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ORIGINAL PAPER

Anthropogenic pressures and spatio-temporal dynamics of forest ecosystems in the rural and border municipality of Kasenga (DRC)

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Abstract

Migration and the dependence of rural communities on forest resources for subsistence have profoundly altered the composition and spatial structure of the landscapes of the border municipality of Kasenga in the southeast of DR Congo. The spatio-temporal dynamics of anthropogenic effects on forest ecosystems were mapped and quantified in the municipality of Kasenga using Landsat image classification from 1989 to 2022, combined with landscape ecology metrics to analyze spatial patterns. Our results show that the landscape has undergone profound disturbances. The area of large patches of forest that used to dominate the landscape has been reduced by a factor of 4 from 1989 to 2022, thus indicating the anthropogenic impact on the fragmentation of forest ecosystems. If in 33 years (from 1989 to 2022) forest has lost more than a third of their coverage through the dissection, fragmentation and attrition of patches, agriculture, grassland and wetland, and built-up and bare land have recorded a progressive dynamic resulting from the creation and aggregation of patches. These anthropogenic transformations, coupled with a lack of land management planning, will compromise the future of forest ecosystems since the level of landscape disturbance has quintupled from 1.1 to 5.5 in 33 years. There is then an urgent need to develop an integrated and participatory land management strategy to preserve forest resources and guarantee their resilience.

Keywords Forests · Ecosystem services · Anthropization of landscapes · Deforestation · Migration flows

Introduction

In sub-Saharan Africa, forests are a survival capital for human populations, especially as they provide various edible forest products (Akinnifesi et al. 2008; Mng'omba et al. 2015), medicinal plants (Moyo et al. 2015; Moura et al. 2018), fuelwood (Dewees et al. 2010), construction materials (Assale et al. 2016), and fodder (Chinomona et al. 2018; Handavu et al. 2019). They also contribute to climate and water flow regulation (Vinya et al. 2019), carbon sequestration (Lusambo et al. 2016), biodiversity conservation (Arroyo-Rodriguez et al. 2020), and soil conservation (Xiao et al. 2017). However, the dependence of sub-Saharan rural communities on forest resources for their livelihoods is increasingly causing deforestation and the degradation of forest ecosystems (Yaovi et al. 2021). As a result, a loss of 129 million hectares of forest was reported between 1990 and 2015 up to almost 151 million hectares in 2020, representing an annual rate of – 0.13% of the forest in sub-Saharan Africa (Keenan et al. 2015; FAO 2020). According to data from Global Forest Watch, while in the early 2000s

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gross primary forest loss averaged 150,000 ha per year, it has been around 450,000 ha per year since 2014 (Karsenty 2020). In Central Africa, the Democratic Republic of the Congo, a country with high diversity and large forest cover, is becoming an illustration of the negative evolution of forest cover (Potapov et al. 2012; Tyukavina et al. 2018), especially since from 1990 to 2010 the deforestation rate remained constant at more than 0.20%, which is equivalent to the loss of 311,000 ha per year (FAO 2010). However, during the decade 2010–2020, the deforestation rate has quadrupled to 0.83%, or 1,101,000 ha of forest lost annually (FAO 2020).

As for woodland, particularly of the *miombo* woodland type, they are experiencing a significant decline in the Katanga region (Khoji et al. 2022), particularly in the Katangese copper belt area (KCA), a region of intense mining activities (Mwitwa et al. 2012; Potapov et al. 2012; Cabala et al. 2017). It should be noted that the *miombo* woodland is a dominant vegetation type in the Zambezian region, characterized by the preponderance of species belonging to the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* of the Caesalpionioideae (Malaisse 2010). The causes of the regression of *miombo* woodland cover, supported by rapid population growth, are mainly agricultural development, charcoal production (peri-)urbanization and the development of mining activities (Useni et al. 2017). The extent of anthropogenic activities is such that the KCA lost 15% of the *miombo* woodland cover between 2002 and 2015 (Cabala et al. 2017). The rural areas of the KCA deserve special attention as they are constantly experiencing unplanned local changes in land cover (Mpanda et al. 2022), while the spatial pattern of the landscape is timidly evolving at the scale of the KCA (Mwitwa et al. 2012). In turn, these changes in the spatial pattern of landscape (composition and configuration) are likely to lead to local climatic disturbances, contributing to global change and affect biodiversity (Bogaert and André 2013; Biaou et al. 2022).

The rural municipality of Kasenga to the northeast of Lubumbashi City is no exception to this trend. Its location on the border with Zambia means that it currently has a custom post open to border traffic, making it attractive to neighboring populations because of the economic opportunities (CAID 2017). Once known as a fishing area due to its proximity to the Luapula River separating it from Zambia (Malaisse 2010), this area has collapsed due to overexploitation of fisheries resources, leading to a rush of people into slash-and-burn agriculture (Mpanda et al. 2022) as well as charcoal production to meet local needs and those of the City of Lubumbashi (Kabulu et al. 2018).

In the rural and border municipality of Kasenga, the forest ecosystems, which are otherwise scarce, have never been the subject of rational management. Constantly subjected to anthropogenic actions, these ecosystems are in an advanced state of degradation, which compromises their ecological stability. Although quantifying the extent of forest cover and its change is crucial to highlight the ecological processes taking place to guide planners, such information is nonexistent for the rural and border municipality of Kasenga. Yet, by analyzing the spatial pattern of landscapes and their dynamics through remote sensing, geographic information systems, and landscape ecology analysis tools, timely conclusions regarding fundamental ecological processes can be defined and vice versa (Bogaert and André 2013). Remote sensing provides accurate and precise data, enabling detailed and reliable monitoring of land cover changes over time (Hemati et al. 2021). In addition, it provides a consistent and reproducible methodology for monitoring land cover dynamics, which is essential for long-term multi-scale studies (Amarnath et al. 2017; Li et al. 2023). As a result, it can be more cost-effective than traditional ground-based methods, particularly for monitoring large areas (Shapiro et al. 2015). On the other hand, it is a non-disturbing method for the areas to be studied (Bakó et al. 2014).

Lisa et al. (2021) used images from the Landsat 5 sensor to estimate the urban extent, count the number of buildings within the border City of Goma (DR Congo) and calculate housing densities, by manually digitizing urban spatial expansion. Yet, several Landsat sensors have been launched, and each new generation brings technological improvements and innovations that make them invaluable tools for monitoring the environment or managing natural resources (Wulder et al. 2022). Since images from recent sensors (e.g. Landsat 8 and Landsat 9) are compatible with those from earlier sensors, it is generally recommended to use multi-date images which enable continuous analysis and long-term monitoring of land cover change (Li and Chen 2020).

However, since several forest cover products are available (e.g., Hansen et al. 2013), in landscape ecology, the impact of spatial scale in the analysis of landscape dynamics is well documented (Bogaert et al. 2005). The reduction of the spatial scale can thus bring to light phenomena that are not observable at large spatial scales (Turner et al. 1989; Wu et al. 1997; Barima et al. 2009). Thus, the analysis of the local dynamics of forest cover would be relevant to understand and highlight local drivers, which potentially contribute to national and global changes (Sabah et al. 2022). Also, in the current context of decentralization in DRC, the study of landscape dynamics at the municipality level seems very timely, as the issues of land cover/use allocation, which have major impacts on the landscape, are the responsibility of traditional chiefs around the city (Mpanda et al. 2022). The municipality scale is therefore relevant for any study that could lead to the implementation of a responsible natural resource management strategy. Also, areas characterized by slash-and-burn agriculture deserve special attention as they correspond to places where the direction of local changes is unplanned and frequent, while the spatial structures of the landscape evolve timidly at the regional scale. Yet, these changes in landscape spatial pattern lead to forest fragmentation, local climatic disturbances (Assani 1999) which in turn contribute to global change.

For this reason, the present study maps and quantifies the spatio-temporal pattern dynamics of forest ecosystems in the rural and border municipality of Kasenga in response to anthropogenic pressures. It tests the hypothesis that, due to a lack of land management planning, overpopulation coupled with unsustainable use in the context of climate change, the landscape dynamics are characterized by a fragmentation of forest ecosystems, materialized by a decrease in the patch area in parallel with an increase in their number, to the benefit of agricultural areas and savannahs, which extend their hold on the landscape and amplify its anthropization level.

Materials and methods

Study area

The present study covers the rural and border municipality of Kasenga, including the City of Kasenga and its periphery. This area corresponds administratively to part of the Kisamamba sector and covers a total area of 783 km^2 (Fig. 1). With an altitude ranging from 925 to 960 m, the municipality of Kasenga has an Aw5 type climate according to the Köppen classification system (Kasongo 2008), with an alternating rainy season (October to April) and dry season (May to September). The dry season is currently being extended at the expense of the rainy season, with temperatures often being harsh. Average annual temperatures vary between 16 and 33 °C, while annual rainfall of around 1260 mm is recorded (CAID 2017). In contrast to previous years, the frequency and volume of rain is currently disturbed, the dry

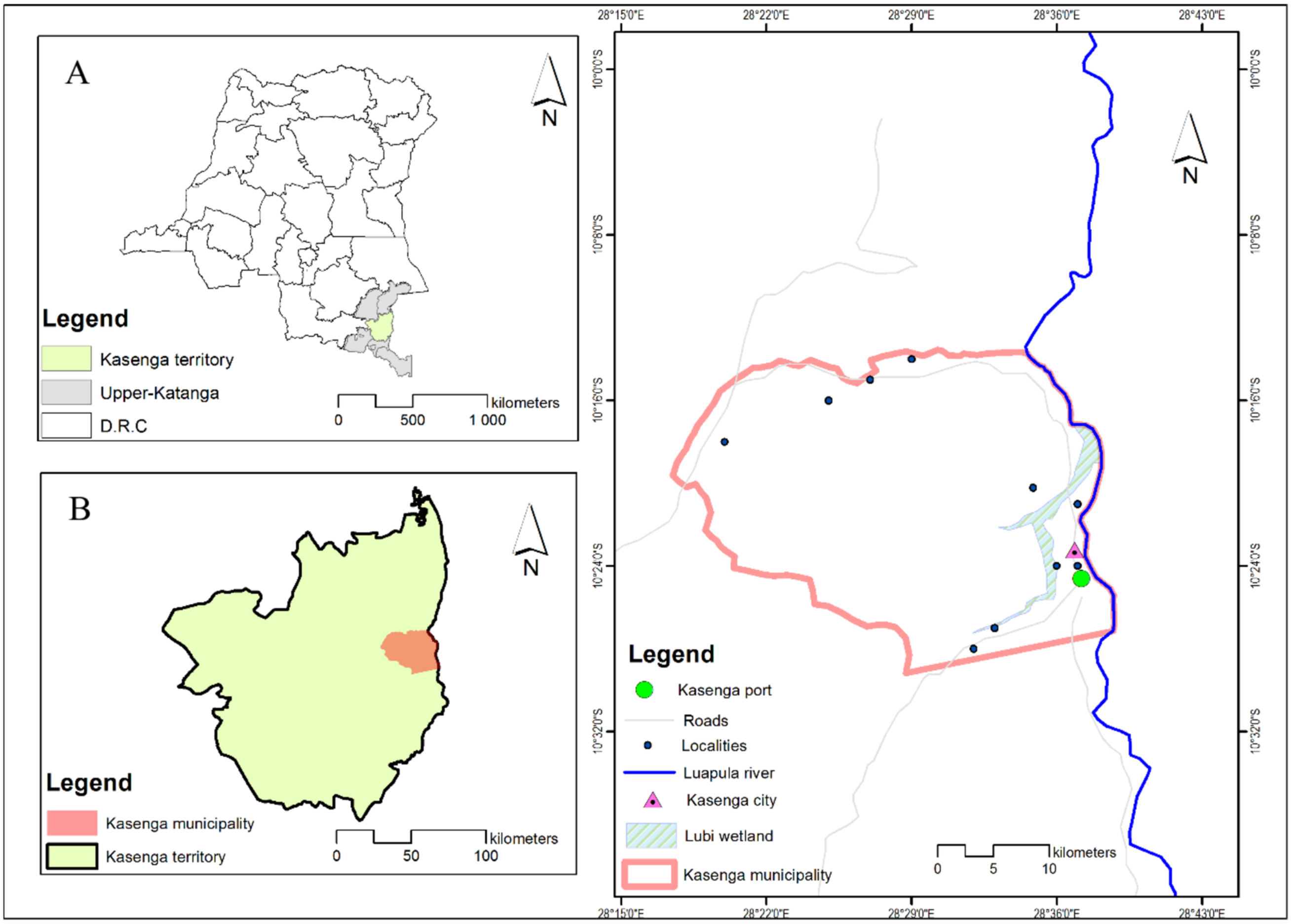


Fig. 1 Location of the rural and border municipality of Kasenga in the southeast of the Democratic Republic of the Congo (**A**), in the territory of Kasenga (**B**), Upper Katanga province. The municipality is located on the border between the Democratic Republic of the Congo and Zambia. The two countries are separated by the Luapula River, on which a border post (port), controlling the movement of people and their goods, is located

season being extended at the expense of the rainy season (Kalombo 2016). In the first half of the last century, the municipality was dominated by *miombo* woodland growing on ferralsols and cambisols (Engelen et al. 2006). This forest is currently fragmented due to extensive anthropogenic activities (Cabala et al. 2017). The precious trees of the *miombo* woodland, mainly the *Pterocarpus tinctorius*, are coveted by economic operators who export them to Asia, where the market value is very high (Mpanda et al. 2022). The municipality, surrounded by savanna, is crossed from north to south by a wetland area in which rice cultivation is developed: the Lubi. Agriculture, charcoal production, residential livestock farming, NTFP collection and small-scale trade are the main activities of the population, whose size has been estimated at around 75,000 people in 2021 (Rapport semestriel de la Commune de Kasenga 2022). Agriculture is the main activity of the inhabitants of Kasenga territory, practiced by farmers with hoes. The main agricultural products are maize, cassava, rice, groundnuts, beans, and sweet potatoes. The periphery of the municipality also produces sugarcane in Makungu in the Kisamamba group (CAID 2017).

Data

To understand the spatio-temporal changes in the rural and border municipality of Kasenga and the resulting landscape structure, six Landsat images (collection 2, level 1) with a spatial resolution of 30 m from the Thematic Mapper (02/06/1989; 26/05/1998; 10/05/2004; 24/05/2009) and OLI (07/06/2014 and 13/06/2022) sensors were used. These images, which were downloaded from the United States Geographical Survey website (https://earthexplorer.usgs.gov), were chosen based on their availability and low cloud cover. To better discriminate the different landscape features, all dates of six images correspond to the dry season in the region. In addition, these dates cover the period before the liberalization of the mining sector and the promulgation of the forestry code (1989 and 1998) and the period after (2004–2022). The period after 2014 also corresponds to when the City of Kasenga was elevated as a rural municipality.

Classification

The Landsat images used in this study are not annual composites, but single images that have received essential pre-processing, including georeferencing. Indeed, the preprocessing consisted first in georeferencing the 1989 Landsat image from the 2022 Landsat image taken as reference for the orthorectification. This operation was carried out using the geographic coordinates of the fixed points, with a geometric accuracy of the setting of 1 pixel, the minimum required for change analysis (Mas 2000). In addition, atmospheric corrections, using the fast line-of-sight atmospheric analysis of spectral hypercubes method based on radiative transfer models (Kruse 2004), were performed to improve sharpness and facilitate visual interpretation. False composite colors combining the green, red and near-infrared bands were created (Byomkesh et al. 2012). The infrared and red bands distinguish vegetation from other land use units (Barima et al. 2009). Next, a series of unsupervised classifications were carried out to provide a rough indication of the main land cover types in the study area and to help identify the training plots based on 296 points collected randomly with a GPS 64st Garmin (accuracy of about 3 m) during the fieldwork from May 21, 2022 to June 30, 2022, with reference to the oldest image (1989). Indeed, a set of 468 points representative of the selected land cover types was used for the supervised classification, with 120 for forest, 105 for agriculture, 70 for savanna, 67 for grassland and wetland, 46 for built-up and bare land and 60 for water. However, the classification data include different polygons of land cover types, which have been located by geographic coordinate points. These training plots were used to train the classification of all years, considering only the stable areas between the old images and recent image for 2022 taken as reference. For this reason, discussions with resource persons in the villages around Kasenga (e.g., traditional chiefs) were decisive to retain only the stable/unchanged polygons of the land cover types over the period of our study. Consequently, the same training zones defined and collected in 2022 were superimposed on all the remaining Landsat images (between 1989–2014).

However, supervised classifications based on the maximum likelihood algorithm were performed. This algorithm uses the statistics of the training areas to calculate the maximum probability that the pixels belong to a predefined land cover (Caloz and Collet 2001). Indeed, by assigning each pixel to a specific class with a probability estimate, the maximum likelihood algorithm provides easy-to-interpret results, especially when the occupancy types are well defined and have distinct spectral signatures (Hassan et al. 2016; Jiménez et al. 2018). Also, it can be applied efficiently to large sets of images considering its adaptation to multispectral imaging (Payne et al. 2018). According to the objective of the study, the following land cover classes were selected: built-up and bare land (bare land, soil background, residential land minimally vegetated with impervious surface), water (water bodies), grassland and wetlands (floodplain grassland and grassy vegetation), agriculture (parcels cultivated or put in rest to be cleared after a few years in a crop rotation system), savanna (wooded and shrubby savanna) and forest (mosaic of multiple forests types: dry and riparian evergreen forest, but with *miombo* woodland remaining dominant). For the validation of classifications obtained, in accordance with good practice recommendations, unbiazed area estimators and estimation of uncertainty were determined from a sample of reference observations of land cover and land change (Olofsson et al. 2014). This implies the use of a statistical approach which accounts for rare classes and provides "misclassification corrected" estimates of classes area (Olofsson et al. 2013). The stratified random sampling technique was used to generate error matrix using reference points distributed within each thematic class (Churches et al. 2014). Eleven strata were selected, of which 6 were for the stable classes ("built and bare soil", "water", "savanna", "grassland and wetlands", "forest", "agriculture") and 5 for the most relevant classes of change, except for the "water" class due to its relative stability over time. The number of points allocated to each stratum depended on its proportion in the landscape. Thus, 400–500 points were allocated to strata occupying a proportion between 21 and 30%, 300–400 points to those occupying between 11 and 20%, 200–300 points to strata occupying between 1 and 10%, and 100–200 points for strata occupying less than 1% of the landscape. A total of 2173 points were sampled for the period 1989–1998, 2201 points for 1998–2004, 2200 points for 2004–2009, 2199 points for 2009–2014 and 2199 points for 2014–2022. Estimates of area and area change were adjusted to account for biases in the change map, resulting in more accurate estimates. The precision of the estimates of area and changes in area was then quantified by calculating confidence intervals (Olofsson et al. 2014). The Eqs. (1)–(3) of Olofsson et al. (2014) were used to calculate the precision measurements, which represent, respectively, the overall precision, the user precision and the producer precision. An "error-adjusted" area estimate of each class and the standard error of the error-adjusted area estimate (calculated using a 95% confidence interval which is obtained by multiplying the standard error by 1.96) using Eqs. (10) and (11) of Olofsson et al. (2014) (Table 1). The image processing operations were carried out using ENVI 5.3 software, while ArcGIS 10.7 software was used for vectorization and map dressing.

Quantifying the spatio-temporal pattern change within the rural and boarder municipality of Kasenga

The human impact on landscape morphology was quantified through landscape metrics, namely the patch number, the class area and the largest patch index (LPI) defined as the ratio of the area of the largest patch to the class area (McGarigal and Cushman 2002). Patch number and class area provided information on the land cover fragmentation between two periods. Indeed, an increase in patch number of a land cover class while the area decreases may be due to its fragmentation (Bogaert and Mahamane 2005). In addition, a disturbance index (U) (O'Neill et al. 1988), defined as the ratio of the cumulative area of anthropogenic land cover (agriculture, built-up and bare land, savanna, grassland and wetland) in the landscape and the cumulative area of natural classes (forest), was calculated. It should be noted that the term "anthropogenic land cover" used in this study designates any entity of the landscape where direct human alteration is remarkable and where ecological patterns and processes are significantly disturbed. This index quantified the level of anthropization of the landscape, a generic term describing the influence of human activities on the environment (Useni 2019). Furthermore, spatio-temporal changes in the landscape pattern were quantified using transition matrices from which a stability index, defined as the ratio between stable areas and the sum of areas lost and gained by a land cover, was calculated (Bogaert et al. 2014). The ecological processes underlying the observed landscape dynamics were qualified using the decision tree of Bogaert et al. (2004) (Fig. 2). To determine the spatial transformation process, the model uses comparisons between the number of patches, area and perimeter of patch type before and after the landscape transformation (Bogaert et al. 2004; Barima et al. 2009; Diallo et al. 2011). Ten spatial transformation processes were defined, namely aggregation, attrition, creation, deformation, dissection, enlargement, fragmentation, perforation, displacement and shrinkage (Bogaert et al. 2004). In the case of anthropogenic landscape dynamics, natural patch types will be characterized by attrition, deformation, dissection, fragmentation, perforation and/or shrinkage. Patch types reflecting anthropogenic activities display aggregation, creation, deformation, enlargement and/or displacement (Bogaert et al. 2011). The value of $t = 0.75$ was used to dissociate the process of fragmentation from dissection, with values above 0.75 suggesting dissection, while those below or equal to 0.75 indicated the prevalence of fragmentation (De Haulleville et al. 2018).

Results

Land cover mapping and accuracy

The results of accuracy assessment and area estimate for land cover and land cover change maps from 1989 to 2022 are presented in the confusion matrix analysis (Table 1). Based on overall accuracy, theses matrices revealed overall accuracy values ranging from 92 to 93%. Furthermore, the matrices show also user's and producer's accuracies for stable and changing land cover types.

Landscape composition dynamics of the rural and border municipality of Kasenga

- Landscape composition dynamics

Table 1 Accuracy assessment and area estimate for land cover and land cover change maps from 1989 to 2022

1989–1998	BBS	Water	Savanna	GW	Forest	Agriculture	BBS loss	Savanna gain	GW gain	Forest loss	Agriculture loss
Accuracy measure											
Prod. acc. (%)	100	100	90	100	100	97	95	92	80	99	61
User acc. (%)	100	100	100	100	99	99	100	73	95	62	66
Overall acc. (%)	92										
Stratified estimators of area ± CI [% of total map area]											
Area (%)	0.14	0.89	8.39	9.71	26.26	10.60	6.84	6.74	20.04	4.58	5.82
95% CI	0	0	0.5	0	0.19	0.22	0.27	0.75	0.78	0.55	0.75
1998–2004	BBS	Water	Savanna	GW	Forest	Agriculture	BBS gain	Savanna loss	GW gain	Forest loss	Agriculture loss
Accuracy measure											
Prod. acc. (%)	100	100	99	100	100	98	81	87	72	77	84
User acc. (%)	100	100	98	99	97	100	100	99	54	54	100
Overall acc. (%)	93										
Stratified estimators of area ± CI [% of total map area]											
Area (%)	0.94	0.74	8.64	16.96	18.92	14.98	0.30	15.02	6.77	2.69	14.05
95% CI	0	0	0.2	0	0.39	0.21	0.11	0.53	0.68	0.46	0.51
2004–2009	BBS	Water	Savanna	GW	Forest	Agriculture	BBS gain	Savanna loss	GW loss	Forest loss	Agriculture gain
Accuracy measure											
Prod. acc. (%)	100	100	100	99	99	100	100	99	74	90	88
User acc. (%)	96	100	96	100	100	98	88	89	100	100	83
Overall acc. (%)	92										
Stratified estimators of area ± CI [% of total map area]											
Area (%)	0.31	0.73	4.74	23.99	15.68	7.64	6.30	11.72	6.81	10.88	11.21
95% CI	0	0	0.1	0	0.14	0.17	0.33	0.52	0.34	0.43	0.75
2009–2014	BBS	Water	Savanna	GW	Forest	Agriculture	BBS gain	Savanna gain	GW loss	Forest loss	Agriculture gain
Accuracy measure											
Prod. acc. (%)	100	100	100	99	100	100	100	71	89	74	93
User acc. (%)	100	100	94	100	100	81	92	93	100	90	100
Overall acc. (%)	93										
Stratified estimators of area ± CI [% of total map area]											
Area (%)	0.51	1.27	13.57	16.02	15.86	17.68	1.95	5.95	5.26	13.81	8.11
95% CI	0	0	0.4	0	0.00	0.82	0.10	0.63	0.31	0.93	0.34
2014–2022	BBS	Water	Savanna	GW	Forest	Agriculture	BBS gain	Savanna loss	GW loss	Forest loss	Agriculture gain
Accuracy measure											
Prod. acc. (%)	100	97	94	99	98	100	100	79	79	88	70
User acc. (%)	99	100	85	100	100	94	98	82	78	98	78
Overall acc. (%)	92										
Stratified estimators of area ± CI [% of total map area]											
Area (%)	0.55	1.01	5.75	13.68	9.83	28.83	2.35	12.54	8.15	10.81	6.50
95% CI	0	0	0.4	0	0.21	0.68	0.06	0.95	0.94	0.44	0.65

GW grassland and wetland, *BBS* built-up and bare soil

In the rural and border municipality of Kasenga, the landscape matrix once dominated by forests has been replaced by an agricultural matrix, occupying more than half of the landscape. Forest, having covered almost half the landscape in 1989 (48.22%), has been divided by almost 3 in 33 years (15.36%). On the other hand, agriculture land has increased significantly, rising from 23.75% in 1989 to 52.16% (2022) at the expense of forest cover. Indeed, forest cover has also declined to the benefit of grassland and savanna (but with a very low percentage), rising from 18.34 to 19.49% and from 8.45 to 11.16%, respectively, between 1989 and 2022. As for built-up and bare land, although only slightly represented in

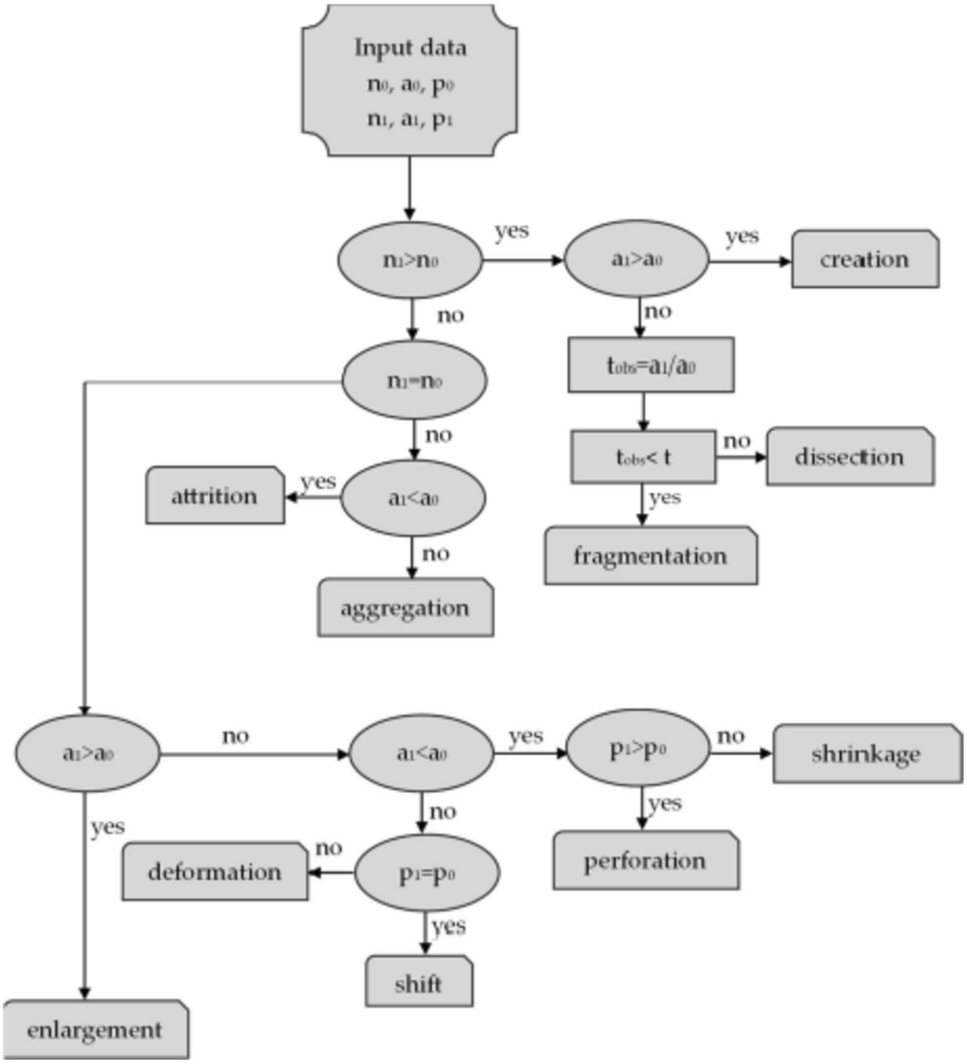


Fig. 2 Decision tree to identify transformation processes that alter the spatial pattern of landscapes. The parameters *a*0, *p*0, and *n*0 refer to the habitat area, perimeter and number of patches before transformation, while *a*1, *p*1 and *n*1 are the reciprocal values after pattern change (Bogaert et al. 2004)

the landscape, its proportion has almost doubled, rising from 0.34 to 0.82% (Table 2).

- Land cover transfer within the rural and border municipality of Kasenga from 1989 to 2022

The regression of the forest is explained by the transfer of its area to savanna, at varying rates depending on the period (5.95% between 1989–1998; 5.53% between 2014–2022). Conversely, a relative reconstitution of forest cover has been observed, mainly at the expense of the savanna. Moreover, the spatial dynamics of the savanna is characterized by an evolution toward agriculture. The regression of savanna cover in the landscape is also explained by their conversion to grassland and wetland (Table 2). In addition, Table 2 also indicates a change in landscape composition in the range of 4.37 to 18.89%, about the shift from grassland and wetland to agriculture. Furthermore, 1.87% of the landscape occupied by grassland and wetland was converted to savanna between 1989 and 1998, compared to 5. 86% between 2014and 2022.

Landscape dynamics are also characterized by the conversion of 4.96% occupied by agriculture to savanna between 1989 and 1998. This transfer rate from agriculture to savanna has fallen by half, moving to 2.22% between 2014 and 2022. Furthermore, while 7.11% of the landscape occupied by agriculture evolved toward grassland and wetland between 1989 and 1998, this rate had fallen significantly to 1.63% between 2014 and 2022. Finally, the transition matrices reveal that the expansion of the built-up and bare land occurs at the expense of the agriculture located on the city's outskirts. Indeed, 0.15% and 0. 34% of the landscape occupied by agriculture were invaded by built-up and bare land, respectively, between 1989 and 1998 and 2014 and 2022 (Table 2).

The analysis of the stability of the land cover shows that forest was the most stable land cover between 1989 and

Table 2 Land cover area transition matrices in the rural and border municipality of Kasenga (%) between 1989 and 1998, 1998 and 2004, 2004 and 2009, 2009 and 2014, and 2014 and 2022. Stability index is defined as the ratio between stable areas and the sum of areas lost and gained by a land cover (Bogaert et al. 2014)

1989–1998

	BBS	Savanna	GW	Forest	Agriculture	Total 1989
BBS	**0.10**	0.00	0.16	0.00	0.09	0.34
Savanna	0.00	**2.99**	2.49	1.82	1.15	8.45
GW	0.08	1.87	**9.62**	1.61	4.37	18.34
Forest	0.00	5.95	8.36	**32.14**	1.75	48.22
Agriculture	0.15	4.96	7.11	0.71	**10.42**	23.75
Total 1998	0.33	15.78	27.79	36.28	17.78	
Stability index	*0.20*	*0.16*	*0.36*	*1.59*	*0.50*	

1998–2004

	BBS	Savanna	GW	Forest	Agriculture	Total 1998
BBS	**0.19**	0.00	0.01	0.00	0.11	0.32
Savanna	0.00	**4.43**	7.25	3.06	0.96	15.70
GW	0.08	2.27	**19.37**	1.25	4.81	27.79
Forest	0.01	2.14	10.38	**23.36**	0.42	36.31
Agriculture	0.05	2.78	9.79	0.33	**4.88**	17.84
Total 2004	0.34	11.62	47.52	27.99	11.80	
Stability index	*0.72*	*0.24*	*0.53*	*1.33*	*0.25*	

2004–2009

	BBS	Savanna	GW	Forest	Agriculture	Total 2004
BBS	**0.26**	0.00	0.00	0.00	0.08	0.35
Savanna	0.01	**1.07**	5.81	2.79	1.95	11.63
GW	0.05	1.76	**30.00**	4.44	10.93	47.48
Forest	0.00	4.71	3.59	**19.19**	0.52	28.00
Agriculture	0.21	0.04	4.66	0.23	**6.40**	11.80
Total 2009	0.53	7.58	44.07	26.65	19.88	
Stability index	*0.75*	*0.06*	*0.95*	*1.18*	*0.34*	

2009–2014

	BBS	Savanna	GW	Forest	Agriculture	Total 2009
BBS	**0.36**	0.00	0.00	0.00	0.17	0.53
Savanna	0.00	**1.11**	2.54	3.46	0.43	7.55
GW	0.02	5.86	**15.41**	3.75	18.89	44.04
Forest	0.00	3.35	5.47	**15.65**	2.24	26.71
Agriculture	0.24	0.72	1.04	1.38	**16.50**	19.89
Total 2014	0.62	11.05	24.67	24.26	38.25	
Stability index	*0.83*	*0.07*	*0.41*	*0.80*	*0.66*	

2014–2022

	BBS	Savanna	GW	Forest	Agriculture	Total 2014
BBS	**0.46**	0.00	0.00	0.00	0.17	0.64
Savanna	0.00	**3.10**	1.02	1.94	5.00	11.07
GW	0.01	0.31	**13.60**	2.58	8.07	24.62
Forest	0.00	5.53	3.03	**9.90**	5.79	24.26
Agriculture	0.34	2.22	1.63	0.93	**33.12**	38.26
Total 2022	0.82	11.16	19.49	15.36	52.16	
Stability index	*0.89*	*0.19*	*0.80*	*0.50*	*1.37*	

Values in bold refer to the proportion of land cover that remained unchanged over the period. In addition, the total of the year in column corresponds to the sum of the values of classes in rows. However, the total of the year in row relates to the sum of the values of classes in columns. For a total area of 783 km^2, 1% corresponds to 7.83 km^2. The totals do not add up to 100% as the water land cover type was excluded from the analyses due to its relative stability in the landscape

Table 2 (continued)

GW grassland and wetland, *BBS* built-up and bare soil

2009. A first transition was noted and concerns the appearance of the built-up and bare land as the most stable land cover between 2009 and 2014, to the detriment of savanna. Between 2014 and 2022, a new transition, materialized by the appearance of agriculture as the most stable land cover, to the detriment of savanna, was recorded (Table 2).

Configurational dynamics of land cover in the rural and border municipality of Kasenga

The results in Fig. 3 indicate that between 1989 and 1998, the forest recorded the fragmentation of patches ($t=0.75$) because the decrease in the class area was accompanied by an increase in patch number. During the same period, it was noted, on the one hand, the aggregation of the savanna patches materialized by an increase in the class area parallel to the decrease in the patch number. On the other hand, the process of spatial transformation characteristic of the agriculture as well as of the built-up and bare land was the attrition of patches, especially since a decrease in the patch number and class area was noted. For grassland and wetland, the creation process was observed, as the increase class area was accompanied by an increase in the number of patches.

In addition, the period of 1998–2004 was characterized by the dissection of forest patches ($t=0.77$) against the fragmentation for agriculture ($t=0.66$) and savanna ($t=0.74$), because the decrease in the class area was accompanied by an increase in patch number. Grassland and wetland recorded an increase in class area in parallel with the decrease in patch number, suggesting aggregation as a spatial transformation process. Finally, the creation was the process of spatial transformation characteristic of the of the built-up and bare land, especially since an increase in the patch number and class area was noted.

On the other hand, between 2004 and 2009, dissection of patches was the process of spatial transformation for the forest and grassland and wetland, as the decrease in class area is accompanied by an increase in patch number ($t=0.95$ for the forest and 0.93 for the grassland and wetland). In addition, the attrition of patches of savanna was the spatial transformation process, since a decrease in the patch number and class area was identified. Finally, agriculture, as well as built-up and bare land, recorded creation as a spatial transformation process, especially since the increase in class area was due to the patch number.

Between 2009 and 2014, the attrition of patches was identified as a spatial transformation process of the forest and grassland and wetland because the decrease in the class area was associated with the reduction in the patch number. In addition, the reduction in the patch number of savanna and agriculture, in parallel with the increase in class area, attests to the aggregation of patches as a spatial transformation process. As for the built-up and bare soil, a simultaneous increase in the class area and patch number was noted, suggesting the creation of patches as a spatial transformation process.

For the period between 2014 and 2022, the attrition of patches persisted as a spatial transformation process of the forest, as well as savanna, was characterized by the decrease in the class area associated with the reduction in the patch number. In addition, grassland and wetland recorded dissection of patches as a process of spatial transformation, illustrated by the decrease of the class area in parallel with the increase of the patch number ($t=0.79$). Finally, agriculture and built-up and bare land recorded an increase in the class area in parallel with the decrease in the patch number, thus suggesting aggregation as a spatial transformation process.

Quantification of landscape anthropization

There was a regression in dominance values for forest over all time periods studied, from 92.59% in 1989 to 21.42% in 2022 (Fig. 4). This suggests that the area of large patches of forest that dominate the landscape has been reduced by a factor of 4 in 33 years (from 1989 to 2022), indicating the anthropogenic impact on the fragmentation of forest ecosystems. Overall, our results confirm a trend toward an increase in the level of anthropization of natural landscapes, especially since the level of landscape disturbance has quintupled from 1.1 to 5.5 in 33 years (Fig. 4).

Land cover mapping

The land cover mapping in 1989, 1998, 2004, 2009, 2014 and 2022 is presented in Fig. 5. The visual analysis shows a regression of forest cover in parallel with an increase in agriculture, as well as in built-up and bare land. The water land cover was excluded from the rest of the analyses because of its relative stability in the landscape.

Discussion

Methodological approach

The use of Landsat images allowed us to map and quantify the landscape dynamics of Kasenga municipality over 33 years (1989–2022). Indeed, among the tools for

Fig. 3 Identification of the land covers spatial transformation processes between 1989 and 1998, 1998 and 2004, 2004 and 2009, 2009 and 2014, and 2014 and 2022 by the decision tree algorithm of Bogaert et al. (2004) based on the evolution of the class area and patch number of forest (**a**), savanna (**b**), grassland and wetland (**c**), fields and fallows (**d**) and built-up and bare land (**e**) in the rural and border municipality of Kasenga for the years 1989, 1998, 2004, 2009, 2014 and 2022. The relative values (of class area and patch number) were obtained from the ratio of the index value for each land cover type to the maximum value recorded. Overall, the forest is characterized by a simultaneous decrease in class area and patch number

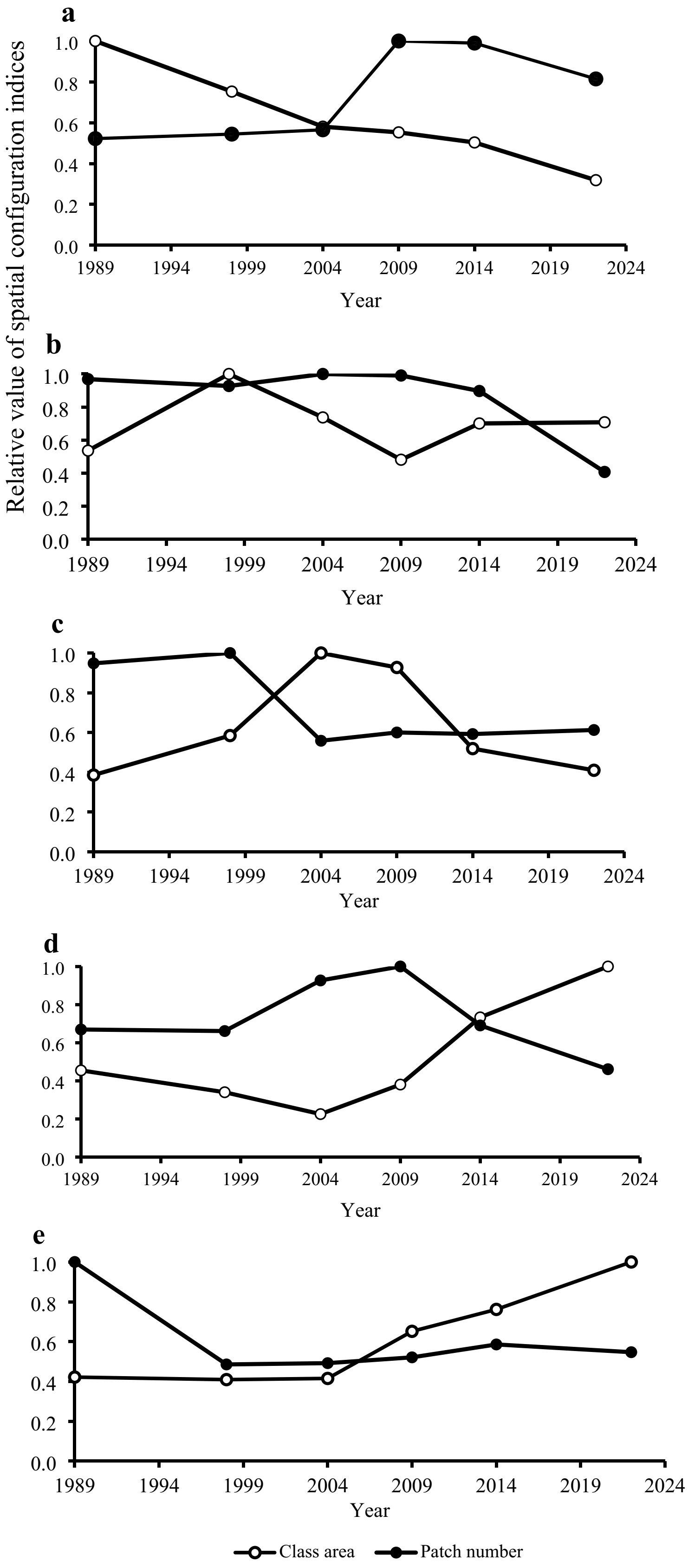
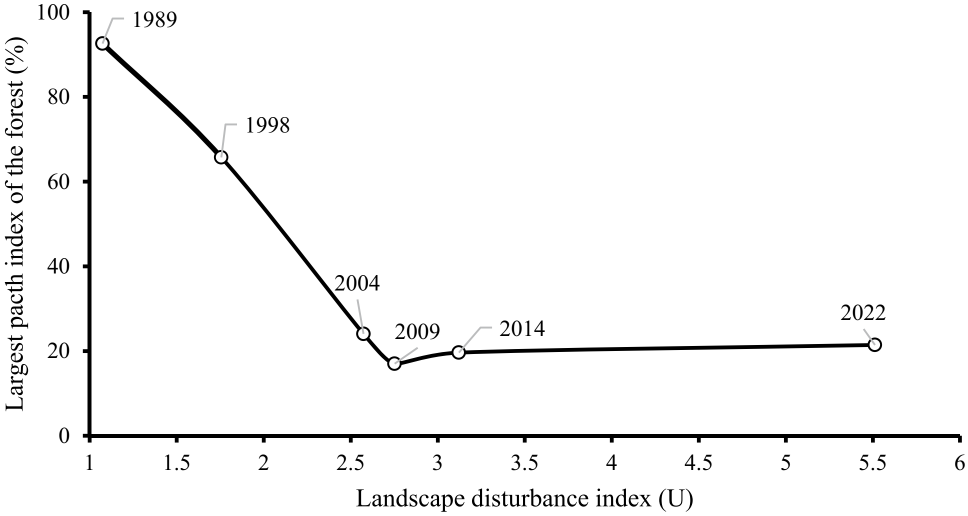


Fig. 4 Evolution of the dominance of forest patches (%) as a function of the landscape disturbance index in the rural and border municipality of Kasenga, southeast of the City of Lubumbashi, based on Landsat image processing data from 1989, 1998, 2004, 2009, 2014 and 2022



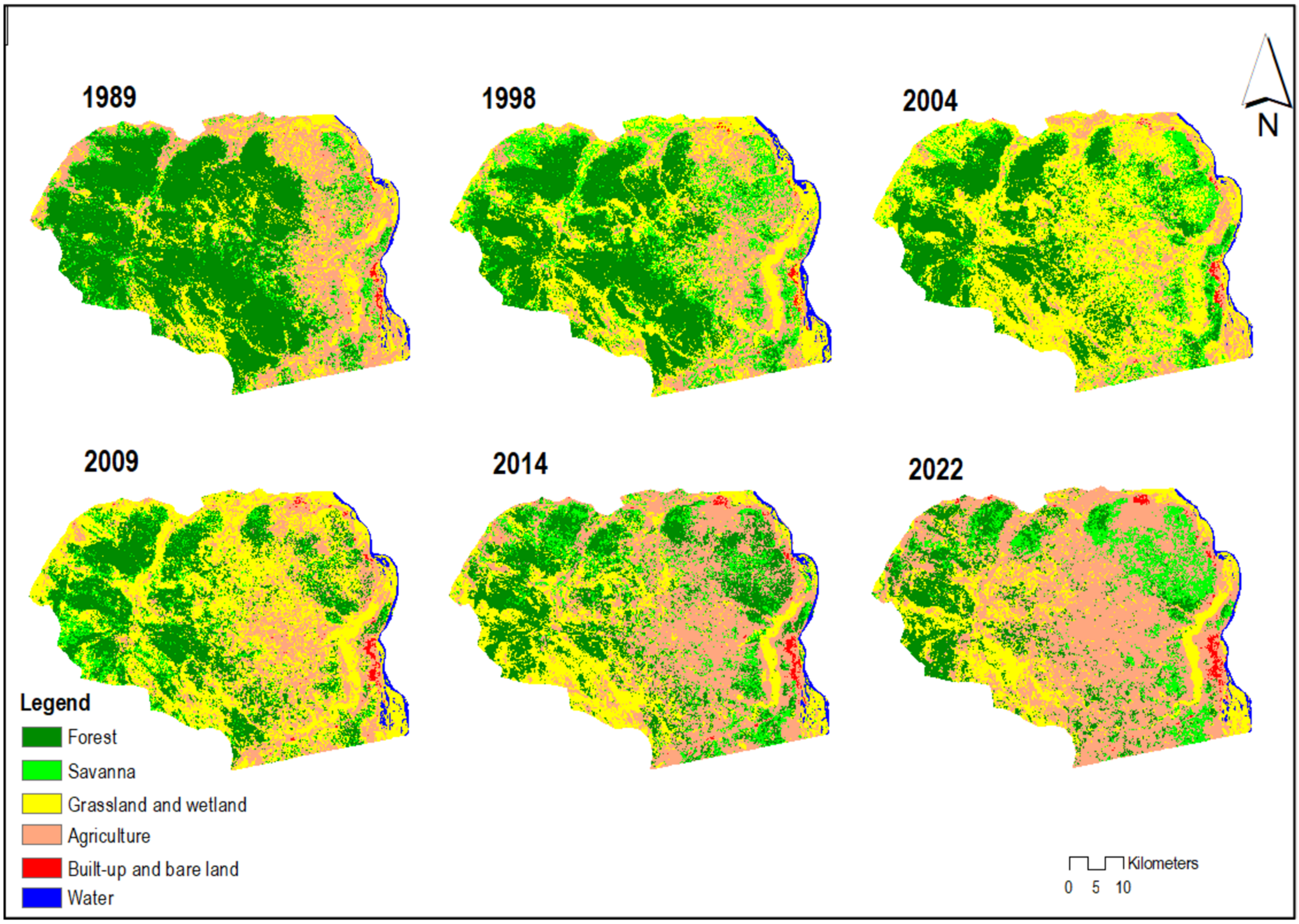


Fig. 5 Land cover maps of the rural and border municipality of Kasenga in 1989, 1998, 2004, 2009, 2014 and 2022 based on supervised classification of Landsat images using the maximum likelihood algorithm. A regression of the forest is visually remarkable between 1989 and 2022

monitoring the dynamics of spatio-temporal phenomena, remote sensing is the most suitable (Bamba et al. 2008; Mama et al. 2013). Furthermore, values from confusion matrices for supervised classification through overall accuracy, user's and producer's accuracies (Lasko et al. 2005; Liu et al. 2007; Rwanga and Ndambuki 2017) show good agreement between classifications and the reference data collected during the field missions. Therefore, many time steps between our Landsat images did not prevent the study to highlights the main trends of landscape evolution in the study area, and our results are very similar to those of previous studies in the region, which used the same approach (Useni et al. 2018a, b; Munyemba et al. 2008) or local population perception (Amisi et al. 2018; N'Tambwe Nghonda et al. 2023). Furthermore, the rapid transitions of the observed land cover types are related to the intense anthropogenic activities in the study area, most often shifting cultivation, charcoal production and human-induced vegetation burning. These activities are recurrent and make the different land cover types very unstable. Based on the overall accuracies, values obtained show the success of the supervised classification, which would be mainly attributable to the knowledge of the study area and quality of images after several pre-processing, which made it possible to define the reliable training plots for all classes.

Furthermore, the calculation of landscape metrics, particularly those related to the area and number of patches, is reliable for appreciating the spatial pattern changes of landscape (Bogaert et al. 2014) within the municipality of Kasenga, resulting from various anthropogenic pressures (Mpanda et al. 2022). Indeed, the anthropization of a natural environment is generally characterized by fragmentation and a progressive dynamic of anthropogenic land cover at the expense of natural land cover types (Bogaert et al. 2011), which is confirmed by our results. The reduced number of landscape metrics calculated diminished redundancy, as several landscape metrics are correlated (Mama et al. 2013). Although the time interval between the images used may seem relatively short, the transition matrix was based on the change/stability of intensity over time of the same pixel (Mama et al. 2013). Moreover, the same training areas were used, regardless of the date of the Landsat image, supported by the with resource persons (Mpanda et al. 2022).

Agricultural development, savanna expansion, (peri)urbanization and deforestation in the rural and border municipality of Kasenga

In the rural and border municipality of Kasenga, except potential natural drivers of landscape dynamics, the dependence of local communities on forest resources has led to remarkable changes in their properties between 1989 and 2022. Indeed, repeated human intrusion into the forest around Kasenga municipality has led to a continuous decline in their cover. In the absence of high spatial resolution data to characterize the land cover change in the municipality of Kasenga, the use of Landsat data made it possible to understand and interpret the landscape dynamics over a period of 33 years. In addition, over time, forest ecosystems are converted, in the absence of a sustainable land use policy, into anthropogenic land cover, and the residual patches are presented in small, very isolated fragments (Sadda et al. 2016). These landscape dynamics are mainly due to the intensification of collection activities of (non-)wood forest products to meet food, medicine and energy needs (Useni et al. 2017; Kabulu et al. 2018; Useni et al. 2018a, b; Khoji et al. 2022; Mpanda et al. 2022; Mutombo et al. 2022). Construction materials are also collected from forests where population growth and poverty amplify dependence on forest ecosystems (Ndenge and Perfet-Mrema 2022) and anthropogenic pressure on them. In addition, studies have shown that high deforestation rates in the *miombo* ecoregion are primarily related to slash-and-burn agriculture (Jew et al. 2017; Rannestad and Gessesse 2020) in a context of fragile soil fertility due to high rainfall and temperature (De Hipt et al. 2018), thus justifying the expansion of agriculture in our study. It should be noted that research conducted by Mpanda et al. (2021) in the same area has shown that the local population lives mainly from agriculture, an agriculture that does not always comply with ecological standards of sustainability. Our results corroborate the findings of Handavu et al. (2019) that household size significantly influences agricultural expansion in rural Zambia and, consequently, land cover changes. In addition, another cause of deforestation within the rural and border municipality of Kasenga is the extraction of wood fuel, generally leading to a savanna expansion process as observed around Lubumbashi City (Useni et al. 2017). It should be noted that when forest resources are available, large-diameter trees are cut for charcoal production (Mama et al. 2014), since charcoal production is the most important strategy used to cope with food shortages (Kalaba et al. 2013). In addition, changes in logging practices are being highlighted through the shift from selective to non-selective logging due to the unavailability of large timber used for charcoal production within the Lufira Biosphere Reserve near Lubumbashi City (Useni et al. 2020b). As a result, frequent tree cutting results in a landscape dominated by scattered, small-diameter trees, giving the initial forest patches the appearance of savannas (Useni et al. 2020a, b). Malaisse (2010) points out that savanna is anthropogenic in origin in the region, which corroborates our results showing an expansion of savanna around Kasenga municipality with increasing levels of landscape disturbance. Furthermore, in Central Africa, bushfire, recognized as a widespread technique for clearing dense vegetation cover and preparing land for cultivation, potentially leads to savanna expansion, as the case around Kasenga municipality (Useni et al. 2023), through changes in species composition, biomass and nutrient levels (Bundschuh et al. 2010; Mganga 2022). Indeed, to prepare the fields and hunting activities in the village around Kasenga City, vegetation is burned almost twice in the dry season (Malaisse 2010).

In addition, deforestation rates reported in this study far exceed those estimated annually at the national level (0.2%; Kyale et al. 2019) and in the Katanga clear forest (0.6–1.8%) (Defourny et al. 2011; Kabulu et al. 2018). This is a result of the proximity of Kasenga municipality to Lubumbashi City, where demand for agricultural products, energy, and pharmacopeia is constantly increasing (Useni et al. 2017). Ideas agree that uncontrolled exploitation of forest resources and resulting deforestation remain largely associated with the expansion of subsistence activities (agriculture and energy) and are indeed more evident around major cities (Bamba et al. 2010; Mwitwa et al. 2012). However, *miombo* plant species used for their fruits or their wood are not maintained in agro-ecosystems since there is therefore a separation between agriculture and forest. As a result, there is a lack of management of tree in agriculture system in the rural area adjacent to Lubumbashi City (Hick et al. 2018). Yet, the depletion of forest patches could have many negative socio-ecological consequences, among them the gradual disappearance of many non-timber resources, gathering products such as honey, mushrooms, but also caterpillars due to selective cutting of host plants, etc. (Bogaert et al. 2011; Maseko et al. 2017). This deforestation also reduces the number of rainy days (Leite-Filho et al. 2021). Also, the consequences related to deforestation are experienced with severity in rural areas where the population survives mainly on forest resources but where paradoxically management measures are still precarious (Mpanda et al. 2022). Consequently, our results suggest a trend toward the fragmentation and isolation of forest patches through the spatial transformation processes of fragmentation and dissection, which may limit the exchange of propagules between species and negatively impact their viability (Cristofoli and Mahy 2010). Indeed, in the mountains of the Eastern Arc of Tanzania, it has been noted that the abundance of dominant species (such as *Maytenus undata* Thunb, *Zenkerella capparidacea* (Taub.) J. Leon, and *Oxyanthus specious* DC.) decreases with a reduction in patch area (Ojoyi et al. 2015).

In addition, savanna-covered formations remained prevalent, but were nevertheless characterized over time by regression–progression sequences. This recovery of the savanna would be largely attributable to their strong capacity for reconstitution. This assertion is supported by Syampungani et al. (2016), who report rapid development of *miombo* recruit stands upon cessation of anthropogenic disturbance (cultivation and charcoal production). Their regression is generally explained by the fact that after the disappearance of large-diameter species, the medium-diameter species, present in savanna are cut and charred (Mama et al. 2014). Furthermore, it is noted that wooded, tree and shrub savannahs are rarely natural in the region and generally result from forest degradation following various anthropogenic activities and therefore their importance increases with the increase of anthropogenic activities. Savannahs with significant woodland, tree and shrub cover when abandoned show an increase in the density of woodland pockets. The continuous reduction in the abundance of the tree stratum allows light penetration, which is favorable to the development of herbaceous species (Rakotondrasoa et al. 2013) and most of which result in the formation of grassy savanna, thus justifying the trend toward the progression of grasslands in the landscapes of Kasenga municipality. In addition, the built-up and bare land records the merging of patches, resulting on the one hand from the process of building expansion within residential plots to absorb new housing demands (Useni et al. 2018a, b) from students and civil servants posted to Kasenga. On the other hand, the merging of built and bare soil can also be explained by the parceling of plots by indigenous populations. In the context of poverty, the indigenous populations sell part of their land to the new arrivals to finalize the construction of their own houses (Groupe Huit 2009). Finally, in the Kasenga housing estate, local land registrars relegate excess housing demands to the outskirts of the municipality on agricultural land. Indeed, in these agricultural areas located to the west of the municipality, the prices of plots, which are otherwise large (at least 900 m^2), are relatively affordable and easy to develop (Useni et al. 2020a, b). Bren d'Amour et al. (2017) point out that the planned expansion of built-up will take place on some of the world's most productive cropland, particularly in Asia and Africa. As in our study, Lasisi et al. (2017) recorded a loss of agricultural land of about 331 ha/year between 1986 and 2014 due to unplanned urban expansion in the peri-urban areas of Olorunda and Osogbo in Ghana. However, the transition from built-up areas to fields, illustrated by the transition matrices, is explained by the influence of (urban) agriculture, which results in the cultivation of spaces that could previously be identified as bare soil. Nevertheless, the similarity of the spectral signatures of bare soils and harvested fields would be a second reason to explain this observed transition (Congedo and Munafo 2012).

Implications for land use planning

Unplanned urban growth and extensive agricultural development are perpetuating the rate of deforestation and causing deep concern, especially in an area of high population density where the shortening of the fallows period no longer allows the forest to recover (Cabala et al. 2017; Khoji et al. 2022). Indeed, the current pattern of agricultural development at the expense of forests contributes to their degradation and reduced abundance in the landscape. As for deforestation related to agricultural development, the production of maize, a crop that requires more soil fertility (Useni et al. 2013), is thought to be one of the leading causes. Furthermore, the ease of penetration into these different forest environments by farmers in the region may explain their vulnerability to anthropization. In this context, the public technical services should promote models based on agroforestry with strong accompaniment of Kasenga farmers, to limit the expansion of extensive agriculture identified by Mpanda et al. (2021) as the agriculture model of this region. The results of Amadu et al. (2020) show that agroforestry improves maize yields among smallholder farmers in the face of climate change, a crucial aspect of sustainable development goals. However, Etshekape et al. (2018) identified farmers' education level among the important factors that positively influence farmers' decision to adopt agroforestry.

Furthermore, our results suggest a shift from selective logging, particularly in terms of tree diameter, to non-selective logging. However, not only are forests with large-diameter individuals becoming scarcer, but also savanna that are supposed to replenish forests are being attacked by tree-cutting activities for carbonization, confirming the trend of results obtained by Useni et al. (2020b) in the context of Lubumbashi City.

Agroforestry with tree plantations of species native to the *miombo* woodland, needed for producing good quality charcoal, should be established. This would allow for the production of maize and charcoal on the same land. On the Batéké plateau in Kinshasa (the Democratic Republic of the Congo), 8000 ha of *Acacia auriculiformis* plantations provide a total charcoal production of 8000 to 12,000 tons per year, to which must be added 10,000 tons of cassava, 1200 tons of maize and 6 tons of honey (Bisiaux et al. 2009).

Finally, the current pattern of one-way expansion of the city (to the west) due to the presence of the Luapula River as a barrier dangerously compromises the persistence of the Lubi Valley, which is crucial for flooded rice production. This situation is amplified by the development of the Kasenga customs post, leading to an influx of civil servants and their families. This is accompanied by an overriding need for decent housing, justifying the expansion of housing on marshy land, which is also used for rice and horticulture. This reduces the soil's water storage capacity (Oiro et al. 2020) and compromises the future of rice cultivation. In addition, although Kasenga municipality offices may have urban planning and development technicians, they are outdated due to lack of practical tools and training like elsewhere in the ecoregion (Chitonge and Mfune 2015). As a result, they become more involved in creating subdivisions and parceling out residential plots, without coherence or overall plan, to increase their own financial availability like in Butembo in the eastern DR Congo (Kasereka and Mate 2018). Kaswamila and Songorwa (2009) findings indicate that the main causes of failure of sustainable land use planning are insufficient stakeholder participation in the planning process, lack of sound, transparent and accountable implementation strategies, lack of qualified staff and lack of a holistic approach to the planning process. It is therefore important to produce a concerted master plan for the development of the rural and border municipality of Kasenga, with zoning scrupulously applied as suggested by Angel et al. (2011). However, there are still several gaps for future research to enable further development of Kasenga border city. Combining data from multiple sources, including satellite imagery, ground-based data and socio-economic data, could provide a more holistic understanding of land cover change drivers and impacts within Kasenga municipality. Indeed, understanding how policy, population growth and economic development impact land cover changes is a line of research to be explored. However, extending the analysis of land cover change over longer time periods, including historical data and predictive modeling into the future, is essential for understanding trends and anticipating potential environmental consequences, especially in the context of climate change and unplanned urbanization. More research is needed to understand the ecological and environmental consequences of land cover changes, such as impacts on biodiversity, water resources, and carbon sequestration. Addressing these gaps will contribute to a more comprehensive understanding of land cover changes, their drivers and their impacts and can help inform better land use planning and environmental management strategies within Kasenga municipality.

Conclusion

This study highlights the relevance of remote sensing, geographic information systems and landscape ecology analysis tools to map and quantify the spatio-temporal dynamics of landscape anthropization in the rural and border municipality of Kasenga. Our results confirm that forest ecosystems undergo surface losses, notably through dissection and fragmentation that removes residual fragments. Indeed, the proportion of forest in the landscape has been reduced by almost 3 in 33 years, especially since its area, which covered 48.22% of the landscape in 1989, has dropped to 15.36% in 2022. This is the result of the development of extensive agricultural activities, but also savanization. Savanization and agricultural development occur mainly in the city's vicinity, which continues to expand its spatial reach. Indeed, our results show that the surface area of buildings has doubled in the landscape in 33 years, notably to the detriment of rice and horticultural areas. The progressive dynamics of anthropogenic land cover, the proportion of which has doubled in 33 years through the creation and merging of patches, has amplified the level of disturbance of the landscape. One of the main causes of the observed landscape dynamics is slash-and-burn agriculture and anarchic urbanization in the context of galloping population growth. It is therefore important to reconcile these results of landscape anthropization with the municipality's agricultural and urban planning policies for sustainable management of the meager forest resources that remain.

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