Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Spatiotemporal dynamics of urbanization and landscape anthropization in Kinshasa, Democratic Republic of Congo, from 2001 to 2024

Kouagou Raoul SAMBIENI
krsambieni@uliege.be

University of Lubumbashi
Jean-Pierre Messina Ndzomo
Université Notre Dame du Kasayi
Trésor Mbavumoja Selemani
Gembloux Agro-Bio Tech
Lea Mukubu Pika
Gembloux Agro-Bio Tech
David PYAME Onyo
Université de Kisangani
Sèdjro David Igor Thierry Kévin Ahouandjinou
Université de Parakou
Julien Bwazani Balandi
Ecole Régionale Postuniversitaire d'Aménagement et de Gestion intégrés des Forêts et Territoires tropicaux

Research Article

Keywords: urbanization, urban expansion, anthropization, land-use and land-cover change, remote sensing, Random Forest, landscape metrics, peri-urban dynamics, Kinshasa

Posted Date: September 7th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10436626/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Rapid urbanization in major African cities is driving profound land-use transformations, with substantial consequences for landscapes, ecosystems, and spatial planning. In Kinshasa, however, recent trajectories of landscape transformation, conversions among land-use and land-cover classes, and spatial variation in the intensity of urban expansion remain insufficiently documented at intra-urban and peri-urban scales. This study analyzes the spatiotemporal dynamics of urbanization and landscape anthropization in Kinshasa, Democratic Republic of Congo, from 2001 to 2024.

The analysis draws on Landsat satellite imagery derived from annual composites processed in Google Earth Engine and classified using the Random Forest algorithm. Eight land-use and land-cover classes were considered: forests, gallery forests, savannahs, wetlands, croplands, bare land, built-up areas, and water. Changes were assessed using land-use and land-cover maps, transition matrices, spatial landscape-structure metrics, the landscape disturbance index, and indicators of the mean annual rate and intensity of urban expansion.

The results reveal progressive anthropization of Kinshasa's landscape over the study period. Although savannahs remained the dominant class, their share decreased from approximately 58% in 2001 to 47.51% in 2024. Forests also declined sharply, from 20.56% in 2001 to 7.76% in 2024. Conversely, cropland increased from 6.39% to 27.43%, while built-up areas expanded from 3.01% to 6.62%. Transition matrices indicate substantial conversion of natural vegetation, particularly savannahs and forests, into croplands and built-up areas. The landscape disturbance index increased from 0.14 in 2001 to 0.56 in 2024, confirming intensifying anthropogenic pressure. Urban expansion was spatially uneven, characterized by centrifugal growth and the advance of urbanization fronts into peri-urban areas.

These findings confirm that urbanization in Kinshasa follows a diffusion-coalescence trajectory, characterized by the expansion of human-modified land uses at the expense of natural vegetation. The study highlights the need to strengthen urban planning, protect remnant ecosystems, and sustainably manage peri-urban areas to limit the environmental and socio-spatial impacts of urban sprawl.

1. INTRODUCTION

Urbanization is one of the major processes transforming contemporary landscapes. Worldwide, urban growth is accompanied by rapid changes in land use and land cover, particularly through the conversion of natural, agricultural, and semi-natural areas into built-up land, infrastructure, and other forms of human land use [1–6]. This process is especially pronounced in the Global South, where urban expansion is driven by population growth, internal migration, the concentration of economic activities, and weak spatial-planning systems [7–10]. Analyzing the spatiotemporal dynamics of urbanization has therefore become essential for understanding trajectories of urban landscape transformation and informing sustainable development policies [11].

Sub-Saharan Africa is currently experiencing one of the world's fastest rates of urban growth. Often characterized by extensive spatial sprawl, this urbanization frequently unfolds amid limited urban governance, infrastructure deficits, mounting land pressure, and unplanned settlement of peripheral areas [10, 12]. Its environmental and socio-spatial consequences are numerous, including fragmentation of natural vegetation, loss of green space, soil sealing, expansion of informal settlements, greater exposure to natural hazards, and degradation of urban ecosystem services [4, 5, 13]. These challenges are particularly acute in large African metropolitan areas, where urban expansion often outpaces institutional capacity for planning, regulation, and development.

Kinshasa, the capital of the Democratic Republic of Congo, is a striking example of this dynamic. Experiencing rapid demographic and economic growth, the city has expanded spatially for several decades, driven by natural population increase, internal migration, the concentration of administrative and economic functions, and the search for employment opportunities and services [14–17]. This expansion has increased built-up and agricultural land, often at the expense of remnant forests, gallery forests, savannahs, and other natural or semi-natural vegetation. In several parts of the city, urbanization proceeds with limited control, particularly in peri-urban areas, interstitial spaces, and ecologically sensitive zones, thereby increasing erosion and flood risks, biodiversity loss, and deterioration of living conditions [18–20].

Several studies have documented the extent of urban sprawl in Kinshasa and its effects on the city’s spatial organization [15, 16, 18, 19, 21–24]. They show that urban growth is accompanied by increasing occupation of peripheral areas and, in some cases, hazard-prone locations such as steep slopes, valleys, and poorly drained land. Despite their substantial contributions, however, these studies provide limited coverage of recent land-use dynamics over an extended period, transitions among landscape classes, spatial processes of landscape transformation, and variation in urban-expansion intensity with distance from the city center.

These dimensions are crucial for understanding not only the magnitude of urbanization, but also its mechanisms, trajectories, and implications for sustainable urban planning.

Recent advances in remote sensing, cloud-based geospatial processing platforms, and supervised classification methods provide new opportunities to analyze urban dynamics across broad spatial and temporal scales [25–28]. Landsat image time series, combined with the processing capabilities of platforms such as Google Earth Engine and SEPAL, make it possible to map land use and land cover, measure landscape change, and identify urban-expansion fronts over several decades. Robust algorithms such as Random Forest improve multispectral image

classification and produce reliable land-use and land-cover maps for spatial-transition analysis [29–32]. Transition matrices, landscape-structure indices, and urban-expansion indicators are also useful for characterizing processes such as fragmentation, aggregation, attrition, dissection, and patch creation [33–37].

Against this background, the present study analyzes the spatiotemporal dynamics of urbanization and landscape anthropization in Kinshasa from 2001 to 2024. It uses Landsat satellite imagery processed in Google Earth Engine, supervised classification with the Random Forest algorithm, transition matrices, spatial landscape-structure indices, and urban-expansion intensity indicators. The objectives are to identify trajectories of land-use and land-cover change, characterize landscape-transformation processes, and determine the areas most affected by urban expansion through a radial approach based on concentric rings around the city center.

We hypothesize that urbanization in Kinshasa from 2001 to 2024 was accompanied by progressive landscape anthropization, reflected in the expansion of built-up and agricultural land at the expense of natural vegetation. We further expect this dynamic to be spatially uneven and to follow a radial diffusion-coalescence pattern, with intensity varying according to distance from the city center and urbanization fronts advancing into peri-urban areas. By documenting these transformations using multitemporal satellite data, this research improves understanding of Kinshasa's recent urban-growth trajectory and provides decision-support evidence for more sustainable and resilient urban planning.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted in Kinshasa, the capital of the Democratic Republic of Congo, in the western part of the country between 4° and 5° S and 15° and 16° E. The study area covers a common area of 1,146 km², delineated from the city's administrative boundaries provided by the Common Geographic Reference Framework of the Democratic Republic of Congo. This area was subdivided into concentric 5-km rings centered on Kinshasa Central Station (4°18'5.07" S, 15°19'1.96" E). This approach captures both the consolidated urban core and the city's peri-urban areas and enables analysis of urbanization dynamics according to distance from the city center [16, 20, 38]. This delineation was selected to encompass not only the densely urbanized area but also the peri-urban spaces where land-use and land-cover transformations are particularly rapid. Here, the peri-urban zone is understood in morphological terms as a transitional space characterized by mixed land use, with a minority of urban settlements embedded within predominantly non-built-up land [39–41].

Kinshasa has an Aw climate according to the Köppen-Geiger classification [42]. Two main seasons occur: a rainy season, generally from October to May, with a short interruption from late December to mid-February, and a dry season from June to September. Mean annual precipitation is approximately 1,432 mm [18, 43].

Historically, the natural vegetation of the Kinshasa region comprised dense forests, savannahs, and semi-aquatic and aquatic vegetation in valleys and around Pool Malebo [18]. This vegetation has declined sharply because of urbanization, agriculture, and the exploitation of plant resources [15]. The present landscape is dominated by grassland savannahs, degraded vegetation, fruit trees concentrated in residential plots, and expanding built-up areas, particularly in peri-urban zones.

2.2. Satellite data

The spatiotemporal dynamics of land use and land cover in Kinshasa's urban landscape were analyzed using Landsat satellite imagery for 2001, 2009, 2014, 2019, and 2024. The images were annual composites downloaded from SEPAL, a platform developed by the Food and Agriculture Organization of the United Nations for remote-sensing-based monitoring of land and forest cover.

The composites were derived from the Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) sensors. The imagery had undergone atmospheric, radiometric, and geometric corrections, making it suitable for diachronic land-use and land-cover analysis.

SEPAL annual composites were selected because they reduce the effects of cloud cover and improve comparability among observation dates. This is especially important in humid tropical regions, where persistent cloudiness often limits the direct use of optical satellite imagery. SEPAL is a cloud-computing platform designed for autonomous land monitoring with remote-sensing data. Its integration with Google Earth Engine and several open-source tools facilitates the processing, analysis, and classification of large volumes of satellite data.

The years 2001, 2009, 2014, 2019, and 2024 were selected to capture several important phases of Kinshasa's recent urban development. The year 2001 marked the beginning of political reconfiguration after several years of instability. The year 2009 followed the 2008 global financial crisis and coincided with a gradual economic recovery, the revival of several urban projects, and continued population inflows to the capital. The year 2014 represented a phase of intensifying urban growth and partial infrastructure modernization amid continuing population growth and often poorly coordinated urban development [17].

The year 2019 marked the first peaceful transfer of power in the Democratic Republic of Congo, which may have influenced investment, planning, and real-estate development. Finally, 2024 provides the most recent available data and captures transformations occurring after this political transition.

2.3. Image preprocessing and classification

Before classification, Landsat imagery was prepared in Google Earth Engine to facilitate identification of the main land-use and land-cover classes. False-color composites were generated from shortwave-infrared, near-infrared, and visible bands to improve visual discrimination among built-up areas, bare land, vegetation, wetlands, and water bodies [44, 45].

Eight land-use and land-cover classes were used in the supervised classification: forests, gallery forests, savannahs, wetlands, croplands, bare land, built-up areas, and water. These classes were defined according to the ecological, morphological, and urban characteristics of Kinshasa's landscape. Sample points were collected through visual interpretation of false-color composites, supported by high-resolution imagery available in Google Earth Engine and Google Earth Pro. The samples were then divided into a training dataset for model calibration and an independent dataset for map validation [27, 46].

Supervised classification was performed using the Random Forest algorithm [29, 30, 47]. This algorithm constructs an ensemble of decision trees to assign each pixel to a land-use and land-cover class based on its spectral characteristics. Random Forest is widely used in remote sensing because of its robustness, its ability to handle complex data, and its strong performance in land-use and land-cover mapping. Several studies report that it performs well and often outperforms other classifiers, including support vector machines, k-nearest neighbors, and maximum-likelihood classification [30, 45, 48, 49].

The entire classification workflow from preparation of the training data to production of the classified maps and evaluation of model performance was implemented in Google Earth Engine [27, 32].

Table 1
Description of the land-use and land-cover classes used in this study for Kinshasa.

Types of land use classes	Description
Forest	Urban and peri-urban relict forests: These forests, often small, are remnants of the vast forest ecosystems that once covered the region. They are found in protected or inaccessible areas.
Forest galleries	Forests are located along rivers and streams; they play a key role in protecting watersheds and provide a habitat for biodiversity.
Savannah	The savannahs of Kinshasa are partly of natural origin, but they are also the result of deforestation and bush fires. The exploitation of forest resources and shifting agriculture have contributed to the transition from forest ecosystems to savannahs. These savannahs are a major component of their ecological landscape. They are located on the periphery and cover a large part of the non-urbanized areas. These ecosystems, typical of tropical regions, are characterized by a predominance of herbaceous vegetation, punctuated by a few trees or shrubs.
Wetland	The wetlands of Kinshasa are essential ecosystems, although they are often neglected or degraded. Located mainly in low-lying areas, near watercourses or in topographical depressions, they play a crucial role in water regulation and local biodiversity.
Field	Fields are mainly concentrated in outlying areas such as Maluku, Nsele, Mont Ngafula and Kimwenza. A few small plots of cultivated land are found in urban interstitial spaces, such as along roads, near dwellings or in flood-prone areas.
Bare grounds	Bare ground in the city of Kinshasa refers to land areas where vegetation and infrastructure are absent or very sparse. These areas, which are often found on the outskirts of cities, on fallow land, or in recently deforested or degraded areas, play a special role in the ecology and urbanization of the city.
Buildings	The buildings of the city of Kinshasa represent man-made infrastructures, including residential, commercial, industrial and institutional buildings.
Water	The waters of the city of Kinshasa include all the water resources present on its territory. They play a crucial role in the ecological, economic and social functioning of the capital, although their management poses many challenges.

2.4. Classification validation

Classification accuracy was evaluated using independent validation points collected in Google Earth Pro for each study year. In total, 1,180 points were used for 2001, 1,150 for 2009, 1,000 for 2014, 1,180 for 2019, and 1,250 for 2024. The points were compared with the mapped classes to construct confusion matrices.

Accuracy was assessed using overall, producer’s, and user’s accuracy for each land-use and land-cover class. Overall accuracy estimates the total proportion of correctly classified pixels; producer's accuracy reflects omission errors, and user's accuracy reflects commission errors. This procedure assesses the reliability of the resulting land-use and land-cover maps before their use in spatiotemporal change analysis [50–52].

2.5. Land-use and land-cover change analysis

Spatiotemporal land-use and land-cover changes were analyzed from the classified maps for 2001, 2009, 2014, 2019, and 2024. Transition matrices were produced for four successive periods: 2001–2009, 2009–2014, 2014–2019, and 2019–2024, to quantify conversions among classes. This approach identifies classes that remained stable, classes that declined, and the main conversion pathways between the initial and final landscape states [50, 53, 54].

In each transition matrix, rows represent land-use and land-cover classes in the initial year, and columns represent classes in the final year. Diagonal cells indicate areas that remained unchanged between the two dates, whereas off-diagonal cells represent conversion from one class to another. Values were expressed as percentages of the total study area to facilitate comparison among observation periods.

A stability index was also calculated for each land-use and land-cover class to assess the proportion of pixels that remained in the same class relative to pixels that changed class. The index identifies the most stable classes and those undergoing frequent transformation. A high value indicates strong stability, whereas a low value indicates greater instability and more frequent land-use and land-cover change [52, 55].

2.6. Analysis of landscape spatial structure and anthropization

Landscape spatial structure was analyzed using class-level landscape metrics. These metrics characterize the spatial organization of landscape patches and identify transformation processes associated with changes in Kinshasa's urban and peri-urban landscape [33, 34, 56]. The selected metrics were class area, number of patches, largest patch index, and perimeter–area fractal dimension.

Class area measures the spatial extent of each land-use and land-cover type. The number of patches indicates the degree of class subdivision or fragmentation. The largest patch index quantifies the spatial dominance of the largest patch within a class, while the perimeter–area fractal dimension measures patch-shape complexity. These metrics were calculated in FRAGSTATS v4.2, which is widely used for quantitative analysis of landscape spatial structure [34, 56].

Spatial landscape-transformation processes were interpreted from joint changes in patch number and total class area using the decision tree proposed by Bogaert et al., [35]. The method distinguishes processes including patch creation, attrition, aggregation, fragmentation, and dissection [35, 57]. A threshold of t = 0.75 was used to distinguish fragmentation from dissection: values greater than 0.75 indicate dissection, whereas values less than or equal to 0.75 indicate fragmentation [58].

The degree of landscape anthropization was assessed using the landscape disturbance index, defined as the ratio of the area occupied by anthropogenic classes to that occupied by natural classes. Here, anthropogenic classes comprise croplands, bare land, and built-up areas, whereas natural classes comprise forests, gallery forests, and savannahs. An index value greater than 1 indicates dominance of anthropogenic classes; a value below 1 indicates dominance of natural classes [33].

2.7. Urban expansion analysis

Urban expansion in Kinshasa was analyzed at two complementary scales. First, the entire study area was considered to evaluate overall built-up expansion from 2001 to 2024. Second, a radial analysis was conducted using concentric 5-km-wide rings centered on Kinshasa Central Station and extending to 50 km. This approach examines spatial variation in urban expansion with distance from the city center and identifies the urban and peri-urban zones most affected by built-up growth.

Two indicators were used to quantify urban-expansion dynamics: the Annual Urban Expansion Rate (AUER) and the Urban Expansion Intensity Index (UEII).

The AUER measures the mean annual growth in built-up area between two observation dates. It indicates the rate at which built-up land increases across the entire study area or within a given spatial unit [36].

$$\mathrm{AUER} = \left[\left(\frac{\mathrm{ULA}_i^{t_2}}{\mathrm{ULA}_i^{t_1}} \right)^{\frac{1}{t_2 - t_1}} - 1 \right] \times 100$$

1

where AUER is the annual urban expansion rate $ULA_i^{t_2}$ and $ULA_i^{t_1}$, and the two area terms denote built-up urban land at times t_2 and t_1, respectively, for each observation period.

The UEII measures the mean annual proportion of newly built-up land relative to the total area of the spatial unit considered. It is particularly useful for comparing urbanization intensity among periods or concentric rings [37]. Index values were interpreted following Abdullahi and Pradhan [59] and Akubia and Bruns [60]: values below 0.28 indicate very slow expansion; 0.28–0.59, slow expansion; 0.59–1.05, medium-speed expansion; 1.05–1.92, rapid expansion; and values above 1.92, very rapid expansion.

$$\mathrm{UEII} = \frac{ULA_i^{t_2} - ULA_i^{t_1}}{TLA_i \times \Delta t} \times 100$$

2

where UEII is the urban expansion intensity index for spatial unit *i*; $ULA_i^{t_2} ULA_i^{t_1}$ the two area terms denote built-up urban land in unit *i* at times t_2 and t_1, respectively; TLA_i is the total land area of spatial unit *i*; and Δt is the observation interval ($t_2 - t_1$).

Using these two indicators together captures both the overall rate of built-up growth and the spatial distribution of urban-expansion intensity. This approach is well suited to rapidly growing metropolitan areas, where urbanization advances unevenly along differentiated fronts across central, intermediate, and peri-urban zones.

3. RESULTS

3.1. Land-use and land-cover classification and mapping

The land-use and land-cover maps for 2001, 2009, 2014, 2019, and 2024 distinguish eight classes: forests, gallery forests, savannahs, wetlands, croplands, bare land, built-up areas, and water (Fig. 2). They reveal a progressive transformation of Kinshasa's landscape, characterized by the expansion of anthropogenic classes primarily croplands and built-up areas at the expense of natural vegetation.

Classification performance was satisfactory, with overall accuracies ranging from 81% to 97% (Table 2). Overall accuracy was 83% in 2001, 81% in 2009, 97% in 2014, 95% in 2019, and 94% in 2024. These values support the reliability of the maps for diachronic land-use and land-cover analysis.

Overall, the maps show the expansion of built-up areas around the urban core and toward peripheral zones, whereas croplands expanded mainly in peri-urban areas (Figure 2). Conversely, forests and savannahs declined, indicating increasing landscape anthropization from 2001 to 2024.

Table 2. Accuracy of supervised classification of Landsat imagery for 2001, 2009, 2014, 2019, and 2024 using the Random Forest algorithm.

Accuracy %										
	2001		**2009**		**2014**		**2019**		**2024**	
Land use type	**Producer**	**User**	**Producer**	**User**	**Producer**	**User**	**Producer**	**User**	**Producer**	**User**
Forest	70	82	92	87	97	96	93	90	95	90
Forest galleries	63	73	86	80	99	99	99	98	95	97
Savannahs	91	83	80	73	93	92	86	88	81	85
Wetland	92	92	77	100	99	99	99	99	98	98
Field	85	100	56	73	93	95	91	91	92	90
Bare ground	78	68	83	83	97	96	91	91	88	94
Buildings	96	80	95	91	99	99	96	95	97	96
Water	93	100	100	100	99	99	99	99	99	99
Overall accuracy	**83**		**81**		**97**		**95**		**94**	

3.2. Changes in landscape composition

Landscape composition in Kinshasa changed substantially between 2001 and 2024 (Figure 3). Savannahs remained the dominant class, but their share progressively declined from 57.94% in 2001 to 47.51% in 2024. Forests also decreased markedly, from 20.56% to 7.76% over the same period. Conversely, anthropogenic classes expanded considerably. Cropland increased from 6.39% in 2001 to 27.43% in 2024, indicating substantial agricultural expansion. Built-up areas more than doubled, from 3.01% to 6.62%, confirming the continued growth of the urban fabric. Gallery forests followed a more variable trajectory, declining between 2001 and 2019 before recovering slightly in 2024. Wetlands and water remained limited in extent and relatively stable. Taken together, these results indicate progressive landscape transformation through the loss of natural vegetation and expansion of anthropogenic land uses.

3.3. Transitions and stability of land-use and land-cover classes

The transition matrices show that the main land-use and land-cover changes involved conversion of natural vegetation into anthropogenic classes (Table 3). Across the 2001-2024 study period, savannahs and forests were the principal sources of change, primarily through conversion to croplands and, to a lesser extent, built-up areas.

From 2001 to 2009, savannahs were largely stable, with 42.93% of the total study area remaining in this class, although 10.30% was converted to croplands (Table 3). Forests also showed relative stability, with 14.97% of the study area remaining forested, although conversion to savannahs and other classes occurred. From 2009 to 2014, conversion of savannahs to croplands remained substantial at 10.57%, while forest decline occurred mainly through conversion to savannahs.

This trajectory continued from 2014 to 2019, when 9.56% of the study area changed from savannahs to croplands and built-up areas expanded onto former forest, savannah, and bare land (Table 3). From 2019 to 2024, transitions were again dominated by conversion of savannahs to croplands (6.68% of the study area), together with the conversion of some forests to savannahs and built-up areas.

The stability index corroborates these patterns (Table 4). Savannahs remained relatively stable throughout the study periods, whereas forest stability declined sharply in 2019-2024. Croplands and built-up areas became increasingly stable over time, reflecting their progressive consolidation in the landscape. Conversely, bare land exhibited low stability, indicating that it functions as a transitional class in urbanization and land-transformation processes.

Table 3. Transition matrices for land-use and land-cover classes in Kinshasa for 2001-2009, 2009-2014, 2014-2019, and 2019-2024, derived from Random Forest classification of Landsat imagery. Row totals represent class proportions in the initial year, and column totals represent class proportions in the final year. Diagonal cells (bold) are stable areas; off-diagonal cells indicate conversions among classes. Cell values are percentages of the total study area.

		2009								
	Land use/cover	forests	forest galleries	savannahs	wetland	fields	bare ground	buildings	water	**Total**
2001	forests	**14.97**	1.74	2.02	0.65	0.33	0.48	0.37	0.01	**20.56**
	forest galleries	1.09	**4.42**	1.6	0.06	0.35	0	0	0.01	**7.54**
	savannahs	1.34	2.53	**42.93**	0.15	10.3	0.29	0.4	0	**57.94**
	wetland	0.11	0.05	0.04	**1.18**	0.01	0.02	0.12	0.04	**1.56**
	fields	0.03	0.08	2.7	0	**3.56**	0.02	0.01	0	**6.39**
	bare ground	0.57	0.01	0.34	0.06	0.01	**1.13**	0.71	0	**2.83**
	buildings	0.25	0	0.25	0.13	0	0.26	**2.12**	0.01	**3.01**
	water	0	0	0	0.02	0	0	0.01	**0.13**	**0.16**
	Total	**18.35**	**8.83**	**49.87**	**2.26**	**14.55**	**2.2**	**3.73**	**0.21**	**100**
		2014								
	Land use/cover	forests	forest galleries	savannahs	wetland	fields	bare ground	buildings	water	**Total**
2009	forests	**11.55**	1.73	3.66	0.51	0.15	0.31	0.43	0	**18.35**
	forest galleries	0.17	**4.44**	3.15	0.34	0.73	0	0	0	**8.83**
	savannahs	0.93	0.64	**37.09**	0.06	10.57	0.28	0.31	0	**49.87**
	wetland	0.87	0.01	0.06	**1.01**	0.01	0.03	0.23	0.03	**2.26**
	fields	0	0.19	3.84	0.04	**10.49**	0.01	0	0	**14.55**
	bare ground	0.3	0.01	0.34	0	0.02	**1.01**	0.51	0	**2.2**
	buildings	0.34	0	0.24	0.06	0.01	0.32	**2.75**	0.01	**3.73**
	water	0.02	0	0	0.04	0	0	0	**0.14**	**0.21**
	Total	**14.19**	**7.02**	**48.38**	**2.06**	**21.96**	**1.96**	**4.24**	**0.19**	**100**

2019										
	Land use/cover	forests	forest galleries	savannahs	wetland	fields	bare ground	buildings	water	**Total**
2014	forests	**10.00**	0.19	2.96	0.07	0	0.24	0.68	0.03	**14.19**
	forest galleries	0.76	**4.03**	1.81	0.07	0.35	0	0	0	**7.02**
	savannahs	1.32	0.68	**35.98**	0.16	9.56	0.14	0.54	0	**48.38**
	wetland	0.09	0.07	0.42	**1.33**	0.08	0	0.04	0.03	**2.06**
	fields	0.01	0.23	4.68	0.04	**17.01**	0	0	0	**21.96**
	bare ground	0.1	0	0.28	0.01	0.02	**0.63**	0.89	0.01	**1.96**
	buildings	0.31	0	0.34	0.05	0	0.2	**3.33**	0.01	**4.24**
	water	0	0	0	0.01	0	0	0	**0.18**	**0.19**
	Total	**12.59**	**5.21**	**46.48**	**1.74**	**27.03**	**1.21**	**5.49**	**0.26**	**100**
2024										
	Land use/cover	forests	forest galleries	savannahs	wetland	fields	bare ground	buildings	water	**Total**
2019	forests	**6.14**	1.05	4.7	0.05	0	0.15	0.48	0.02	**12.59**
	forest galleries	0.08	**3.67**	1.13	0.1	0.21	0	0.01	0	**5.21**
	savannahs	1.09	2.08	**35.16**	0.55	6.68	0.11	0.81	0	**46.48**
	wetland	0.02	0.03	0.18	**1.38**	0.02	0	0.06	0.05	**1.74**
	fields	0	0.49	5.65	0.19	**20.5**	0.01	0.19	0	**27.03**
	bare ground	0.12	0	0.15	0	0	**0.25**	0.69	0	**1.21**
	buildings	0.3	0.01	0.54	0.05	0	0.21	**4.37**	0.01	**5.49**
	water	0.01	0	0	0.01	0	0.01	0.01	**0.23**	**0.26**
	Total	**7.76**	**7.34**	**47.51**	**2.32**	**27.43**	**0.72**	**6.62**	**0.3**	**100**

Table 4. Stability index for each land-use and land-cover class in Kinshasa during the four transition periods.

Stability index	forests	forest galleries	savannahs	wetland	fields	bare ground	buildings	water
2001-2009	1.67	0.59	1.95	0.81	0.26	0.41	0.84	1.30
2009-2014	1.23	0.64	1.54	0.44	0.67	0.47	1.12	1.40
2014-2019	1.48	0.97	1.57	1.17	1.14	0.33	1.09	2.00
2019-2024	0.76	0.71	1.49	1.05	1.53	0.17	1.30	1.92

3.4. Landscape spatial structure and anthropization

Landscape metrics reveal a progressive reorganization of Kinshasa's spatial landscape structure between 2001 and 2024 (Table 5). Depending on the period, natural vegetation, particularly forests and savannahs, was primarily affected by attrition, fragmentation, or dissection. These changes reflect a reduction in total class area and increasing disruption of spatial configuration.

Forests declined continuously, with particularly pronounced fragmentation during 2019-2024 (Table 5). Although savannahs remained dominant, they also underwent substantial transformations, notably dissection and progressive conversion to other classes. Conversely, croplands and built-up areas exhibited patch-creation or aggregation dynamics, indicating their expansion and consolidation in the landscape.

The landscape disturbance index confirms this anthropization trend (Fig. 4). It increased progressively from 0.14 in 2001 to 0.26 in 2009, 0.40 in 2014, 0.50 in 2019, and 0.56 in 2024. Although natural classes remained dominant overall, this increase indicates growing anthropogenic pressure associated with the expansion of cropland, bare land, and built-up areas.

Overall, the landscape became progressively more human-modified, with natural vegetation declining and becoming increasingly fragmented, while anthropogenic classes gained both area and spatial continuity (Table 5; Fig. 4).

Table 5. Landscape-pattern dynamics and spatial transformation processes (STP) in 2001, 2009, 2014, 2019, and 2024, identified using the decision-tree algorithm of Bogaert et al. (2004). NP, number of patches per class; CA, class area (km²); LPI, largest patch index (%); PAFRAC, perimeter–area fractal dimension.

	Forest	Forest galleries	Savannahs	Wetland	Field	Bare ground	Buildings	Water
NP_2001	27101	30963	32166	6025	36148	15572	15743	982
CA_2001	2180.07	799.20	6144.54	165.83	677.29	299.74	319.48	17.55
LPI_2001	7.61	0.50	20.13	0.36	0.35	0.42	0.87	0.04
PAFRAC_2001	1.43	1.45	1.43	1.45	1.43	1.45	1.48	1.51
NP_2009	26362	32180	58030	18888	63494	11954	12770	1419
CA_2009	1945.70	936.20	5289.25	238.99	1542.83	233.30	395.43	21.99
LPI_2009	5.07	0.35	18.33	0.34	2.44	0.17	1.04	0.04
PAFRAC_2009	1.46	1.45	1.46	1.47	1.51	1.40	1.46	1.47
STP_2001-2009	**Attrition**	**Creation**	**Dissection**	**Creation**	**Creation**	**Attrition**	**Aggregation**	**Creation**
NP_2014	12158	11361	43694	7066	32216	10809	9221	747
CA_2014	1504.37	744.07	5130.82	218.39	2328.46	207.61	449.65	20.33
LPI_2014	4.51	0.50	19.30	0.35	4.15	0.14	1.67	0.04
PAFRAC_2014	1.44	1.38	1.45	1.42	1.43	1.45	1.45	1.48
STP_2009-2014	**Attrition**	**Attrition**	**Attrition**	**Attrition**	**Aggregation**	**Attrition**	**Aggregation**	**Attrition**
NP_2019	18763	17111	83525	6384	43047	14975	16121	922
CA_2019	1334.54	551.88	4928.60	184.57	2865.91	128.41	582.03	27.76
LPI_2019	1.80	0.26	10.40	0.35	4.82	0.07	2.12	0.05
PAFRAC_2019	1.47	1.44	1.49	1.39	1.44	1.46	1.48	1.49
STP_2014-2019	**Dissection**	**Fragmentation**	**Dissection**	**Attrition**	**Creation**	**Fragmentation**	**Creation**	**Creation**
NP_2024	22441	28930	77559	13612	30575	14274	17120	1105
CA_2024	822.15	778.38	5038.24	246.21	2908.13	76.62	701.77	32.20
LPI_2024	1.62	0.41	12.43	0.33	3.75	0.01	2.63	0.05
PAFRAC_2024	1.51	1.46	1.49	1.41	1.46	1.46	1.44	1.50
STP_2019-2024	**Fragmentation**	**Creation**	**Aggregation**	**Creation**	**Aggregation**	**Attrition**	**Creation**	**Creation**

3.5. Urban-expansion dynamics

Urban-expansion indices show a clear increase in built-up land across Kinshasa between 2001 and 2024 (Figure 5). At the scale of the entire study area, urban expansion was moderate in 2001-2009 and 2009-2014, with intensity classified as medium-speed expansion. It accelerated sharply in 2014-2019, when both AUER and UEII reached their highest values, corresponding to very rapid expansion. Expansion slowed slightly in 2019–2024 relative to the preceding period but remained high.

The radial distribution of built-up land shows progressive expansion of urban fabric between 2001 and 2024 (Fig. 6). In 2001, the largest built-up areas were concentrated mainly in rings close to the center, with high values at distances of 10-20 km. This pattern persisted in 2009 and 2014, although built-up areas increased generally at intermediate distances. By 2019 and 2024, expansion was most pronounced at 15-30 km, where built-up areas reached their highest values.

This trajectory indicates consolidation of the urban fabric in intermediate zones and the advance of the urbanization front into peri-urban areas. Beyond 40 km, built-up areas decreased sharply, showing that urbanization remained limited in the most distant peripheral zones.

Changes in AUER across the concentric rings confirm that urban expansion was spatially differentiated (Figure 7). During 2001-2009 and 2009-2014, expansion rates varied considerably, with higher values at intermediate distances, particularly at approximately 20-35 km. The highest values occurred in 2014-2019, especially at 15-25 km, where AUER peaked, indicating acceleration of the urbanization front in peri-urban areas.

Expansion remained sustained in 2019–2024, with high values at approximately 25–35 km and a notable increase near 50 km.

UEII likewise confirms that the strongest expansion dynamics were concentrated at intermediate distances (Figure 8). The highest values occurred in 2014-2019, with a pronounced peak at approximately 20 km that indicates very rapid expansion in the inner peri-urban zone. Intensity also remained high in 2019-2024, primarily at 20-35 km, reflecting the continued outward expansion of built-up land. Beyond 40 km, UEII values were very low or close to zero, indicating that urbanization remained limited in the most distant peripheral zones.

4. DISCUSSION

4.1. Progressive anthropization of Kinshasa's landscape

The findings reveal rapid transformation of Kinshasa's landscape from 2001 to 2024, characterized by the expansion of anthropogenic classes at the expense of natural vegetation. The decline in forests and savannahs, coupled with the expansion of croplands and built-up areas, confirms continued anthropization of the urban and peri-urban landscape. This trajectory is consistent with observations from several African metropolitan areas, where population growth, expanding economic activities, and mounting land pressure rapidly convert natural and semi-natural areas into built-up and agricultural land [2, 4, 10, 13].

In Kinshasa, this dynamic is particularly evident in the sharp decline in forests and the expansion of croplands. Forest loss reflects pressure on remnant vegetation, whereas cropland expansion highlights the growing importance of agriculture in peri-urban areas. This finding agrees with earlier studies reporting rapid transformation of Kinshasa’s peripheral landscapes through the combined effects of urbanization, agriculture, and exploitation of plant resources [16, 19, 21, 22, 24].

It also confirms that urbanization in Kinshasa extends beyond the growth of built-up land and involves a broader reorganization of land uses.

The progressive increase in the landscape disturbance index reinforces this interpretation. Although natural classes still occupy a substantial share of the study area, their decline in favor of anthropogenic classes indicates increasing pressure on urban and peri-urban ecosystems. This trend may reduce ecological connectivity, disrupt hydrological regulation, threaten biodiversity conservation, and diminish the landscape’s capacity to provide essential ecosystem services [4, 5, 60, 61].

4.2. Natural vegetation conversion and land-use consolidation

The transition matrices identify savannahs and forests as the principal source classes for conversion. Savannahs were converted mainly to croplands, while portions of forest changed to savannah, cropland, or built-up land. This pattern suggests two concurrent pressures: agricultural pressure that converts savannahs to cultivated land, and urban pressure that progressively transforms bare land, vegetation, and some interstitial spaces into built-up areas. Similar trajectories have been reported in other tropical urban settings, where both urban and agricultural expansion are major drivers of land-use and land-cover change [61–65].

Cropland’s expansion demonstrates the importance of agriculture in Kinshasa's peri-urban dynamics. It may represent a response to food demand from a growing urban population, but it also places additional pressure on savannahs, gallery forests, and remnant forests. Peri-urban agricultural expansion is therefore an ambivalent process: it contributes to the city’s food supply while also degrading natural vegetation where sustainable planning and land-management practices are lacking [16, 20, 66–68].

The increasing stability of croplands and built-up areas indicates that these classes are becoming consolidated within the landscape. Conversely, declining forest stability, particularly during the most recent period, points to the increasing vulnerability of natural vegetation to land conversion. This contrast between increasingly stable anthropogenic classes and increasingly unstable natural classes confirms a progressive transition toward a landscape dominated by human land uses.

4.3. Landscape fragmentation and the diffusion-coalescence process

Landscape metrics show that natural vegetation underwent attrition, fragmentation, or dissection depending on the period. Fragmentation of forests and savannahs reduces the spatial continuity of natural habitats, potentially restricting ecological flows and increasing the isolation of remnant patches. These findings are consistent with established landscape-ecology theory, according to which urbanization changes not only the area of land-use and land-cover classes, but also their spatial configuration, connectivity, and morphological complexity [33, 35, 56, 57].

In contrast, built-up areas and croplands exhibited patch creation, aggregation, or consolidation. This pattern indicates a shift from initially discontinuous urbanization toward a more compact spatial configuration in some sectors. It partly supports the diffusion-coalescence hypothesis, whereby urban growth often begins through the diffusion of scattered built-up patches that subsequently merge into more continuous urban structures [2, 38, 69–74].

In Kinshasa, this process is expressed through consolidation of built-up land in established urban zones and the emergence of new urbanization fronts in peri-urban areas. Coalescence describes the progressive merging of urban patches near the central core, whereas diffusion corresponds

to the outward extension of built-up land into more distant sectors. This dynamic explains the radial progression observed in the intermediate rings and confirms that Kinshasa's urbanization does not follow a uniform model, but instead proceeds along a spatially differentiated trajectory.

4.4. Radial and peri-urban expansion

The analysis shows that built-up growth varied strongly with distance from the city center. During the earlier periods, urbanization remained relatively concentrated around the urban core, whereas the more recent periods especially 2014–2019 and 2019–2024, showed intensification at intermediate and peri-urban distances. This trajectory indicates that urbanization fronts have progressively shifted beyond the consolidated center [75, 76].

This peri-urbanization is consistent with patterns previously described for Kinshasa, where urban growth often occurs through progressive occupation of peripheral land, sometimes outside a robust planning framework [7, 15, 19, 77]. It also resembles trends observed in several large cities of the Global South, where recent urban growth is characterized by rapid spatial sprawl, discontinuous occupation of peripheral areas, and intense pressure on infrastructure and urban services [8, 24, 78, 79]

High urban-expansion intensity in the intermediate rings indicates that these areas have played a central role in Kinshasa's recent growth. They are transitional zones where residential, agricultural, land-market, and infrastructure dynamics converge. This warrants particular attention because peri-urban areas often concentrate land-use conflicts, infrastructure deficits, exposure to environmental hazards, and rapid loss of remnant ecosystems.

4.5. Implications for urban planning and environmental management

The findings have several implications for urban planning in Kinshasa. First, forest loss, savannah fragmentation, and the expansion of anthropogenic land uses highlight the need to conserve remnant ecosystems, particularly gallery forests, wetlands, valleys, and remaining vegetated spaces in urban and peri-urban areas. These ecosystems are important for water regulation, erosion control, biodiversity conservation, and improved urban living conditions [4, 68].

Second, the expansion of built-up land across the peri-urban rings demonstrates the urgency of strengthening planning and land-use control. Planning informed by up-to-date spatial data could guide densification in already urbanized areas, limit uncontrolled sprawl, protect ecologically sensitive zones, and better anticipate infrastructure needs. Such approaches are essential to prevent urban expansion from exacerbating socio-spatial inequalities, increasing natural-hazard exposure, and placing additional pressure on resources [80–83].

Third, rapid cropland expansion calls for integrated management of peri-urban agricultural areas. Urban policy should recognize these areas not merely as potential land reserves, but also as essential components of food security, the local economy, and territorial resilience. Sustainable farming practices, soil conservation, ecological restoration, and green corridors could reduce the adverse effects of anthropization while maintaining the landscape's productive functions.

4.6. Study contribution and limitations

A principal contribution of this study is its integration of multiple analytical levels: multitemporal land-use and land-cover classification, transition matrices, landscape metrics, an anthropization index, and ring-based urban-expansion indicators. This framework moves beyond a simple measure of built-up growth to provide a more detailed assessment of Kinshasa's landscape-transformation trajectories. It therefore helps address the limited understanding of the spatial processes underlying the city's recent urbanization.

Several limitations should nevertheless be acknowledged. The spatial resolution of Landsat imagery may limit detection of small built-up patches, gardens, interstitial agricultural plots, and highly fragmented vegetation. Spectral confusion may also occur among bare land, built-up areas, croplands, and dry savannahs despite the use of Random Forest and validation with independent points. Finally, the study focuses primarily on spatial and landscape change and does not directly model the socioeconomic, land-tenure, or institutional factors driving these transformations.

These limitations point to several avenues for future research. Higher-spatial-resolution imagery, integration of demographic and socioeconomic data, and prospective modeling of urban expansion would improve understanding of the landscape transformation and help anticipate future urban-growth trajectories in Kinshasa.

CONCLUSION

This study analyzed the spatiotemporal dynamics of urbanization in Kinshasa from 2001 to 2024 using Landsat imagery, Random Forest classification, transition matrices, landscape metrics, and urban-expansion indicators. The findings reveal progressive landscape anthropization, characterized by the decline of natural vegetation and the expansion of anthropogenic land-use and land-cover classes.

Between 2001 and 2024, savannah cover decreased from 57.94% to 47.51%, and forest cover from 20.56% to 7.76%. Conversely, croplands increased from 6.39% to 27.43%, and built-up areas from 3.01% to 6.62%. These changes were accompanied by an increase in the landscape disturbance index from 0.14 to 0.56, indicating growing anthropogenic pressure.

The radial analysis shows that urban expansion was spatially uneven. Growth was concentrated primarily at intermediate and peri-urban distances and intensified markedly from 2014 to 2019. These results support a diffusion-coalescence dynamic that combines consolidation of the existing urban fabric with the outward expansion of built-up land.

The findings underscore the need to strengthen urban planning in Kinshasa, particularly in peri-urban areas, to limit uncontrolled sprawl, conserve remnant ecosystems, and guide urban growth toward more sustainable forms.

Declarations

Author contributions

K.R.S.: conceptualization, methodology. K.R.S., T.M.S.: data and formal analysis. S.D.I.T.K.A., K.R.S., T.M.S., J.-P. M.N., D.P.O., S.D.I.T.K.A., J.B.B.: wrote the first draft of the article. K.R.S.: supervision and validation. K.R.S., T.M.S., J.-P. M.N., D.P.O., S.D.I.T.K.A., J.B.B.: Writing - review & editing. All authors have read and agreed to the submitted version of the manuscript.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

Data will be made available on request.

Declarations Ethical approval and Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Clinical trial number

Not applicable.

References

1. Clark C. Urban Population Densities. J Royal Stat Soc Ser (General). 1951;114. 10.2307/2981088.
2. Angel S, Sheppard SC, Civco DL. The Dynamics of Global Urban Expansion. Washington D.C: The World Bank; 2005.
3. Angel S. *Making Room for a Planet of Cities*; Lincoln Institute of Land Policy: Cambridge, MA, 2011; ISBN 978-1-55844-212-2.
4. Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM. Global Change and the Ecology of Cities. Science. 2008;319:756–60. 10.1126/science.1150195.
5. Seto KC, Güneralp B, Hutyra LR. Global Forecasts of Urban Expansion to 2030 and Direct Impacts on Biodiversity and Carbon Pools. *Proc. Natl. Acad. Sci. U.S.A.* 2012, *109*, 16083–16088. 10.1073/pnas.1211658109
6. Scheuer S, Haase D, Volk M. On the Nexus of the Spatial Dynamics of Global Urbanization and the Age of the City. PLoS ONE. 2016;11:e0160471. 10.1371/journal.pone.0160471.
7. Angel S, Lamson-Hall P, Blanco ZG. Anatomy of Density: Measurable Factors That Constitute Urban Density. Build Cities. 2021;2:264–82. 10.5334/bc.91.
8. Cohen B. Urbanization in Developing Countries: Current Trends, Future Projections, and Key Challenges for Sustainability. Technol Soc. 2006;28:63–80. 10.1016/j.techsoc.2005.10.005.
9. Montgomery MR. The Urban Transformation of the Developing World. Science. 2008;319:761–4. 10.1126/science.1153012.
10. Turok I, McGranahan G. Urbanization and Economic Growth: The Arguments and Evidence for Africa and Asia. Environ Urbanization. 2013;25:465–82. 10.1177/0956247813490908.
11. *The Value of Sustainable Urbanization*; UN-Habitat, Ed.; World cities report, editor. ; UN-Habitat: Nairobi, Kenya, 2020; ISBN 978-92-1-132872-1.
12. Cobbinah PB, Erdiaw-Kwasie MO, Amoateng P. Africa's Urbanisation: Implications for Sustainable Development. Cities. 2015;47:62–72. 10.1016/j.cities.2015.03.013.

13. Güneralp B, Lwasa S, Masundire H, Parnell S, Seto KC. Urbanization in Africa: Challenges and Opportunities for Conservation. Environ Res Lett. 2017;13:015002. 10.1088/1748-9326/aa94fe.
14. Wolff E, Delbart V. Extension Urbaine et Densité de La Population à Kinshasa: Contribution de La Télédétection Satellitaire. *belgeo* 2002, *1*, 45–99. 10.4000/belgeo.15451
15. Mavunda CA, Kanda M, Folega F, Egbelou V, Bosela B, Drazo NA, Yoka J, Dourma M, Akpagana K. Dynamique spatio-temporelle des changements d'occupation du sol sous incidence anthropique dans la ville de Kinshasa (RDC) de 2001 à 2021. Revue Geo-Eco-Trop. 2021;46:137–48.
16. Ndzomo J-PM, Sambieni KR, Fendoung PM. La croissance de l'urbanisation morphologique à Kinshasa entre 1979 et 2015: analyse densimétrique et de la fragmentation du bâti. Bull de la Société Géographique de Liège (BSGLg). 2019;73:85–103.
17. World Bank Revue de l'urbanisation En République Démocratique Du Congo: Des Villes Productives et Inclusives Pour l'émergence de La République Démocratique Du Congo; The World Bank. 2018; ISBN 978-1-4648-1205-7.
18. Flouriot JK. 2005. Trente ans après la publication de l'Atlas de Kinshasa. *com* 2013, *66*, 29–55. 10.4000/com.6770
19. Kayembe Wa Kayembe M, De Maeyer M, Wolff E. Cartographie de La Croissance Urbaine de Kinshasa (R.D. Congo) Entre 1995 et 2005 Par Télédétection Satellitaire à Haute Résolution. *belgeo* 2009, *3–4*, 439–456. 10.4000/belgeo.7349
20. Sambieni KR, Messina JPN, Biloso M, Halleux J-M, Occhiuto R. Les Statuts Morphologiques d'urbanisation Des Communes de Kinshasa En République Démocratique Du Congo. *Tropicultura* 2018, *36*.
21. Wolff E, Delbart V. Extension urbaine et densité de la population à Kinshasa: contribution de la télédétection satellitaire. *belgeo* 2002, 45–99. 10.4000/belgeo.15451
22. Kibala Ntondele G. Analyse de La Dynamique Des Espaces Industriels de Kinshasa (RD Congo). *ld* 2022, 30–32. 10.14428/ld.vi22.67163
23. Yoka LM, Jacquemot P. Kinshasa, la fabrique urbaine: Gestes et langages de la résilience. Afrique contemporaine. 2021;269–270:109–34. 10.3917/afco.269.0109.
24. Rish-Naw MY. L'étalement urbain et occupation de l'espace à Kinshasa. *TRANSLANG* 2017, *16*, 175–182. 10.52919/translang.v16i1.629
25. Weng Q. Remote Sensing of Impervious Surfaces in the Urban Areas: Requirements, Methods, and Trends. Remote Sens Environ. 2012;117:34–49. 10.1016/j.rse.2011.02.030.
26. Zhu Z, Woodcock CE. Continuous Change Detection and Classification of Land Cover Using All Available Landsat Data. Remote Sens Environ. 2014;144:152–71. 10.1016/j.rse.2014.01.011.
27. Phan TN, Kuch V, Lehnert LW. Land Cover Classification Using Google Earth Engine and Random Forest Classifier—The Role of Image Composition. Remote Sens. 2020;12:2411. 10.3390/rs12152411.
28. 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. 10.1016/j.rse.2017.06.031.
29. Breiman L, Random Forests. Mach Learn. 2001;45:5–32. 10.1023/A:1010933404324.
30. Gislason PO, Benediktsson JA, Sveinsson JR. Random Forests for Land Cover Classification. Pattern Recognit Lett. 2006;27:294–300. 10.1016/j.patrec.2005.08.011.
31. Rodriguez-Galiano VF, Ghimire B, Rogan J, Chica-Olmo M, Rigol-Sanchez JP. An Assessment of the Effectiveness of a Random Forest Classifier for Land-Cover Classification. ISPRS J Photogrammetry Remote Sens. 2012;67:93–104. 10.1016/j.isprsjprs.2011.11.002.
32. Shelestov A, Lavreniuk M, Kussul N, Novikov A, Skakun S. Classification of Multi-Temporal Satellite Imagery for Crop Mapping. Front Earth Sci. 2017;5. 10.3389/feart.2017.00017. Exploring Google Earth Engine Platform for Big Data Processing:.
33. O'Neill RV, Krummel JR, Gardner RH, Sugihara G, Jackson B, DeAngelis DL, Milne BT, Turner MG, Zygmunt B, Christensen SW, et al. Indices of Landscape Pattern. Landsc Ecol. 1988;1:153–62. 10.1007/BF00162741.
34. McGarigal K, Marks BJ. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; 1995.
35. Bogaert J, Ceulemans R, Salvador-Van Eysenrode D. Decision Tree Algorithm for Detection of Spatial Processes in Landscape Transformation. Environ Manage. 2004;33:62–73. 10.1007/s00267-003-0027-0.
36. Liu X, Li X, Chen Y, Tan Z, Li S, Ai B. A New Landscape Index for Quantifying Urban Expansion Using Multi-Temporal Remotely Sensed Data. Landsc Ecol. 2010;25:671–82. 10.1007/s10980-010-9454-5.
37. Lu S, Guan X, He C, Zhang J. Spatio-Temporal Patterns and Policy Implications of Urban Land Expansion in Metropolitan Areas: A Case Study of Wuhan Urban Agglomeration, Central China. *Sustainability* 2014, *6*, 4723–4748. 10.3390/su6084723
38. Sikuzani YU, Kaleba SC, Halleux J-M, Bogaert J, Kankumbi FM. Caractérisation de La Croissance Spatiale Urbaine de La Ville de Lubumbashi (Haut-Katanga, RD Congo) Entre 1989 et 2014. *Tropicultura* 2018, *36*.
39. André M, Mahy G, Lejeune P, Bogaert J. Vers une synthèse de la conception et une définition des zones dans le gradient urbain-rural. Biotechnol Agronomie Société et Environ (BASE). 2014;18:61–74.

40. Bogaert J, Vranken I, André M. Anthropogenic Effects in Landscapes: Historical Context and Spatial Pattern. In *Biocultural Landscapes*; Hong, S.-K., Bogaert, J., Min, Q., Eds.; Springer Netherlands: Dordrecht, 2014; pp. 89–112 ISBN 978-94-017-8940-0.
41. Ortiz-Báez P, Cabrera-Barona P, Bogaert J, ANALYSIS OF LANDSCAPE, TRANSFORMATIONS IN THE URBAN-RURAL GRADIENT OF THE METROPOLITAN DISTRICT OF QUITO. *JURA* 2022, *14*, 10.37043/JURA.2022.14.2.4
42. Peel MC, Finlayson BL, McMahon TA. Updated World Map of the K¨oppen-Geiger Climate Classification. Hydrol Earth Syst Sci 2007.
43. Imwangana FM, Vandecasteele I, Trefois P, Ozer P, Moeyersons J The Origin and Control of Mega-Gullies in Kinshasa (, Congo DR.). *CATENA* 2015, *125*, 38–49. 10.1016/j.catena.2014.09.019
44. Myint SW, Gober P, Brazel A, Grossman-Clarke S, Weng Q. Per-Pixel vs. Object-Based Classification of Urban Land Cover Extraction Using High Spatial Resolution Imagery. Remote Sens Environ. 2011;115:1145–61. 10.1016/j.rse.2010.12.017.
45. Liu X, Hu G, Chen Y, Li X, Xu X, Li S, Pei F, Wang S. High-Resolution Multi-Temporal Mapping of Global Urban Land Using Landsat Images Based on the Google Earth Engine Platform. Remote Sens Environ. 2018;209:227–39. 10.1016/j.rse.2018.02.055.
46. Zhao Q, Yu L, Li X, Peng D, Zhang Y, Gong P. Progress and Trends in the Application of Google Earth and Google Earth Engine. Remote Sens. 2021;13:3778. 10.3390/rs13183778.
47. Xia J, Falco N, Benediktsson JA, Du P, Chanussot J. Hyperspectral Image Classification With Rotation Random Forest Via KPCA. IEEE J Sel Top Appl Earth Observations Remote Sens. 2017;10:1601–9. 10.1109/JSTARS.2016.2636877.
48. Toosi NB, Soffianian AR, Fakheran S, Pourmanafi S, Ginzler C, Waser LT. Comparing Different Classification Algorithms for Monitoring Mangrove Cover Changes in Southern Iran. Global Ecol Conserv. 2019;19:e00662. 10.1016/j.gecco.2019.e00662.
49. Zeferino LB, Souza LFTD, Amaral CHD, Fernandes Filho EI, Oliveira TSD. Does Environmental Data Increase the Accuracy of Land Use and Land Cover Classification? Int J Appl Earth Obs Geoinf. 2020;91:102128. 10.1016/j.jag.2020.102128.
50. Verburg PH, Kok K, Pontius RG, Veldkamp A. Modeling Land-Use and Land-Cover Change. In *Land-Use and Land-Cover Change*; Lambin, E.F., Geist, H., Eds.; Global Change - The IGBP Series; Springer Berlin Heidelberg: Berlin, Heidelberg, 2006; pp. 117–135 ISBN 978-3-540-32201-6.
51. Olofsson P, Foody GM, Stehman SV, Woodcock CE. Making Better Use of Accuracy Data in Land Change Studies: Estimating Accuracy and Area and Quantifying Uncertainty Using Stratified Estimation. Remote Sens Environ. 2013;129:122–31. 10.1016/j.rse.2012.10.031.
52. Pontius GR, Malanson J. Comparison of the Structure and Accuracy of Two Land Change Models. Int J Geogr Inf Sci. 2005;19:243–65. 10.1080/13658810410001713434.
53. Turner MG. Spatial Simulation of Landscape Changes in Georgia: A Comparison of 3 Transition Models. Landsc Ecol. 1987;1:29–36. 10.1007/BF02275263.
54. Turner MG, Ruscher CL. Changes in Landscape Patterns in Georgia, USA. Landsc Ecol. 1988;1:241–51. 10.1007/BF00157696.
55. Muller MR, Middleton JA. Markov Model of Land-Use Change Dynamics in the Niagara Region, Ontario, Canada. Landsc Ecol. 1994;9:151–7. 10.1007/BF00124382.
56. McGarigal K. Landscape Pattern Metrics. In *Wiley StatsRef: Statistics Reference Online*; Kenett, R.S., Longford, N.T., Piegorsch, W.W., Ruggeri, F., Eds.; Wiley, 2014 ISBN 978-1-118-44511-2.
57. Bogaert J, Mahamane A. Ecologie Du Paysage: Cibler La Configuration et l'echelle Spatiale. Ann des Sci Agronomiques. 2009;7. 10.4314/asab.v7i1.43277.
58. De Haulleville T, Rakotondrasoa OL, Rakoto Ratsimba H, Bastin J-F, Brostaux Y, Verheggen FJ, Rajoelison GL, 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;14:135–46. 10.1007/s11355-017-0340-z.
59. Abdullahi S, Pradhan B. Urban Expansion and Change Detection Analysis. In *Spatial Modeling and Assessment of Urban Form*; Pradhan, B., Ed.; Springer International Publishing: Cham, 2017; pp. 155–170 ISBN 978-3-319-54216-4.
60. Akubia JEK, Bruns A. Unravelling the Frontiers of Urban Growth: Spatio-Temporal Dynamics of Land-Use Change and Urban Expansion in Greater Accra Metropolitan Area, Ghana. *Land* 2019, *8*, 131. 10.3390/land8090131
61. Fenta AA, Yasuda H, Haregeweyn N, Belay AS, Hadush Z, Gebremedhin MA, 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;38:4107–29. 10.1080/01431161.2017.1317936.
62. Dewan AM, Yamaguchi Y. Land Use and Land Cover Change in Greater Dhaka, Bangladesh: Using Remote Sensing to Promote Sustainable Urbanization. Appl Geogr. 2009;29:390–401. 10.1016/j.apgeog.2008.12.005.
63. Li C, Li J, Wu J. Quantifying the Speed, Growth Modes, and Landscape Pattern Changes of Urbanization: A Hierarchical Patch Dynamics Approach. Landsc Ecol. 2013;28:1875–88. 10.1007/s10980-013-9933-6.
64. Dadi D, Azadi H, Senbeta F, Abebe K, Taheri F, Stellmacher T. Urban Sprawl and Its Impacts on Land Use Change in Central Ethiopia. Urban Forestry Urban Green. 2016;16:132–41. 10.1016/j.ufug.2016.02.005.
65. Terfa BK, Chen N, Zhang X, Niyogi DS. Configuration and Extent Explains the Urban Heat Mitigation Potential Due to Green Spaces: Analysis over Addis Ababa, Ethiopia. Remote Sens. 2020;12:2876. 10.3390/rs12182876.

66. Sambieni KR, Sikuzani YU, Kaleba SC, Moyene AB, Kankumbi FM, Occhiuto R, Bogaert J. Les espaces verts en zone urbaine et périurbaine de Kinshasa en République Démocratique du Congo. *Tropicultura* 2018, 478–491. 10.25518/2295-8010.648
67. Mahmoudzadeh H, Abedini A, Aram F. Urban Growth Modeling and Land-Use/Land-Cover Change Analysis in a Metropolitan Area (Case Study: Tabriz). Land. 2022;11:2162. 10.3390/land11122162.
68. Wu C, Li C, Ouyang L, Xiao H, Wu J, Zhuang M, Bi X, Li J, Wang C, Song C, et al. Spatiotemporal Evolution of Urbanization and Its Implications to Urban Planning of the Megacity, Shanghai, China. Landsc Ecol. 2023;38:1105–24. 10.1007/s10980-022-01578-7.
69. Dietzel C, Oguz H, Hemphill JJ, Clarke KC, Gazulis N. Diffusion and Coalescence of the Houston Metropolitan Area: Evidence Supporting a New Urban Theory. Environ Plann B Plann Des. 2005;32:231–46. 10.1068/b31148.
70. Xu C, Liu M, Zhang C, An S, Yu W, Chen JM. The Spatiotemporal Dynamics of Rapid Urban Growth in the Nanjing Metropolitan Region of China. Landsc Ecol. 2007;22:925–37. 10.1007/s10980-007-9079-5.
71. Wu J, Jenerette GD, Buyantuyev A, Redman CL. Quantifying Spatiotemporal Patterns of Urbanization: The Case of the Two Fastest Growing Metropolitan Regions in the United States. Ecol Complex. 2011;8:1–8. 10.1016/j.ecocom.2010.03.002.
72. Li S, Liu X, Li Z, Wu Z, Yan Z, Chen Y, Gao F. Spatial and Temporal Dynamics of Urban Expansion along the Guangzhou–Foshan Inter-City Rail Transit Corridor, China. *Sustainability* 2018, *10*, 593. 10.3390/su10030593
73. Sun Y, Zhao S, Qu W. Quantifying Spatiotemporal Patterns of Urban Expansion in Three Capital Cities in Northeast China over the Past Three Decades Using Satellite Data Sets. Environ Earth Sci. 2015;73:7221–35. 10.1007/s12665-014-3901-6.
74. Balandi JB, To Hulu JPPM, Sambieni KR, Sikuzani YU, Bastin J-F, Musavandalo CM, Nguba TB, Molo JEL, Selemani TM, Mweru J-PM et al. Urban Sprawl and Changes in Landscape Patterns: The Case of Kisangani City and Its Periphery (DR Congo). *Land* 2023, *12*, 2066. 10.3390/land12112066
75. Sikuzani YU, Malaisse F, Kaleba SC, Kankumbi FM, Bogaert J. Le Rayon de Déforestation Autour de La Ville de Lubumbashi (Haut-Katanga, RD Congo): Synthèse. *Tropicultura* 2017, *35*, 215–221.
76. Bamba I, Yedmel MS, Bogaert J. Effets des Routes et des Villes sur la forêt Dense dans la Province Orientale de la République Démocratique du Congo. Eur J Sci Res. 2010;43:417–29.
77. Salomon W, Useni Sikuzani Y, Sambieni KR, Kouakou ATM, Barima YSS, Théodat JM, Bogaert J. Land Cover Dynamics along the Urban–Rural Gradient of the Port-Au-Prince Agglomeration (Republic of Haiti) from 1986 to 2021. Land. 2022;11:355. 10.3390/land11030355.
78. Bastin J-F, Clark E, Elliott T, Hart S, Van Den Hoogen J, Hordijk I, Ma H, Majumder S, Manoli G, Maschler J, et al. Understanding Climate Change from a Global Analysis of City Analogues. PLoS ONE. 2019;14:e0217592. 10.1371/journal.pone.0217592.
79. Bamba I, Barima YSS, Bogaert J. Influence de la densitÉ de la population sur la structure spatiale d'un paysage forestier dans le bassin du Congo en R. D. Congo. Trop Conserv Sci. 2010;3:31–44. 10.1177/194008291000300104.
80. Sikuzani YU, Kaleba SC, Khonde N, Mwana A, Malaisse F, Bogaert J, Kankumbi FM. Vingt-Cinq Ans de Monitoring de La Dynamique Spatiale Des Espaces Verts En Réponse à l'urbanisation Dans Les Communes de La Ville de Lubumbashi (Haut-Katanga, RD Congo). *Tropicultura* 2017, *35*, 300–311.
81. Mukubu Pika L, Mbavumoja Selemani T, Jesuka R, Meniko To Hulu JPP, Sambieni KR, Useni Sikuzani Y, Bogaert J. Practice and Biodiversity of Informal Ornamental Horticulture in Kinshasa, Democratic Republic of Congo. Ecologies. 2024;5:83–100. 10.3390/ecologies5010006.
82. Bosch M, Jaligot R, Chenal J. Spatiotemporal Patterns of Urbanization in Three Swiss Urban Agglomerations: Insights from Landscape Metrics, Growth Modes and Fractal Analysis. Landsc Ecol. 2020;35:879–91. 10.1007/s10980-020-00985-y.
83. Öncel H, Levend S. The Effects of Urban Growth on Natural Areas: The Three Metropolitan Areas in Türkiye. Environ Monit Assess. 2023;195:816. 10.1007/s10661-023-11383-7.

Figures

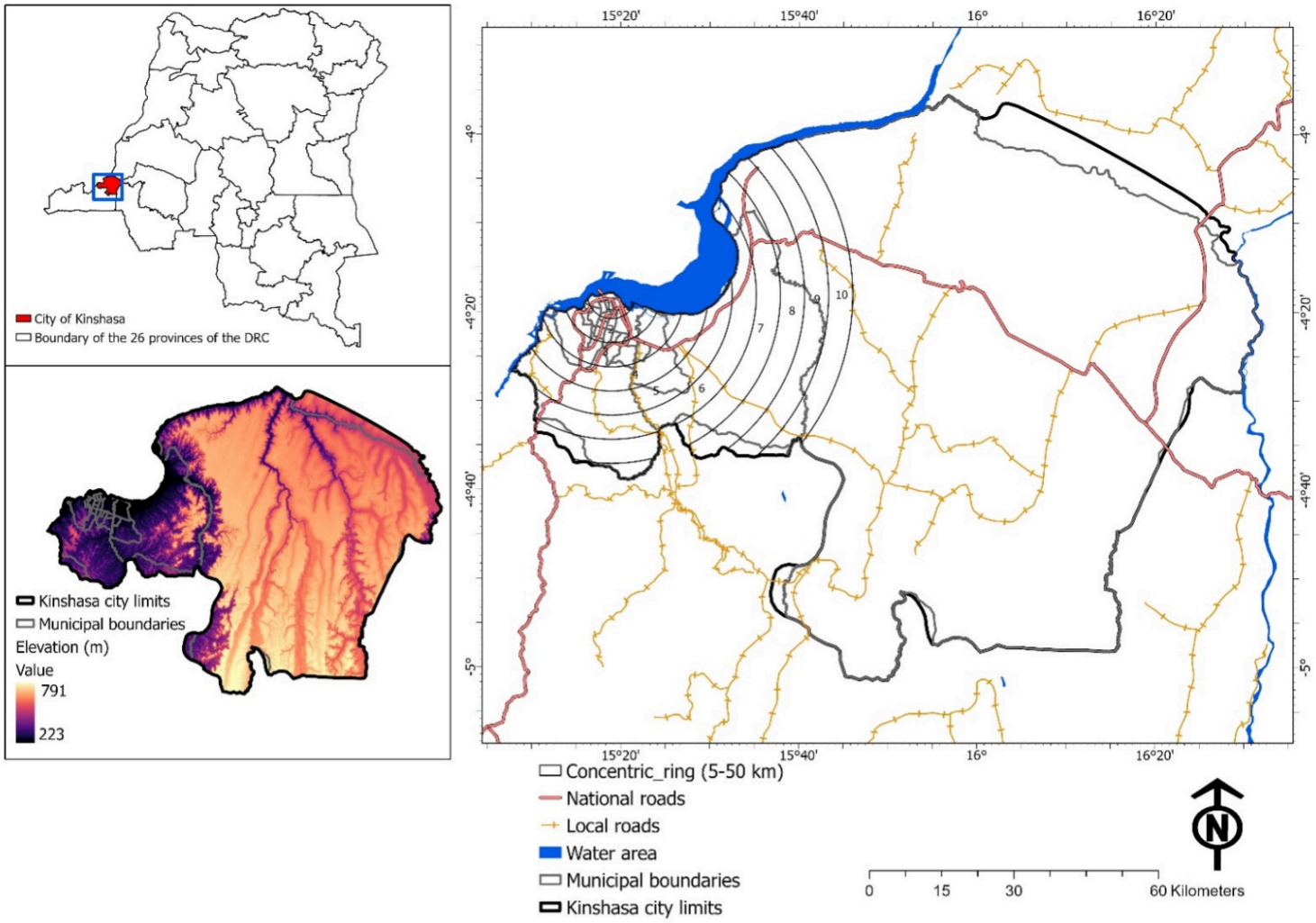


Figure 1

Location and boundaries of the study area in Kinshasa. Concentric 5-km rings were generated around Kinshasa Central Station (4°18'5.07" S, 15°19'1.96" E).

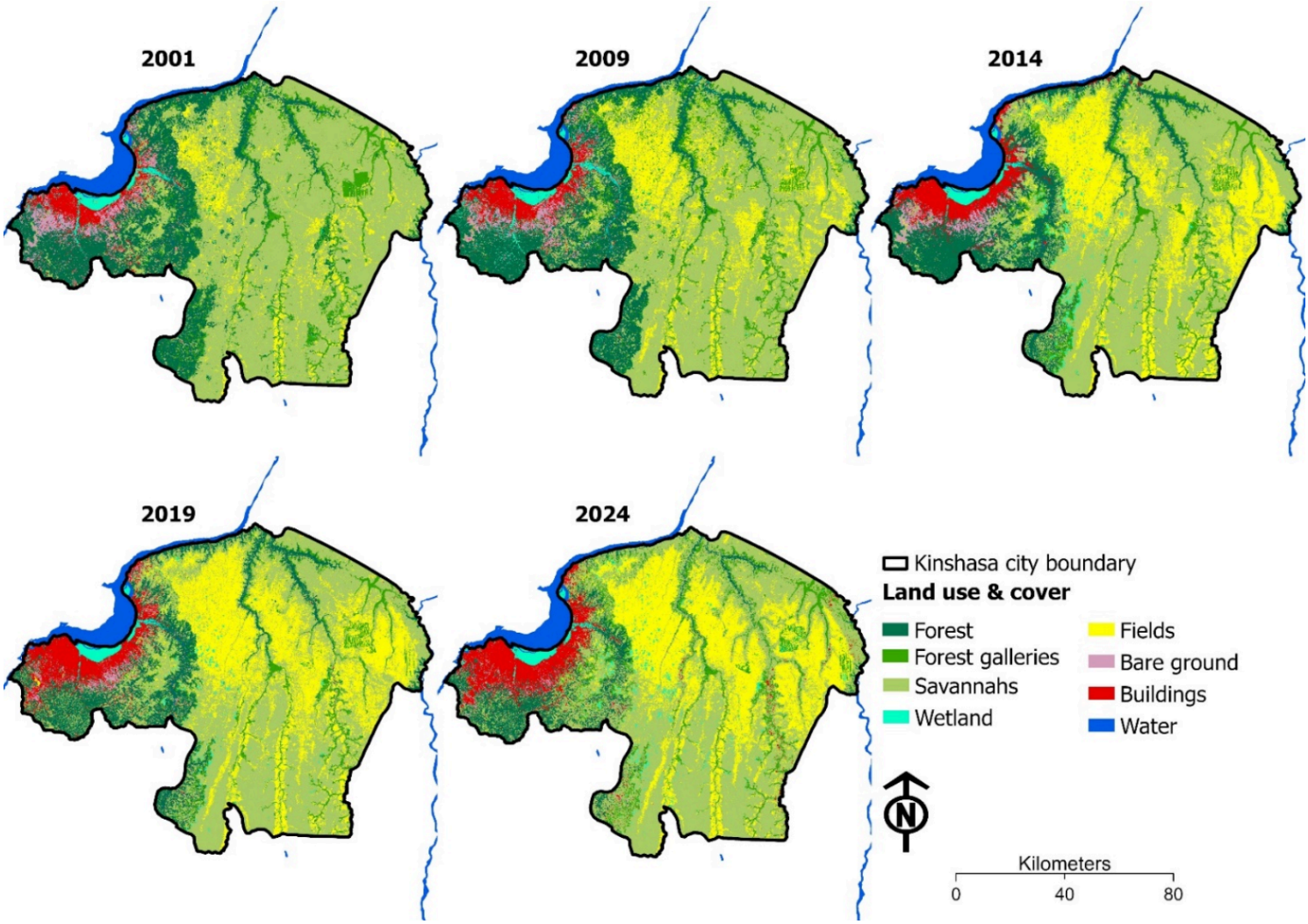


Figure 2

Land-use and land-cover patterns and landscape composition in Kinshasa in 2001, 2009, 2014, 2019, and 2024.

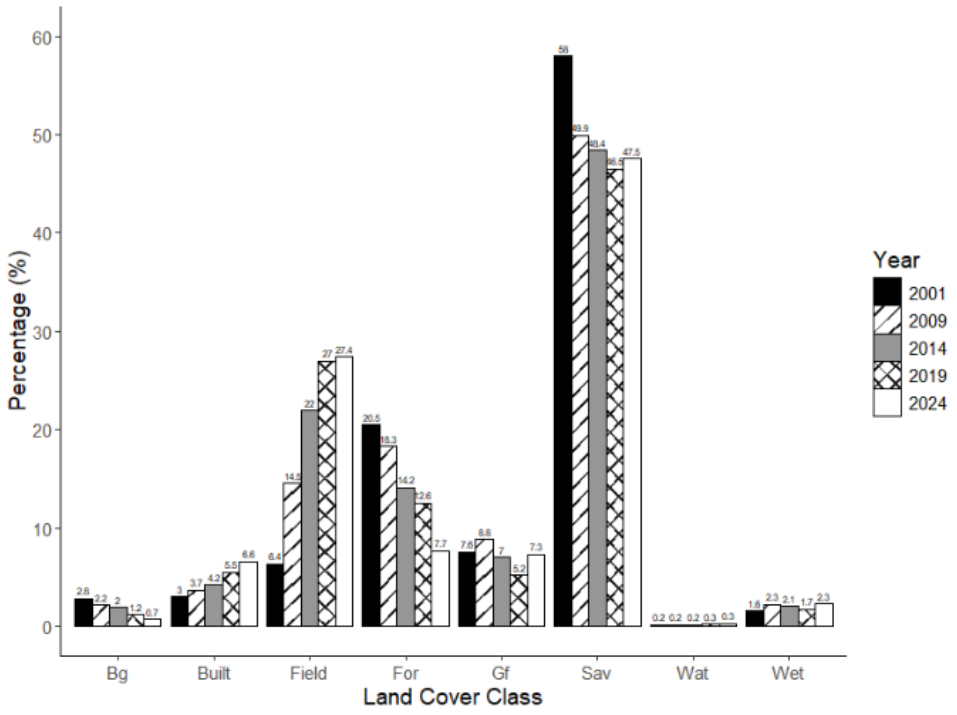


Figure 3

Changes in the proportional area of land-use and land-cover classes in Kinshasa during the study period. Bg, bare land; Built, built-up areas; For, forest; Gf, gallery forest; Sav, savannah; Wet, wetland; Wat, water.

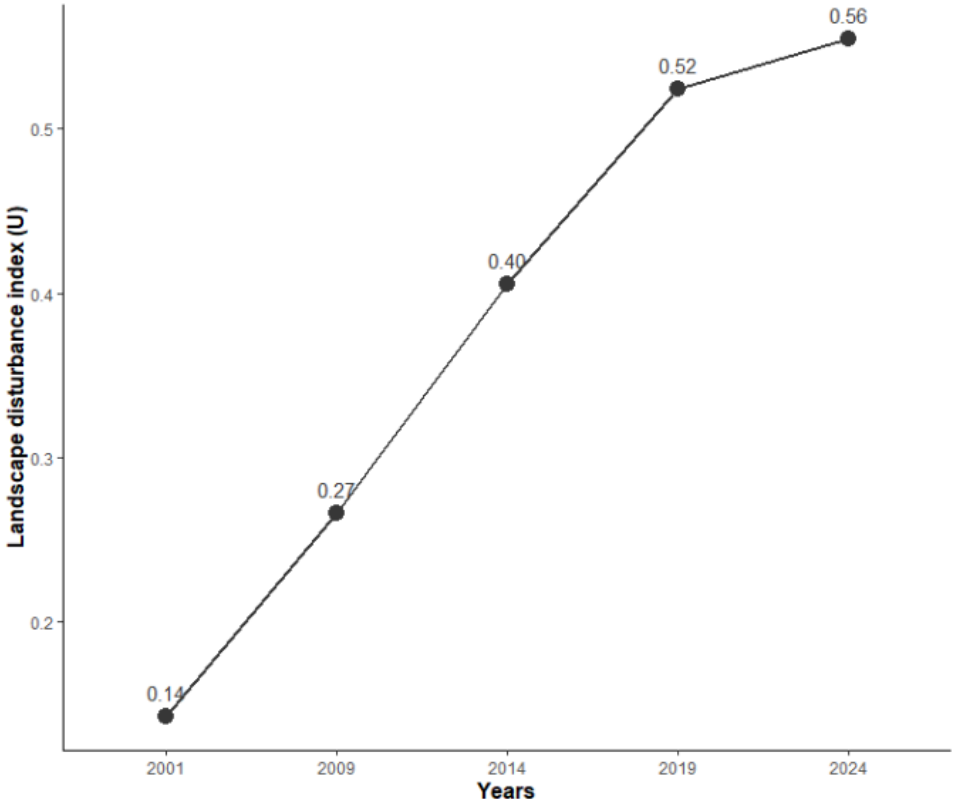


Figure 4

Landscape disturbance index for the city of Kinshasa observed between 2001, 2009, 2014, 2019 and 2024.

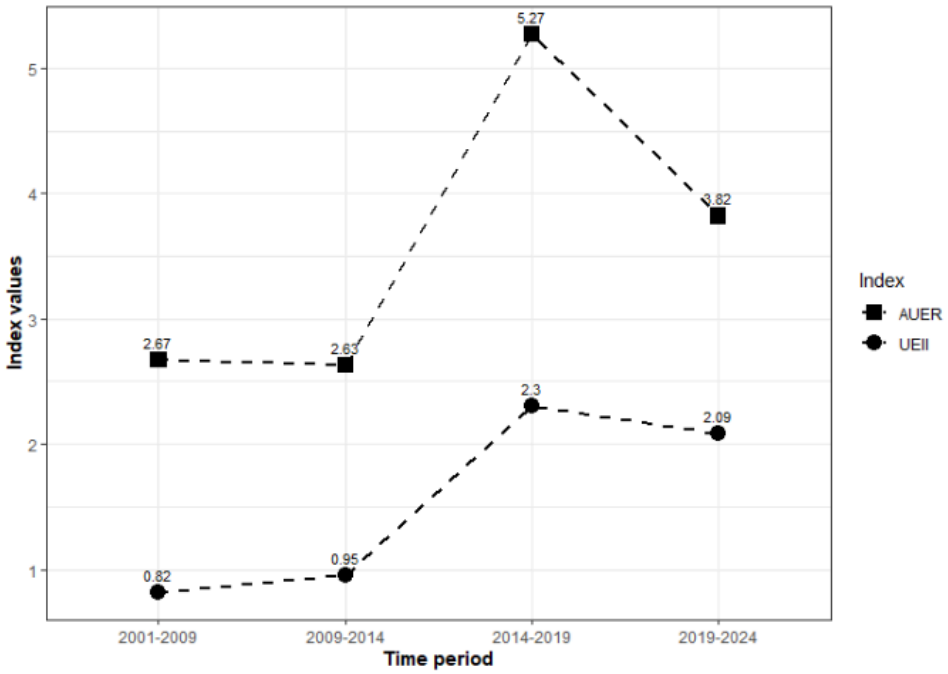


Figure 5

Changes over time in the annual urban expansion rate index (AUER) and the urban expansion intensity index (UEII) across the Kinshasa cityscape. To estimate these indices, we used the administrative area of the city of Kinshasa, which is 1146 km². This area, delimited by concentric rings (Fig. 1), covers much more than the entire urban and peri-urban areas of the city [20].

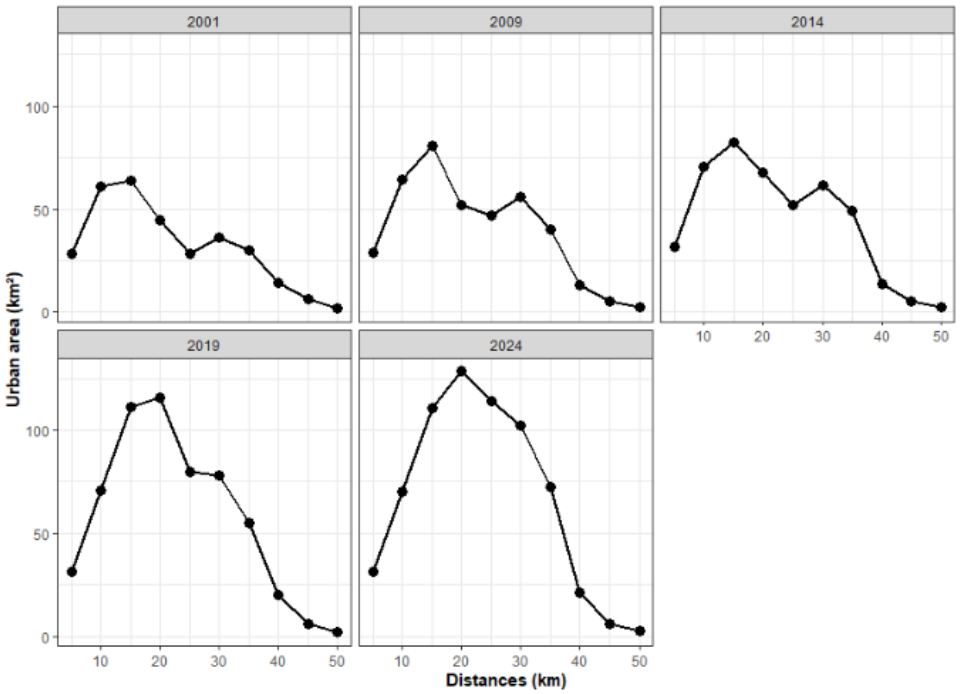


Figure 6

Surface area occupied by the urban area in rings equidistant by 5 km from the centre per year

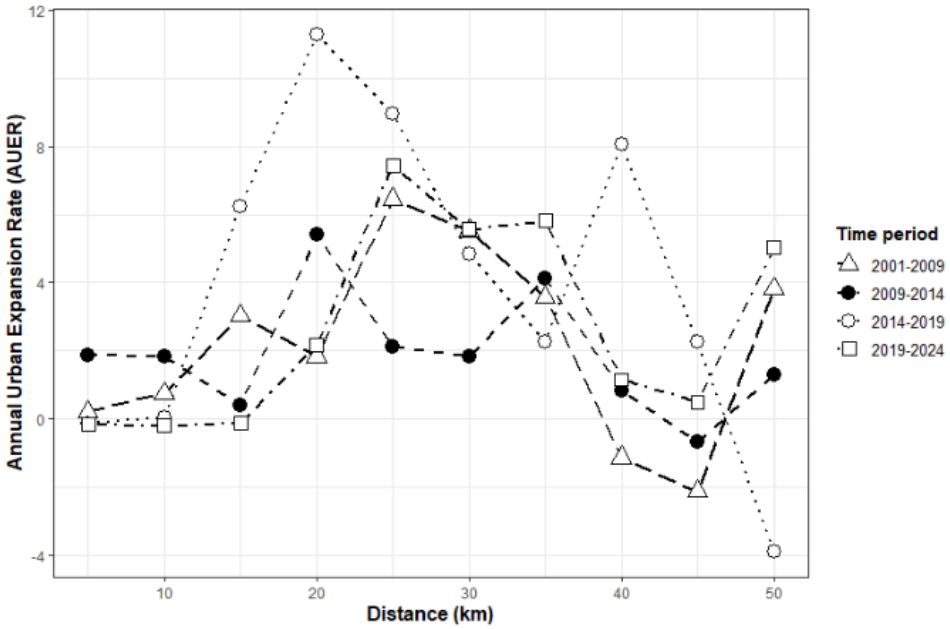


Figure 7

Annual Urban Expansion Rate (AUER) within concentric 5-km rings around the city center during each transition period.

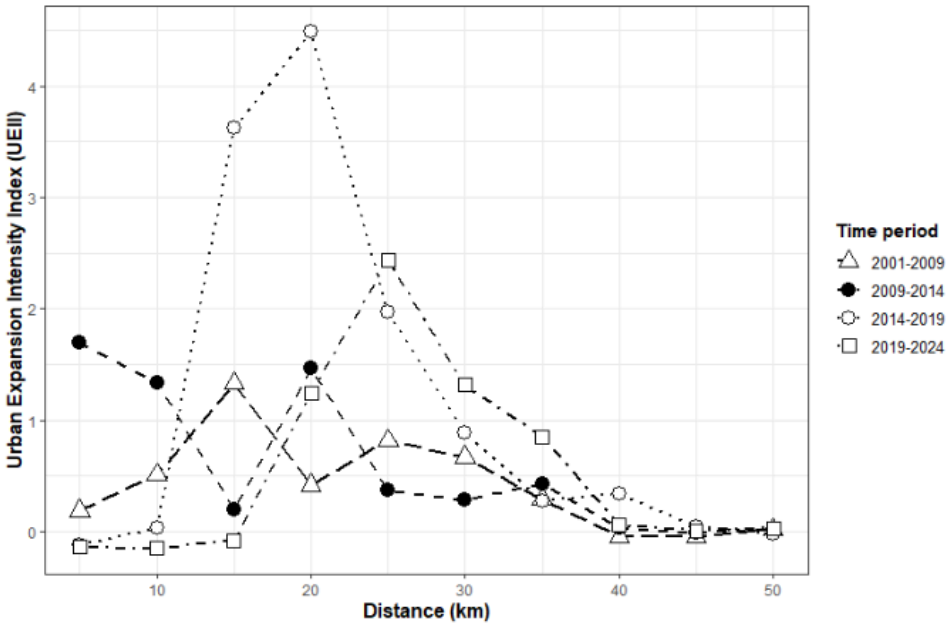


Figure 8

Urban Expansion Intensity Index (UEII) within concentric 5-km rings around the city center during each transition period.