Amplification of Anthropogenic Pressure Heavily Hampers Natural Ecosystems Regeneration within the Savanization Halo Around Lubumbashi City (Democratic Republic of Congo)

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Abstract

Located in the south-east of the Democratic Republic of Congo (DR Congo), Lubumbashi city is surrounded by a belt of savanna, referred to as “savanization halo”, where rare miombo woodland patches could be spotted. This study evaluated the impact of anthropogenic activities on changes in the spatio-temporal pattern within that savanization halo between 2002 and 2017. A mapping approach coupled with landscape ecology analysis tools enabled highlighting both the diagnosis of land cover changes and the processes underlying the spatio-temporal dynamics. Results globally attested that the savanization halo was in constant mutation from 2002 to 2017. Importantly, it was apparent that the dissection, fragmentation and attrition of miombo was amplified by the creation and aggregation of savanna and built-up-bare land complex. Wetland attrition was found to be an additional manifestation of natural ecosystem degradation, with the resulting bare soils suggested as being flooded through the creation of waterbody patches. Agricultural and infrastructural development, supported by rapid population growth, no longer allows natural formations (forest and wetland) to recover from disturbances. It is important to reverse the current trend towards complete anthropization within the savanization halo through selective protection of natural ecosystems according to their values.

Keywords: Landscape; Anthropisation; Spatial dynamics; Remote sensing; Savanization halo; Lubumbashi

Introduction

During centuries, humans have profoundly altered the Earth’s ecosystems through exploitation of natural resources and geographical area occupation [1]. This situation has been amplified since the beginning of the 20th century [2], and as consequence, landscapes are radically affected by anthropogenic disturbances [3]. One of the most critical human impacts is the removal of the original vegetation cover [4] followed, among others, by soil exposure to water and wind erosion [5], but also by a reduced availability of non-timber forest products, leading to persistent poverty and food insecurity [6]. This situation could be worse for Sub-Saharan African countries that already experience higher land use pressure than European countries [7]. As landscape constitutes a set of interacting ecosystems, its state largely affects that of soils, water and biodiversity, including human [8]. Consequently, spatio-temporal disturbances of natural landscapes are believed to be indicators for assessing ecosystems health [9].

In the Democratic Republic of Congo (Congo DR), population and urban growth associated with poor socio-economic conditions lead to activities that frequently alter landscape state [10]. In the Upper Katanga province, anthropogenic activities regularly reduce the remnant forest patches [11-14], particularly miombo woodland, the most extensive tropical woodland formation in Africa with particular ecological and economic importance [15,16].

Around Lubumbashi (the most important city in the Upper Katanga province), the loss of natural vegetation is closely linked to agricultural development, charcoal production, city expansion and mining activities [16]. The visible consequences of these practices are, notably, the deforestation followed by forest fragmentation [17] leading to an anthropised landscape. For this reason, Lubumbashi city is surrounded by an area characterized by grassy and shrubby savanna, which reflects the anthropisation
of forest ecosystem, often referred to as ‘savannization halo’ or ‘deforestation radius’ [16,18,19]. According to Useni et al. [20], the savannization halo around Lubumbashi led to an annual forest cover loss of nearly 6% between 2002 and 2008. However, local discrepancies may be observed, notably in areas close to sites of mining activities. Although Lubumbashi city represents a primary degradation nucleus of the surrounding landscapes [17,18], the presence of a mining site may constitute a secondary nucleus [21] from which human activities might be diffused into natural ecosystems. This could lead not only to land saturation, but also to amplifications of conflicts between actors [22]. Therefore, there is an urgent need to preserve the rare natural ecosystems; however, to date, no clear approach is defined as to how to intervene in the savannization halo where people largely depend on natural resources.

As anthropogenic pressure on natural landscapes, coupled with demographic change, will increase during the coming decades, this situation requires the development of adequate techniques to evaluate society and natural resources interactions [23]. Indeed, landscape dynamics generally modifies the ecological functioning that can be demonstrated by an assessment of their properties [24]. During the last decades, the ability to quantify landscape dynamics has been strongly enhanced by the use of remote sensing, Geographic Information System (GIS), and landscape ecology analysis tools [8, 25-27]. This is crucial in understanding the causes and consequences of landscape transformation [2], in order to develop effective tools for land-use planning and rational management of natural resources for sustainable development [22].

This study aims at appreciating, through land cover change analysis, the anthropisation of landscapes within the savannization halo between 2002 and 2017. It is verified whether the amplification of anthropogenic activities within the savannization halo, over time, could lead to complete landscape anthropisation and loss of ecosystem services [28].

Materials and Methods

The study area

This study focuses on the savannization halo around Lubumbashi city. Geographically, the study area (11° 21’-11° 23S and 27° 26’-27° 46E) covers 407.6 km² and is located in the southern part Congo DR (Upper Katanga province). The outskirts of Lubumbashi city benefit from a Cw climate according to Köppen classification system, characterized by a dry season (May to September), a rainy season (November to March) and two transitional months (April and October) [29]. Nevertheless, Malaisse [30] has defined five seasons from phenological observations on vegetation: the cold dry season (May-July), the hot dry season (August-September), the early rainy season (October-November), the full rainy season (December-February) and the late rainy season (March-April). This pattern remains valid, although recent studies show a tendency to a later onset of rainfall and lower annual average rainfall [31]. The study area is crossed by a stream, the Kifumanshi River. During the second half of the last century, the average annual temperature was 20.1°C [6], though Kalombo [31] highlighted ongoing warming. The vegetation around Lubumbashi consists of wetland and remnant forest patches (miombo woodland or miombo; dense dry forest or muhulu; gallery forest or mushitu) in a matrix of savanna [32]. Ferralsols are the most dominant soil type in the study area [33]. As to population growth in the city, the annual growth rate is estimated at 4.6% based on statistics from 2000-2016 [34], while the national average urbanization rate is believed in the vicinity of 1.2% [35]. Mining activities are highly developed and give important socio-economic impulse to the study area. Within the savannization halo, shifting agriculture and traditional charcoal production are additional socio-economic activities of importance [36]. Furthermore, this area is prone to new housing demands without any consistent urban planning [37].

Materials

In order to detect land cover changes, the choice of adequate satellite images determines the success of the results to be obtained, as well as subsequent results interpretations [38]. The following cloud-free remotely sensed images, with a spatial resolution of 30 m, were analysed: Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images acquired on July 23, 2002, May 18, 2005, September 07, 2013 and Landsat 8 Operational Land Imager (OLI) acquired on August 25, 2017. All images were acquired during dry season in order to highlight the larger spectral differences between land cover classes, and to minimize the seasonal effect [39]. These images were analyzed using ENVI 4.5 and ArcGIS 10.0 software. Field survey data included ground control points and training zone, collected using Global Positioning Systems (GPS).

Methods

The Universal Transverse Mercator (UTM Zone 35 S), based on the WGS84 reference ellipsoid (World Geodesic System), was used as coordinate system. As there are unsystematic errors in available remote sensing data, geometric correction was needed to reduce the errors [40]. The images used in this study were geometrically corrected using a Landsat OLI image from 2017 as a reference. Forty randomly distributed ground control points were used to rectify satellite images. Root mean square error was limited to 0.5 pixels, in accordance with recommendation for studies of land cover changes [41]. A false color composite was applied by combining the green bands with those that best discriminate vegetation (near infrared and red bands) [17]. An unsupervised classification led to sixteen land cover classes that were grouped based on their radiometric and thematic similarity. This grouping was supported by our knowledge gained from field visits and verifications on old maps. However, a botanical inventory was also conducted to objectively separate shrubby savanna from miombo. Ninety training zones were recorded with a GPS in order to perform the supervised classification based on the maximum likelihood classifier [42] and integrated into a GIS to assess the accuracy of the supervised classification.
Traditionally, classification accuracy refers to the comparison of two datasets, one based on analysis of remotely sensed data, and the other based on reference information [43]. Using field data and geographical features available on land cover maps, an accuracy assessment was performed, and the results were obtained in a confusion matrix [9,40]. The Kappa coefficient, which indicates how the classified data matches with the field reference data, was calculated; values exceeding 60% are deemed acceptable [44].

A number of landscape metrics were employed to appreciate the changes in landscape attributes [2]: number of patches, class (total) area and total perimeter. Class (total) area depicts the relative abundance of each land cover type; number of patches is sensitive to landscape fragmentation; total perimeter is associated with landscape complexity [45]. Accordingly, these metrics make possible the assessment of landscape fragmentation, as well as the quantification of human impact [17]. The conversion between land cover classes was quantified using transition probability matrices, while spatial transformation processes were identified using a decision tree proposed by [46]. The input data for the decision tree include number of patches, class area and class perimeter between two dates, with the obtained variation allowing the identification of one of the following spatial transformation processes: aggregation, attrition, creation, deformation, dissection, enlargement, fragmentation, perforation, shift and shrinkage. In the case of anthropogenic landscape dynamics, the patches of natural classes will be characterized by attrition, deformation, dissection, fragmentation, perforation and/or shrinkage; the land cover associated to human activities display aggregation, creation, deformation, and enlargement and/or shift [12].

To differentiate fragmentation to dissection, $t_{obs}$ (ratio of class area at the first date/class area at the second date) was calculated with a threshold value set at 0.5 [17]. A value of $t_{obs} < 0.5$ is synonymous of fragmentation while a value of $t_{obs} \geq 0.5$ reveals dissection.

Results

Supervised classification and mapping

Five land cover classes have been selected, namely miombo (forest), savanna (grassland and shrub), wetland, waterbody (river, water reservoirs), and built-up-bare soil complex (built-up, bare soil, agricultural lands). The results of the confusion matrix showed overall accuracy values from around 91% to 96%. The Kappa coefficient varied between 90% and 95% (Table 1). These values suggest that the supervised classification carried out was reliable and that land cover classes have been generally well discriminated (Figure 1).

Table 1: Accuracy of supervised classifications of Landsat images from 2002, 2007, 2013, and 2017 supported by the maximum likelihood algorithm.

| Indices (%) | 2002  | 2007  | 2013  | 2017  |
|-------------|-------|-------|-------|-------|
| Overall accuracy | 90.8  | 95.3  | 94.6  | 96.2  |
| Kappa       | 89.7  | 94.2  | 93.3  | 95.4  |

Figure 1: Geographical location of the study area at the North part of Lubumbashi (White area) in the territory of Kipushi (limited with red line), Upper Katanga Province in the South-eastern part of the DR Congo.
It was shown that the land cover pattern within the savanization halo has changed greatly from 2002 to 2017 (Figure 2). The visual analysis globally revealed that the identified land cover classes have recorded, in terms of spatio-temporal pattern changes, a regression trend (loss of area) and progressive trend (gain in area). The built-up-bare soil complex, waterbody and savanna have expanded rapidly across the landscape, resulting in miombo and wetland loss (Figure 2).

**Table 2**: Transition probability matrices describing the conversion of area between 2002-2007, 2007-2013 and 2013-2017 according to the supervised classification of Landsat images. Data are expressed in percent of land cover class in the landscape with 1 percent corresponding to 4.07km². The values in bold correspond to the proportion that remains unchanged for each land cover between two dates.

|          | 2007/2002 | 2007/2013 | 2013/2017 |
|----------|-----------|-----------|-----------|
| Miombo   | 58.4      | 29        | 19.7      |
| Wetland  | 0         | 3         | 2.3       |
| Savanna  | 12.2      | 0         | 0.4       |
| Built-up-bare soil complex | 2.1 | 0 | 0 |
| Waterbody| 0         | 6.3       | 8         |
| Total    | 100       | 100       | 100       |

*Figure 2*: Land cover maps in 2002, 2007, 2013, 2017 based on the supervised classification of Landsat images supported by the maximum likelihood algorithm.
Conversion dynamics

Over all periods investigated in this study (2002-2007, 2007-2013 and 2013-2017), miombo was the most stable land cover class between 2002-2013, while savanna was the most stable class from 2013 to 2017. Between 2002 and 2017, 38.4% of the landscape occupied by miombo evolved to savanna, 2.1% to wetland, 0.9% to built-up-bare soil complex while 0.4% of the landscape leaned towards flooded zones. A further landscape change was noticed from 2013 to 2017, consisting in the transformation of savanna into a new landscape matrix. No tendency to miombo regeneration was observed in all periods studied within the savanization halo. A relatively large area of the landscape previously occupied by savanna was either flooded between 2002 and 2017 (2%) or invaded by built-up-bare soil complex (9.6%). Over the same period of time, the wetland zone lost nearly 86% of its total area. In fact, 14.1% of the landscape occupied by wetland has evolved to built-up-bare soil complex (6.1%) and waterbody (6.4%). The wetland regeneration within the savanization halo was almost nil. The built-up-bare soil complex has increased significantly at the expense of savanna and wetland, but also at the miombo expense to a lesser extent.

In summary, within the savanization halo, three situations have been observed. Firstly, a progression of the anthropogenic classes (built-up-bare soil complex, savanna) at the expense of natural classes (miombo, wetland), but also the interconversion between anthropogenic classes. Secondly, a progression of waterbody at the expense of savanna and wetland. Finally, almost no regeneration of miombo and wetland classes (Table 2). Clearly, current result demonstrated that the amplification of anthropogenic pressure no longer allows the regeneration of natural ecosystems within the savanization halo around Lubumbashi city (Figure 3).

Figure 3: Illustration of the land cover conversion dynamics within the savanization halo around Lubumbashi city, a landscape overexploited for charcoal production, agriculture, urbanisation and mining. Solid arrows refer to effective land conversion between land cover classes. Dashed arrows refer to absence of conversion.

Changes in landscape pattern and spatial transformation processes

Table 3: Synthesis of landscape metrics characterizing the studied area in 2002, 2007, 2013 and 2013. with n the number of patches and at the class (total) area (km²). Total perimeter did not interfere with the identification of spatial transformation processes observed in the context of this study and its values are therefore not presented.

|          | Miombo | Wetland | Savanna | Built-up-bare Soil Complex | Waterbody |
|----------|--------|---------|---------|-----------------------------|-----------|
| **2002** |        |         |         |                             |           |
| n        | 2111   | 4224    | 5420    | 1423                        | 603       |
| a_t      | 240.1  | 67.2    | 73.3    | 20.4                        | 6.1       |
| **2007** |        |         |         |                             |           |
| n        | 1753   | 3446    | 4393    | 1747                        | 628       |
| a_t      | 237.7  | 49.7    | 85.9    | 25.6                        | 8.1       |
| **2013** |        |         |         |                             |           |
| n        | 3301   | 1468    | 1798    | 2230                        | 924       |
| a_t      | 118    | 13.8    | 174.2   | 68.4                        | 32.6      |
| **2017** |        |         |         |                             |           |
| n        | 5889   | 1200    | 1842    | 2323                        | 945       |
| a_t      | 80.2   | 9.4     | 206.3   | 72.4                        | 38.7      |
Synoptic analysis of landscape metrics provided an overall summary of the savanization halo composition and configuration from 2002 to 2017. The number of patches and the total area of miombo decreased, suggesting patches attrition as spatial transformation process between 2002-2017. In parallel, the next period was characterized by a fragmentation and a dissection of miombo patches, respectively from 2007 to 2013 (t obs 0.44±0.5) and 2013 to 2017 (t obs 0.98±0.5), since the area decreased but number of patches increased. Between 2002-2017, wetland have experienced attrition as spatial transformation process marked by number of patches and total area decrease. The aggregation materialized by a decrease in number of patches accompanied by total area increase was characteristic of savanna between 2002-2013. From 2013 to 2017, the number of patches and the total area of the savanna class increased simultaneously, suggesting patches creation as the dominant spatial transformation process. Waterbody and built-up-bare soil complex creation was noted between 2002 and 2017 as the number of patches and their total area increased (Tables 3 & 4).

Table 4: Identification of spatial transformation processes within the savanization halo around Lubumbashi city 2002-2007, 2007-2013, 2013-2017 according to decision tree algorithm of Bogaert et al. [46].

| Land cover                        | 2002-2007         | 2007-2013         | 2013-2017         |
|-----------------------------------|-------------------|-------------------|-------------------|
| Miombo                            | Attrition         | Fragmentation     | Dissection        |
| Wetland                           | Attrition         | Attrition         | Attrition         |
| Savanna                           | Aggregation       | Aggregation       | Creation          |
| Built-up-bare soil complex        | Creation          | Creation          | Creation          |
| Waterbody                         | Creation          | Creation          | Creation          |

Discussion

Methodology

The assessment of landscape characteristics results from the Pattern / process paradigm, which is the central hypothesis of landscape ecology according to which landscape structures influence the ecological processes and vice versa [45]. The verification of this central hypothesis within the savanization halo was based on the analysis of four Landsat images with different selection criteria (i.e. cloud saturation (<10%) and seasonality) [39]. A supervised classification was conducted and generated a reliable level of accuracy.

Our study selected and tested landscape metrics referring to the number of patches, class area and total perimeter by land cover, which are considered as essential elements for landscape configuration characterization [2,25,47,48]. In addition, these metrics are considered as a strong indicator of human impact on landscape morphology [25,27]. In our study, few metrics were used because most are highly correlated [26]. The three metrics, coupled with decision tree [46] provide more information on spatial transformation processes underlying landscape dynamics and their potential drivers [2].

Anthropization of natural ecosystems within the savanization halo around Lubumbashi city: spatial dynamics and drivers

Around Lubumbashi city, rural people heavily rely on natural resources as source of wellbeing. Unsustainable exploitation of these resources is one of the root causes of deforestation [49], consequences of which result in very complex chain reactions [50]. Our results have revealed through transitions probabilities matrix that the savanization halo is dominated by savanization, urbanization, and deforestation. And concomitantly, the destruction of wetlands is leading to the flood of parts of the study area. These phenomena, caused by anthropogenic disturbances, have already been reported by other researchers in the same region [16,18,19,51]. In fact, direct drivers (i.e. slash-and-burn farming, charcoal production, lumber exploitation, uncontrolled wildfires...), as well as indirect drivers (i.e.: current demographic explosion), underlie spatio-temporal dynamics within our study area. The savanization halo could possibly be considered as an ecologically eroded landscape with some intrinsic characteristic’s loss (structure, composition, functionality and productivity). This could lead to recurrent fragility of ecosystems and living conditions [52].

Indeed, when agricultural land productivity decreases, populations are forced to migrate and explore new forest sites, where soils are deemed to be rich in nutrients that are essential to crops development [15]. Fookoor & Coffie [53] findings around Freetown (Sierra Leone) showed that about 14% of evergreen forest have been converted to agricultural land. Our results show that forest and wetland regression rate might have been underestimated [18,20]. This may result from spatial extent differences between study area, showing the importance of spatial scale in landscape ecology [2,54]. In certain areas around the city, spaces allocated for horticultural activities are such concentrated along wetlands that their expansion could explain, at least partly, the regression of wetland acreage. In particular, the disappearance of some wetland patches may be accompanied by lateralization resulting from the combined effects of high temperatures and abundant amounts of water on bare ferralitic soils [33]. Our results corroborate this trend and [55] confirmed the frequent flooding in neighborhoods where built-up have invaded wetland in Lubumbashi city. In addition, bare soil, where rainwater often remain stagnating, favors in some areas the proliferation of Anopheles mosquito larvae transmitting malaria [56]. The increase of waterbody area could also be in relation with the creation of fish ponds. In fact, owing to the current context of socio-economic crisis witnessed in Lubumbashi city and surrounding area, crop and animal production stands as a rescue activity for up to one third of households [57].

Our results reflect the general landscape dynamics tendency within the savanization halo, where peri-urbanisation linked with a rapid population growth induces an anarchic expansion of the city [58]. Lubumbashi city and its urban dwellers put a
big pressure on surrounding ecosystems [18]. In fact, there is a direct correlation between population growth and the demand for land, food and energy [10]. In addition, Kabulu et al. [59] reveal that the remnant forest patches in the Upper Katanga province are facing extreme pressure for charcoal production to meet the ever-increasing energy needs of the Lubumbashi city. Surprisingly, small motorized equipment, such as chainsaws, are the most commonly used tools for cutting trees which then will allow charcoal production. For this reason, Kabulu et al. [59] concluded that charcoal production is one of the main causes of forest fragmentation and degradation in the Upper Katanga province. Bangirinama et al. [60] also showed that the use of woody charcoal as energy source for urban population is a serious problem for forest cover conservation in Burundi. On another hand, the proximity of mining site could favor landscape anthropization due to economic opportunities for both urban and rural population [21].

Although the landscape is primarily composed by anthropogenic land cover classes, some forest patches still remain present and are potentially threatened by the lack of rigorous land use planning strategies [16]. Another manifestation of landscape anthropization and miombo forest degradation is the significant regression of trees diameter over time, which greatly affects ecosystem regeneration and long-term ecosystem services supply (i.e.: charcoal production) [12]. By reducing the patches area, simplifying their morphology and increasing their spatial isolation [46], the fragmentation of natural ecosystem services has completely altered the spatial configuration of the landscape in the savanization halo and can surely alter the evolution of biological diversity. Yet, many studies have revealed the importance of miombo species for food and other social needs of local populations [12,16,51,61].

Conclusion

The use of landscape ecology approach associated with remote sensing and GIS were useful for landscape spatial pattern change evaluation within the savanization halo. Current results show that the study area is facing a rapid and consistent spatiotemporal dynamic. Due to cutting wood for charcoal production that led to savanization, and the expansion of the built-up-bare soil complex, the miombo ecosystem is significantly decreasing from 2002 to 2017. Within the study area, wetland destruction has given way to bare soils that are regularly being flooded. The aforementioned changes were supported by five spatial transformation processes (i.e., dissection, fragmentation, attrition, creation and aggregation). Human activities have significantly altered natural ecosystems within the savanization halo, affecting their resilience. Although we already highlighted some processes and drivers linked with this landscape transformation, a need still subsists for better understanding the socio-environmental impact of charting and agricultural practices for long term landscape sustainability.

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