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Miombo woodland, an ecosystem at risk of disappearance in the Lufira Biosphere Reserve (Upper Katanga, DR Congo)? A 39-years analysis based on Landsat images

Yannick Useni Sikuzani [a,*], Héritier Khoji Muteya [a], Jan Bogaert [b]

[a] Unité Ecologie, Restauration Ecologique et Paysage, Faculté des Sciences Agronomiques, Université de Lubumbashi, 1825, Lubumbashi, DR Congo

[b] Unité Biodiversité et Paysage, Université de Liège Gembloux-Agro BioTech, 5030, Gembloux, Belgium

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ABSTRACT

Lufira Biosphere Reserve (LBR) is a protected area located in Southeastern DR Congo, created for the conservation of *Miombo* woodland, an ecosystem threatened by anthropogenic activities developed in the region. However, scientific studies regarding land cover dynamics within the LBR are non-existent to date. This study maps and quantifies the land cover dynamics within and around the LBR, based on diachronic analysis of five Landsat images (1979, 1986, 1998, 2008 and 2018) and field verification missions. Landscape metrics were utilized to understand changes in landscape pattern. The results indicate that *Miombo* woodland area have been reduced by a factor of three in the LBR, as they covered 11.2 km^2 in 2018 compared to 85.3 km^2 in 1979. The annual deforestation rate between 1979 and 2018 was 1.8%, almost eight-fold higher than the rate registered at the country level. Within the LBR, this deforestation has been offset by an increase in areas occupied by grassy savanna (+16.9 km^2), as well as fields and fallows (+53.3 km^2). Further, water and wetland area increased by 17.9 km^2 in 39 years whereas the wooded savanna, the bare soil and built-up decreased by 24.9 km^2 and 4.0 km^2 respectively. In general, analysis of landscape spatial pattern dynamics through landscape metrics, showed a process of creation and aggregation of grassy savanna, water and wetlands, as well as fields and fallows, as opposed to dissection and attrition of *Miombo* woodland, wooded savanna, bare soil and built-up. Overall, the LBR has undergone a major transformation, mainly due to demographic pressure and the development of subsistence activities in a precarious economic context. The study concludes that in the absence of any land use planning policy, LBR risks losing its status following lost of the rare *Miombo* woodland patches still existing.

1. Introduction

In the Zambezian region, *Miombo*, a dominant woodland that covers almost 2.4 million km^2, is characterized by the predominance of species belonging to *Brachystegia*, *Julbernardia* and *Isoberlinia*genera of the Caesalpionioideae sub-family (Malaisse, 2010). The (non-)wood forest products provided support the survival of more than 100 million people across

* Corresponding author.
E-mail addresses: sikuzaniu@unilu.ac.cd, yannickuseni@gmail.com (Y.U. Sikuzani).

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Angola, the Democratic Republic of Congo (D.R. Congo), Burundi, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe and the Republic of South Africa (Dewees et al., 2010; Malaisse, 2010; Mwitwa et al., 2012). In DR Congo, *Miombo* woodland occupies nearly 286,000 km^2, corresponding to almost 11% of the total Zambezian woodland area (Malaisse, 2010). However, more than 70% of the *Miombo* woodland are located in Katanga region (Southeastern DR Congo), where paradoxically, more than 350,000 ha of their areas were lost over the period 2000–2010 (Potapov et al., 2012), under the pressure of slash-and-burn agriculture, woodfuel production, mining, timber exploitation and urbanization (Cabala et al., 2017; Useni et al., 2017). Indeed, in the absence of fertilizers, the supply of mineral elements to crops is largely dependent on *Miombo* woodland, through the transfer of forest litter to the fields and the release of elements associated with slash-and-burn crops (Ryan et al., 2016). However, this fertility can only be valued in a few years and consequent forest clearing is collocated with local population centres (Chidumayo and Kwibisa, 2003). In addition, in Upper Katanga region, the supply of electrical energy to households is relatively limited (Banza et al., 2016) and they are consequently developing alternative approaches such as woodfuel for cooking food and bricks (Useni et al., 2017; Kabulu et al., 2018). Indeed, charcoal production is a major driver of forest cover loss (Potapov et al., 2012; Bangirinama et al., 2016).

To reduce the threats posed by human activities to forest ecosystems, the Congolese government has allocated 11% of the territory to protected areas, which are the cornerstone of biodiversity conservation; the ultimate objective being to reach 15% of the national territory (Pelissier et al., 2015). This policy is based, among other things, on the interest of current and future generations in conserving biodiversity because of the resulting ecosystem services (Kalaba et al., 2013; Ryan et al., 2016; Useni et al., 2017). However, the administration is struggling to implement a coherent (sustainable) protected area management policy (Pélissier et al., 2015) and, as an illustration, studies carried out in the central basin of D.R. Congo and in the Kivu region have shown that forest ecosystems located within protected areas have decreased in area (Potapov et al., 2012; Balolé et al., 2015; Kyale et al., 2019). Moreover, the quantification of this deforestation is intensely based on remote sensing data (Hansen et al., 2008; Bamba et al., 2010; Potapov et al., 2011; Cabala et al., 2018; Useni et al., 2019), the acquisition of which generally requires (very) good quality of internet connection and the commitment of significant financial costs (Semeki et al., 2016). In this context, Oszwald et al. (2011) and Potapov et al. (2012) consider that in DR Congo, the use of (free) Landsat images to assess forest landscape dynamics remains the most economical and practical solution. Additionally, this focus on land cover dynamics using remote sensing data is justified by the pattern/process paradigm which states that landscape and ecological processes are conditioned by spatial patterns, and vice versa (Bogaert et al., 2014). Therefore, landscape metrics are largely used to quantify land cover change and patterns in order to establish principles of sustainable development (Skupinski et al., 2009; Li et al., 2013; Bogaert et al., 2014).

The annual deforestation rate in DR Congo is relatively low compared to other tropical countries such as Brazil or Indonesia, due to the low level of agriculture or forestry intensification (Hansen et al., 2008). This rate may vary from 0.18 to 0.46% depending on regions, the methodological approaches used, the type of forest or the periods considered (de Wasseige et al., 2012; Potapov et al., 2012). Cabala et al. (2017) recorded an annual rate of *Miombo* woodland deforestation of around 1.1% within the Katangese copper belt. However, case studies and precise analyses of local dynamics are still lacking to shed light on the processes involved.

D.R. Congo has three Biosphere Reserves[1] (Yangambi, Luki and Lufira) covering a total area of 28,2414 ha, which were created primarily to provide an ecological research framework, but also to provide an *in situ* conservation of biodiversity. Apart from the Luki and Yangambi Biosphere Reserves that are subject to (still) timid monitoring (Declee et al., 2018; Kyalé et al., 2019), LBR, located in an area where *Miombo* is the dominant vegetation, has not benefited of land cover change-related studies. Yet, its location between two major urban centres in the Katangese copper belt (Lubumbashi with more than 2 million inhabitants and Likasi with nearly 800,000 inhabitants) makes it a particularly interesting protected area model to study in a context of tensions between biodiversity conservation and the survival of populations that pay little attention to resource sustainability (Vermeulen et al., 2011). It must be noted that its boundary is contiguous to agricultural productions sites and housing, there is not watertight barrier between this site and its surrounding. Consequently, economic activities and the influx of populations around this site are likely to disrupt ecological processes and thus limit the regeneration of woody species. The search for new and more fertile land is one of the major causes of deforestation, along with carbonization to supply the two adjacent urban centres with woody energy. Indeed, this protected area is in perpetual degradation as a result of pressure from local populations whose interests have not been taken into account in the management systems. In addition, its protection has been disrupted by the weakening of the public Authority that is supposed to regulate its management. This weakening has generated an interruption in *Miombo* woodland conservation actions and, more generally, has created areas where, locally, national laws have not been respected. Thus the absence of local management structures within this protected area has favoured the infiltration of agricultural households and the exploitation of its *Miombo*woodland resources. Therefore, understanding the dynamics of land cover within the LBR could support the development of a management plan and

[1] According to article 1 of Law No. 14/003 of 11 February 2014 on nature conservation in the Democratic Republic of Congo, a biosphere reserve is a category of protected areas created by the competent Authority and recognized by the United Nations Educational, Scientific and Cultural Organization to promote sustainable development based on combined efforts of local communities and the scientific world.Specifically, a biosphere reserve should contain (i) a core area with long-term protection of biological diversity for research; (ii) a buffer zone surrounding or adjacent to the core area and used for ecologically sustainable activities, including ecotourism; (iii) A transitional, flexible zone (or cooperation area) which may include a number of agricultural activities, human settlements and other operations, and in which local communities, management agencies, scientists, non-governmental organizations, cultural groups, economic interests and other partners work together for sustainable management and development of resources of the region.

governance rules better adapted to the situation either in the LBR or in similar environments in the DR Congo. The objective of this study was to map and quantify the land cover dynamics within and around the LBR, and to assess its extent. We hypothesized that, over time, the maintenance of the traditional agrarian system, logging and carbonization, linked to the growing demand for woodfuel and charchoal by the riparian populations and major urban centres, has accentuated the degradation and depreciation of the LBR landscapes through the accompanied disaggregation and savanization of forest ecosystems.

2. Materials and methods

2.1. Lufira Biosphere Reserve

The LBR is located in the South-Eastern part of the D.R. Congo, in the Upper Katanga province. It was created in 1982 (http://www.bakasbl.org/en/news/zoom.php5?id=31) and its closest boundary to the city of Likasi is less than 20 km away at the East, while Lubumbashi city is nearly 80 km away at the West. It covers a legal area estimated to about 14,700 ha (of which 2800 ha of core area). In the context of this study however, both the reserve and its close periphery are considered, taking the study coverage acreage to 23,230 ha (Fig. 1). It is the only area of *Miombo* woodland to be declared as a reserve in DR Congo. The reserve also includes wetlands in the (periodically) flooded lowlands and step-like vegetation in the highlands. The diversity of plant species is extraordinarily high (UNESCO, 2019). This information should be taken with caution as no in-depth studies have been conducted for most taxonomic groups. The LBR known a tropical climate characterized by a rainy

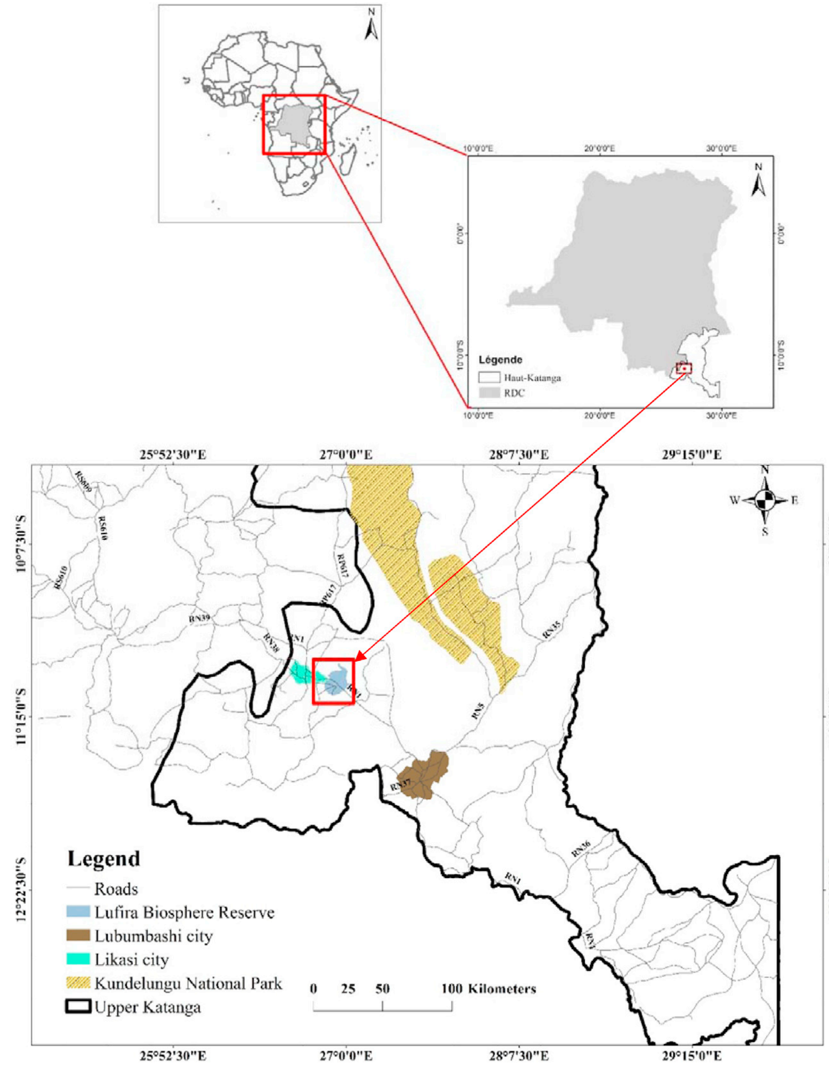

Fig. 1. Location of Lufira Biosphere Reserve in Upper Katanga, Southeastern part of the D.R. Congo.

season (November–March) separated from the dry season (May–September) by two transitional months (April and October) (Cabala et al., 2018). However, it has been suggested that there are 5 seasons defined from phenological observations of vegetation (Malaisse, 1978): the cold dry season (May–July), the hot dry season (August–September), the early rainy season (October–November), the peak rainy season (December–February) and the late rainy season (March–April). This pattern remains valid, although recent studies show a trend towards change, including later onset of rainfall and lower average annual rainfall (Kalombo, 2015). For the second half of the last century, the average annual temperature was around 20.1 °C (Malaisse, 2010), but an ongoing warming has been highlighted (Kalombo, 2016). Annual precipitation generally exceeds 1000 mm (Kalombo, 2016). The reserve is bordered to the North-East by the Tshangalele lake, and crossed in its Northern part by the Panda river, which drains the effluents of Likasi's mining companies via Lufira river (Katemo et al., 2010). The lake holds a variety of fish, and presents extensive wetlands in its surroundings (Squadrone et al., 2016). Moreover, the region is rich in birdlife (BirdLife International, 2015). The reserve and its periphery contain the agglomerations of Luisha and Kapolowe as well as various villages. The national road number 1 crosses the reserve, thus easing the movement of the population within the region and major urban centres including Lubumbashi and Likasi (Fig. 1). The LBR is currently experiencing serious degradation due to slash-and-burn agriculture, logging (the manufacture of works of art and cooking utensils), charcoal production, hunting and fishing. In 1998, these activities supported nearly 15,000 people living on the reserve (UNESCO, 2019).

2.2. Satellite images

Systematic records of land cover data scarcely exist in DR Congo. For example, the area being investigated (LBR) does not have any official statistics on land cover patterns, and even the Master Plans are missing maps or quantitative statements on existing and historical land cover. For this reason, Landsat images (Path and row 173/068), separated by a time step of 7–12 years, were used to map and quantify land cover dynamics in the LBR. Five dates have been selected: 1979 (Multispectral Scanner, June 16, 1979; 57m spatial resolution), 1986 (Multispectral Scanner, June 01, 1986), 1998 (Thematic Mapper, July 04, 1998; 30m spatial resolution), 2008 (Thematic Mapper, July 15, 2008) and 2018 (Operational Land Imager, July 11, 2018; 30m spatial resolution). All images used in this study were selected based on data availability and quality (low cloud cover). And due to the fact that the study area has a high cloud cover during the rainy season, only images acquired during the dry period were preferred for the study (Potapov et al., 2012). In addition, the dates were selected to coincide with key periods of the development of the region and the reserve: the period before (1979) and after (1986) the creation of the LBR; the period of socio-political conflict (1998) and the period following the liberalisation of the mining sector in D.R. Congo (2008 and 2018).

2.3. Preprocessing of landsat images

The pre-processing of the Landsat images consisted mainly on geometric corrections in the UTM (Universal Transverse Mercator)/Zone 35S system covering the LBR and based on the reference ellipsoid WGS 84 (World Geodesic System). The Landsat images used in this study were geometrically corrected using a Landsat OLI image from 2018 as reference. At least 50 well-distributed ground control points were used in the rectification process. The root mean square error (RMSE) was inferior to 0.5 pixel; this suggest that the analysis of changes is efficient (Mas, 2000). To correct the difference in spatial resolution between Landsat images, the cubic resampling, known to improve the sharpness of the images while maintaining their radiometry (Mama et al., 2013), was utilized to normalize the spatial resolution of all images (30 m).

2.4. Selection of training zones and classification

For better vegetation discrimination, a false-composite color obtained with the spectral bands blue, red and near infrared was applied. It should be noted that the red and near infrared bands are the most commonly used for vegetation studies since they allow the best possible discrimination of vegetation (Barima et al., 2009). The geographic coordinates corresponding to each land cover were recorded using a Garmin MAP 64stc GPS between June and July 2019. Training data were generated through visual interpretation on Landsat images, supported by higher resolution images in Google Earth (Li et al., 2015). In addition to forests, five other land cover categories (i.e., grassy and wooded savannah, fields and fallows, bare land and built-up areas, water and wetlands; Table 1) were included. As the Landsat images were acquired in the same season, a hierarchical sampling scheme was implemented to collect stable formation data. With the help of Google Earth, training data were collected with greater confidence, focusing on sampling units that remained the same during the study period (Olofsson et al., 2013). Indeed, the use of good practices during training data collection can help reducing possible biases caused by the sampling units (Olofsson et al., 2014). This sampling methodology was repeated for all years between 1979 and 2018. A supervised classification supported by the maximum likelihood classifier was subsequently applied to each image. This method has the advantage of providing each pixel, in addition to the class to which it has been assigned, with an index of certainty related to this choice (Barima et al., 2009). Such an algorithm has been found to yield superior results from remotely sensed data (Skupinski et al., 2009).

Table 1
6-Categories land cover description.

Land cover	Number of pixels	Description
Forest	59	Mosaic of multiple forests types (dry and riparian evergreen forest), but with *Miombo* woodland remaining dominant (Photos 1 and 2). Dense evergreen forests are plant formations with closed stands with quasi absence of the herbaceous stratum. Riparian evergreen forests include forest ecosystems that colonize along rivers and islets, and thus benefit from special soil conditions in areas characterized by a long dry season. *Miombo* woodland is a type of vegetation, dominant in the Zambezian region, characterized by the preponderance of species belonging to the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*.
Wooded savanna	29	Woody vegetation cover dominated by shrub species (Photo 3). It is distinguished from forest by the low density or abundance of the tree stratum and the height of the trees. There are trees and herbaceous vegetation.
Grassy savanna	39	Grassland dominated open space with almost absence of tree and shrub cover (Photo 4).
Fields and fallows	30	Parcels cultivated or put in rest to be cleared after a few years in a crop rotation system
Bare soil and built-up	30	Bare land sparsely vegetated, soil background; Residential land minimally vegetated with impervious surface or rarely paved roads.
Water and wetland	141	Vegetated lands with a high water table; standing water including river and water ponds.

2.5. Accuracy assessment and area estimate

Statistically robust and transparent approaches for assessing accuracy and estimating area of change are critical to ensure the integrity of land change information (Olofsson et al., 2014). A sample of reference observations of land cover and land change was collected for construction of unbiased area estimators and for estimating uncertainty compliant with good practice guidance (Olofsson et al., 2014). Through the elaboration of the error matrix, a post-classification analysis was carried out to evaluate the accuracy. Area and area change estimates were adjusted to account for bias in the change map, resulting in more accurate estimates. Next, the precision of the area estimates and area changes were quantified through the calculation of confidence intervals. The selection of subsets of the change map was carried out following a stratified sampling design, which forms the basis for the assessment of precision. Twelve strata were considered, of which 6 were from stable classes (forest, wooded savanna, grassy savanna, fields and fallows, bare soil and built-up, water and wetlands) and 6 from the most relevant classes of change. Approximately 100 points were taken per stratum according to the recommendations of Congalton and Green (2008). In total, 1614 points were sampled for the 1979–1986 change map, 1841 points for the 1986–1998 map, 1713 points for the 1998–2008 map and finally 1974 points for the 2008–2018 map. The pixel was the unit of spatial assessment, with previous Landsat and Google Earth images used as the sources of the reference data. The precision measurements used in this study were calculated manually using equations (1)–(3) of (Olofsson et al., 2014), representing respectively the overall precision, the user precision and the producer precision. The information on the accuracy of the map as provided by the error matrix was used to estimate class areas. And the baseline data was used to adjust the area estimate obtained from the map, which was based on equation (6) while the error of the stratified estimator of the proportion of area was calculated using equations (10) and (11) of Olofsson et al. (2014). The 95% confidence interval was obtained by multiplying the standard error by 1.96. The 95% confidence interval was obtained by multiplying the standard error by 1.96. ArcGIS 10.5 software were used for image (pre)processing and Geographic Information System (GIS) creation respectively (Table 2).

2.6. Change detection

To highlight the human impact on landscape dynamics, the spatial pattern of the landscape was characterized for each land cover class on the basis of patch number (PN), class area (CA), the largest patch index (LPI) and the shape index (SI). These indices were considered relevant to provide information on landscape fragmentation (Bogaert et al., 2005; Bogaert and Mahamane, 2005; Li et al., 2013). Indeed, the more elongated or irregular the patches are, the higher the SI value will be, and this value will decrease as the shapes become regular (circular, square or rectangle; Bogaert and Mahamane, 2005). On the other hand, the increase in the number of patches of a land cover class, as well as the decrease in its total area or the area of its largest patch, may be due to the fragmentation of this class (Mama et al., 2013). Based on the class area and perimeter of each land cover (Bogaert et al., 2000), the shape index (SI) was given by the following formula:

$$SI = \frac{CA}{P^2} \tag{1}$$

The dynamics of conversions within the studied landscape were obtained using the transition matrix created to identify the transition frequencies between land cover classes over the studied time interval (Barima et al., 2009). This matrix is obtained by crossing land cover maps from two comparative periods (1979–1986, 1986–1998, 1998–2008 and 2008–2018). Indeed, the transition matrix is one of the main models for evaluating landscape changes (Barima et al., 2009). It is a chart presenting transitions between classes in a given period, thus the percentages of transition observed in a finite time.

Table 2
Accuracy assessment and area estimate for land cover and land cover change maps from 1979 to 2018.

1979 −1986	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Water and wetland	Forest loss	Wooded savanna gain	Grassy savanna loss	Bare soil and built-up loss	Field and fallows gain	Water and wetland gain
Accuracy measure											
Prod. acc.	100%	100%	62%	97%	100%	70%	73%	91%	69%	99%	93%
User acc.	98%	99%	74%	97%	98%	90%	85%	82%	100%	73%	87%
Overall acc.	91%										
Stratified estimators of area ± CI [% of total map area]											
Area	23.3%	18.2%	1%	0.9%	7%	8.7%	8.4%	9.4%	4.6%	5.1%	13.4%
95% CI	0.56%	0.28%	0.4%	0.03%	0.18%	0.98%	0.9%	0.63%	0.84%	0.41%	1.15%

1986 −1998	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Field and fallows	Water and wetland	Forest loss	Wooded savanna loss	Grassy savanna gain	Bare soil and built-up gain	Field and fallows gain	Water and wetland gain
Accuracy measure												
Prod. acc.	100%	99%	76%	90%	98%	100%	81%	67%	76%	100%	51%	67%
User acc.	83%	93%	90%	100%	81%	72%	79%	99%	98%	95%	97%	93%
Overall acc.	85%											
Stratified estimators of area ± CI [% of total map area]												
Area	11.3%	13.6%	2%	0.4%	5.5%	17.1%	11.8%	1.2%	12.9%	1.9%	8.2%	13.9%
95% CI	0.73%	0.67%	0.36%	0.04%	0.48%	1.53%	0.93%	0.35%	1.06%	0.06%	1.15%	1.36%

1998 −2008	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Field and fallows	Water and wetland	Forest loss	Wooded savanna gain	Grassy savanna gain	Bare soil and built-up gain	Field and fallows gain	Water and wetland loss
Accuracy measure												
Prod. acc.	100%	96%	99%	100%	97%	97%	99%	61%	64%	60%	67%	93%
User acc.	98%	99%	100%	99%	74%	99%	93%	83%	60%	98%	99%	75%
Overall acc.	86%											
Stratified estimators of area ± CI [% of total map area]												
Area	8.7%	6.3%	7%	0.8%	4.2%	10.1%	16.9%	12%	6.5%	2.3%	12.3%	13%
95% CI	0.2%	0.29%	0.18%	0.01%	0.44%	0.35%	0.99%	1.35%	1.03%	0.54%	0.82%	1.12%

2008 −2018	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Field and fallows	Water and wetland	Forest loss	Wooded savanna loss	Grassy savanna loss	Bare soil and built-up gain	Field and fallows gain	Water and wetland gain
Accuracy measure												
Prod. acc.	100%	99%	100%	95%	97%	100%	90%	100%	100%	68%	61%	100%
User acc.	97%	99%	97%	99%	96%	100%	99%	95%	74%	99%	99%	96%
Overall acc.	93%											
Stratified estimators of area ± CI [% of total map area]												
Area	4.3%	13%	0%	1.9%	4.4%	10.8%	5%	19%	15%	2.7%	13.7%	10.1%
95% CI	0.12%	0.3%	0%	0%	0.2%	0%	0.3%	0.6%	1.2%	0.6%	1.3%	0.3%

Therefore, it constitutes an exact and highly condensed summary of the whole changes occurred within a period of study. The (annual) rate of change in land cover (by period) in the study area was calculated using the following equation (Caloz and Collet, 2001):

$$R = \frac{CA_2 - CA_1}{CA_1} \, x \, 100 \qquad (2)$$

where CA_2 is the area occupied by the land cover class in the final year of the considered period and CA_1 is the area occupied by the land cover class in the initial year of that period. The spatial transformation processes underlying the observed spatial changes (Bogaert et al., 2008; Mama et al., 2013; Barima et al., 2016) have been identified through the decision tree (Bogaert et al., 2004). This method is based on a comparison of the class area, perimeter and number of patches before and after transformation (Bogaert et al., 2004, 2008; Vranken et al., 2011; Mama et al., 2013; Useni et al., 2019); the detailed literature on this decision tree could be found in Bogaert et al. (2004), Barima et al. (2009; 2016). A threshold set at t = 0.5 was used to dissociate the fragmentation process from dissection, with values greater than 0.5 suggesting dissection, while those less than or equal to 0.5 indicated the prevalence of fragmentation (Barima et al., 2009). According to Bogaert et al. (2004), dissection can be defined as the carving up or subdividing of an area or patch using equal-width lines while fragmentation is the breaking up of an area into smaller parcels, resulting in unevenly separated patches or the breaking up of extensive landscape features into disjointed, isolated, or semi-isolated patches.

3. Results

3.1. Land cover mapping

Six land cover maps were produced from these analyses. Visual analysis reveals that each of the six land cover classes selected, in terms of spatial extension over time, has either a regressive or a progressive trend. In detail, LBR recorded a

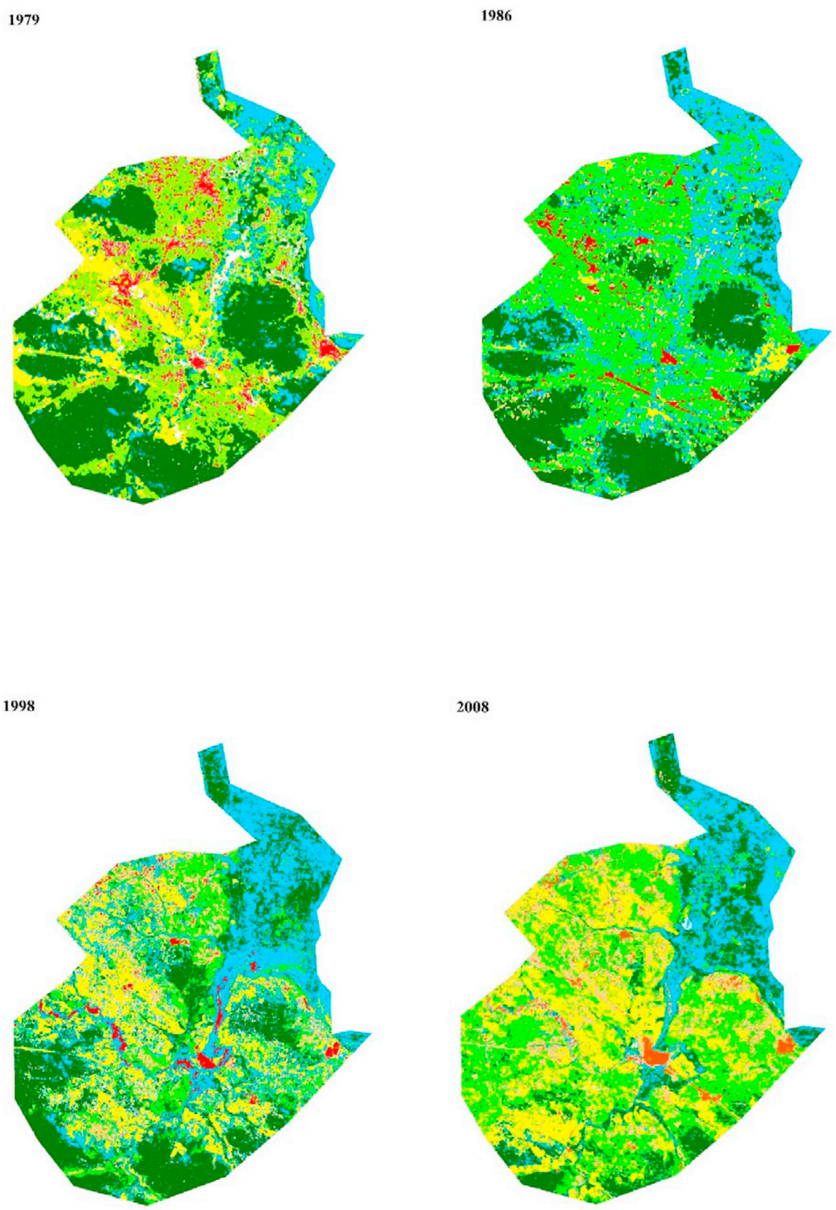

Fig. 2. Land cover maps for 1979, 1986, 1998, 2008 and 2018 in Lufira Biosphere Reserve and its peripheral.

decrease in forest cover in 2018 compared to 1979. Indeed, the large forest areas that dominated the landscape in 1979 were replaced by savanna, the fields and fallows in 2018 (Fig. 2).

3.2. Land cover composition in LBR

Changes in land cover between 1979 and 2018 generally show a decrease in the extent of forest (Tables 3 and 4). Indeed, the forest that constituted the dominant matrix of the landscape (36.7%) in 1979, experienced a spatial regression with a strong tendency to disappear in 2018 (11.2%). In fact, the annual rate of deforestation was −0.28% between 1979 and 1986, but doubled over the period from 1998 to 2008, before dropping to 0.24% per year between 2008 and 2018. Surprisingly, the forest has registered a positive rate of evolution between 1986 and 1998, synonymous with regeneration, but this has not managed to compensate for the losses recorded over all the periods studied. It was also noted that the coverage of wooded savanna and that of bare soil and built-up declined, with its proportion in the landscape decreasing from 32.4% to 21.7% and from 5.3% to 3.5% between 1979 and 2018 respectively. Meanwhile, the acreage of grassy savanna as well as that of fields and fallows significantly increased, with the proportion of grassy savanna in the landscape almost doubling (from 11.7% in 1979 to 19% in 2018). Similarly, fields and fallows, quasi inexistent in the landscape until 1998, spread over an area equivalent to 22.9% of the landscape in 2018, becoming the new landscape matrix. The water and wetland, which covered 13.9% of the landscape in 1979, has almost doubled its area to nearly 22% in 2018.

3.3. Land cover transfers between 1979 and 2018

Overall, forest was found to be the most stable land cover class between 1979 and 1986, 1986−1998, and 1998−2008 (Table 5). In contrast, wooded savanna became the new more stable class in the landscape over the periods 2008−2018. And a new land cover class (fields and fallows) emerged in the landscape, namely at the expense of forest (2.0%), wooded savanna (3.1%) and grassy savanna (1.0%). Between 1979 and 1986, 7.3% of forests evolved towards wooded and 3.6% in other land cover classes. Over the same period, it was noted that wooded savanna, water and wetland have increased, to varying degrees, their area at the expense of all other land cover classes. Grassy savanna and bare soil and built-up decreased mainly at the expense of wooded savanna as well as water and wetlands. Over the period from 1986 to 1998, forests, grassy savanna, fields and fallows, water and wetlands increased their area mainly at the expense of wooded savanna. Indeed, 3.2%, 4.4%, 8.5% and 8.7% of landscape occupied by wooded savanna evolved toward forest, field and fallows, grassy savanna, water and wetlands. The area of bare soil and built-up increased mainly at the expense of wooded and grassy savanna (0.5%). From 1998 to 2008, the area of forest in the landscape was divided by half, in favor of wooded savanna (9.4%), grassy savanna (1.7%), and fields and fallows (2.0%). Over the same period, 6.9% of water and 7.9% of wetlands have evolved towards grassy savanna, and fields and fallows. In the same period, bare soil and built-up lost its area mainly in favor of grassy savanna (1.2%). Over the period 2008−2018, forest declined by about 20%, mainly in favor of wooded savanna (1.2%), grassy savanna (1.0%) as well as fields and fallows (1.3%). Wooded savanna lost almost 30% of its area in the landscape mainly in favor of fields and fallows. Surprisingly, bare soil and built-up increased its area in the landscape by invading grassy savanna (1.3%) and wooded savanna (0.8%).

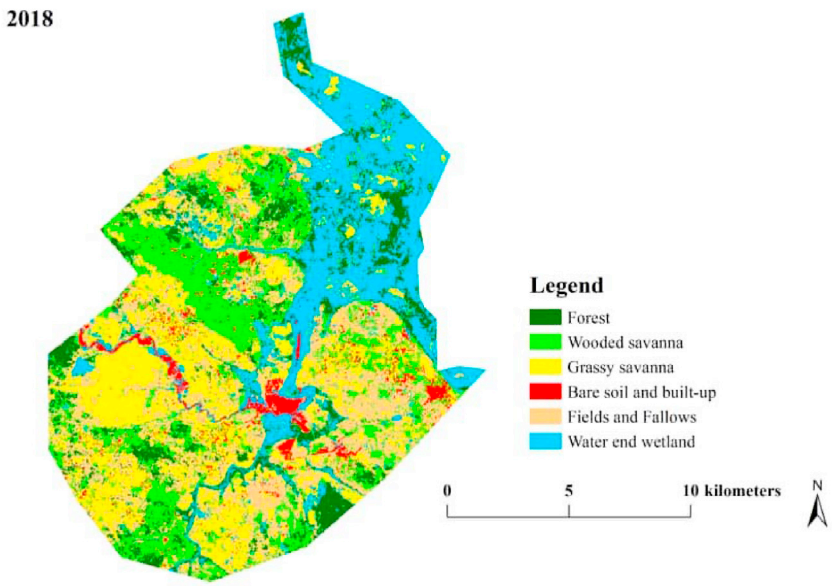

Fig. 2. (*continued*).

Table 3
Composition of land cover in 1979, 1986, 1998, 2008 and 2018 in the Lufira Biosphere Reserve. Values outside brackets are expressed in km^2 and those in brackets in percentage.

Year	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Field and fallows	Water and wetland
1979	85.3 (36.7)	75.3 (32.4)	27.3 (11.7)	12.2 (5.3)	0.0	32.2 (13.9)
1986	60 (25.8)	92.1 (39.6)	6.1 (2.6)	4.9 (2.1)	14.6 (6.3)	54.6 (23.5)
1998	65.1 (28)	36 (15.5)	42.8 (18.4)	5.4 (2.3)	16.3 (7)	66.7 (28.7)
2008	34.2 (14.7)	73.1 (31.5)	51.5 (22.2)	4.8 (2.1)	32.3 (13.9)	36.4 (15.7)
2018	26.1 (11.2)	50.4 (21.7)	44.2 (19)	8.2 (3.5)	53.3 (22.9)	50.1 (21.6)

3.4. Spatial pattern dynamics

Between 1979 and 1986, forest, grassy savanna, bare soil and built-up experienced a decrease in class area and number of patches, suggesting a predominance of the attrition process within these land cover classes (Tables 6 and 7). Water and wetlands registered the aggregation as spatial process since the increase in class area was followed by the decrease in the number of patches. Wooded savanna, field and fallows were characterized by the increase in class area and patch numbers, echoing creation as spatial process. Over the period 1986–1998, wooded savanna recorded an increase in the number of patches in parallel with a decrease in the class area. It is evident from the observed t-value < 0.5 that the dominant transformation process was fragmentation. For the other land cover classes studied, there was an increase in the class area and patch number. The spatial transformation processes observed over this period was creation. Between 1998 and 2008, forest, water and wetlands were characterized by attrition of patches, especially since the decrease in class area resulted in the decrease of patch number. Conversely, the creation of patches dominated wooded savanna and field and fallows since the increase of their patch number was followed by an increase in class area. Bare soil and built-up recorded an increase in the number of patches in parallel with a decrease in the class area. It is evident from the observed t-value > 0.5 that the dominant transformation process was dissection. Finally, during the period 2008–2018, forest, wooded savanna and grassy savanna were characterized by attrition of patches, as the decrease in class area resulted in the decrease of patch number. Conversely, bare soil and built-up knew an increase in patch number followed by an increase in class area, suggesting that patch creation was the dominating spatial process. Water and wetlands as well as fields and fallows were characterized by an increase in class area in parallel to a decrease in patch number, indicating that aggregation of patches was the dominant spatial process in these land cover classes.

The ratio of the largest patch area by the class area or the largest patch index (LPI) which was low in 1979–1986 for bare soil and built-up, fields and fallows, and water and wetlands increased remarkably in 2018. The LPI remained unchanged for wooded savanna and grassy savanna between 1979 and 2018. However, LPI decreased three fold for forest between 1979 and 2018, reflecting the extent of environmental degradation, thus the landscape anthropisation that is further evidenced by the evolution of SI. In fact, the value of this index decreased between 1979 and 2018 especially for forest, which can be interpreted as a decrease in the complexity of the shapes as well as a trend towards more compact shapes of patches.

4. Discussion

The protected areas of the D.R. Congo are threatened by various anthropogenic pressures requiring frequent and accurate monitoring (Semeki et al., 2016). These changes have been monitored over the past 20 years using data with increasingly high spatial, spectral and temporal resolutions (Skupinski et al., 2009), justifying the use of Landsat-type satellite images in this study. In addition, landscape are dynamics and therefore subject to constant change that can be highlighted using landscape metrics, which are also able to reveal ecosystem properties, otherwise difficult to be observed a priori (Antrop and Eetvelde, 2000). Therefore, measures, including class area, patch number as well as shape index, are a reliable indicator of human impact on landscape morphology (Bogaert et al., 2004). Detection of land cover changes is a process based on the identification of differences in the state of objects or phenomena through observations at different times. Thanks to land cover flows, the transition matrix allowed the observation of the different transfers between land cover classes. This approach has already been used by many authors to highlight land cover changes for various landscapes, be it forest or savanna (Barima et al., 2016; Bamba et al., 2018). Moreover, through this approach, the dynamics of specific landscape conversions can be linked to well-identified initiators (Useni et al., 2019).

In D.R. Congo, most protected areas do not have a very strong conservation status and are regularly subject to illegal exploitation (Potapov et al., 2012). Indeed, with a human development index that places it 186th out of 187 countries worldwide, and more than 85% of its population living with less than USD 1.25 per day, the D.R. Congo faces major ecological, demographic and economic challenges simultaneously (UNDP, 2017). Waves of looting, the post-war political climate and more recent political tensions over presidency of the State have generated instability and insecurity for the population in many regions across the country, including the area of the Katangese copperbelt where the LBR is located. The poverty and population growth that characterize this area has led to a significant degradation of natural resources, reflected notably by (i) a reduction in class area, thus a drastic decrease in the production of non-timber forest products, (ii) exposure of soils to wind and water erosion, and (iii) vulnerability of households to chronic food insecurity (Malaisse, 2010; Barima et al., 2011). In and

Table 4
Annual rate of change in land cover over the period 1979–1986, 1986–1998, 1998–2008 and 2008–2014 in the Lufira Biosphere Reserve.

Period	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Field and fallows	Water and wetland
1971–1986	−0.28	0.22	−0.78	−0.60	0.00	0.69
1986–1998	0.09	−0.61	6.02	0.10	0.12	0.22
1998–2008	−0.48	1.03	0.20	−0.11	0.98	−0.45
2008–2018	−0.24	−0.31	−0.14	0.71	0.65	0.38

Table 5
Transition probability matrix (in percentage of the class area) illustrating the conversion of land cover classes area between 1979 and 1986, 1986–1998, 1998–2008, 2008–2018 in the Lufira Biosphere Reserve and its peripheral. Values in bold illustrate the stability of land cover area.

1979–1986	**Forest**	**Wooded savanna**	**Grassy savanna**	**Bare soil and built-up**	**Fields and fallows**	**Water and wetland**	**Total**
Forest	**25.8**	7.3	0.6	0.1	2.0	0.9	36.7
Wooded savanna	0.0	**23.0**	0.8	0.8	3.1	4.6	32.4
Grassy savanna	0.0	6.2	**1.2**	0.4	1.0	2.9	11.7
Bare soil and built-up	0.0	3.1	0.0	**0.7**	0.3	1.2	5.3
Field and fallows	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0
Water and wetland	0.0	0.0	0.0	0.1	0.0	**13.9**	14.0
Total	25.8	39.6	2.6	2.1	6.3	23.5	100.0
1986–1998	**Forest**	**Wooded savanna**	**Grassy savanna**	**Bare soil and built-up**	**Fields and fallows**	**Water and wetland**	**Total**
Forest	**24.1**	0.7	0.3	0.1	0.6	0.0	25.8
Wooded savanna	3.2	**14.0**	8.5	0.8	4.4	8.7	39.6
Grassy savanna	0.5	0.3	**1.6**	0.1	0.1	0.0	2.6
Bare soil and built-up	0.1	0.5	0.5	1.0	0.0	0.0	2.1
Field and fallows	0.0	0.0	5.6	0.3	**0.4**	0.0	6.3
Water and wetland	0.0	0.0	2.0	0.0	1.5	**20.0**	23.5
Total	28.0	15.5	18.4	2.3	7.0	28.7	100.0
1998–2008	**Forest**	**Wooded savanna**	**Grassy savanna**	**Bare soil and built-up**	**Fields and fallows**	**Water and wetland**	**Total**
Forest	**14.7**	9.4	1.7	0.1	2.0	0.0	28.0
Wooded savanna	0.0	**11.2**	1.4	0.3	1.8	0.8	15.5
Grassy savanna	0.0	8.5	**8.5**	0.1	0.3	1.0	18.4
Bare soil and built-up	0.0	0.4	1.2	**0.7**	0.0	0.0	2.3
Field and fallows	0.0	2.0	2.5	0.4	**1.9**	0.1	6.9
Water and wetland	0.0	0.0	6.9	0.5	7.9	**13.4**	28.7
Total	14.7	31.5	22.2	2.1	13.9	15.3	100.0
2008–2018	**Forest**	**Wooded savanna**	**Grassy savanna**	**Bare soil and built-up**	**Fields and fallows**	**Water and wetland**	**Total**
Forest	**11.2**	1.2	1.0	0.0	1.3	0.0	14.7
Wooded savanna	0.0	**20.5**	1.5	0.8	7.3	1.4	31.5
Grassy savanna	0.0	0.0	**13.0**	1.3	6.7	1.3	22.2
Bare soil and built-up	0.0	0.0	0.2	**1.4**	0.5	0.0	2.1
Field and fallows	0.0	0.0	2.3	0.0	**6.2**	5.4	13.9
Water and wetland	0.0	0.0	1.1	0.0	0.9	**13.6**	15.6
Total	11.2	21.7	19.0	3.5	22.9	21.6	100.0

around the LBR, human actions favoring degradation of the natural environment are well known, among which excessive logging and soil clearing for cultivation are recurrently cited. In Zambian protected area network (Luangwa Valley), Watson et al, (2014) found that, from 1965 to 2011, human encroachment extended from major roads as fast as 2 km/year, averaging virtually 18 ha per hour of daylight throughout a 159,805 km^2 study area. In our case, the strong growth in demand for woodfuel in the urban centres adjacent to the LBR (Lubumbashi and Likasi cities), is due to population growth. This population is highly dependent on wood energy for their daily needs (Kabulu et al., 2018). Deforestation in general and encroachment in particular are well recognized problems in natural resource management of protected areas in *Miombo* ecoregion, as they generally eliminate designated buffer zones in some areas, decreasing forest patches connectivity (Watson et al., 2014; Gizachew et al., 2020). Similarly, Katumbi et al. (2015) findings revealed that charcoal production (40%) and firewood production (32%) are the main driving forces to *Miombo* deforestation and degradation in Dzalanyama forest reserve in Malawi.

The socio-political instability experienced by the country since the 1990s has exacerbated the situation of environmental fragility and food insecurity through recurrent decline in agricultural production and the influx of people from conflict areas (Cabala et al., 2018). Since agriculture has always been and still is the refuge sector by excellence in rural areas of Katanga (Lebailly, 2010), ensuring a certain “food security” in such a context is a real matter of survival for local populations. This is why we observe an extension of the classes relating to crops, particularly from 1998, a period of socio-political conflict in the D.R. Congo. However, prolonged cultivation leads to a significant decrease in organic matter levels, meaning a decrease in soil fertility (Cabala et al., 2018). In addition, in the study area, maize, a major crop that requires high soil fertility, is the main food

Table 6
Synthesis of the spatial pattern indices in the Lufira Biosphere Reserve and its peripheral zone in 1979, 1986, 1998, 2008 and 2018. PN: Patch number, CA: Class area (km^2), SI: Shape index, LPI: Largest patch index.

Indices	Forest	Wooded savanna	Grassy savanna	Bare soil and built-up	Fields and fallows	Water and wetland
1979						
PN	1032	1119	814	1500	0	2563
CA	85.3	75.3	27.3	12.2	0.0	32.2
SI	0.048	0.047	0.048	0.047	0.000	0.049
LPI	0.20	0.25	0.17	0.06	0.00	0.23
1986						
PN	836	1129	433	392	2045	2039
CA	60.0	92.1	6.1	4.9	14.6	54.6
SI	0.052	0.052	0.052	0.052	0.054	0.052
LPI	0.17	0.62	0.15	0.06	0.01	0.46
1998						
PN	6386	5947	3671	857	3161	12507
CA	65.1	36.0	42.8	5.4	16.3	66.7
SI	0.051	0.051	0.049	0.052	0.051	0.052
LPI	0.20	0.15	0.10	0.09	0.03	0.31
2008						
PN	3812	6122	3905	1028	7284	6181
CA	34.2	73.1	51.5	4.8	32.3	36.4
SI	0.049	0.050	0.049	0.051	0.050	0.052
LPI	0.07	0.10	0.12	0.18	0.03	0.52
2018						
PN	3711	5654	2431	2308	6224	2511
CA	26.1	50.4	44.2	8.2	53.3	50.1
SI	0.049	0.051	0.047	0.053	0.049	0.051
LPI	0.06	0.24	0.17	0.15	0.10	0.70

product (Useni et al., 2013). Indeed, forests are considered by farmers as the environment with the most fertile soil, hence the most favorable for farming. Thus, in the LBR, the period of political instability was characterized by an increase in deforestation and the emergence of fields. Nackoney et al. (2014) in the Luo Science Reserve (D.R. Congo) and Barima et al. (2016) in the forest reserves of the classified forest of Haut-Sassandra (Ivory Coast) confirmed this observation. Allan et al. (2017) found that Niassa National Reserve (Mozambique) lost 108 km^2 of forest, with the majority (89 km^2) of forest loss occurring due to expanding agriculture around settlements and along main roads.

Indeed, in rural D.R. Congo, the creation of protected areas has not significantly contributed to improving the relationship between local populations and the natural resources of these areas. Consequently, one of the key developments in land cover dynamics in the LBR is the degradation of *Miombo* woodland, which can be compared with the significant increase in the human population (almost 3% per year; INS, 2015). These populations still consider protected areas as their traditional territory (Havyarimana et al., 2017). The natural resources of protected areas are generally subject to anthropogenic pressures leading to their degradation, as illustrated by our results and those obtained by other researchers in Yangambi Biosphere Reserve, D.R. Congo (Kyale et al., 2019), in Mondo Missa Hunting Estate east of Garamba National Park, D.R. Congo (Semeki et al., 2016), in Meru Catchment Forest Reserve, Tanzania (Giliba et al., 2011), in Dzalanyama Forest Reserve, Malawi (Katumbi et al., 2015), South Luangwa, North Luangwa, Luambe, and Lukusuzi national parks in Zambia (Watson et al., 2014). Our results differ however with those reported by Havyarimana et al. (2017) in the Bururi forest reserve in Burundi, possibly due to differences in the level of control (Balolé et al., 2015). Likewise, Kouakou et al. (2018) underlined the absence of protective measures as the main driver of a complete disappearance of forest ecosystems in Marahoué National Park (Ivory Coast) between 1974 and 2015.

The D.R. Congo's forestry code has not been truly put into practice. Provincial tax documents complement this single framework document, which explains the preponderance of the tax collection role played by provincial services in the face of the weak supervisory role of the actors involved in the exploitation of forest resources. The small forest patches that persist within the reserve owe their existence to the unsuitable nature of their soils or their inaccessibility (Useni et al., 2017), due to their location on hills. The increase in the proportion of grassy savanna is a tangible evidence of the degradation of past forest resources. Indeed, according to Malaisse (2010), the importance savanna is increasing with the increase in human activities in the Zambezian region. The increase in savanna area (wooded or grassy) resulting from repeated deforestation or bushfires is reported in southern Katanga (Malaisse, 2010; Useni et al., 2017), as well as in the *Miombo* ecoregion (Chidumayo, 2013; Ryan and Williams, 2011).

However, the declining wooded savanna coverage, which seems suggestive that anthropogenic pressure on wood resources is particularly high in this area where population pressure and poverty impose opting for short-term survival objectives over long-term conservation objectives (Vermeulen et al., 2011). All large-diameter woody species of forest are cut down, accelerating the transformation of forest landscape into wooded savanna (Mama et al., 2014). Wooded savanna are in turn cultivated or their individuals of reduced stem diameter are also cut for carbonization. Indeed, wood energy production is seen as an essential supplement to household income, which accelerates deforestation and regression of wooded savanna

Table 7
Identification of spatial transformation processes of land cover classes between 1979 and 1986, 1986–1998, 1998–2008 and 2008–2018 in the Lufira Biosphere Reserve from the decision tree algorithm (Bogaert et al., 2004).

Landcover	1979–1986	1986–1998	1998–2008	2008–2018
Forest	Attrition	Creation	Attrition	Attrition
Wooded savanna	Creation	Fragmentation	Creation	Attrition
Grassy savanna	Attrition	Creation	Creation	Attrition
Bare soil and built-up	Attrition	Creation	Dissection	Creation
Field and fallows	Creation	Creation	Creation	Aggregation
Water and wetland	Aggregation	Creation	Attrition	Aggregation

area (Trefon et al., 2010; Münkner et al., 2015). Indeed, even if the search for wood energy is not directly highlighted (Bangirinama et al., 2016; Kabulu et al., 2018), it might have contributed significantly to the destruction of forest ecosystems alone over the period 1979–1998 or associated with agricultural activities over the period 1998–2008. Similarly, the increase in urban demand for wood energy results in increased pressure on the forest resources (Münkner et al., 2015; Gillet et al., 2016). Indeed, in the absence of a diversification of domestic energy sources, forest species are cut down, then carbonized and sold in large urban centres, as in Lubumbashi city where Münkner et al. (2015) reported that in 2015 charcoal was the main source of energy for more than 97% of households, against 72% of households in 2008 (Kabulu et al., 2018). This situation is particularly alarming in the absence of incentives for the restoration or sustainable management of this resource (Schure et al., 2019). The conversion of savanna into fields and fallows can be justified by the lesser amount of efforts required to clear savanna for agriculture purpose, comparatively to the necessary energy in forest conditions where the density of trees is higher (Havyarimana et al., 2018). In the context of the current study, the decline in grassy savanna coverage could be explained by the fact that indigenous and displaced populations generally need building materials coming mainly from the savanna (grasses for house coverage). However, the progression of wetlands may be due to the disappearance of trees from the gallery forest along watercourses, removal of which promotes the penetration of light that is beneficial to the development of the herbaceous mat on a soil with permanent humidity (Rakotandrosoa et al., 2013).

Another notable fact, despite the expansion Kapolowe and Luisha agglomerations, is the decline in the proportion of the bare soil and built-up in the landscape of the study area. This situation could be justified by bushfire, particularly for bare soil. Indeed, bare soil by late burning is particularly vulnerable since the herbaceous stratum is eliminated to the maximum and its young regrowth has not yet developed to the point of offering protection against the violence of the first storm showers (Murphy et al., 2014). The development of mining activities could justify the sequence in which bare soils appear in the landscape, followed by their recovery through colonization by cupro-cobalt flora species probably. In fact, Vranken et al. (2013) found greater fragmentation and lower presence of woody vegetation in polluted areas within the Katangese copper belt. Finally, the decline in built-up area could be explained in relation with findings by numbers of authors suggesting that mining and industrial activities drive rural people to abandon their land in search for more profitable activities (Nkuku and Rémon, 2006; Megevand et al., 2013; Gillet et al., 2016).

5. Conclusion

This study contributes to the interpretation of landscape dynamics in and around Lufira Biosphere Reserve, in Southeastern D.R. Congo, and highlights the relevance of the cartographic approach based on satellite images coupled to landscape ecology analysis tools. Results altogether confirm an obvious dynamic and rapid changes occurring in the Lufira Biosphere Reserve environments. The ecological balance of forest areas, and wooded savanna to a lesser extent, is severely disrupted by slash-and-burn agriculture and carbonization. The transformation of these massifs has affected both their area and their number of patches. Moreover, the forests, once dominant, have been largely transformed into savanna formations, then fields and fallows. The study also reveals that current human pressures on forest resources are breaking with the regeneration capacities of natural plant formations, which are thus seriously threatened. Bushfires, pollution from mining activities and the departure of certain segments of the population to artisanal mining activities could justify the decline of bare soils and built-up in the landscape. Another significant development was the decline in wooded savanna cover, due to carbonization, bushfires, but also to the densification of woody vegetation. We conclude that over time, high dependence on natural (wooded) resources and agriculture would have led to high competition and land pressure within the Lufira Biosphere Reserve, resulting in reduced forest cover and significant agricultural development. Demographic pressure, not accompanied by an improvement in the standard of living of local communities or improved agricultural techniques, are important factors underlying the observed spatial changes. It seems therefore urgent to develop an integrated and participatory management strategy at the local level in order to preserve the still-existing natural resources in a sustainable manner.

Author contributions

Conceptualization: YUS & JB; Data curation: YUS, HKM & JB; Formal analysis: YUS & HKM; Funding acquisition: JB; Investigation: YUS & HKM; Methodology: YUS, HKM & JB; Project administration: YUS & JB; Resources: YUS; Software: HKM;

Supervision: YUS & JB; Validation: YUS, HKM & JB; Writing - original draft: YUS & HKM; Writing - review & editing: YUS, HKM & JB.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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