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Assessment of Land Use and Land Cover Changes (LULC) in the North Talihya River Watershed (Lubero Territory, Eastern DR Congo)

Moïse Musubao Kapiri[1,2], Jonathan Ahadi Mahamba[1,2], Gloire Kayitoghera Mulondi[1,2], Walere Muhindo Sahani[1,2]

[1]Laboratory of Ecology, Geomorphology and Geomatics (LEGG), Butembo, Democratic Republic of the Congo
[2]Department of Water and Forests, Faculty of Agronomic Sciences, Université Catholique du Graben (UCG), Butembo, Democratic Republic of the Congo
Email: musubaokapiri@gmail.com

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Abstract

On the Equator, the Talihya North watershed is a vast area of nearly 581.7 km^2 that extends from the Cool Highlands on the Congo-Nile Crest in Lubero Territory to the Rift Valley in the Virunga National Park in Beni Territory. This vast territory has an agropastoral vocation. Indeed, agricultural activities combined with the high population density in this watershed generate modifications in the landscape structure. The objective of this paper is to study the dynamics of land use from 1987 to 2020. To achieve this, two Landsat TM+ and ETM+ images and one Sentinel-2 image were analyzed. After the classification of the images based on the Maximum Likelihood algorithm, this study shows that two processes are evident in the landscape of the North Talihya watershed: deforestation and savannization. Forests that occupied 253.11 km^2 in 1987 have decreased to 201.12 km^2 in 2001 and to 123.04 km^2 in 2020. These area balances indicate that the natural forest formations in the North Talihya watershed have been converted primarily to croplands and fallows. The estimated annual deforestation rate between 1987 and 2020 is 2.18%. With this high rate of deforestation, mechanisms to restore degraded forest ecosystems in this watershed will need to be put in place. The sustainable management of residual forest ecosystems that have escaped human pressure is necessary for the conservation of biodiversity for future generations.

Keywords

Landscape, Deforestation, Savannization, Cool Highlands, Congo-Nile Crest

1. Introduction

Since the beginning of human civilization, humans have always lived in close relationships with nature. Although man's interdependence with the environment is greater than that of any other organism, his relentless pursuit of progress, comfort, and security have resulted in increased pressure on the environment, leading to changes in land use and cover over time (Jaiswal et al., 1999). Indeed, change in land use and land cover is a relatively recent addition to the focus of the international community because of its major role in the study of global change (Meyer & Turner, 1996; Reis, 2008).

Anthropogenic impact on the landscape has increased enormously in intensity and scale over the past few centuries, primarily through the expansion of agriculture, which has been the most significant historical change in land use and land cover (Butsic et al., 2015; Yang et al., 2014). Nearly one-third of the Earth's land surface is composed of croplands and pastures, and more than half of the cultivated area has been cleared in the past century (Reid et al., 2000). For example, it is estimated that the global expansion of croplands since 1850 has resulted in the conversion of some 6 million km^2 of forests/woodlands and 4.7 million km^2 of savannah/pastures/steppes. Within these categories, 1.5 and 0.6 million km^2 of croplands have been degraded, respectively (Lambin et al., 2001).

In recent decades, the conversion of grasslands, woodlands, and forests to croplands and pastures have increased spectacularly in the tropics (Reid et al., 2000; Song & Deng, 2017). During 1980-2000, more than 55% of new agricultural land in the tropics was developed at the expense of intact forests, while an additional 28% came from disturbed forests (Song & Deng, 2017). This acceleration has raised new concerns about the role of land-use change in the loss of biodiversity, soils and their fertility degradation, water and air quality, global warming and increased vulnerability to floods and droughts (Houghton et al., 2012; Lambin et al., 2001; Reid et al., 2000; Reis, 2008; Song & Deng, 2017; Talukdar et al., 2020), soil erosion, and landslide (Talukdar et al., 2020). In addition, land use and land cover activities are estimated to contribute 20% - 75% of all atmospheric emissions of important greenhouse gases (Houghton et al., 2012; Pielke et al., 2011; Reid et al., 2000).

These concerns have led to a large body of research on the causes and consequences of land use and land cover changes. Since the time of Malthus, many have supported the notion that human population growth leads to land scarcity and conversion of wildlands to agriculture and other uses, and thus to land use and land cover change (Falcucci et al., 2007; Lambin et al., 2001, 2003; Reid et al., 2000). Population growth can push the rural poor onto marginal lands. Despite its strong logic, population density and land use are not always linked, especially at the local scale; environmental change can occur with expanding, declining, or no population change (Reid et al., 2000).

With over 145 million hectares of tropical forests (Damania et al., 2016), the DRC is the second largest forest in the world (Damania et al., 2016; Ickowitz et al., 2015) and contains over 60% of the Congo Basin forest area. These forests are of global importance, as they represent the second largest carbon sink in the world (Damania et al., 2016). However, few studies have focused on the extent of deforestation in this country unlike other tropical countries (Ickowitz et al., 2015). Indeed, shifting agriculture has been identified as the main cause of land use change in the Democratic Republic of Congo (DRC) (Molinario et al., 2017; Molinario et al., 2020; Moonen et al., 2016). During the period 2000-2015, subsistence agriculture was the main driver of deforestation, both for the expansion of settled areas and for pioneer clearings removed from settled areas as less than 1% of clearing was directly attributable to land uses such as mining, plantations and logging (Molinario et al., 2020).

North Kivu is one of the provinces in the DRC with a significant area of tropical forest. Agriculture and livestock are the backbones of socio-economic development (De Marinis et al., 2021). Furthermore, with the exception of the city province of Kinshasa, North Kivu has the highest annual population growth rate in the DRC according to 2010 statistics and its population increased by more than 15% between 2010 and 2015. Consequently, agricultural activity, which is the main economic activity in North Kivu, has increasingly led to the loss of forest cover (Philippe & Karume, 2019).

The motors of deforestation in Lubero territory are similar to those mentioned in the tropical zone in general. Many areas of the North Talihya watershed are characterized by the rarity of wooded areas as a direct consequence of deforestation since the 18th century through the creation of croplands and pastures (Vyakuno, 2006). This watershed drained by the Talihya Nord River is located in the Lubero Highlands. These highlands are a typical case of overpopulation and are home to highly anthropized communities in the Lubero territory where the forest is receding in an alarming manner, particularly in the agricultural region that extends from Kyondo to Masereka. Forests remain only in the form of forest refuges or forest patches (Moïse et al., 2022; Vikanza, 2011; Vyakuno, 2006). These forest formations mark the anthropization in these environments. Some areas that have been deforested for centuries are struggling to evolve towards the mountain forest climax and remain at the savannah stage due to the climate and repetitive bushfires that slow down spontaneous reforestation and cause the phenomenon of savannization of the rift valley (Vyakuno, 2006).

Therefore, understanding observations of landscape mutations is crucial due to interactions with human activities (Jaiswal et al., 1999; Mama et al., 2013; Yang et al., 2014). Landscape dynamics may contribute to understanding the ecological processes taking place in the landscape. An intensification of anthropogenic pressure on natural resources due to poor cultivation practices has been observed (Bamba et al., 2008; Mama et al., 2013; Mamane et al., 2018). The study of landscape dynamics is increasingly essential for land management (Mahamba et al., 2022). It can clarify different tendencies of spatial transformation processes (Lambin et al., 2001) that are amplified by demographic pressures and overexploitation of available resources (Mahamba et al., 2022; Mama et al., 2013). In addition, the analysis of forest formation dynamics can also be part of global climate change mitigation initiatives and strategies (Mamane et al., 2018).

Remote sensing and GIS technique offer advantages for land use and land cover mapping and analysis of relevant changes (Fahad et al., 2020; Liu et al., 2002). The main advantages of remote sensing techniques include the capacity for repeatable coverage, an essential for global change discovery studies (Fahad et al., 2020). Therefore, this study relies on approaches that combine remote sensing and Geographic Information Systems (GIS). The objective of this paper is to evidence the spatio-temporal changes of forest formations in the watershed drained by the North Talihya River. The results of this research are of importance for the rational and sustainable management of this watershed. Moreover, these results are necessary for the prediction of probable evolution scenarios in the future.

2. Materials and Methods

2.1. Study Area

The study was conducted in the watershed drained by the North Talihya River (area 581.7 km^2). This watershed is situated in the province of North Kivu in the northeast of DR Congo (**Figure 1**). More than half of the watershed is located in the Cool Highlands of Lubero. These Cool Highlands of Lubero are called the high mountains or the upper stage of the Lubero Mountains range (Kasay, 1988; Vyakuno, 2006) because they are located between 2000 and 3100 m. They correspond to the tierras frias of the Lubero Mountains. They correspond to the tierras frias of the Andes according to Vyakuno (2006) if one adapts them to the staging of the climate and vegetation of tropical mountains proposed by Demangeot in 1976 and 1999. They have Precambrian schistose and granitic rocks and a dissected and steep hilly relief. Here, the temperature and rainfall averages, which would be of the equatorial type, are low because of the altitude: 15˚C to 17˚C and 1110 to 1330 mm. The forest here is specifically mountainous with orophilous species (Vyakuno, 2006). Dominating the rift valley of the Western Albertine Rift, the Cool Highlands are characterized by their high altitude, the age of their rocks, the steepness of their relief, the thickness and chemical poverty of their soils, the coolness of their climate and the specifically mountainous character of their forests. The relief of the Cool Highlands is the result of the Tertiary orogeny concomitant to the formation of the tectonic divide. This relief has a hilly, but very rugged appearance (Vyakuno, 2006).

The North Talihya River originates at the foot of Mount Kasongwere and flows northward to join the Semliki River. Its valley is excessively deep and V-shaped. The difference in elevation between its bed and the surrounding hills is about 300 m, according to De Heinzelin (1950). The North Talihya Valley and several other valleys in the Cool Highlands show an unmistakably youthful stage. The thalwegs are normally very deep and incised. The shaping of the slopes is intense. The slopes are steep. Landslides are not rare. Slope breaks and waterfalls

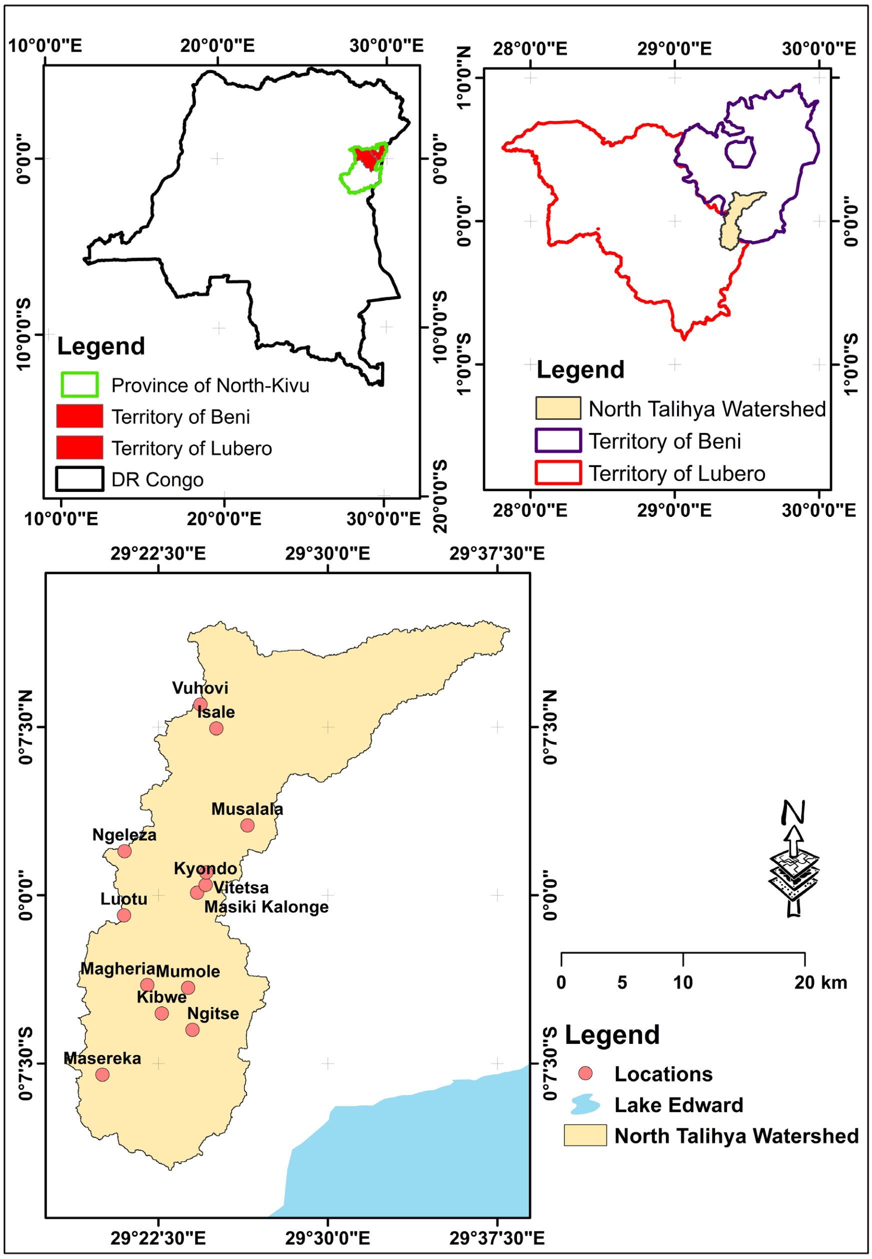

Figure 1. Location of the North Talihya River watershed.

are frequent, and the landforms themselves give a still irregular and disordered impression. This erosive capacity of the numerous rivers coupled with demographic pressure and unsuitable farming practices exacerbate the problems of soil water erosion (Vyakuno, 2006). The settlements in the Talihya North watershed are occupied by the *Nande*, who are the largest ethnic group in the Beni-Lubero region. They are traditionally known as *Yira*. The ethnic group is often considered dynamic because of its socioeconomic organization (Mirembe, 2005). The economy of the populations in the Talihya North watershed is based on subsistence agriculture, which is carried out by farmers using rudimentary tools such as the hoe and machete.

2.2. Methods

2.2.1. Data Acquisition

Satellite images were acquired from the Earth Explorer website (http://earthexplorer.usgs.gov) in geoTiff format by selecting those with the least amount of disturbance, including cloud cover. This site allows the downloading of earth observation data belonging to the US Geological Survey and NASA. It presents free of charge a very large collection of archival satellite images acquired with different generations of LANDSAT satellites (from July 23, 1972 to the present). The Radar (SRTM) images, essential for the delimitation of the studied watershed, have been downloaded from http://dwtkns.com/srtm. The characteristics of the satellite images used are presented in Table 1.

2.2.2. Image Pre-Processing

Landsat TM satellite images from 1987 and ETM$^+$ from 2001 and Sentinel-2 from 2020 have undergone various pre-processings. Several color compositions were performed in order to associate the bands that contain the maximum amount of information. The color composition for Landsat-5 TM images of 1987 and Landsat-5 ETM$^+$ of 2001, the color composition was made possible by combining bands 4 (red), 3 (green) and 2 (blue) while for Sentinel-2 of 2020, bands 8, 4 and 3 were used as red, green and blue respectively.

Subsequently, radiometric enhancements were applied to the images to increase the contrast of the images and facilitate their interpretation (Barima et al., 2009). Pixel resampling was performed when the images (Landsat and Sentinel-2) do not have the same resolution. This operation allows them to be superimposed when implementing the transition matrix. The nearest neighbor resampling method is the one adopted in this study. Indeed, this method uses the value of the nearest pixel without any interpolation to create the value of the rectified pixel. Therefore, the radiometric values of the pixels are not affected during resampling (Sangne et al., 2015).

Finally, the area of interest was extracted from the watershed limit. This extraction was done from the multispectral images obtained, following the North Talihya watershed limit by the "Resize data" tool in Basic Tools under ENVI 4.6 software. The creation of a mask was done after extraction of the study area to avoid that pixels outside the watershed could also be classified.

Table 1. Characteristics of the images used.

Sensor	Date of acquisition	Spatial resolution (m)	Path/Row	Projection
Landsat 5-TM	**1987**-08-07	30 × 30	173/060	UTM/WGS84, 35 N-S
Landsat 7-ETM+	**2001**-03-14	30 × 30	173/060	UTM/WGS84, 35 N-S
Sentinel-2	**2020**-06-01	10 × 10	-	UTM/WGS84, 35 N-S

2.2.3. Image Classification

In this study, the Maximum Likelihood algorithm was chosen for image classification. It assigns each pixel to the class to which it has the highest probability of being assigned (Brun et al., 2018; Katembera Ciza et al., 2015; Soro et al., 2013) by highlighting the standard error margin between pixel values and those of different training sites (ROI) (Solefack et al., 2012). This is thus a Bayesian approach to probability. The mean and variance are then estimated from the training sites. The preference for this method is its robustness in identifying spectrally close classes (Oszwald et al., 2010; Soro et al., 2013), which provides a good generalization capability (Soro et al., 2013). The classification of the 2020 Sentinel-2 image was done based on terrain data from the same year, while the classification of the 1987 and 2001 Landsat images was done in a retrospective and deductive way (based on the spectral similarity of the classes in the 2020 Sentinel-2 image), due to the impossibility of having terrain data for these years. In addition, to eliminate isolated pixels and homogenize the thematic classification, a 3 × 3 pixel filter was applied to the classified images.

For each land use unit, ROIs (training areas) were delineated away from the transition areas to avoid including mixed pixels that could be classified into two separate classes. Observations collected in the terrain identified four land use classes: 1) Forests (forest relics and forest plantations), 2) Savannahs, 3) Croplands and fallows, and 4) Bare lands and buildings (plowed fields, roads, buildings). By land use class, GPS points constituting training areas were used for verification/validation. These GPS points must have a spatial distribution over the entire study area. For Solefack et al. (2012), the mission terrain and/or ground-truth missions allow the validation of the boundaries of the different land-use units resulting from the interpretation and influence of the accuracy of the classification. In this phase, vectorization was performed on the classified images. These were transformed into a shapefile in order to determine the areas of each land use class.

2.2.4. Classification Accuracy

The accuracy of the classifications obtained in this study was evaluated through the use of a confusion matrix or contingency table. It highlights the confrontation between the results of the supervised classification and the reference data that represent the ground truth (Barima et al., 2009; Kaleba et al., 2017; Kyale Koy et al., 2019; Soulama et al., 2015). The Kappa index, producer accuracy, user accuracy, and errors of omission and commission were calculated from the confusion matrix. Overall accuracy characterizes the ratio of the number of well-ranked pixels to the total pixels surveyed (Adjonou et al., 2019; Kaleba et al., 2017). Cohen's Kappa index evaluates a confusion matrix against a matrix with randomly drawn values. A value of 0 indicates a similar match to that obtained randomly, while a value of 1 corresponds to perfect accuracy. For a Kappa index equal to 0.75, we can say that 75% of the pixels are not randomly classified. For a contingency table with more than two classes, the Kappa index is calculated as follows (Bekele et al., 2022):

$$K = \frac{N\sum_{i=1}^{r} Xii - \sum_{i=1}^{r}(xi + * x + i)}{N^2 - \sum_{i=1}^{r}(xi + * x + i)} \quad (1)$$

With r = number of rows in the matrix; Xii = number of observations in row i and column i (elements of the diagonal); $x + i$ and $xi+$ = represents the marginal total of rows r and columns i and N = number of observations.

The Kappa index, which ranges from 0 to 1 and reflects a higher level of agreement the closer its value is to 1. It is divided into five categories: very low agreement from 0 to 0.20; low agreement from 0.21 to 0.40; moderate agreement from 0.41 to 0.60; substantial agreement from 0.61 to 0.80; and near perfect agreement from 0.81 to 1 (Kundel & Polansky, 2003; Landis & Koch, 1977; Soro et al., 2013; Moïse et al., 2022). A study can be validated if the Kappa index is between 50% and 75% (Kaleba et al., 2017).

2.2.5. Change Detection

The classified images were transformed into a shapefile so that the areas of each land use unit could be determined. This made it possible to establish the transition matrix. It allows us to highlight the different forms of conversion undergone by the land use units between two dates t_0 and t_1, and to describe the changes that occurred in the North Talihya watershed. The transition matrix is in the form of a square matrix and consists of X rows and Y columns (Arouna et al., 2017; Avakoudjo et al., 2014; Ayena et al., 2017; Moïse et al., 2020). The number of rows in the matrix indicates the number of land use units at time t0 (1987), the number Y of columns in the matrix is the number of converted units at time t1 (2020), and the diagonal contains the areas of the units left unchanged (Avakoudjo et al., 2014; Ayena et al., 2017; Bamba et al., 2008). The transformations are done from rows to columns. The cells of the matrix contain the value of a variable that moved from an initial class i to a final class j during the period from t_0 to t_1. The column and row values represent proportions of the areas occupied by each land use class at the corresponding time (Ayena et al., 2017; Bamba et al., 2008; Moïse et al., 2022). **Table 2** illustrates the transformations that occur from rows to columns when computing a transition matrix.

Table 2. Transformation model when computing a transition matrix (Ayena et al., 2017).

Category i to time t_0	Category j to time t_1			Sum of the Eit0 of the rows
	Category 1 (j = 1)	Category 1 (j = 2)	Category 1 (j = 3)	
Category 1 (i = 1)	a (1, 1)	a (1, 2)	a (1, 3)	Σa (1, j), j = 1, n
Category 1 (i = 2)	a (2, 1)	a (2, 2)	a (2, 3)	Σa (2, j), j = 1, n
Category 1 (i = 3)	a (3, 1)	a (3, 2)	a (3, 3)	Σa (3, j), j = 1, n
Sum of the Ejt1 of the culumns	Σa (i, 1), i = 1, m	Σa (i, 2), i = 1, m	Σa (i, 3), i = 1, m	Σa (i, j), i = 1, m

The annual deforestation rate was calculated for the period considered. The standardized formula proposed by Puyravaud (2003) was used to calculate the annual deforestation rate (Ndavaro et al., 2021; Tankoano et al., 2016; Moïse et al., 2022):

$$T(\%) = \frac{1}{t_1 - t_0} \ln\left(\frac{S_1}{S_0}\right) * 100 \quad (2)$$

With S_0 = forest area in the initial year; S_1 = forest area of the final year; t_0 = exact acquisition date of the image for the initial year and t_1 = exact acquisition date of the image for the final year.

3. Results

3.1. Accuracy of Classifications

The overall accuracy and Kappa index values are excellent (above 75%). These values provide reassurance that the image classifications can be validated (**Table 3**).

For the year 1987, the commission errors for the bare lands and buildings class were 3.23% and 1.92% for the savannah class. For the same year, 0.43% of the pixels in the savannah class and 0.07% in the forest class were omitted (**Table 4**). For the year 2001, the percentages of commission errors in the land

Table 3. Accuracy of image classifications.

LULC	Year 1987		Year 2001		Year 2020	
	PA	UA	PA	UA	PA	UA
Savannah	99.57	98.08	99.98	99.41	95.66	78.11
Bare lands and Buildings	100	96.77	96.05	59.15	98.50	92.68
Crop lands and Fallows	100	100	95.11	33.82	75.24	26.33
Forests	99.93	100	92.77	99.93	90.57	99.74
OA	99.91		97.39		91.35	
Kappa Index	0.99		0.96		0.77	

Legend: PA = Producer Accuracy (%); UA = User Accuracy (%); OA = Overall Accuracy (%).

Table 4. Errors of commission (COM) and omission (OM) of image classifications (%).

LULC	Year 1987		Year 2001		Year 2020	
	COM	OM	COM	OM	COM	OM
Savannah	1.92	0.43	0.59	0.02	21.89	4.34
Bare lands and Buildings	3.23	0	40.85	3.95	7.32	1.50
Crop lands and Fallows	0	0	66.18	4.89	73.67	24.76
Forests	0	0.07	0.17	7.23	0.26	9.43

cover classes are high for the bare lands and buildings class (40.85%) and the croplands and fallows class (66.18%) (Table 4). The percentages of omission errors for the year 2001 are low. These values of percentages of omission errors are not such as to taint the results of the classification. For the year 2020, 24.76% of the pixels in the class croplands and fallows were omitted during the image classification compared to 9.43% for forests and 4.34% for savannahs. Commission errors are high for the discrimination of the croplands and fallows (73.67%) and savannahs (21.89%) classes from the other land cover classes (Table 4).

3.2. Land Use and Land Cover Dynamics

The evolution of land use between 1987 and 2020 demonstrates a regression of forests, an increase in croplands and fallows as well as savannahs (Figure 2). The land use and land cover maps are presented in Figure 3.

3.3. Detection of Changes: Transition Matrix between 1987-2001 and 2001-2020

Table 5 and Table 6 indicate the percentages of change (gains and losses) between the different land use classes between 1987 and 2020. As a reminder, the surface area of the North Talihya watershed is 581.7 km^2, so 1% corresponds to about 5.817 km^2. The analysis of the transition matrix between 1987 and 2001 (Table 5) demonstrates that the proportion of bare and built-up land increased from 33.5% in 1987 to 37.63% in 2001. A slight increase occurred in the “Fields and fallows” class whose proportion increased from 15.62% in 1987 to 17.14% in 2001. On the other hand, savannahs also increased from 7.24% in 1987 to 10.62% in 2001. Finally, forests decreased from 43.63% in 1987 to 34.60% in 2001.

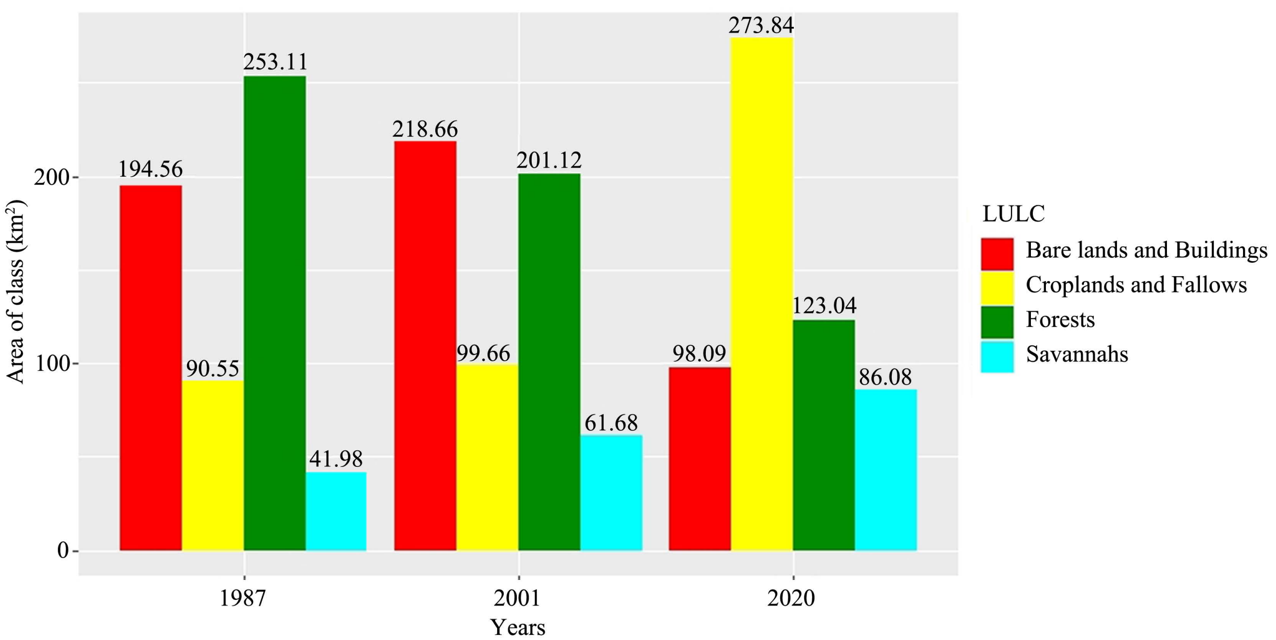

Figure 2. Observed change in land use classes in terms of surface in km^2.

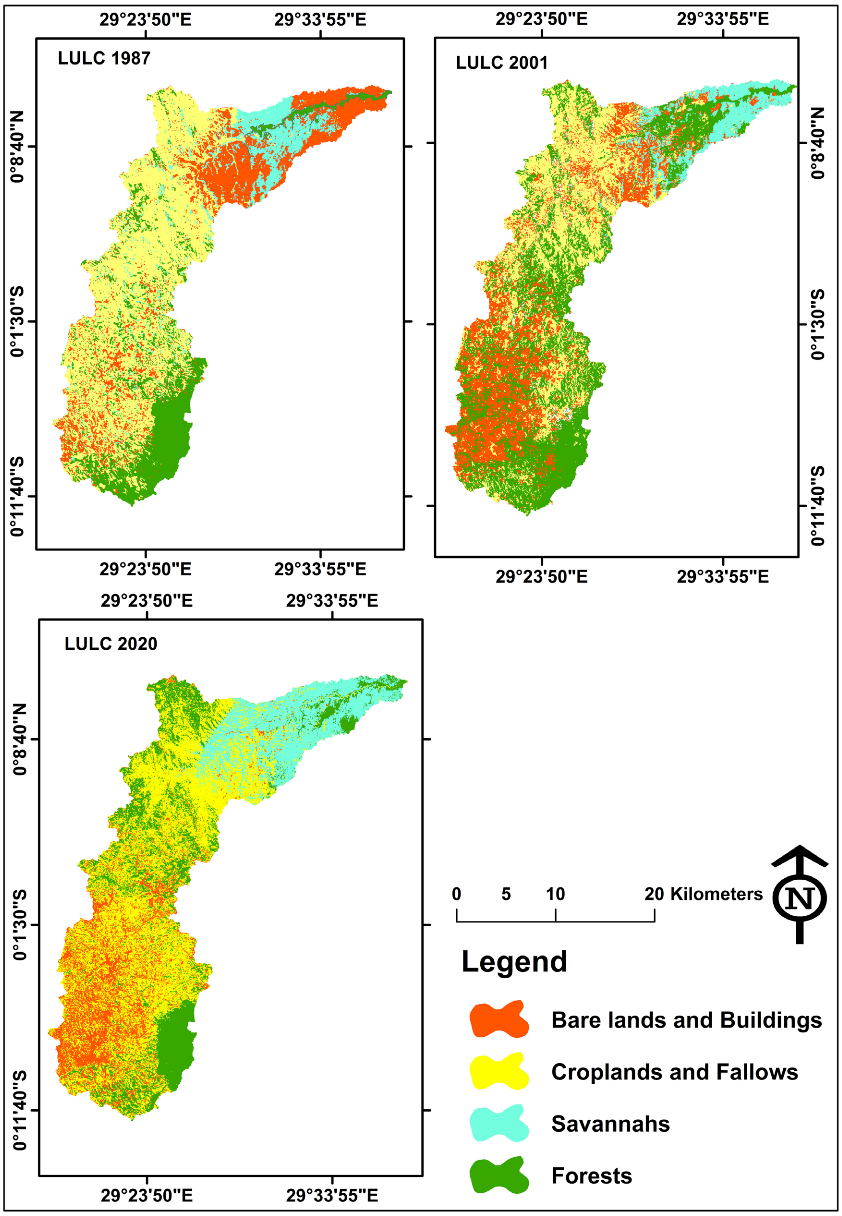

Figure 3. Mapping of land use and land cover (LULC) in the North Talihya Watershed between 1987 and 2020.

Table 5. Land use transition matrix in the North Talihya watershed between 1987 and 2001.

2001 \ 1987	Bare lands and Buildings	Crop lands and Fallows	Savannah	Forests	Total
Bare lands and Buildings	23.00	3.99	2.18	8.47	37.63
Crop lands and Fallows	2.56	8.56	0.15	5.87	17.14
Savannah	3.80	0.08	3.88	2.86	10.62
Forests	4.16	2.99	1.03	26.42	34.60
Total	33.52	15.62	7.24	43.63	100

Table 6. Land use transition matrix in the North Talihya watershed between 2001 and 2020.

2001 / 2020	Bare lands and Buildings	Crop lands and Fallows	Savannah	Forests	Total
Bare lands and Buildings	8.38	2.56	0.11	5.83	16.88
Crop lands and Fallows	18.38	11.09	1.72	15.96	47.16
Savannah	7.44	0.64	5.88	0.86	14.81
Forests	3.43	2.87	2.90	11.96	21.16
Total	37.63	17.14	10.62	34.60	100

The change matrix between 2001 and 2020 (**Table 6**) reveals that fields and fallows have almost tripled from 17.16% in 2001 to 47.16% in 2020. On the other hand, grassy savannah increased from 10.61% in 2001 to 14.81% in 2020. In the same way as between 1987-2001, forests decreased between 2001 and 2020 from 34.61% (2001) to 21.16% (2020). Indeed, of the 37.63% of the landscape occupied by bare and built-up land in 2001, 8.47% was forest in 1987. Of the 17.14% of the landscape occupied by fields and fallow land in 2001, 5.87% was forest in 1987.

From the transition matrices (**Table 5** and **Table 6**), two processes of transformation are observed: the decrease in forest areas accompanied by an increase in crop lands and fallows, and the savannahization of certain areas. The first process is deforestation. Of the 17.14% of the area occupied by croplands and fallows in 2001, 5.87% came from the conversion of forests in 1987. Similarly, it can be seen that between 2001 and 2020, 15.96% of the forests were converted into croplands and fallows. The second process is the savannahization of certain areas. Between 1987 and 2001, 2.86% of forests were converted to savannahs. From 2001, savannahs increased from 10.62% to 14.81% in 2020.

The annual deforestation rate calculated from the forest areas at date t_0 (1987) and t_1 (2020) is 2.18% in the North Talihya watershed.

4. Discussion

4.1. Validation of Classifications

The Maximum Likelihood classification algorithm performed well. The preference of this classification algorithm is due to its qualities related to its robustness in identifying classes that are spectrally close enough (Oszwald et al., 2010; Soro et al., 2013), which provides a good generalization capability (Tente et al., 2019). It has performed well in the work of several authors (Soro et al., 2013) by the fact that it assigns each pixel to the class to which it has the highest probability of belonging by highlighting the standard error margin between pixel values and those of different training sites (ROI). Furthermore, the application of this supervised image classification with four classes for the North Talihya watershed yielded very good Kappa index values (above 75%) based on the rating scale proposed by Landis and Koch (1977). Thus, the Kappa index values obtained in this study are in the range of 0.75 to 1 which is estimated to be satisfactory in maximum likelihood assisted classification for the tropical environment (Sangne et al., 2015). Given the complexity of the landscape in this watershed, such a result can be explained by the quality of the images and the choice of thematic classes and training areas guided by ground truth. In addition, the use of the 2020 Sentinel-2 high spatial resolution image also contributed to the improvement of the classification quality. According to Adjonou et al. (2019), the Sentinel-2 image has better performance in discriminating land cover types.

Although Cohen's Kappa index is widely used in work on land use dynamics for classification validation (Barima et al., 2009; Kyale Koy et al., 2019), it is the subject of much criticism related to its excessive use. According to Golden (2006), the Kappa index is normally used in the case of systematic, random sampling. Nevertheless, despite opinions tending to question the quality of the precision provided by Cohen's Kappa index, no index has yet been able to validly replace it in terms of evaluating and validating the results of supervised classification of the various land use units (Agbanou, 2018).

4.2. Land Use Dynamics and Deforestation Rates in the Watershed between 1987 and 2020

Land use and land cover maps were used to assess the dynamics of land use and forest cover across the watershed between 1987 and 2020. The annual deforestation rate between 1987 and 2020 was estimated at 2.18%. The annual deforestation rate in the North Talihya watershed is comparable to the estimate obtained by Ndavaro et al. (2021) who found an annual deforestation rate of 2.2% in the Lubero Cool Highlands. A similar deforestation rate was obtained by Bweya et al. (2019) of 2.7% in the Beni region, which contains part of the Talihya Nord watershed. In the South Talihya watershed, Moïse et al. (2022) found a deforestation rate of 1.6%, which is lower than the rate obtained in the North Talihya watershed. The values of annual deforestation rate estimated at the level of two watersheds in this study are much higher than those obtained in the Congo Basin. Ernst et al. (2012) note that the deforestation rate in the Democratic Republic of Congo doubled from 0.15% in 1990-2000 to 0.22% in 2000-2005. While the annual deforestation rate between 1984 and 1998 was about 0.4% (Debroux et al., 2007) compared to a tropical deforestation rate averaged 0.6% per year between 1990 and 1995, an annual loss of nearly 14 million ha (Hervé et al., 2015). Around the Yangambi Biosphere Reserve, Kyale Koy et al. (2019) estimated the annual net deforestation rate at 0.18% while a value of 0.13% was obtained by Katembera Ciza et al. (2015) around the Yangambi Biosphere Reserve. In this context, Debroux et al. (2007) believe that an average hides strong disparities between regions. But also, the divergence of data sources and processing methods, added to the difficulties of collection and harmonization, often lead to notable differences in the different assessments of deforested areas (Hervé et al., 2015).

4.3. Land Use Change in the North Talihya Watershed

4.3.1. Deforestation

The analysis of changes in land use units in the North Talihya watershed has evidenced the different evolutionary processes that have occurred in the landscape during the period 1987-2020. These changes are mainly related to the regression of natural formations (deforestation process) such as closed forest formations in favor of crop-fallow mosaics and bare lands and buildings that have experienced an increase in their area. The most common factors cited as having strongly contributed to the reduction of forest areas are inappropriate agricultural practices, logging and charcoal production, and wildfires (Vyakuno, 2006; Adjonou et al., 2019; Mulondi et al., 2019; Moïse et al., 2022). In the North Talihya watershed, the manifestations of these factors are increasingly felt with the ever-growing population in the area, increasing needs tenfold and increasing pressures on natural resources (Vyakuno, 2006). In the Lubero highlands, where more than half of the North Talihya watershed is located, population density is high and varies with altitude (Kasay, 1988; Vyakuno, 2006). According to these authors, between 1200 m and 1500 m, the density is 42 inhabitants per km^2, between 1500 m and 1800 m, it reaches 88 inhabitants per km^2, between 1800 m and 2100 m, the density is 107 inhabitants per km^2 and between 2100 m and 2400 m, the density reaches 200 inhabitants per km^2. However, most of the Talihya watershed is made up of dense settlements located between 2000 and 2500 m in altitude (Vyakuno, 2006). This trend is similar to that observed in the province of Bas-Congo/Kongo Central (D.R. Congo) where studies conducted on the influence of anthropogenic actions on the spatio-temporal dynamics of land use had revealed such a demographic boom that occurred mainly at the expense of vegetation cover (Bamba et al., 2008). In addition, several other authors, notably Lambin et al. (2001), Lambin et al. (2003), Mégevand et al. (2013), Gillet et al. (2016) and Katembera Ciza et al. (2015), have also blamed population growth and certain modes of exploitation as the main culprits of land degradation resulting in the disruption of ecological stability. This is a particularly notable phenomenon in sub-Saharan Africa where high population densities and the crisis of agricultural space lead populations to seek new land for survival. The increase in cultivation areas and settlements or any changes in surface conditions have repercussions on the water resources of the environment (Chishugi et al., 2021).

4.3.2. Savannahization

The analysis of land use and land cover shows a process of savanization in the North Talihya watershed. Savannahs that occupied 41.98 km^2 in 1987 compared to 61.68 km^2 in 2001 and 86.08 km^2 in 2020. The savannahization of certain areas in the Cool Highlands of Lubero has been and still is the focus of interest for many researchers. According to Vyakuno (2006), the vegetation of the Lubero rift valley remains in the savanna stage not only because of the climate, but also because of the repetitive bush fires. These fires slow down or prevent spontaneous reforestation and cause the savannahization of the rift valley (Lebrun, 1947). The savanna of the plain, regularly maintained by fire, has become a pyroclimax or fire-climax (Lebrun, 1947). Fire favors the development of pyrophilous plants, which now constitute an evolutionary stage that the environment can no longer surpass. These pyrophilous plants are succulent plants and grasses with clumping tufts such as *Aristida* and *Eragrostis* (Lebrun, 1947). The savanna, artificially maintained by fire, favors savanna herbivores, such as antelopes, to the detriment of other herbivores, such as elephants, that like bushes (Lebrun, 1947). The same phenomenon can be encountered in high altitude regions.

In addition, some savannahs observed in the cool and warm highlands appear to be a consequence of human action. While recognizing the influence of climate and soil on their presence, these formations seem to be the result of human action, in this case burning and plowing practiced for centuries. For example, Vyakuno (2006) observed several anthropogenic savannas in the highlands of South Kivu. Their main cause is a fire set by man: Biotic grassland occupies any soil at any age when the fire has destroyed the indigenous vegetation. The destruction of this flora has occurred in multiple degrees with equivalent regressive stages. In the Lake Kivu basin, Vyakuno (2006) also attributes certain grasslands and savannahs to man, wind and cattle. This author reports that human actions have created grasslands or savannahs throughout, and the clearing of hilltops has been made permanent by the action of wind and livestock. These observations seem to apply to certain savannahs in the highlands of Lubero. In the location of these savannahs, there was initially a forest. This would have been cut down by man to install crops or pastures. Burned regularly to maintain the pastures or to clean up the dead vegetation from the brushwood, these formerly forested lands would have been eroded by runoff water. The soil would have been degraded and would currently struggle to return to a forest climax. **Figure 4** below demonstrates a hill dominated by a fern savannah *Pteridium aquilinum centrafricanum* east of Masereka locality in the North Talihya watershed.

Figure 4. Savannahization process: fern-dominated hills of the species *Pteridium aquilinum centrafricanum* east of Masereka locality in the North Talihya watershed (Picture K.G. Mulondi, August 2021).

These slopes, with a few scattered woody plants in an environment that would allow forest development, would probably be of anthropogenic origin. Indeed, in the highlands, fallows spread over several years is generally conquered by bush, that is, by a vegetation formation consisting of grasses, shrubs or small trees. Bush is not a climax. It results from the degradation of the forest and prepares its reconstitution. The absence of woody plants on an entire hillside in a zone that is supposed to be forested leads us to assume that the vegetation is very advanced. According to Vyakuno (2006), such a phenomenon is recurrent in highly anthropized tropical mountains. Furthermore, Vyakuno (2006) notes that mountain vegetation recovers only slowly because of the cold. Deforestation has thus led to a generalized savannization of the mountains: where there was a forest, there are now, in addition to crops, large slopes covered with very ordinary grasses or ferns. If this process is not controlled, its exacerbation can trigger the desertification process. It appears that many regions in the tropical zone have undergone this process of savannization. In the highlands of Bamenda in Cameroon, Ndenecho (2005) also noted this phenomenon that reduced the natural dense mountain forests to a xerophilic environment. According to the same author, pyrogenic and anthropological factors were at the origin and maintenance of the savannahs of Bamenda. This article led to the conclusion that savannahization is a manifestation of poor natural resource management in mountain regions (Ndenecho, 2005). In the heart of the Indonesian rainforests, Riswan & Hartanti (1995) noted a process of savannization due to population growth inducing a decrease in forest reserves that had forced shifting cultivators to extend the cropping period and shorten fallow beyond tolerated levels, usually accompanied by repeated brush fires. This has led to a progressive savannahization of tropical forest areas with an expansion of areas dominated by *Imperata cylindra* (Riswan & Hartanti, 1995). These observations fit well with the arguments that are put forward to explain savannization in the North Talihya watershed. In this watershed, the extension of savannas is located in the rift valley where the vegetation is regularly subjected to fire (Pecrot & Leonard, 1960).

Many other works have made projections that have inferred the savannization of tropical forests (Collevatti et al., 2011), with the expansion of savanna-like vegetation in South America. A number of studies based on the fossil pollen record now available show that during the Early Holocene period, the climate was drier in most South American savannas and the distribution of savanna-like vegetation in central and southeastern Brazil was more extensive in the Early Holocene than in the Late Holocene. Indeed, the fossil record shows that the expansion of savanna in the Quaternary, particularly in southeastern Brazil, was characterized primarily by herbaceous savannas that were favored by the drier and highly seasonal climate (Collevatti et al., 2011). In an article based on the analysis of Landsat TM images covering 3.9 million/km^2 of Amazonian forests, Nelson (1994) reported natural changes and disturbances on the scale of decades to centuries: deforestation and savanization. This author reports that 600 km^2 of sub-climax fern savannas were created by the Yanoama Indians. It follows from the different works that the process of savannization in tropical mountain regions is mainly of anthropic origin (Ndenecho, 2005; Nelson, 1994; Riswan & Hartanti, 1995).

5. Conclusion

This study is based on the use of open access spatial data and GIS for the diachronic analysis of land use in the North Talihya watersheds in eastern DR Congo. It revealed that in the North Talihya watershed, natural forests have disappeared and have been converted into cropland and fallows. Due to the high population density in this mountainous watershed, the rate of deforestation is higher than the national average in DR Congo. In addition, in this area, a process of savannahization is observed in some areas. In this context, all actors concerned with sustainable development and the rational use of fragile natural resources should pool their efforts to consider mitigation strategies that are compatible with local customs and that reconcile holistic approaches to sustainable development. The Cool Highlands of Lubero territory will thus recover their vocation and continue to play their long-standing role as the granary of the DRC.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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