesa, Mokambo, and Sakania. Urbanization is significantly more intense in Kasumbalesa, whereas relative stability was noted in Kipushi between 1990 and 2023.

However, the border cities of Kipushi, Kasumbalesa, Mokambo, and Sakania, along with their surrounding areas, experienced a progressive anthropization of their landscapes (Table 3). In 1990, the largest forested patch covered approximately 80% of the class area, with an average distance between patches of less than 70 m. However, this largest patch area decreased by approximately 10%, whereas the average distance between forest patches was multiplied nearly threefold by 2023. Concurrently, an inverse trend was observed for agriculture, savannas, and built-up and bare soil. Over the 33 years from 1990 and 2023, the average distance between their patches decreased, and the size of their respective largest patches increased (Table 3), suggesting a trend towards fragmentation and degradation of landscapes.

Additionally, during the period of 1990–2023, a significant increase in the disturbance index was observed within the landscapes of the studied border cities (Figure 6). In Kipushi, this index was multiplied by 14, increasing from 0.5 in 1990 to 6.5 in 2023. In Kasumbalesa, an even more pronounced increase was noted, with a multiplication factor of 53, raising the index from 0.2 in 1990 to 11.8 in 2023. For Mokambo, the index was multiplied by 10, increasing from 0.3 in 1990 to 2.8 in 2023. Lastly, in Sakania, the index was multiplied by 37, reaching 7 in 2023 compared to an initial value of 0.2 in 1990 (Figure 6). These increases reflect a significant intensification of human activity in these regions over this 33-year period.

Table 3. Evolution of the largest patch index (LPI) and mean Euclidean nearest neighbor (ENN) of forest, built-up and bare soil, agriculture, and savanna patches between 1990 and 2023 in the landscapes of the border cities of Kipushi, Kasumbalesa, Mokambo, and Sakania. A trend towards fragmentation and degradation of landscapes around the studied border cities is noted.

	Border City							
	Kipushi		Kasumbalesa		Mokambo		Sakania	
Indices	**LPI**	**ENN**	**LPI**	**ENN**	**LPI**	**ENN**	**LPI**	**ENN**
				1990				
Forest	63.84	68.54	79.75	68.40	74.67	67.01	82.43	67.08
Savanna	14.83	83.19	6.35	87.13	10.33	82.27	3.30	87.52
Agriculture	0.01	1986.84	0.00	530.87	0.00	263.60	0.00	438.33
Built-up and bare soil	3.09	210.96	0.21	220.15	0.16	303.63	0.15	271.01
				2000				
Forest	53.53	64.60	49.44	71.96	66.30	66.33	64.16	73.56
Savanna	12.15	69.37	23.41	77.27	12.09	75.40	10.09	80.00
Agriculture	0.00	217.59	0.11	163.93	0.01	160.89	0.00	266.45
Built-up and bare soil	3.74	187.15	0.87	132.25	0.11	171.10	0.20	189.77
				2010				
Forest	10.29	75.76	12.53	75.50	15.31	70.99	16.65	77.33
Savanna	55.22	67.24	48.43	73.97	43.32	71.58	52.43	73.17
Agriculture	0.05	163.54	0.02	151.23	0.01	156.72	0.04	183.45
Built-up and bare soil	5.84	119.31	2.43	153.99	0.70	289.83	0.90	171.13
				2023				
Forest	3.02	88.55	1.14	99.56	13.69	77.15	3.96	91.52
Savanna	75.18	70.95	77.07	77.98	64.43	66.78	78.77	74.15
Agriculture	0.02	138.42	0.02	157.16	0.02	199.42	0.05	132.63
Built-up and bare soil	6.14	133.83	10.33	136.26	1.89	195.50	4.32	180.06

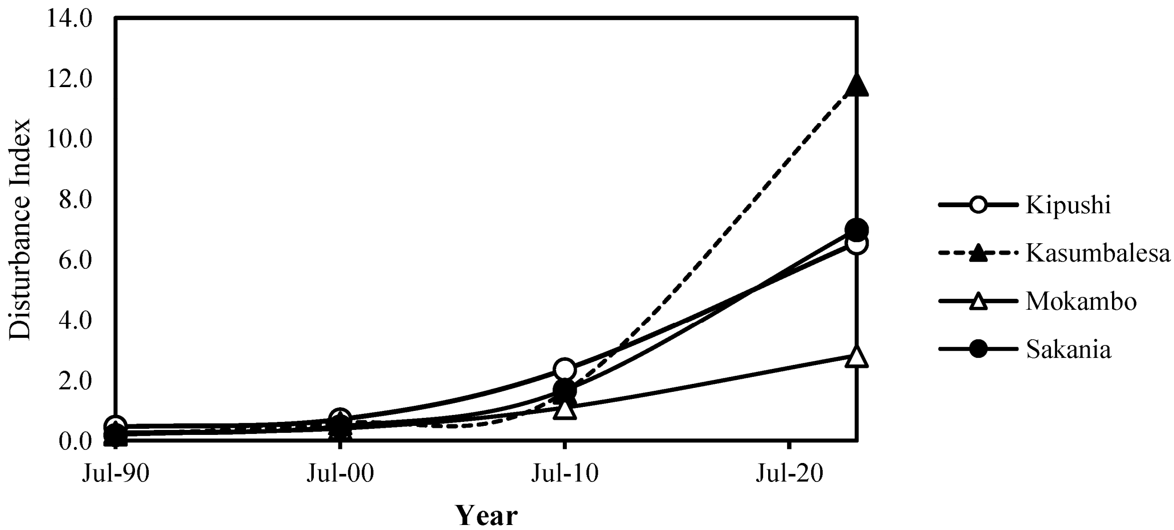

Figure 6. Evolution of the landscape disturbance index of the cities of Kipushi, Kasumbalesa, Mokambo, and Sakania between July-1990 and July-2023. There is an increase in the disturbance index across the time, reflecting a significant intensification of human activity in these cities.

3.4. Analysis of Landscape Spatial Pattern Dynamics

Applying the decision tree algorithm of Bogaert et al. [57] on the data in Table 4, our findings underscore that between 1990 and 2000, the forest experienced an increase in PN and a decrease in CA for the cities of Kipushi, Kasumbalesa, Mokambo, and Sakania, suggesting a spatial transformation process of dissection (0.83 > 0.75). Conversely, the savannas, agriculture, and built-up and bare soil recorded an increase in both PN and CA, indicating a creation process.

Table 4. The variation in class area (CA in km^2) and patch number (PN) of land cover classes in the landscapes of the border cities of Kipushi, Kasumbalesa, Mokambo, and Sakania in 1990, 2000, 2010, and 2023. This variation in CA and PN between two dates enabled the identification of spatial transformation processes using the decision tree algorithm of Bogaert et al. [57]. Forest is characterized by the dissection and attrition of patches, as opposed to the creation and aggregation of patches observed in agriculture, built-up and bare soil, and savannas in the landscapes of the four studied border cities.

	Border City							
	Kipushi		Kasumbalesa		Mokambo		Sakania	
Indices	**CA**	**NP**	**CA**	**NP**	**CA**	**NP**	**CA**	**NP**
1990								
Forest	209.0	2335.0	437.3	1567.0	332.1	1994.0	393.4	1431.0
Savanna	86.3	3869.0	89.0	5915.0	90.2	6010.0	73.1	5633.0
Agriculture	0.0	16.0	0.2	119.0	0.4	476.0	0.1	89.0
Built-up and bare soil	11.8	400.0	7.6	613.0	1.9	385.0	1.8	190.0
2000								
Forest	178.7	3032.0	336.2	4468.0	300.1	3009.0	314.5	2994.0
Savanna	113.6	6349.0	179.3	6844.0	119.1	7112.0	149.8	7039.0
Agriculture	0.6	546.0	3.9	1643.0	2.8	1683.0	0.6	552.0
Built-up and bare soil	14.1	644.0	14.9	1390.0	2.7	1206.0	3.4	917.0
2010								
Forest	91.4	4058.0	204.1	7081.0	201.7	5084.0	174.6	5855.0
Savanna	189.2	2717.0	295.4	3920.0	213.6	4162.0	277.2	3967.0
Agriculture	2.5	1582.0	4.6	2083.0	5.1	2091.0	3.4	1503.0
Built-up and bare soil	23.9	2132.0	30.4	1206.0	4.3	391.0	13.3	1141.0
2023								
Forest	40.7	4085.0	41.7	5211.0	111.1	8181.0	58.6	6040.0
Savanna	236.1	878.0	418.7	1147.0	299.3	2581.0	378.6	1387.0
Agriculture	3.0	1624.0	5.9	2191.0	6.2	2212.0	4.9	2189.0
Built-up and bare soil	27.2	1504.0	67.9	2428.0	11.0	697.0	26.0	924.0

During the period from 2000 to 2010, fragmentation was the dominant spatial transformation process for the forest for all studied border cities (0.58 < 0.75), since the decrease in CA was accompanied by an increase in PN. Savannas exhibited an increase in CA and a decrease in PN, suggesting an aggregation-type spatial transformation process. Agriculture and built-up and bare soil were characterized by an increase in PN and CA, indicating creation as the spatial transformation process. From 2010 to 2023, the forest showed an increase in PN and a decrease in CA for the border cities of Kipushi, Mokambo, and Sakania, indicating a process of fragmentation (0.38 < 0.75). However, around the border city of Kasumbalesa, there was a simultaneous decrease in both the PN and CA of forest, indicating attrition as the spatial transformation process. Agriculture exhibited a process of patch creation, as the increase in CA resulted from an increase in PN. Finally, for savannas and built-up and bare soil, there was noted a decrease in PN alongside an increase in CA, suggesting an aggregation-type spatial transformation process.

4. Discussion

4.1. Urban Expansion Intensity and Associated Landscape Dynamics

The period of 1990–2001 was characterized by a slow urban expansion along the RD Congo–Zambia border due to political conflicts, leading to economic and social instability. Moreover, political tensions can disrupt commercial activities and hinder economic growth, thereby limiting employment opportunities and urban development [64]. Additionally, during conflict periods, priorities often shift towards addressing immediate security and political stability issues, relegating urbanization projects to the background [65]. Conversely, we found an acceleration in the urbanization extent during 2000–2010, which corresponds to the period of progressive mining liberalization, favoring increased foreign and domestic investments and stimulating economic growth and creating jobs. This economic growth also resulted in an increased demand for labor, attracting a growing population to urban areas near mining zones [66,67]. The findings of Khoji et al. [25] and Cabala et al. [37] corroborate the acceleration of the urbanization of main agglomerations within the KCA during the same period. Furthermore, mining companies could finance the construction of housing for mine workers, promoting the expansion of border cities [68].

The decade of 2010–2023 is characterized by a new phase of rapid urbanization of the Congolese border cities due to political stabilization and economic recovery after the global financial crisis. Indeed, the increasing demand for mineral resources attracted new investments and labor, thereby stimulating urban growth. Yet, the increasing demand for housing among new citizens is driving uncontrolled urban expansion, extending beyond any form of government control. Indeed, Congolese cities are generally surpassing their own limits and encroaching on adjacent rural areas. Consequently, given the expensive urban lifestyle prevalent in many urban centers, a significant portion of the population in border cities opts for areas that maintain their rural essence, where land resources remain relatively affordable [69]. Concurrently, during this decade, the roads connecting the city of Lubumbashi to Sakania via Mokambo and Kasumbalesa have all been asphalted. This process has had a significant impact on the spatial expansion of Mokambo, notably by promoting the purchase of plots with traditional houses and their transformation into modern houses for customs officers and their families. This pattern aligns with Arimah's [70] findings regarding infrastructure's role in enhancing the prosperity of African cities. However, this trend of urban modernization can induce the loss of female local knowledge, particularly regarding the painting of traditional houses.

Unfortunately, the spatial urban expansion observed in border cities between the DRC and Zambia is largely driven by self-construction, leading to urban sprawl, as revealed by the increase in CA and PN simultaneously, as well as in UIIE. This self-construction is due to inadequate urban planning, gaps in land management, corruption, and the influence of political and economic interests on urban decisions [71]. This process often leads to the development of informal settlements with excessive low built-up density and limited access to basic services, as illustrated by Groupe Huit [72] in the city of Lubumbashi. Additionally, the self-construction favors land speculation and amplifies socio-economic disparities and food insecurity due to persistent displacement of agricultural activities [73], despite the general trend of increase in the CA of agriculture between 1990 and 2023. Indeed, most farmers lack ownership titles, making their land vulnerable. On the other hand, land speculation makes the conversion of agricultural land into buildable land economically profitable in the short term and with lower risk [74]. Consequently, the spatial expansion of border cities leads to the exurbanization of some producers, transforming urban agriculture into peri-urban and then rural agriculture. This shift is exacerbated by limited land availability and the prioritization of infrastructure over agricultural activities in (peri-)urban areas [75].

The expansion of built-up areas is accompanied by a decline in forest cover and an increase in savannas around the studied border cities. Urbanization often leads to direct deforestation for building, road infrastructures, and other urban installations. Trees are cut down to make space, reducing forest cover, as demonstrated by Cabala et al. [41] in the Lubumbashi plain and Bamba et al. [76] in the Kisangani region in the DR Congo. Additionally, urban growth can favor the exploitation of surrounding natural resources for fuel, wood, or other forest products. Yet, excessive exploitation leads to a significant decrease in forest cover [50,77]. Moreover, urban expansion can stimulate the conversion of forested lands into agricultural lands to compensate for the loss of agricultural lands encroached upon by urbanization to meet the growing food needs of the urban population, as observed in Freetown [74]. However, the felling of trees promotes sunlight penetration, a crucial element for the development of herbaceous vegetation dominating savannas [78], justifying the progression of savannas in the surrounding areas of the studied border cities. Furthermore, the fragile fertility of agricultural lands in these regions often leads to their rapid abandonment after 2 to 3 years of cultivation, favoring their colonization by herbaceous vegetation.

Our research findings affirm the impact of city size on deforestation, a notion supported by previous research [65,76]. The rapid urban expansion observed in Kasumbalesa can be attributed to the benefit from significant commercial flows due to its strategic position at national borders. This dynamic commercial activity creates employment opportunities, attracts investments, and stimulates economic growth, leading to rapid urban expansion. In contrast, territorial capital border cities or mining towns (i.e., Kipushi and Sakania) exhibited different characteristics, since they may face specific challenges. These cities are more focused on a specific industry, which can limit their ability to diversify their economy and attract a more varied population. Similarly, territorial capital border cities are more focused on administrative and governmental functions, which can impact their economic dynamism and attractiveness to investors and migrants. Moreover, when examining the environmental impact of Kisangani, a city of considerable economic and demographic influence, in contrast to Ubundu, a city of moderate importance, Bamba et al. [76] discovered a more significant deforestation trend around Kisangani.

Urban expansion significantly impacts deforestation through several mechanisms. It leads to the direct conversion of forested land into urban areas, roads, and infrastructure, reducing forest cover and fragmenting habitats [79]. Urban demand for resources like timber and agricultural products drives deforestation in surrounding rural areas. Urban areas also alter local climate and hydrology, affecting forest ecosystems. Increased infrastructure development, population growth, and economic activities in urban areas exert more pressure on nearby forests, accelerating deforestation rates [80]. However, the relationship between city size and deforestation is complex. Larger cities may have stricter environmental regulations, but their size and intensive land use exert substantial pressure on forests [81]. Higher per capita consumption rates in larger cities drive deforestation in surrounding regions to meet urban needs [82]. Urban expansion for infrastructure, housing, and industrial zones leads to habitat loss and fragmentation. Economic activities in larger cities increase land and resource demand, accelerating deforestation. The physical expansion of cities fragments forest habitats, disrupting wildlife corridors and ecological processes, further impacting biodiversity and ecosystem health [83].

In Kasumbalesa, high UEII correlates with rapid urban expansion driven by economic activities such as mining, resulting in significant forest cover loss, and decreased forest LPI suggests fragmentation due to extensive land conversion for urban development, highlighting the need for stricter zoning and conservation measures. For Sakania and Kipushi, moderate UEII alongside substantial forest cover loss indicates a balance between urban growth and environmental impact. However, lower forest LPI reflects fragmented landscapes due to mixed-use development and agricultural expansion, necessitating targeted reforestation and buffer zone establishment. In Mokambo, moderate UEII with noticeable landscape diversity indicates slower urban expansion amidst efforts to preserve remaining community forests, thus confirming the relative stable forest LPI.

However, our results underline urban densification in Kipushi that can be attributed to the stable supply of electricity and water in the area. When infrastructures such as electricity and water are consistently available, it creates an environment conducive to the extension of former buildings. However, the recent trend of populations moving from Lubumbashi to settle in Kipushi could justify the urban sprawl observed in this city. This population movement can be attributed to the increasing insecurity in Lubumbashi. Additionally, job opportunities in the mining industry may attract workers and their families. In contrast, the situation in Sakania is different due to the nature of its mining workforce. Though the town hosts a significant number of mine workers, it is important to note that many of these workers come from other regions of the country and do not have their families and residence in Sakania.

It is important to note that the impact of mining activities on landscape dynamics can be minimal within the studied landscapes because, in some cases, extraction is performed through underground mines. This can result in minor surface changes, and significant transformations may occur underground. However, waste materials are generally brought to the surface. After the mining activity, it is essential to implement actions such as habitat restoration to mitigate the environmental impact and promote ecological recovery. Habitat restoration involves rehabilitating the affected areas to their natural state, which can help restore biodiversity and ecological functions.

4.2. Implications for Regional Urban Planning

Our findings highlight a rapid urban expansion and a trend towards urban sprawl in the studied border cities. Yet, urban sprawl contributes to community fragmentation, increased traffic congestion, and diminished quality of life through reduced green spaces and environmental degradation. It results also in escalated costs for infrastructure and public services, heightened transport inefficiencies, and reduced productivity associated with extended commuting times. To mitigate these effects, sustainable urban planning strategies are imperative. These encompass the implementation of urban densification policies aimed at optimizing the utilization of existing spatial resources, promotion of mixed-use urban development to minimize travel distances, and targeted investments in efficient public transportation infrastructure. Additionally, preserving green spaces and adopting urban growth management policies are pivotal for enhancing urban resilience and fostering balanced and sustainable urban development. The expansion of mining cities presents significant environmental and social challenges. Environmentally, it leads to deforestation, soil erosion, water pollution, and loss of biodiversity [84]. Socially, issues such as population influx, increased crime rates, health risks from pollutants, and conflicts over land use are common, often resulting in displacement and loss of traditional livelihoods. Effective management requires integrated urban planning, strengthened environmental regulations, stakeholder dialogue, and the adoption of sustainable mining practices. Diversifying the local economy beyond mining can also contribute to more balanced and resilient development [85].

Our findings reveal that urban expansion leads to the disappearance of forests, posing threats to biodiversity conservation. Countless adverse effects of deforestation can be observed in the region, such as the gradual disappearance of numerous non-timber forest resources [86], the noticeable reduction in wildlife [38], and the reduction in albedo, resulting in fewer rainy days [87]. Also, preserving agricultural land is crucial for ensuring food security in the area given its susceptibility to urban expansion. It is crucial to adopt environmental protection policies such as creating protected areas, strengthening land use regulations, and promoting sustainable agricultural practices. For illustration, the establishment of the Bururi Forest Reserve (near the city of Bururi, Burundi), with active ecoguards, has facilitated the regeneration of forest resources [88]. Concurrently, in the plateau des Batéke in Kinshasa (DR Congo), agroforestry practices that involve combining

Acacia trees with maize crops enable households to enhance their yield and obtain wood for charcoal production in close proximity [89]. Certainly, reforestation solutions exist near the city of Kipushi [86]. However, despite ongoing progress, it has become evident that this positive human influence on the landscape through the planting of exotic species will not be sufficient to offset the loss of forest [90], while posing the risk of further ecosystem degradation [91]. It is crucial to utilize native species in reforestation projects and to enhance collaboration between traditional authorities and city managers to make more land available on the outskirts of cities for reforestation projects [92]. Additionally, there is a need to enhance the capacity of technical public service agents in terms of methodology and technical expertise to better supervise these types of reforestation projects and preserve reforested land in the long term [93]. Finally, the promotion of urban forestry in cities where green spaces are neglected and surrounding forests are disappearing is also an essential strategy for improving quality of life and the environment. By reducing air pollution, providing shade, lowering temperatures, and encouraging community participation through the planting of fruit trees, this approach creates healthier, more resilient, and more livable urban environments [94,95]. This integrated method is crucial for addressing the environmental and social challenges of contemporary urban areas, thereby promoting sustainability and collective well-being.

Based on substantial landscape transformations observed in border cities between 1990 and 2023, tailored land management policies are recommended to address specific challenges. In Kasumbalesa, where rapid urban expansion has led to a significant decline in forest cover, sustainable urban planning should be prioritized. Strict zoning regulations should be implemented to control sprawl and preserve remaining forests. Furthermore, compact, mixed-use development should be encouraged to minimize land conversion and maintain crucial green spaces. Kipushi has experienced a substantial decrease in forest cover and a noticeable shift towards heterogeneous landscapes. To address this, the focus should be on reforestation efforts with native species. Additionally, sustainable agricultural practices should be promoted, and effective buffer zones established around forests to prevent further fragmentation. Mokambo, which has transitioned from high forest cover to more diverse landscapes, requires enhanced monitoring and conservation efforts for remaining forest patches. Support for agroforestry initiatives and adoption of sustainable land use practices are crucial to improve ecological connectivity and enhance landscape resilience. In Sakania, where forest cover has decreased significantly, urgent measures should include establishing protected areas and enforcing strict regulations on land conversion. Indeed, without a rigorous control and management mechanism, the overexploitation of forest resources in the region's protected areas degrades their biological value, ultimately resulting in their downgrading [96]. However, reforestation programs using native species should be promoted to restore degraded areas and ensure long-term ecosystem health.

For regional land planners, establishing robust monitoring systems is crucial for regularly assessing landscape changes and evaluating policy effectiveness. These systems should incorporate several key elements to enable adaptive management strategies. First, they should utilize satellite imagery and geographic information systems (GIS) for continuous monitoring of land cover and land use changes. Additionally, implementing long-term data collection protocols allows for the identification of trends over time and assessment of policy impacts on the landscape. However, developing specific indicators and metrics is essential to evaluate landscape health, biodiversity, and ecosystem services effectively. These metrics should be scientifically sound and relevant to the goals of the policies being implemented. Moreover, engaging local communities, policymakers, and scientists in the monitoring process ensures comprehensive data collection and considers multiple perspectives. This collaborative approach enhances the reliability and actionability of the data gathered. In the same way, regular reporting of monitoring results to all stakeholders is crucial. It establishes feedback loops that enable policymakers to adjust strategies based on new findings, ensuring ongoing effectiveness. Finally, aligning monitoring systems with existing environmental and land management frameworks enhances coherence and avoids duplication of efforts.

5. Conclusions

The study delves into the intricate spatial urban growth and associated landscape dynamics of Kipushi, Kasumbalesa, Mokambo, and Sakania along the border with Zambia, an area of variable cross-border trade. Employing a robust methodology that integrates remote sensing, GIS, and landscape ecology analysis tools has facilitated a comprehensive mapping and quantification of landscape dynamics over time. The findings confirm the substantial landscape changes within these cities, materialized by the transformation of natural landscapes into sprawl urban zones. Population growth and economic activities significantly influence urban landscape change, with demographic factors driving the expansion of built-up areas. However, there is variance in the extent of urban expansion among cities, with those experiencing lower customs activity levels demonstrating more restrained spatial urban growth. This discrepancy underscores the influential role of economic factors in shaping border urban dynamics, highlighting the intricate interplay of factors driving urban development in these regions. Additionally, the study has identified a marked acceleration in urban spatial growth since the early 2000s, indicating a swift transformation of these border agglomerations. This leads to an ecosystem shift, marked by a decline in forest cover previously dominant in the landscapes of the cities studied in 1990, except for Kipushi, which was replaced by emerging and merging savanna patches in the landscape in 2023. The anthropization of the landscape of these cities and their heterogeneity are further intensified over time by the continuous creation of agricultural patches. These observations lead to the conclusion that border urban areas in the DRC-Zambia region are undergoing significant spatial changes driven by a complex interplay of economic, demographic, and infrastructural factors. Understanding these dynamics is crucial for informed urban planning and policy formulation. Sustainable development strategies must be devised to address challenges such as managing urban sprawl, promoting economic resilience, and fostering cross-border cooperation in border regions.

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