

Forest cover affects gully expansion at the tropical watershed scale: Case study of Luzinzi in Eastern DR Congo



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ABSTRACT

This study aimed at assessing the land use and land cover change and its effect on the gully expansion in an agricultural and woodland tropical watershed. We used the case study of Luzinzi watershed in South-Kivu, eastern Democratic Republic of Congo (DRC) where gullies are in development. We used very high-resolution (VHR) images downloaded from Google Earth and unmanned aerial vehicles (UAV) images. ArcGIS 10.7 software helped for spatial analysis and images georeferencing while ENVI 5.3 tools were used for classification. The gullies were then digitized and characterized to determine their width, length, depth, surface and volume. The digital elevation model (DEM) was used to determine the contributing area as well as the slope at the gully headcut. The land use at the headcuts and in the gully was extracted from the different land uses obtained from classified images and validated by field measures. Results showed significant changes in land use and land cover throughout the watershed; changes that affected gully expansion. From 2011 to 2020, number of gullies passed from 38 to 201. These gullies were increasing not only in number but also in characteristics such as gully length and headcut. Their volumes increased from year to year in the same trend as woodland and forest reduction. Forest played important role in gully stabilization: gullies located in forest presented a linear retreat rate (~ 4.6 m) than those in other land uses (~ 2.4 m) from 2010 to 2020. The forest cover reduced gully surface at linear rate while the depth rate still increased. A forest cover of $\sim 10\%$ led to a gully expansion of ~ 700 m³ yr⁻¹ and reduced to 300–400 m³ yr⁻¹ with 30% forest coverage. Thus, forest cover at the gully headcut and in the contributing area helped to stabilize gullies. The permanent maintenance of forest and woodland covers as well as the reduction of anthropogenic activities in gullies are to be promoted at the watershed scale along with other measures to contribute to effective land resource management in the region.

1. Introduction

Like for many other developing countries across the world and in the African continent in particular, significant changes in terms of land use and land cover (LULC) have been observed (Moore et al., 2012; Aleman et al., 2016). In Democratic Republic of Congo (DRC)'s provinces and mostly in the eastern part, such changes are increasingly experienced. Anthropogenic activities coupled with a rapidly increasing population (the eastern DRC's provinces having the country highest population growth rates and densities) led to rapid deforesta-

tion for cultivation, livestock rearing, wood products, and settlements (Bagalwa, 2006; Karamage et al., 2017; Lukongo, 2018; Chuma et al., 2020). Furthermore, other deforestation causes are related to armed conflicts and mining (Lukongo, 2018), natural disasters such as landslides (Depicker et al., 2018) and volcanic eruptions (Phillipe and Karume, 2019). Some changes are short term and of exploitative nature while others maybe long term and stable (Phillipe and Karume, 2019; Shapiro et al., 2021).

Studies focusing on forest cover in eastern DRC were conducted using indirect methods as direct measurement technologies were lacking. Hence, outcomes of estimates of forest cover and degree of deforesta-

Abbreviations: DRC/DR Congo, Democratic Republic of Congo; LULC, Land Use and Land Cover; UEA, Université Evangélique en Afrique; UAV, Unmanned Aerial Vehicles; VHR image, Very High Resolution images; LRM, Land Resources Management; GER, Gully Expansion Rate; GRR, Gully Retreat Rate.

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tion varied greatly. Despite the importance of land-cover data for land-resource managers and decision-makers in resolving conflicts that often arise between the ways humans use natural resources and the ecosystem functionality, no reliable LULC information exists in South-Kivu territories. In such a case, the use satellite images with high to very high spatial resolution, aerial photographs and unmanned aerial vehicles (UAV) images could contribute much in generating reliable data on territorial LULCs for different time periods. These data could then be used for planning appropriate land resource management (LRM) in South-Kivu province (Luehtje et al., 2014; Kranz et al., 2017).

Soil erosion caused by runoff water is the most important land degradation in the world and particularly in tropical regions (Borrelli et al., 2020). It first appears under the form of sheet erosion which develops in rills and gully erosion (Mararakanye and Sumner, 2017). Gullies have been identified as one of the most impacted soil depletion (Poesen et al., 2003). They cause severe damage to either forest, pasture and mostly agricultural lands in rural areas and constructions (bridges, buildings, roads) in urban environments. Thus, gully erosion is a critical issue worldwide (Poesen et al., 2003; Ben Slimane et al., 2016; Mararakanye and Sumner, 2017).

Evidence links between LULC and gullies expansion have been studied in many regions; from Spain (Lesschen et al., 2007) to Brazil (De Oliveira et al., 2020), Ethiopia (Nyssen et al., 2006), India (Galang et al., 2007; Jahantih and Pessaraki, 2011) and South Africa (Podwojewski et al., 2020). These researches reported that LULC plays an important role in the formation, expansion, or retreat of gullies. In fact, Lesschen et al. (2007) reported that the potential vulnerability of lands in Spain was increased by different land use and land cover scenarios. Morgan and Mngomezulu (2003) showed that changes in terms of land use and land cover (LULC) and particularly conversion of forest to agricultural lands accelerated erosion. This is much pronounced with factors like slope and rainfall. In terms of gully erosion parameters, studies showed significant seasonal differences (Hu et al., 2009). Thus, to correctly understand the association between environmental data (such as climate, vegetation cover, etc.), soil erosion susceptibility and land uses remains a challenge in LRM.

Most research conducted on gullies in DRC focused mainly on urban areas, and thus little evidence exists on gully expansion, retreat, and characterization in rural areas. In eastern part, deforestation and grassland conversion to agricultural land and other anthropogenic activities (artisanal mining, stone quarry, brickmaking, etc.) have strongly increased the rate of land degradation and soil erosion (Chuma et al., 2021). These processes are aggravated by inappropriate cropping and tillage systems (Karamage et al., 2016; Heri-Kazi, 2020; Heri-Kazi and Bielders, 2021). Benefits of tree planting in and around gullies for reducing sediment yields and flood discharges were demonstrated; the tree cover in the gullies is better and denser than that on the flat ridges and the slopes (Li, 1992). Erosion processes are described and presented as the major causes of food insecurity among smallholder households in the Kivu region but the causes or the prevalence of erosion phenomena are not quantified (Tollens, 2004; Bisimwa et Mambo, 2009). It thus appears that the occurrence of erosion in the Kivu region is currently well recognized, but with little scientific data regarding the actual state of the phenomenon. The causes, processes, prediction and control of all erosion types have attracted the interest of many researchers in different environments and particularly in DRC (Makanzu et al., 2014; Ilombe, 2019; Lutete, 2019). Most of them have focused on characterization of urban area gullies, their characteristics and impacts. Up to now, no research has focused on gullies developed in rural areas and how a factor such as the land use and land cover affects its expansion.

Studies on LULC changes at the watershed scale are rare in South-Kivu province and in Walungu territory in particular. The few studies that have been undertaken are in agreement with the general assumption of massive deforestation, a significant decline of forest cover and rapid increase in bare soils, settlements and agricultural lands in the area (Bagalwa, 2006; Bahati, 2020).

The effect of land use and land cover changes on soil degradation and surface runoff's empirical studies are limited in South-Kivu. Firstly, these processes require the knowledge and monitoring of several parameters and, therefore, obtaining data implies a high cost, time, and logistics; which are limiting factors. Secondly, such study does not seem to interest decision-makers and scientists in the zone. In such a case, remote sensing coupled with local field data could allow studying these processes with limited expenses. Freely accessible satellite images and UAV images can be used to fill gaps in data collection at small scales. However, they require validation in the field. Remote sensing is increasingly used but generally restricted to visible forms of erosion, i.e., gullies (Vrieling, 2006). Photogrammetric or structure from motion technologies also allows quantification of erosion (Di Stefano et al., 2017; Pineux et al., 2017), although monitoring of interrill or even rill erosion requires very high-resolution (VHR).

Despite its importance, there is a lack of knowledge regarding the relationship between the land use and land cover changes and the gully erosion development at the microscale (such as watershed) in eastern DRC. The scale is a critical issue in soil erosion research because it influences our understanding of the factors to be accounted for in the model development (Cotler and Ortega-Larrocea, 2006). Understanding the scale at which soil erosion occurs is also important in a policy context because it defines the institutions and the kind of public policy needed. As commonly acknowledged, it is very difficult to understand broad-scale soil erosion processes without studying those occurring at a smaller scale. For sustainable LRM in the integrated approach, analysis and management at the watershed level has to be promoted (Mekuriaw, 2017).

In this study, we focused on Luzinzi watersheds located in Walungu territory, eastern DRC. It is representative of other watersheds of the country, with significant economic importance at the territorial scale. Indeed, it extends to the Kaziba chiefdom that is one of the main production areas for firewood, timber, embers, and other wood products. In its northern part, it extends to one of the most important gold mining sites of the province (Birhejira et al., 2014). Unfortunately, not much information or scientific evidence exists regarding erosive processes and gully expansion in this area. Local findings and perceptions seem to show significant development of rill and gully processes. With an increasing population, agricultural production, and other human activities, soil erosion is becoming a more serious threat in the area (Mali, 2020).

Thus, the objectives of this study were to (a) examine the land use and land cover changes in the Luzinzi watershed; (b) determine some morphological and hydrological characteristics of the watershed that may affect the runoff process; (c) characterize gullies in the Luzinzi watershed from 2010 to 2019 using very high resolution satellites images, UAV and field measure data; (d) evaluate the effect of woodland and forest cover on gully expansion in the watershed.

2. Materials and methods

2.1. Study area

a) Location

This study was focused on the Luzinzi watershed located in Walungu territory, in the province of South-Kivu, eastern DRC. The Luzinzi watershed is between 28°46' and 28°48' East (Longitude) and 2°45' and 2°58' South (Latitude). It has a surface area of 154 km² (Fig. 1) and extends to four chiefdoms: Kaziba, Ngweshe, Luhwindja, and Bafulero. However, a large part of the Luzinzi watershed is located in the Kaziba chiefdom (Ganza, 2018). Although belonging to the Ulindi River basin, it throws its waters into the Ruzizi River and, is therefore, part of the great Ruzizi watershed.

a) Topography and soils

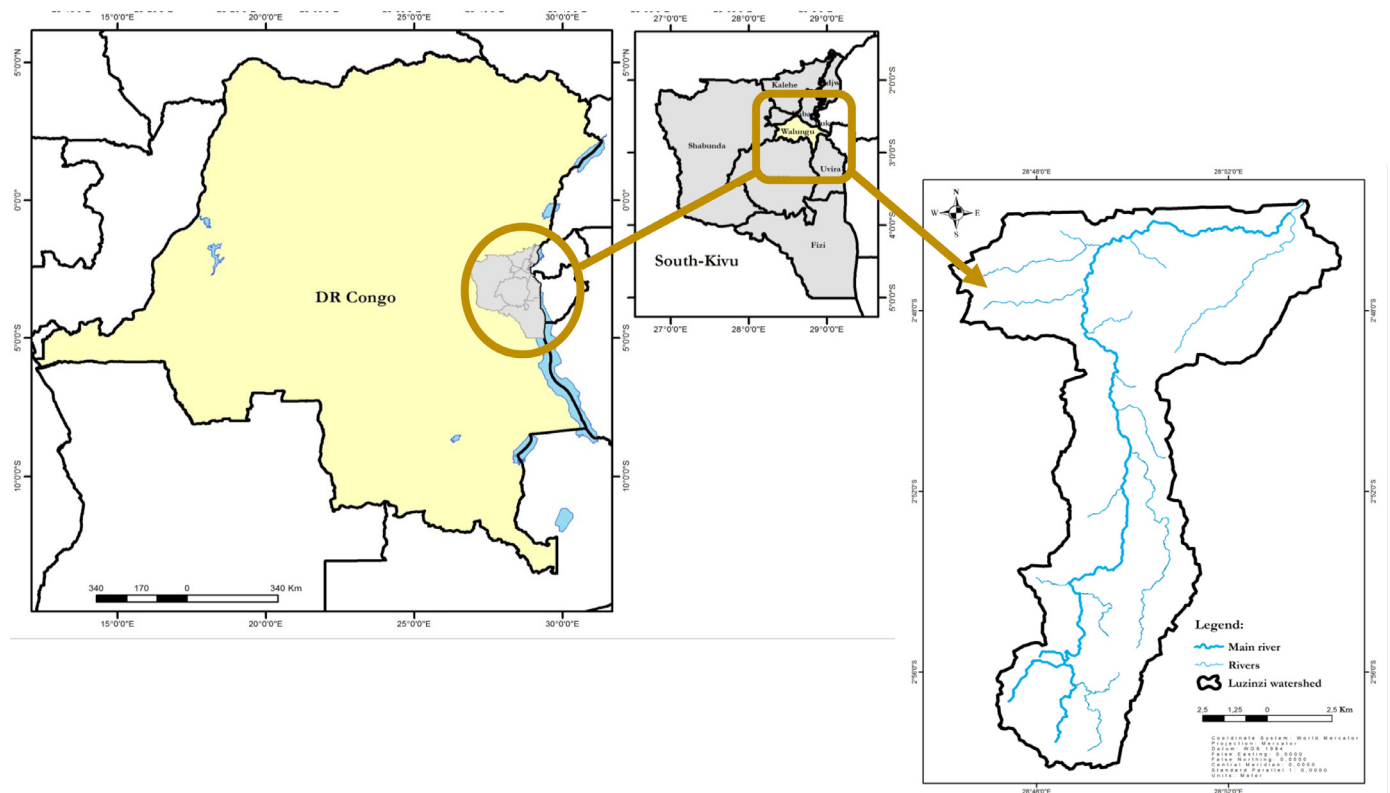


Fig. 1. Luzinzi watershed in Walungu territory, South-Kivu province, Eastern DR Congo.

Luzinzi watershed and the Kaziba chiefdom extend over the high mountains of the central African Graben to the east of the Congo River, at an altitude ranging between ~1500 and ~3200 m above sea level. The Fig. 2 shows the slope classes and elevations (in m) generated using digital elevation model (DEM) (of 30 m resolution). The region is dominated by elevations above 2000 m (70%). However, steep slopes (30%) are dominant while lowlands, inland valleys, and wetlands appear in the watersheds' center. This is referred to as the Luzinzi wetland that is named after the main river.

Concerning the soil, three soil types dominate the watershed. Ferralsols are the most dominant, and therefore, more used for agriculture and agroforestry. They are mostly found at the center and the southern side of the watershed. Cambisols are found in the north and west of the watershed in small proportion. Acrisols are found in the west and at the watershed downstream towards the outlet (in the Ruzizi plain). All these soil units are generally susceptible to erosion as they have low structural stability, low organic matter content and thus high erodibility (Heri-Kazi and Biielders, 2021). Few studies have focused on studying the distribution of these soils on a watershed, territorial, or provincial scale. However, the data and map presented in "Soil and Terrain Database for Central Africa" (SOTERCAF) showed the same trend in chemical and physic properties (Batjes, 2007; Batjes, 2008).

a) Climate and vegetation

The study area is under a humid tropical climate influenced by elevation and characterized by two seasons: the dry season going from June to August and the rainy season covering September to May. The average annual temperature is ~19 °C in the south and ~10 °C in the north. The average annual rainfalls are ~1200 to ~1700 mm. Fig. 3 presents the meteorological data of the watershed from 2000 to 2019. These data are presented daily (a) and annually (b).

Vegetation is dominated by grassland and shrub savannah in high altitude. Above ~2200 m altitude, there are mountain and bamboo forests. The study area borders the Natural Reserve of Itombwe (RNI) in

the western part. Thus, part of the forest found in the zone is an extension of this reserve. *Pinus*, *Eucalyptus*, and *Grevillea* woodlands are also found throughout the zone.

a) Hydrography

The hydrography of the area is generally rich in rivers, streams, and springs. Luzinzi watershed is drained mainly by a large Luzinzi River and other small rivers such as the Lushinji River, Mugusa River, Kazinzi, Kiko, Chishi, Shaliro, Mugaba, Ntyazo, and Nachibundo flows.

2.2. Methods

2.2.1. Luzinzi watershed morphological and hydrological characteristics

Hydrological and morphological parameters were collected to characterize the Luzinzi watershed. We used the digital elevation model (DEM) to found or extract some parameters. These parameters helped us to understand some watershed hydrological behaviors. These parameters were: watershed shape estimated using the Gravelius index, unity shape factor, watershed shape factor, compactness coefficient, drainage texture, total relief, hypsometric curve, etc. Formulas used to determine these parameters are presented in the **Supplementary file data**. Other parameters were calculated using hydrology in spatial analysis tools of ArcGIS 10.7 software (Esri, California, USA).

2.2.2. Diachronic analysis of land use and land cover change in Luzinzi watershed

To reduce variability due to differences in image-taking periods, all the images used in this study were taken in June up to August for each year. Satellite images were first of all pre-processed; it is vital and began with radiometric and geometric corrections (Vicente-Serrano et al., 2008). Landsat 7TM and 8 OLI/TIR were used. Their Worldwide Reference System (WRS) row and path are 173 and 062, respectively. Sentinel 2A was also used for land use and cover. These corrections helped us to geo-reference and transform the image data into a format that can be

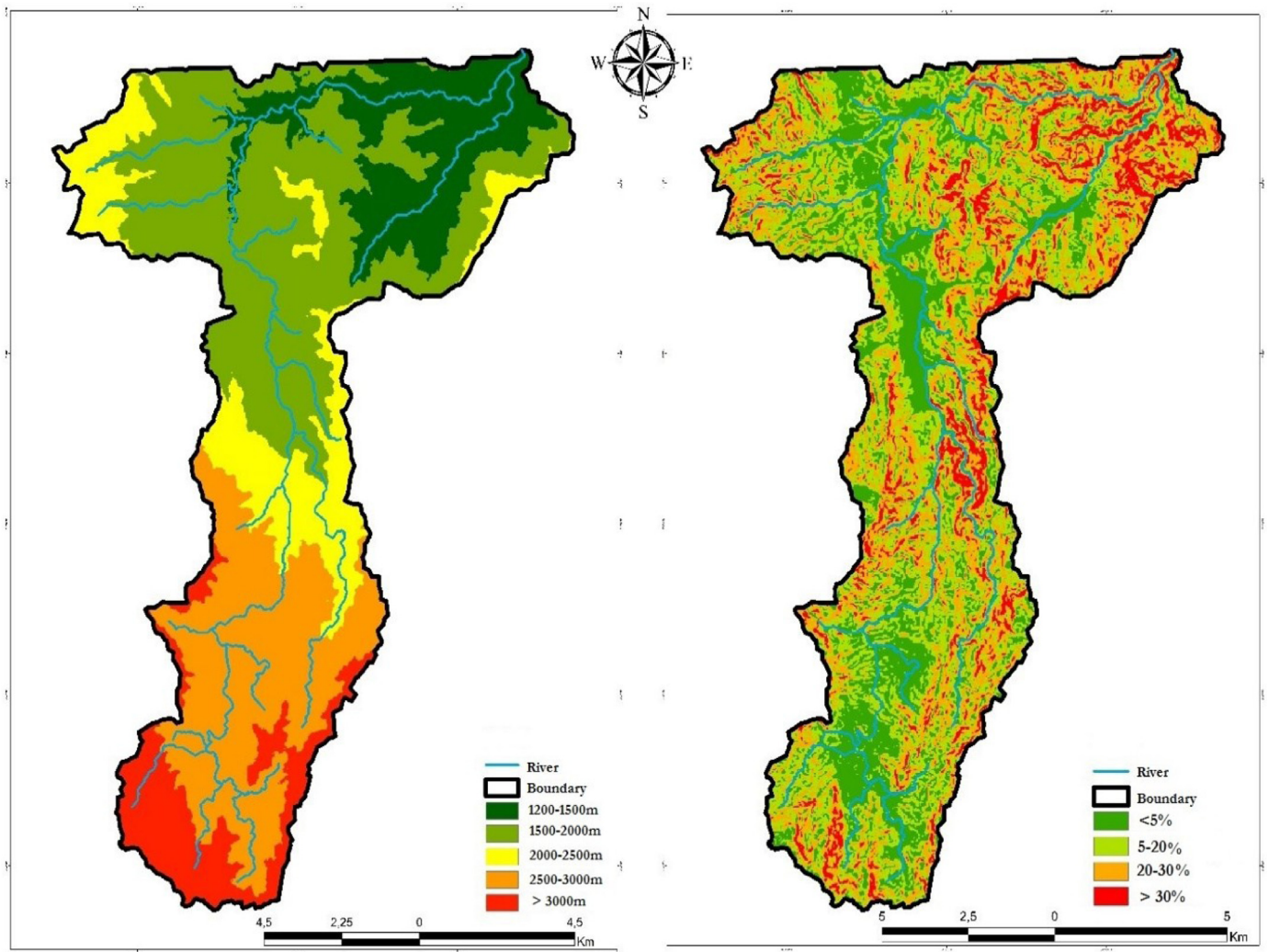


Fig. 2. Slope and elevation classes in Luzinzi watershed, eastern DR Congo.

readily interpreted in terms of earth surface attributes. After the satellite images were ready for interpretation, they were layer stacked; the single bands combined together into one file to use the spectral information of different bands of the images. Layer stacking technique was performed to group the needed bands together. Image enhancement was also done to improve the appearance of the image to make image interpretation easier in general. After completing all these processes, image classification was conducted.

To assess the land use and land cover in Luzinzi watershed, Sentinel 2A satellites images; Landsat 7 TM and 8 TIR/OLI were used. Characteristics of these images are presented in **Supplementary file data**.

The classification method used was the “Supervised Classification” using ENVI 5.3 Tools.

Due to the cloud cover around the watershed, only five years were considered to evaluate the land use and land cover: 1996, 2000, 2010, 2015 and 2019. Four classes were considered: “Woodland and Forest, Savannah, Farmland and Bare soil and settlement”. Post classification analysis based on the calculation of the confusion matrix, overall accuracy and Kappa index were used to validate the classification made. Once the Kappa index was superior to 0.70 (70%), the classification was considered (Foody, 2020). The results obtained as confusion matrix were merged and presented as an alluvial plot to see the areas gained or lost for each class. The percentages of each class as a function of the total area of the watershed and that of each class were also presented.

2.3.3. Gully characterization and estimation of factors affecting gully expansion rate

We used georeferenced VHR satellite images available on Google Earth and some UAV images to digitize and map gullies. We used these image types to refine the gully maps (Fig. 11). The validation and determination of other parameters such as the number of gully heads, length and width were also corrected with field data. The geographic coordinates of the gully headcut were also collected and helped to extract its LULC. Other information was simultaneously collected and included the presence or absence of vegetation at the gully headcut and inside the gully contributing area. The type of vegetation (if grasses, trees or bare soil) was noted. The location of the gully in each LULC class was first extracted from the classified images and then validated by the field observations. Database was completed, finalized and then imported into R Studio and R 3.4.3 version (R core Team, 2019) for statistical analysis and for the graphs drawing.

To evaluate the development of gullies; the expansion and retreat rates were calculated using the following formula: $GER = \frac{\partial s}{\partial t} = \frac{s_X - s_Y}{X - Y}$ and $GRR = \frac{\partial R}{\partial t} = \frac{R_X - R_Y}{X - Y}$

With: GER (Gully Expansion Rate) and GRR (Gully Retreat Rate), S: gully expansion morphological characteristics (volume, surface, depth, length, width for T=X-Y time (X and Y represented selected years in which the data were collected ranged from 2010 to 2020). As some ravines were expanding while others were retreating, it was more

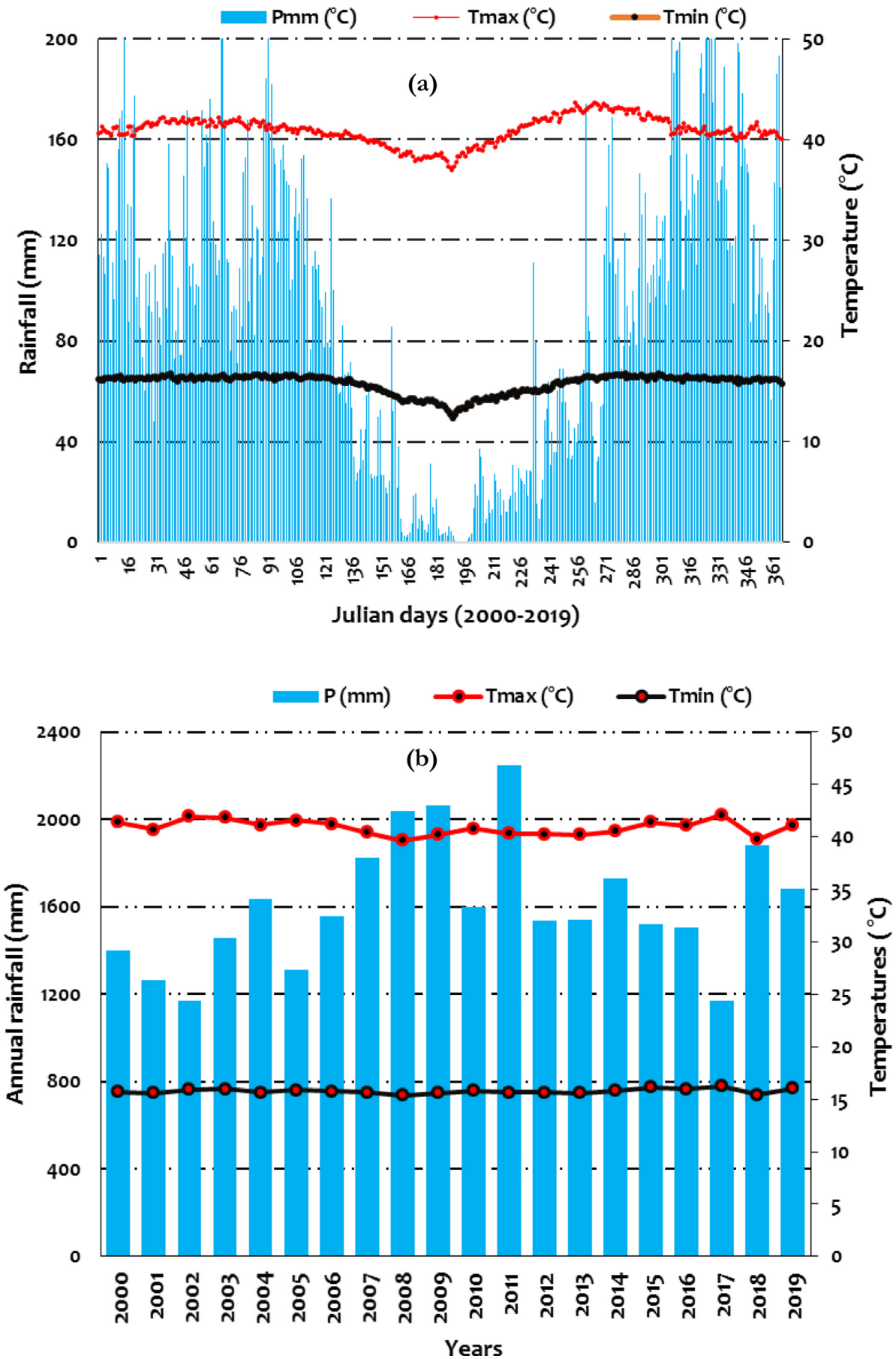


Fig. 3. Daily (a) and annual (b) minimum and maximum temperatures (in °C) and rainfall (in mm) in the Luzinzi watershed in Walungu territory, South-Kivu, eastern DR Congo (Data downloaded from <https://power.larc.nasa.gov/data-access-viewer/> and edited and analyzed in MS Excel).

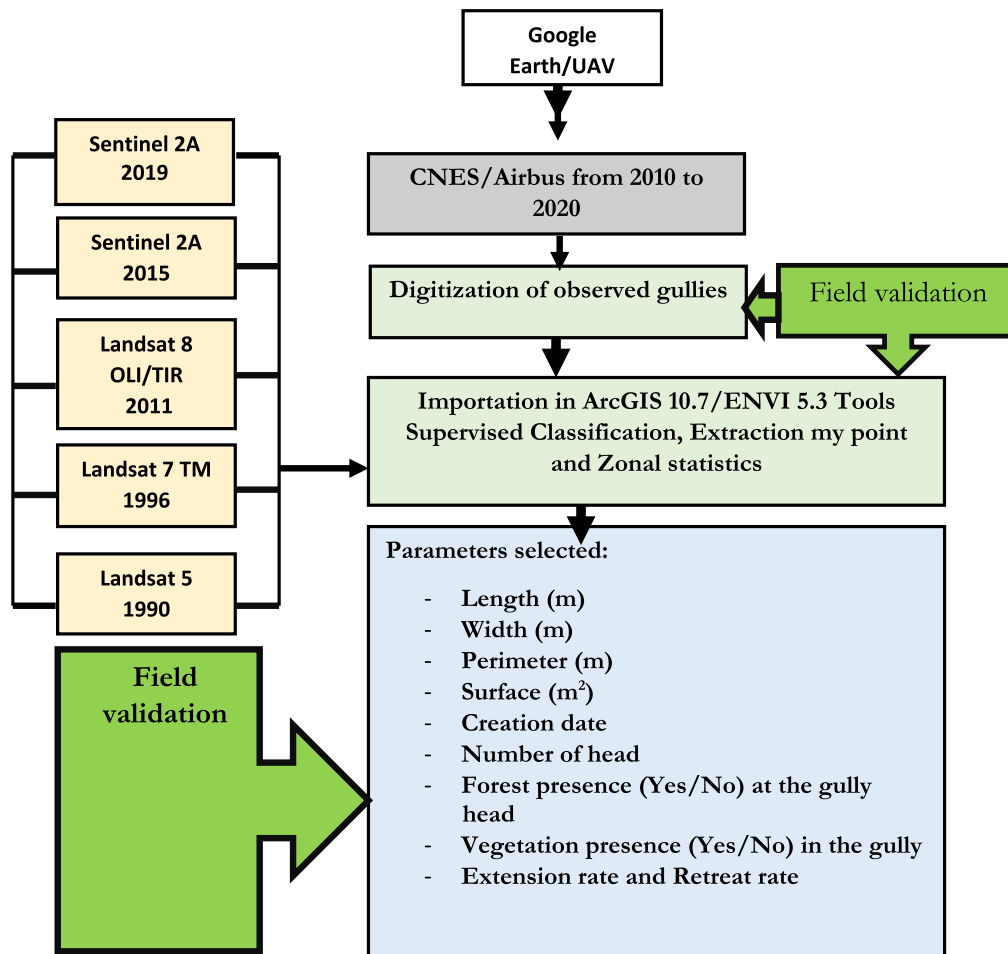


Fig. 4. Steps' flowchart of gullies characterization in Luzinzi watershed. Combination of digitized gullies shapefile with field data for validation, extraction of analyzed LULC from Landsat and Sentinel 2A images.

a question of focusing on those that were retreating in time and space.

To evaluate the effect of morphological, environment and other factors, linear models were done with the GER and GRR. Logistic regression was performed to evaluate the factors that contribute to the gullies' stabilization. Thirteen (13) predictors were included in the model. The analysis was performed only on over time stabilized gullies (46).

Fig. 4 presents a flowchart of steps involved in determining gully characteristics. It also shows how the VHR satellite images and UAV were used for gullies digitization (Supplementary data), followed by land-use and land cover extraction on the classified images obtained after classification of the watershed Landsat and Sentinel 2A images; validation by field data also took place.

3. Results

3.1. Effect of the land use and land cover change in Luzinzi watershed

a Variation in terms of land use and land cover

Results obtained from land use and land cover change after analysis of classified images from 1990 to 2019 are presented on Fig. 5. It shows four land use and land cover (LULC) types and their distribution across the Luzinzi watershed. Fig. 5a shows specifically the LULC of the 1990 year. For this year, woodland and forest, savannah, farmland, and bare soil and settlement covered ~ 31.93 ; 50.45 ; 40.86 and 26.20 km^2 , respectively. Savannah lands were the dominant LULC type with ~ 50.45 km^2 (34%); they were followed by cultivated lands (farmlands)

with ~ 40.86 km^2 (31%) while woodland and forest had ~ 31.93 km^2 (21%) and bare soil and settlements ~ 26.20 km^2 (18%) (Fig. 5). The same Figure shows the similar trend six years later (in 1996) with an increase in cultivated lands (46.64 km^2), bare soils and settlements (30.65 km^2) while savannah (45.18 km^2) and woodland and forest (26.99 km^2) showed decrease (Fig. 5b).

Fig. 5c shows the LULC types of the year 2011, in which farmlands, bare soils and settlements increased and covered ~ 50.40 km^2 (34%) and ~ 32.58 km^2 (22%), respectively; while savannah (~ 41.85 km^2 ; 28%) and woodlands and forest (~ 24.63 km^2 ; 16%) decreased. In 2015, the dominant LULC type was savannah and cultivated lands (farmlands) that covered ~ 53.27 (36 %) and ~ 44.47 km^2 (30%), respectively. Woodland and forest (27.09 km^2) and bare soil and settlements (24.64 km^2) showed the least coverage. For the year 2019, farmlands, savannah and bare soil and settlements covered ~ 55.64 (34%); ~ 38.53 (31%) and ~ 34.50 km^2 (18%), respectively (Fig. 5e). Woodland and forest with only 20.78 km^2 (14%) represented the least coverage. Variations in terms of area (in km^2) for each year are presented in Table 1. In analyzing the confusion matrix obtained after the post classification analysis, the overall accuracy and Kappa index used to evaluate the precision of our map are presented in Table 1.

3.2. Trend and magnitude of LULC changes in Luzinzi watershed, eastern DR Congo

The magnitude of LULC of the 29 years is presented in Fig. 6 while the trend of gained and lost areas is illustrated within the alluvial plot on Fig. 7. Cultivated land and savannah were most dominant LULC types.

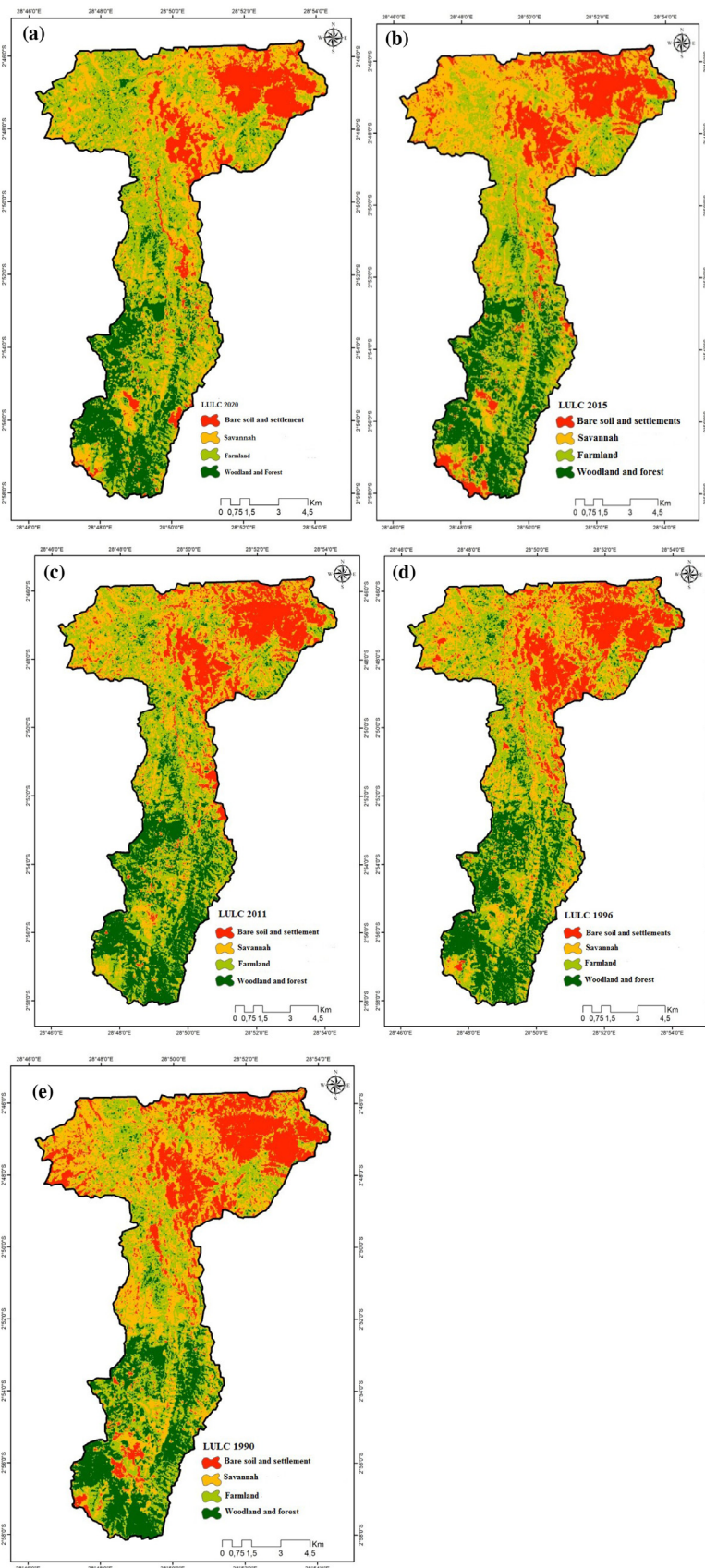


Fig. 5. Land use and land cover changes in Luzinzi watershed from 1990 to 2019.

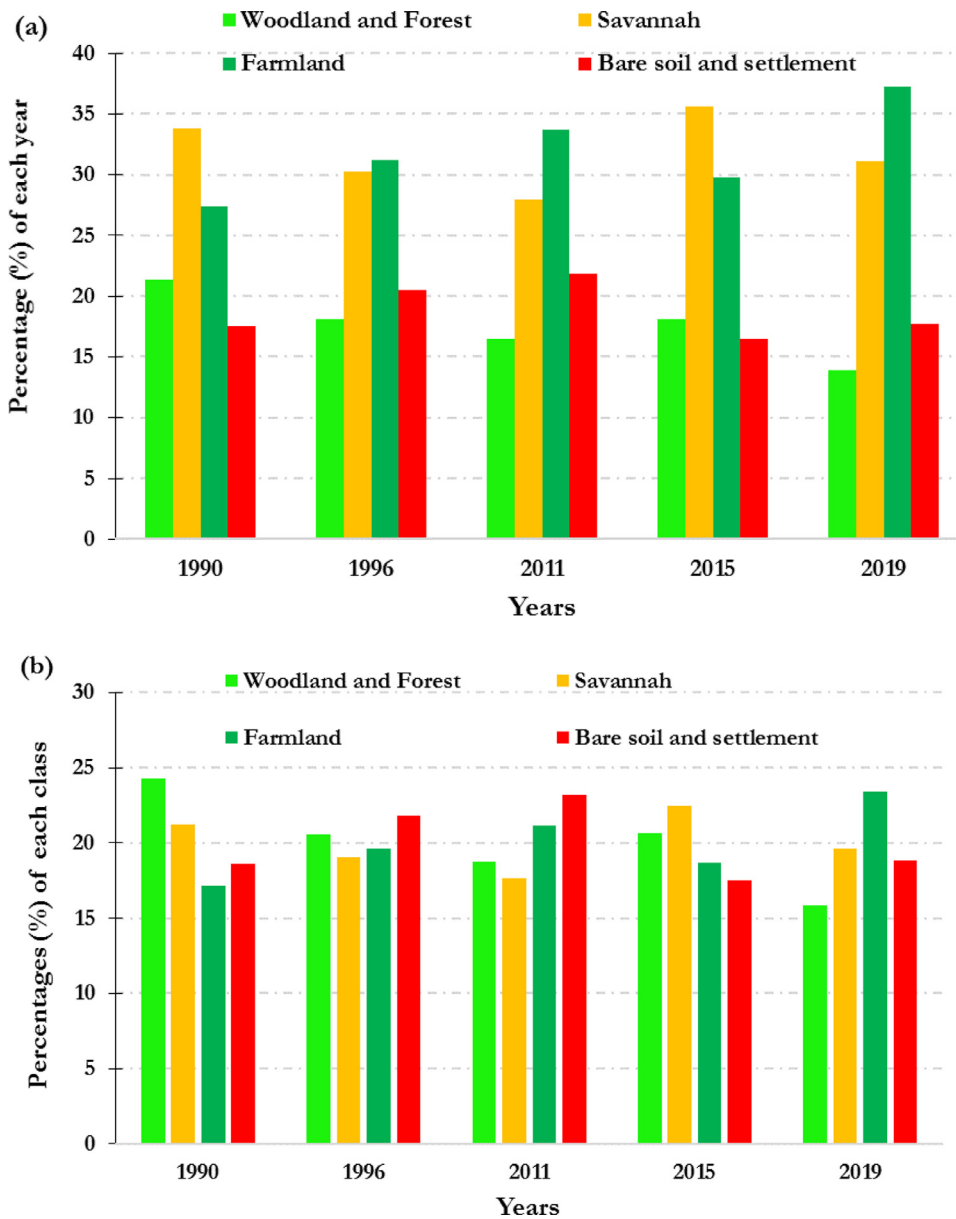


Fig. 6. Changes in land use and land cover of each use class (a) and each year (b) from the 1990 to 2019 in the Luzinzi watershed.

Table 1
Changes (in km²) of land use and land cover in Luzinzi watershed from 1990 to 2019.

Land use and land cover	Covered area (km ²)				
	1990	1996	2011	2015	2019
Woodland and forest	31.93	26.99	24.63	27.09	20.78
Savannah	50.45	45.18	41.85	53.27	38.53
Farmland	40.86	46.64	50.40	44.47	55.64
Bare soil and settlement	26.20	30.65	32.58	24.64	34.50
Overall accuracy (%)	96.10	91.29	98.47	84.44	98.38
Kappa coefficient	0.95	0.88	0.97	0.83	0.98

From 1990 to 2019, farmland accounted for ~27; 31; 34; 30 and 37% in 1990, 1996, 2011, 2015 and 2019, respectively, showing a generally increasing trend. By comparing the starting year of observations (1996) to the ending year (2019), Fig. 6 (a and b) and the alluvial plot (Fig. 7) show a decrease of 14.78 km² (~34.9%) of the woodland and forest and 11.9 km² (~23.6%) for savannah area. Cultivated lands and bare

soil and settlement presented an increase of 14.8 km² (~36.2%) and 8.3 km² (~31.7%), respectively as compared to 1990.

Since 1996, 2011 and 2019, farmland was dominant in terms of occupied surface area while bare soil and settlement and woodland and forest showed the least coverage. Woodland and forest represented a class combining ‘natural forest’ (not man-made) while woodland represented tree plantations (specifically *Pinus*, *Grevillea*, *Eucalyptus* sp.).

According to the alluvial plot (Fig. 7); it was found that over the past 29 years (between 1990 and 2019), there were both negative and positive changes. In one hand, there was a reduction in woodland and forest land cover by ~6% even though there was introduction and expansion of tree plantations in the study area (in 2015 mainly). On the other hand, there was an increase in cultivated lands and bare soils and settlements. Loss in woodlands and forest were distributed among savannah, farmland and bare soil and settlement. From the 11.15 km² recorded loss from woodland and forest, half (~7.39 km²) was gained by savannah, 4.2 km² by woodlands and 3.19 km² by bare soils and settlements. While loss recorded for savannah (11.95 km²) was distributed among bare soil (~4.9 km²), farmland ~5.3 km² and woodland and forest (~4.9 km²). In 2019, most of the bare soils and settlements increase came from farmland (~8.3 km²).

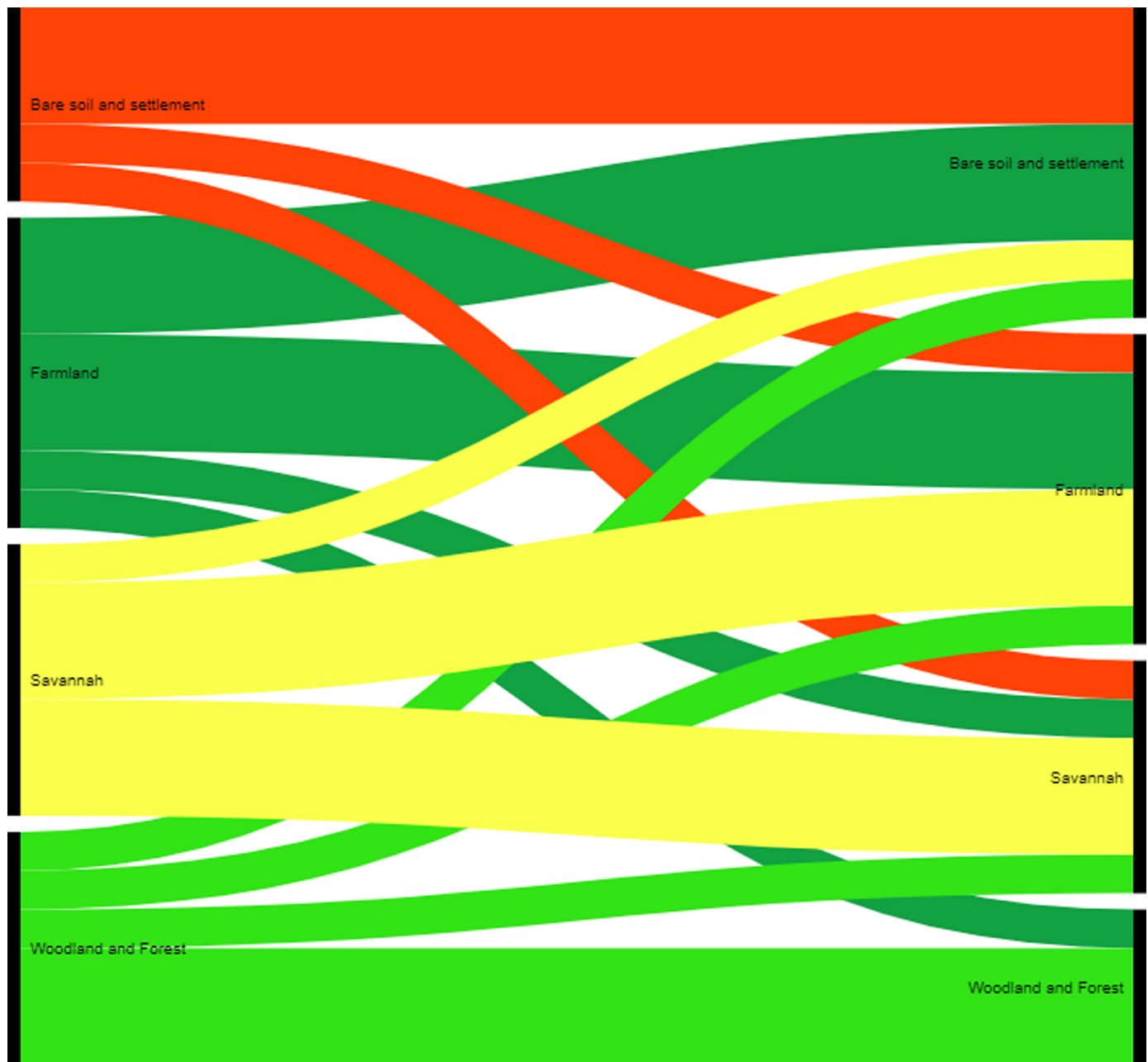


Fig. 7. Alluvial plot showing dynamics of land use and land cover changes in Luzinzi watershed, eastern DR Congo.

The total area covered by cultivated land (farmland) was ~27% in the year 1990, which increased to ~31% in the 1996 and to ~34% in the year 2011 (Fig. 6 and 7). During the study period, between 2011 and 2015, the area under farmland use decreased by ~4%. In general, bare soils and settlements increased only from 1990 to 2011 from ~18 to 22%. Since 2015 the bare soil and settlement seemed stabilized with a slow increase of ~2%.

a Classification accuracy

Table 1 shows the area variation (in km²) for the four identified classes. It also shows the classification accuracy from 1996 to 2019. Overall accuracies obtained from confusion matrix between classified image and reference image during the classification of bare soil and settlement, woodland and forest, savannah and farmland were above 87%. It was 96, 91, 98, 89 and 98% for 1990, 1996, 2011, 2015 and 2019, respectively. Based on results presented in Supplementary data

file, woodland and forest and farmland were properly classified with highest producer's accuracy levels of 94 and 92%, respectively; whereas savannah and bare soil and settlement had lowest producer's accuracy levels of 86 and 84%, respectively. These overall accuracy levels led to Kappa statistic indices of ~0.95, 0.88, 0.97, 0.87 and 0.98 for each of the years, respectively. These values imply that the classification process controlled the errors at 95, 88, 97, 87 and 98% for each the selected years, respectively.

3.3. Luzinzi watershed characteristics

Table 2 presents some Luzinzi watershed characteristics. We combined some morphological and hydrological watershed characteristics to help understanding the watershed profiles. Luzinzi watershed is made of a total area of ~149.47 km² and a perimeter of ~85.74 km.

Table 2
Luzinzi watershed morphological and hydrological characteristics.

Parameters	Symbol	Unity/Formula	Luzinzi	Reference
Perimeter	P	km	85.74	Delineation with ArcGIS
Stream length ratio	R_L	$L_e - L_{a-1}$ (m)	320	Horton (1945)
Drainage density	Dd	La/A	0.466	Schumm (1956)
Surface	A	km ²	149.47	Delineation with ArcGIS
Minimum elevation	H_{min}	m	852	Extracted from Asterdem
Watershed relief	H_{mean}	$H_{max} - H_{min}$ (m)	1596	Hadley and Schumm (1961)
Relief ratio	Rr	$Rr = H/Le$	40.87	Schumm (1956)
Maximum elevation	H_{max}	m	3435	Extracted from Asterdem
Elevation median	$H_{50\%}$	m	2282	Extracted from Asterdem
Slope index	lg	km/km	0.038	Strahler (1952)
Main talweg length	L_p	km	38.75	Strahler (1952)
Average slope of the watershed	P_{mean}	$\Delta H/Le$ (m/km)	56.67	Carlier and Leclerc (1964)
Width of overland flow	le	km	8.96	Horton (1932)
Length of overland flow	Le	km	39.05	Horton (1932)
Circularity ratio	Rc	$Re = 4 \cdot \pi \cdot A/P^2$	0.255	Miller (1953)
Gravelius index	K_G	$0.2821 \cdot P/A^{0.5}$	1.9	Strahler (1952)
Moving time	Ta	h	6.46	Musy (2001)
Relative relief	Rp	H/P	18.61	Melton (1959)

Luzinzi watershed presents a width and length of overland flow of ~8.86 and ~39.05 km, respectively. The stream length ratio, drainage density, slope index and average watershed slope are ~320, 0.466, 0.038, and 56.67, respectively. The highest elevation point is at ~3435 m above sea level while the lowest downstream point is at ~852 m. Thus, there is ~1596 m elevation difference between the highest and lowest points of the Luzinzi watershed. A high relief ratio was obtained after calculation. From the same Table 2, it was found that the main talweg length was ~56.67 while the moving time and Gravelius index (considered as Compactness Coefficient) were ~6.46 h and ~1.9, respectively. The information gives the shape and the time that a drop of water makes from upstream to the outlet of the watershed.

3.4. Gullies characterization in the Luzinzi watershed

a) Length and width

Fig. 11 presents the spatial distribution of gullies at the Luzinzi watershed scale from 2011 to 2020. Fig. 8 (a-d) presents the evolution of gully's length, width, surface and volume. From Fig. 8a, the mean gully length of ~72.2 m in 2011 passed to ~53.6, 60.5, 64.6, 82.9, and 87.1 m in 2014, 2016, 2017, 2019, and 2020, respectively. The gullies increased in length across years.

Gullies had a minimum length of ~23.8 m (in 2011) while the largest had a maximum length value estimated at ~143.0 m (in 2020).

According to gullies' width, it increased slightly from one year to another (except from 2019 to 2020 where it increased faster than in other years). The minimum width was ~9.4 m (observed in 2016) and the maximum was ~45.8 m (2019 and 2020). From 2011 to 2020, the observed widths were of ~10.6, 10.3, 9.4, 10.3, and 9.4 m, respectively. Therefore, Fig. 8 illustrates that the observed gullies seemingly increased slightly in width with time in the Luzinzi watershed. The combination of these two measurements enabled us to determine the gullies' area. This area (Fig. 8c) combined with the gullies' depth provided the volume shown in Fig. 8d.

b) Gullies' surface and volume

Fig. 8c presents the evolution of gullies' surface during the selected period. Figs 8c and 8d show the same trend of increasing gully surface area over time. Since 2011, the gully surface area (and even the volume) has continuously increased. The gullies in 2011 had an average surface area of ~1761 m² and a volume of ~8713 m³ that increased in 2020 to 2566 m² and 13387 m³, respectively. There were gullies with smaller areas (~674.4 m²) and large gullies of up to ~3789 m². The same trend was observed in terms of volumes (smaller 2540 m³ and larger 28978

m³). All these Fig.s (8 a to d) show that all these parameters were constantly increasing over time at the watershed scale. The change in depth and slope at the gully head is shown in Fig. 9 (a and b).

c) Depth and slope at the gully head cut

Fig. 9 (a and b) presents gully depth (in m) and gully head slope from 2011 to 2020. Fig. 9a shows an increase of gully depth over time. In 2011 and 2014, gullies had mean depth ~9.1 m that increased to ~9.3 and 9.6 m in 2017 and 2020, respectively. Fig. 9b shows that gully head slope slightly changed from ~9.8 to ~12.6% for 2011 and 2020, respectively. Some gullies presented very high head slope (~38.7%) while others presented very low head slope (<5%). However, gullies head slope did not vary significantly with time.

d) Gullies retreat and expansion rates

Fig. 10 presents change in terms of gully's surface and volume expansion and retreat rates. Expansion rates presented in Figs. 10a and 10b slightly varied from year to year. Both surface and volume expansion rates slightly changed over time. Fig. 10a shows slightly decrease of gully surface retreat rates during the selected period. From 2014 to 2017, surface retreat rate had been reduced from ~85.3 to 75.3 m² yr⁻¹ and stabilized in 2019 and 2020 at ~71.7 m² yr⁻¹. These changes in terms of retreat rates are explained by the linear retreat rate and not width retreat rates. Linear retreat rate was ~2.4 m yr⁻¹ from 2014 to 2016; that increased to ~3.45 m yr⁻¹ in 2019 and 2020. Gully volume retreat rates in Fig. 10b slightly increased during the selected period. From 2014 to 2016, volume retreat rate was ~332.33 m³ yr⁻¹ and increased to ~639.94 m³ yr⁻¹ in 2017 before decreasing or stabilizing in 2019 and 2020.

3.5. Number of gullies, gullies surface, volume expansion and retreat rates of gullies located in forest and other land use types

Fig. 12a presents the number of gullies digitized and validated with field measures, Fig. 12b shows their evolution trend in different land covers (between forest and woodland and other land covers). Fig. 12c shows active and stabilized (no active) gullies.

Fig. 12a present gullies found in the watershed from 2011 to 2020. In total, 270 gullies were identified. In 2011, only 38 gullies existed. This number passed to ~78, 68, 93 and 139 in 2014, 2016, 2017 and 2019, respectively. In 2020, the number of gullies rose up to 201. Thus, during the study period, gullies increased in time. From these gullies, only ~17.04% (46) are stabilized (no active) and ~82% (224) are still active as presented in Fig. 12c.

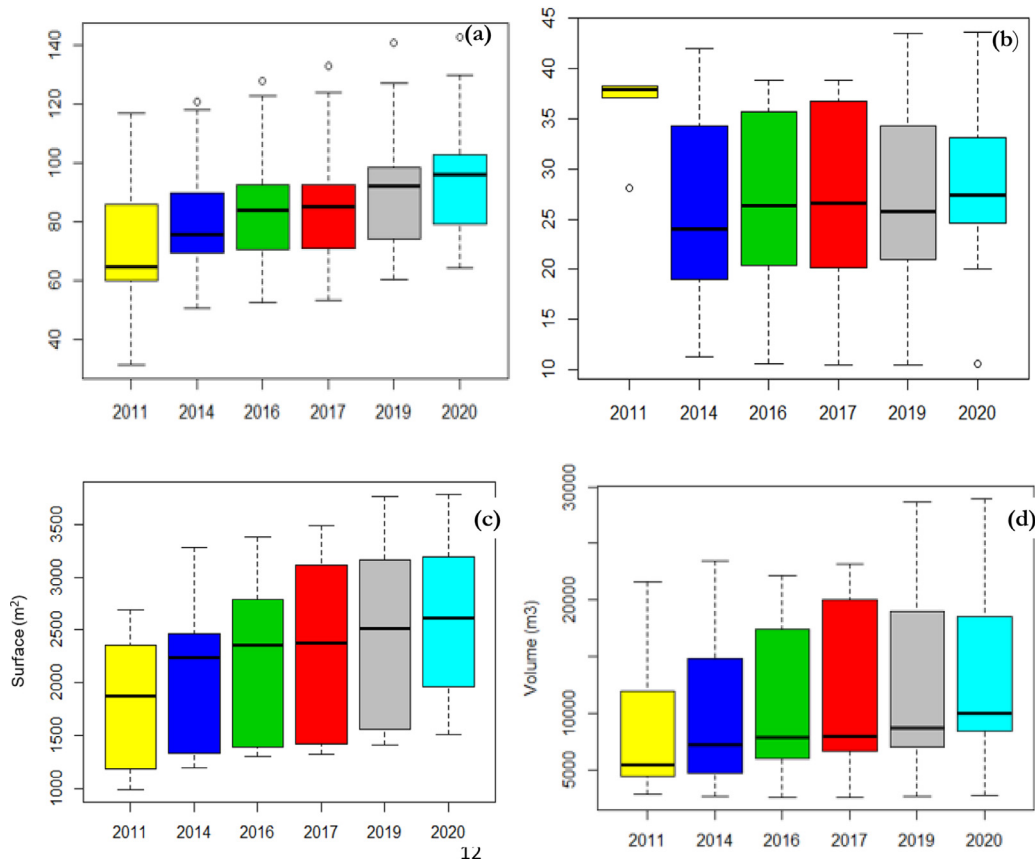


Fig. 8. Variation of length in m (a), width in m (b), area in m² (c) and volume in m³ (d) of gullies located in the Luzinzi watershed from 2011 to 2020.

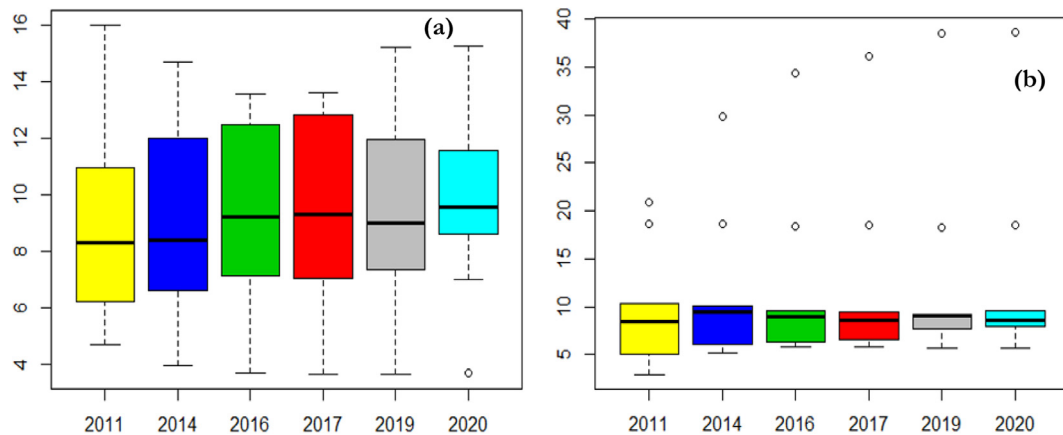


Fig. 9. Evolution of gully depth in m (a) and slope at the gully headcut (b) for identified gullies in Luzinzi watershed, eastern DR Congo.

Fig. 12b divides these gullies in two types according to land use and cover change (and specifically at the headcut). In 2011, among 38 gullies inventoried, ~6 were located in woodland and 32 in forest and other land use. From 2014 to 2020, the number rose from ~15, 12, 25, and 32 to 29 in woodland and forest cover, respectively. For other land covers, the numbers of gullies were ~63, 56, 68, 107, and 172, respectively, from 2014-2020. Thus, gullies located in woodland and forest tended to stabilize while those in other land covers increased in number and importance. Woodland and forest covers induced gullies stabilization.

3.6. Factors affecting gully stabilization in Luzinzi watershed

Statistical model developed on factors affecting gully stabilization rate is presented in Table 3. Thirteen factors have been integrated in the model. Seven factors significantly affected gullies stabilization in Luzinzi watershed. These factors were grouped into environmental factors (annual rainfall, presence of vegetation in the gully or at the headcut, and vegetation types), management factors (dump of household and agricultural waste, settlements at less than 5 m and other man activities around) and physical factors (slope aspect, contributing area, length and width, moving of gully headcut, slope at the gully headcut).

The first group of factors considered included environmental factors that significantly affected gullies stabilization. Annual rainfall for each

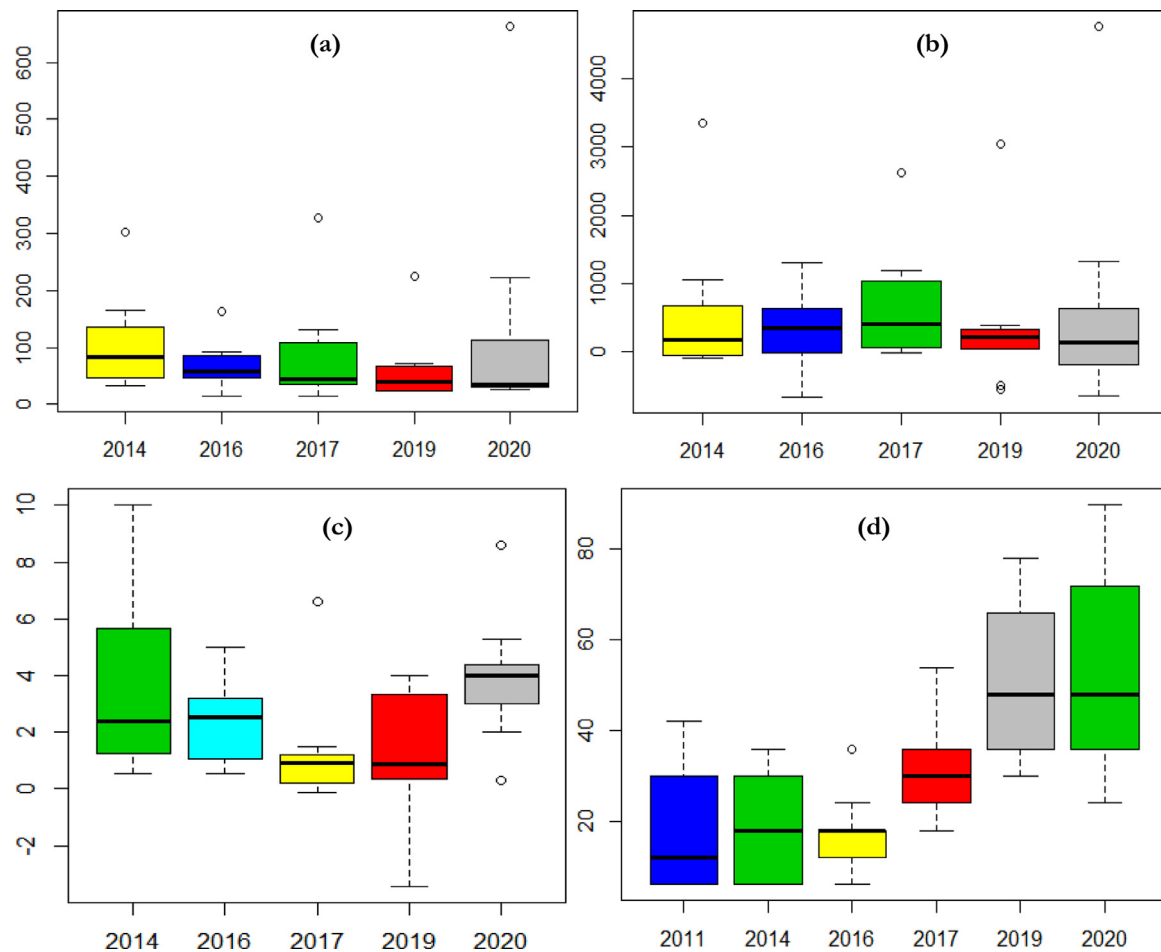


Fig. 10. Surface in $\text{m}^2 \text{yr}^{-1}$ (a) and volume in $\text{m}^3 \text{yr}^{-1}$ (b) retreat and expansion rates (c and d) rates of gullies monitored in Luzinzi watershed during the selected period (2014 to 2020). Data making Fig. 10c were transformed using logarithm.

selected year for gullies digitation, and monthly rainfall were considered. The more the annual rainfall increased the less gullies were active and not stabilized (no active). Vegetation presence in the gully or at the gully headcut and the vegetation types significantly affected stabilization. The more vegetation, and especially woodland and forest cover, the more gullies were stabilized.

The second group of factors included management factors such as man activities around gullies which significantly affected the gully stabilization. Some of these activities such as gold mining, stone and rock extraction negatively affected the stabilization while increased their expansion by moving the gully headcut. The more a gully headcut moved, the less it stabilized. From the selected physical factors, only contributing area affected gullies stabilization. Other factors such as slope aspect at the gully headcut, gully length (or width) had no effect on gully expansion.

Fig. 13 shows the regressions between the contributory area and average gully expansion rate (Fig. 13a) and gully area and length (Fig. 13b). The first regression was performed on 120 gully data. This resulted in a significant effect of the contributory area on the rate of gully expansion. With each increase in the contributory surface area, the gully rate of expansion also increased ($R^2=62.16$, $p<0.05$). The relationship was linear. Fig. 13b, on the other hand, shows the regression between the surface area and the length of the gullies. The relationship was exponential ($R^2=91.98$, $n=87$). Thus, the wider the gullies, the larger the surface area, and the greater the volume of the gullies was. However, the relationship was obvious for only a few gullies ($n=87$).

Fig. 13c shows negative correlation between the effect of forest cover and the rate of gully expansion ($R^2=82.5$, $p=0.021$). Thus, at nearly $\sim 70\%$ forest cover, a rate of expansion of less than $\sim 200 \text{ m}^3$ per year was observed. On the other hand, with a low forest cover of $\sim 30\%$, the expansion rate was high (~ 300 to 400 m^3 per year). With a forest cover of only $\sim 10\%$, the rate of expansion could exceed 700 m^3 per year.

Vegetation cover slightly affected the volume and surface area of the gullies (Fig. 14a and 14c) but also the depth (Fig. 14b). Fig. 14 shows that there is a difference between gullies with vegetation in the contributing area (as well as on the headcut of the gullies) compared to other land use. Thus, the more the contributing area is predominantly covered by forest, the less wide the gullies would be for the surface area (Fig. 14a), and volume (Fig. 14c), while they would be very deep (Fig. 14b). Gullies with a contributory area covered by forest had a volume and surface area of $\sim 285.2 \text{ m}^3$ compared to other land uses ($\sim 422.7 \text{ m}^3$). The same trend was observed for surface area (~ 92.8 and $\sim 72.9 \text{ m}^2$ for other land use and woodland and forest cover, respectively). As for the depth of gullies, it was slightly greater in forest areas ($\sim 4.6 \text{ m}$) than other land uses ($\sim 2.4 \text{ m}$). Fig. 15 shows human activities at the bottom of the gullies. These are predominantly the stone mining and the extraction or artisanal mining, especially the gold mining.

Table 3
Factors affecting gully stabilization in Luzinzi watershed, eastern DR Congo.

Variables	Coefficients	Df	Std. Err	z value	Pr (> z)	AIC
Slope at the gully headcut	0.012	3	0.041	0.127	0.7629ns	479.5
Annual rainfall (Pmm)	-0.139	5	1.204	2.273	0.029 *	480.2
Man activities around	0.045	1	0.005	-2.107	0.043*	494.7
Moving of the gully headcuts	0.034	1	1.367	-3.339	0.045*	501.3
Vegetation in the gully	-1.871	1	3.953	-2.172	0.003 *	500.6
Vegetation types	-0.896	3	0.012	-1.826	0.053ns	493.6
Vegetation on gully headcut	-0.213	1	1.545	2.279	0.049*	501.8
Settlements at less than 5 m	-0.006	1	0.041	1.545	0.6987ns	496.0
Dump of household and agricultural wastes	1.042	1	1.082	2.269	0.0482*	493.4
Contributing area (m²)	1.395	1	1.571	3.237	0.002**	502.0
Slope aspect	0.0273	7	0.021	0.138	0.132ns	486.4
Length (or width) of the gully	0.486	3	0.023	0.107	0.431ns	483.9
LR χ^2 (12)	187.03					
Prob> χ^2	0.000***					
Log likelihood	-20.28					
Pseudo R²	0.578					
AIC	584.93					
AUC	0.972					

*, **, ***: significant at $\alpha = 0.05$, 0.01 and 0.001, respectively, ns: no significant.

4. Discussion

4.1. Dynamic changes in term of land use and land cover in the Luzinzi watershed, eastern DR Congo

Results from this study showed dynamic LULC changes in Luzinzi watershed of the eastern DRC. Woodland and forest cover majorly became savannah and farmland; others were destroyed for settlement or left bare (Table 1 and Fig. 5). These LULC changes can be linked to different factors: direct or indirect factors (Geist and Lambin, 2002). These LULC changes are inevitable as they are majorly derived from social and economic development (Wu, 2018). Factors such as agricultural activities, extraction of wood and NTFP (Non Timber Forest Products) in woodlands and forest, rural infrastructure and livestock extension can be firstly considered as drivers of these LULC changes in the Luzinzi watershed. Secondly, political, economical and demographic factors (specifically socio-cultural) are among these drivers of changes (Verburg et al., 2006; Lambin et al., 2006).

There was extension of agricultural land and bare soil and settlement during the last five years (2015 to 2019) that mainly was driven by rapid population growth, implementation of projects to improve productivity of valleys and marshes in the Luzinzi watershed or other human activities such as small-scale mining; school and road construction, etc. (Mutabazi, 2013). Woodland and forests were converted into agricultural lands. This was quite obvious due to the relatively high soil fertility status of the forest soils compared to other soils in the area. Trees were, therefore, cut down and gave place to agricultural land. On the other hand, other forests were transformed to pastures by cutting trees. Many other reasons could have explained these changes. According to Bantider (2007), biophysical characteristics such as nature of the topography, soil and climate, and the type of human activities that can be practiced in an area would shape the land cover of that area. Moreover, these results follow the general trend of LULC changes in DRC which are

characterized by increase in cultivated land (farmland) and bare soils at the expense of woodland and grassland areas (Shapiro et al., 2021).

These dynamics have potential local and regional consequences, including long-term loss of soil fertility, increased soil erosion, reduction of biological diversity, hydrological changes, and a modification of local climatic conditions (Egeru et al., 2010). Inappropriate land use has been recognized as an important driver of land degradation and climate change and that is exacerbated by a number of human activities and natural processes (Frankl et al., 2013; Mekonnen and Hoekstra, 2016).

In fact, expansion of land area under cultivation by subsistence farming is motivated by the need to meet the demands of population, a change linked to rapid population growth. Other factors are linked to change in policies that included land tenure and settlement rights. Since 1991, Houghton (1991) demonstrated that tropical forest ecosystem has been subjected to higher rates of deforestation and conversion into mainly cropland and pasture. It is obvious that cultivated land expansion exerts high pressure on the watershed natural resources. This is coupled with poor farm management that has imposed a greater impact on the soil quality and productivity of farms in eastern DRC (Heri-Kazi, 2020).

From 2011 to 2015, reduction of cultivated land is most probably related to declined productivity of farmlands because of land degradation. Consequently, farmers were forced to leave their land and converted it to grazing land. When crop fields became unproductive, farmers stopped growing crops and left farmlands for animal grazing as grazing lands. Tree cover analysis showed an increasing trend during that period (Fig. 5).

Tree planting projects were initiated and promoted in the area, tree species were distributed to schools, churches and other local non-governmental organizations (NGOs); and thus, the population slightly abandoned agriculture in favor of reforestation.

Since 2015, farmland and settlement and bare soil had once again increased. This might be associated with the encroachment of the various natural land covers by different human activities mainly by agricultural practices and settlements development, as indicated by similar

studies in the region (Bagalwa, 2006; Phillippe and Katcho, 2019). Unfortunately, these changes often came with environmental costs such as the expansion of cultivated land which resulted in water pollution, sedimentation, erosion and biodiversity loss (DeGife et al., 2019). Hence, proper management of bare soils and settlements land uses and degraded agricultural lands has immense importance for the sustainability of the watershed resources. In connection with such changes, opting for an integration of agriculture and trees through agroforestry approaches would increase soil cover and thus reduce soil erosion (Sepúlveda and Carrillo, 2015).

Pressure on the land, the lack of water retention, and the removal of vegetation in the lower watershed have contributed to frequent crop failure and low productivity, leading to food insecurity in the region. Sufficient action has not been taken by stakeholders and decision-makers, as seen from the dwindling productivity. Knowledge and understanding of farmers and other watershed actors about the problem and remedial measures can lead nowhere without integrated action and involvement of other stakeholders (Moges and Holden, 2007; Moges and Holden, 2009).

With regard to rural urbanization and town or city development, it is known that settlements expansion causes LULC change through conversion of land use classes such as farmland and woodland and forest to settlements (built-up) areas (Anteneh et al., 2018). From 1990 to 2011 (Table 1), rapid expansion of settlements and bare soil can be associated to population displacement from the villages to the major centers (agglomerations) or towns in the area such as Kaziba and Kamanyola but also with the displacement after the various civil wars in the eastern DRC and neighboring countries (Rwanda and Burundi) (Namegabe, 2004; Geenen and Mutokanyi, 2013). Thus, LULC changes are triggered by the interaction of complex driving factors including a set of political, social, economical and biophysical factors (Degife et al., 2019).

4.2. Gullies' characteristics

In Lunuzi watershed, results obtained showed that the gullies were wide in length and width. Their depth varied slightly over time even in the slope at gullies' headcut. The average gully length increased from ~53 m to ~87m from 2010 to 2020; while the width increased from ~23 to ~26 m. The same tendency was observed for gullies surface and the volume. The widely varying morphological parameters of permanent gullies as observed in this study were within the range of values reported by similar studies in urban zones of DRC (Makanzu et al., 2014; Ilombe, 2019; Lutete, 2019) and elsewhere (Hu et al., 2009). Many studies developed approaches to characterize gullies at tropical watershed, town, cities, and country scales (Makanzu et al., 2014). The variability in volume and area was expected since gullies may have formed at different times and their expansion rates may have differed due to local conditions such as rainfall intensity, runoff volume, and soil characteristics (Zucca et al., 2006; Muñoz-Robles et al., 2010). Jetten et al. (2006) found a strong relationship between maximum gully depth and gully width, which they attributed to the increased influences of bank and bed erosion. However, weak relationships between gully depth and top width were reported by Wu and Cheng (2005) and Li et al. (2017).

Width and depth reflect the environmental setting (climate, topography, soil, and vegetation) of the area where that gully has developed (Li et al., 2017). Wu et al., (2018) used the same gully characteristics (depth, length and width) as fundamental parameters but suggested other derived parameters such as gully head curvature, gully width-depth ratio, and gully bottom-to-top width ratio. These derived parameters were not used in this study but we used others such as surface area and gully volume. The rates measured in this study were within the range of 0.002-430 m³ yr⁻¹ as reported by Vanmaercke et al. (2016) based on data compiled for 933 individual and actively retreating gullies from ~70 study areas worldwide. Ghimire et al. (2006) estimated much higher values of 731 (±57) to

2793 (±201) m³ yr⁻¹ over a period of two years in the Siwalik Hills, Nepal, though the environmental setting in their study area is different from ours.

Wu et al. (2018) characterized gullies in China and found that gully surface areas varied between 384.1 and 2090.3 m² with a median of 834.7 m². Gully volumes varied between 602.8 m³ and 2696.2 m³ with a median of 1545.5 m³. These values are similar to the values obtained in Lunuzi watershed, where from 2010 to 2020, gully area varied from ~1761 m² to 2566 m².

High coefficients of determination (R²) of 62.12, 91.9 and 87.2 between expansion rate and contributing area, gully area and length, and woodland and forest cover and retreat rate indicate that contributing area, length and forest cover in the contributing area were good parameters for describing gully stabilization. Usual factors such as soil physical properties and land use and cover played an important role in affecting the gully slower growing rates in the Lunuzi watershed site. Capra et al. (2009) and Vanmaercke et al. (2016) reported that gully headcut retreat rates are well correlated with gully runoff drainage area, rainfall intensity, and other local factors, land use, soil characteristics, and topography. In general, our results indicated that the gully headcut retreat rate varied with LULC and, thus, site-specific investigation of the controlling factors is crucial to understand the driver(s) of gully headcut advancement and to determine appropriate mitigation measures. Lunuzi gullies seemed to be landscape features which have at some time experienced rapid growth. These areas are almost always associated with accelerated erosion and landscape instability as shown by Morgan (2001). Such acceleration is in relation with the land use and cover change.

Nevertheless, factors such as land management practices, low ground cover which affect soil crusting, and high intensity storms may also have had a strong effect on gullying. Moreover, Gutiérrez et al. (2009) reported that land uses that increase vegetation cover can increase gully development thresholds, whereas reduced vegetation cover (through increases in cultivated areas, conversion of forests to pasture, and overgrazing) tends to reduce the thresholds and increase the risk of gully erosion. Billi and Dramis (2003) and Dong et al. (2013) reported the role of gully bank vegetation in reinforcing soils and intercepting runoff and sediment. In our case, gully distribution within the watershed might have been affected by the change in term of land use and cover from which contributing area, vegetation on headcut, rainfall and other anthropic factors influenced significantly the gully development (Table 3).

Gully characteristics obtained were higher than those found by Heri-Kazi (2020) at the farms' scale in eastern DRC. His results showed also that soil erosion by rills and gullies showed significant spatial (between and within sites) and temporal variations. Trees and grasses grow several times faster in the gullies than on the relatively dry ridge summits and slopes, and thus give better economic yields. In such a case, we assumed that natural forest and man-made forest established in Lunuzi may have reduced sediment yields and gully expansion. Other factors such as soil types and land management practices could have affected also gully expansion. Unfortunately, these parameters were not taken into account in this study. However, complementary to agricultural land use, the occurrence of infrastructure, such as irrigation canals, and especially roads and footpaths were integrated with field work, as they can concentrate runoff, and thus favoring the development of new gullies and increasing the expansion rates of existing ones (Fu et al., 2002). Clarification of the role of some influencing factors such as slope gradient and aspect, vegetation cover and other characteristics and a study of changes of gully distribution and development in time over the last 200 years based on the comparison of topographic maps were highlighted with Ionita et al. (2015)'s works.

4.3. Woodland and forest cover affects gullies expansion rate

Many studies have been conducted to characterize tropical and worldwide gullies. Jahantigh and Pessarakli (2011) concluded that gullies develop because of a decrease in soil surface resistance to erosion

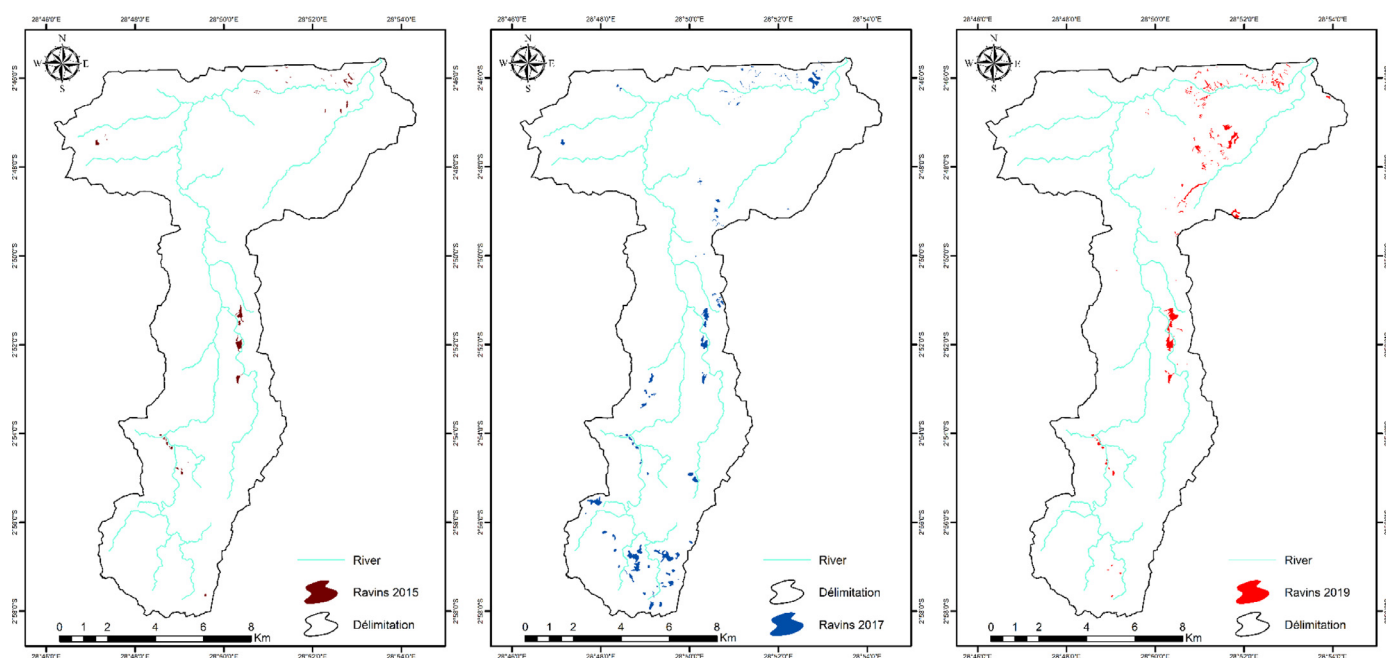


Fig. 11. Spatial distribution of gullies in Luzinzi in 2010, 2017 and 2019 (legend: ravins=gullies, délimitation=watershed boundary).

or an increase in the erosive forces acting on the land surface. In Dashtyari (Iran), gullies were developed due to men activities, overgrazing, and intensive and short-period rainfall. These authors indicated also that longest gullies appeared in flat plains. Agricultural activities and in our case deforestation combined with local gold mining clearly have played a key role in triggering gully formation. Fig. 11 presents the relation between forest cover and gully extension rate (in $\text{m}^3 \text{yr}^{-1}$). In fact, forest and trees in general provide protective cover to the soil; they also prevent soil erosion (rill and gully types) because their roots hold the soil particles in place and prevent them from being washed away as well as break impact of raindrops (splash effect). This implies that the loss of forest and vegetation in the Luzinzi watershed through deforestation, overgrazing, over cultivation as shown in this study's results, had caused the soil to lose its structure and cohesiveness, and thus became more easily eroded.

The effect of woodland and forest in controlling gully erosion has been demonstrated by many studies (Li, 1992; Lutete, 2019). Forest intervenes in reducing runoff and sediment yields from the flat ridges and slopes which have no control measures. Boardman et al. (2003) emphasized that land degradation in the form of rill and gully erosion is always accompanied with reduction of grassland by shrub vegetation, species diversity declination and ground cover reduction. In a region with bare soil and settlements, gullies up to ~ 8 m deep and 3500 m^2 surface could be developed. These characteristics lead to expansion rate varying from ~ 2.4 to $75.3 \text{ m}^2 \text{ yr}^{-1}$, while in woodland and forest, the rate was reduced to $\sim 4.6 \text{ m}$. Gullies with a contributory area covered by forest had a volume and surface area of $\sim 285.2 \text{ m}^3$ compared to other land uses ($\sim 422.7 \text{ m}^3$). The same trend was observed for surface area ($\sim 92.8 \text{ m}^2$ and $\sim 72.9 \text{ m}^2$ for other land uses and woodland and forest cover, respectively).

The extension and height of the planted trees (mainly *Pinus*, *Eucalyptus*, *Grevillea*, etc.), reached a critical threshold, making further development of gullies impossible. However, a quarter ($\sim 25\%$) of the watershed area was still protected by the primeval forest (Gabris et al., 2003). Since the agricultural land had been extended, the gully formation rate accelerated and the vegetation practically disappeared from the slopes dissected by gullies. The same study concluded that, vegetation change has been very significant during the last 200 years. The forest area diminished from 58.2 to 26.2%, arable land and pasture increased from

37.0 to 62.2%. These changes have triggered gully initiation and development.

Heri-Kazi (2020) showed that in South-Kivu watersheds, cassava-based cropping systems tended to be associated with high rill erosion rates, while high rainfall increased both rill and gully erosion rates. Overall, the very high measured rill erosion rates suggest the need for rapid implementation of erosion control methods. The author suggested that results could be used to prioritize sites at risk of water erosion in order to install mitigation measures at the small watershed scale.

Results by Heri-Kazi (2020) in the same territory showed the same trend in term of the effect of soil cover on rill and gully erosion rates. In agricultural crop systems found in Walungu and Kabare, positive relationships have been found between minimum rill erosion rates or gully erosion rates and soil organic carbon (SOC) content, slope gradient and soil textural classes such as clay and sand content. Also, when analyzing the effect of cropping systems at the watersheds scale, there was no general trend regarding their effect on seasonal minimum rill erosion rates. This study showed that at the farm scale, land use practices observed in Walungu and Kabare currently affect rill and gully characteristics and extension.

Gully erosion rates increased with low soil organic carbon (SOC) which is evident in Walungu soil and Luzinzi in particular, as these areas are dominated by ferralsols and Acrisols unit types. These soil unities are very poor in SOC. This may explain also why gully retreat rate seemed higher in woodland and forest. In fact, forest soils have high organic matter (OM) contents giving them certain stability.

Although the retreat rate was low, differences were observed between the gullies in the forest and wooded areas as compared to those from other land uses. The highest erosion expansion rate was observed on bare ground and settlements (Fig. 13). Effect of land use and land cover dynamics as drivers and environmental implications was highlighted in Ethiopian watersheds by Degife et al. (2019). These authors also showed that agricultural activities, wood extraction and infrastructure extension are main causes of gully expansion (Degife et al., 2019). In the case of eastern DRC and in Luzinzi particularly, expansion of agricultural land, urban and infrastructure expansion, high wood demand and uses of trees for income generation and other biophysical factors (slope and accessibility), underlying drivers, population growth pressure and land tenure policy explained such an expansion.

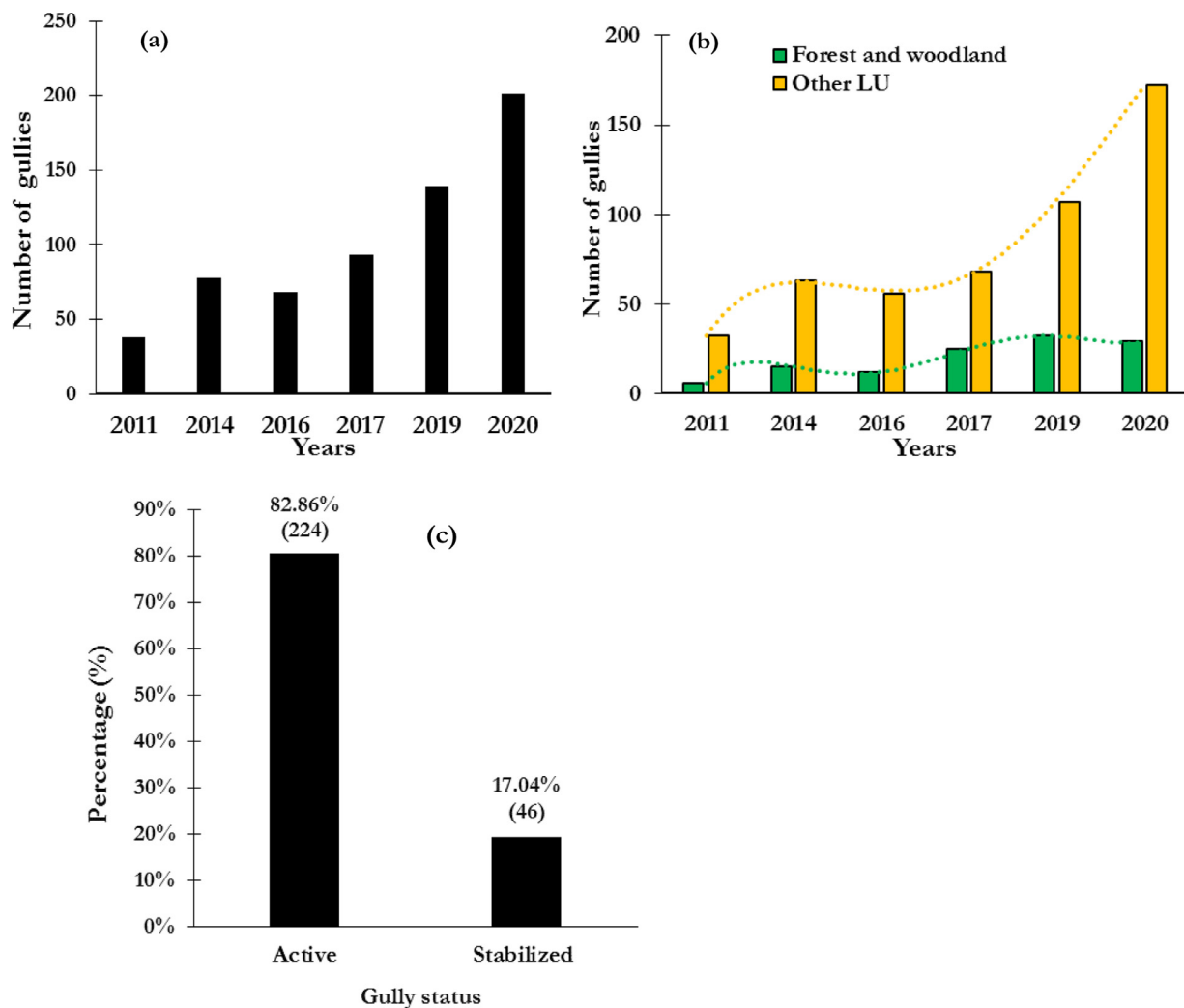


Fig. 12. Number of gullies from 2011 to 2020 (a) and their evolution in woodland and forest and other soil cover types (b), frequencies of active and stabilized (no-active) gullies (c) located in Luzinzi watershed, eastern DR Congo.

4.4. Study limitation

Due to lack of experimental and validation data for old gullies (from the years 2011 to 2018); soil loss estimates for these areas have not been made, and thus, only the year 2019-2020 has been validated with fieldwork. This implies that a database will have to be set up to better study this process. Some gullies were removed from the model during analysis due to a lack of validation data. This study did not take into account the shape of the gully (either U-shaped or V-shaped) that are important parameters in the characterization of gullies. The gullies depth and headcut slope were not accurately estimated. It only took into account larger gullies; smaller gullies (of less than 2 m resolution) that would not be well identifiable with the images used (CNI/Airbus) from Google Earth were not considered. However, the use of UAVs allowed integrating only few gullies found in the field during the field validation. Human activities in gullies were not addressed. However, Li (1992) suggested that in such case the afforestation should begin first in the small lateral gullies and gradually expand to the lateral gullies and eventually to the main gullies (in the initial stages, the trees should be planted away from the flood channels). Because there was no precision in terms of the types of cover or species present in past years but only in 2020, we had to extract these elements from the classified images of this area. The approach thus finds limits in this sense. However, some of the points

included in the regressions (Fig. 12) have been removed to smooth the trend of the graph and were, therefore, considered as outliers.

Population growth and activities seemed to play important roles in gullies expansion; unfortunately due to lack of population statistics data, their effects were not integrated.

5. Conclusion

This study investigated the land use and land cover changes in Luzinzi watershed. It has also analyzed watershed characteristics; gullies morphological characteristics and estimation of gullies headcut retreat rates, and contributing factors for their stabilization. Correlations between gully morphological parameters and retreat rate were also highlighted.

From 2010 to 2020, 201 gullies were identified. Expansion was observed in more than 82% of the observed gullies while only ~17% gullies were stable. The regression analyses showed that gullies stability in the watershed is explained by the intensity of rainfall in the area, human activities in the vicinity, or in the gullies, gullies headcut displacements, percentage and types of land cover and contributing area. Thus, preventive interventions should consider these parameters.

Even though presenting some limits, the used methodology enabled a better understanding of the land use and land cover, gullies characterization and how woodland and forest affect gully expansion. Man

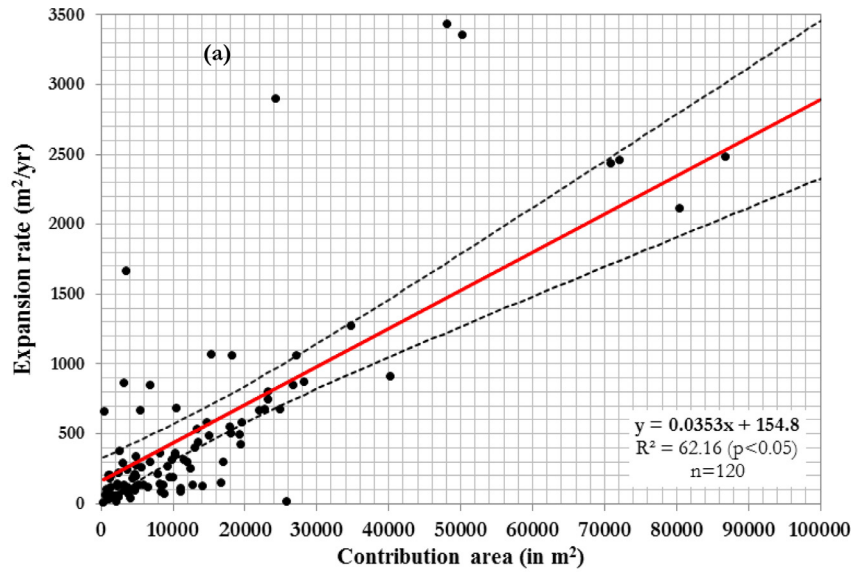
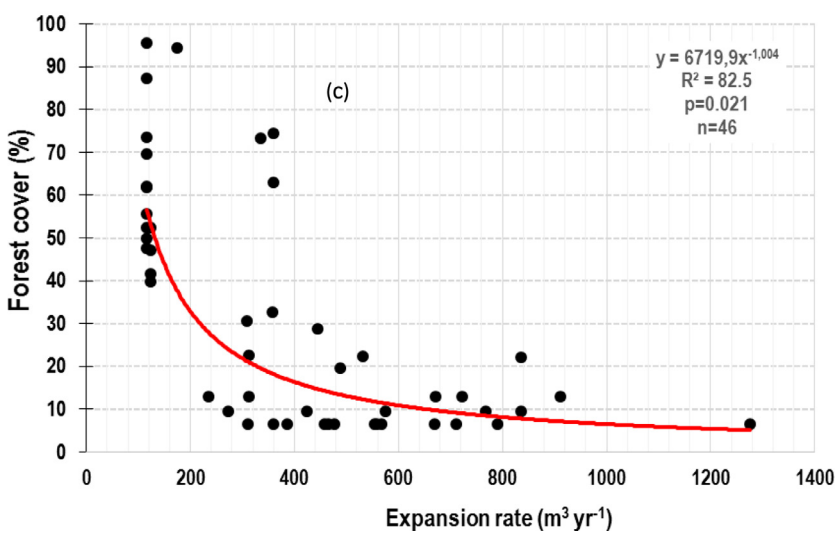
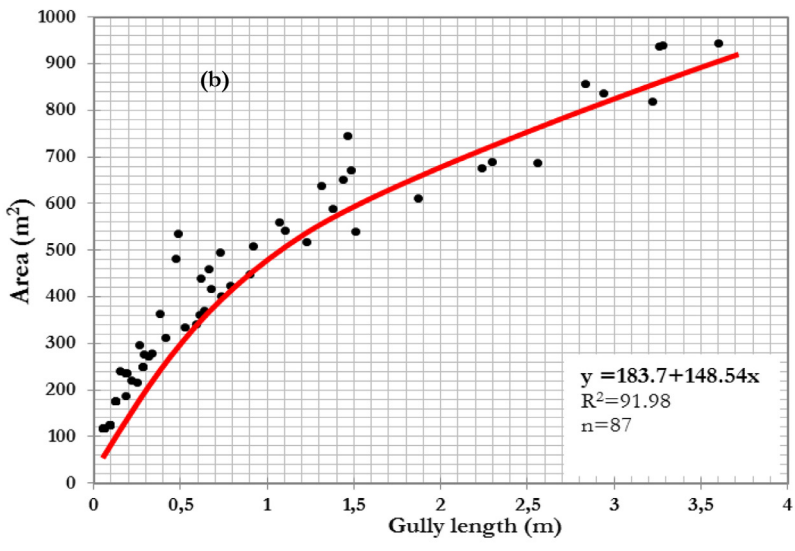


Fig. 13. Correlation between contributing area and gully expansion rate (a), gully area and gully length (transformed using logarithm) (b), correlation between expansion rate ($m^3 yr^{-1}$) and woodland and forest cover at the gully headcut and contributing area (c) in Luzinzi watershed, eastern DR Congo.



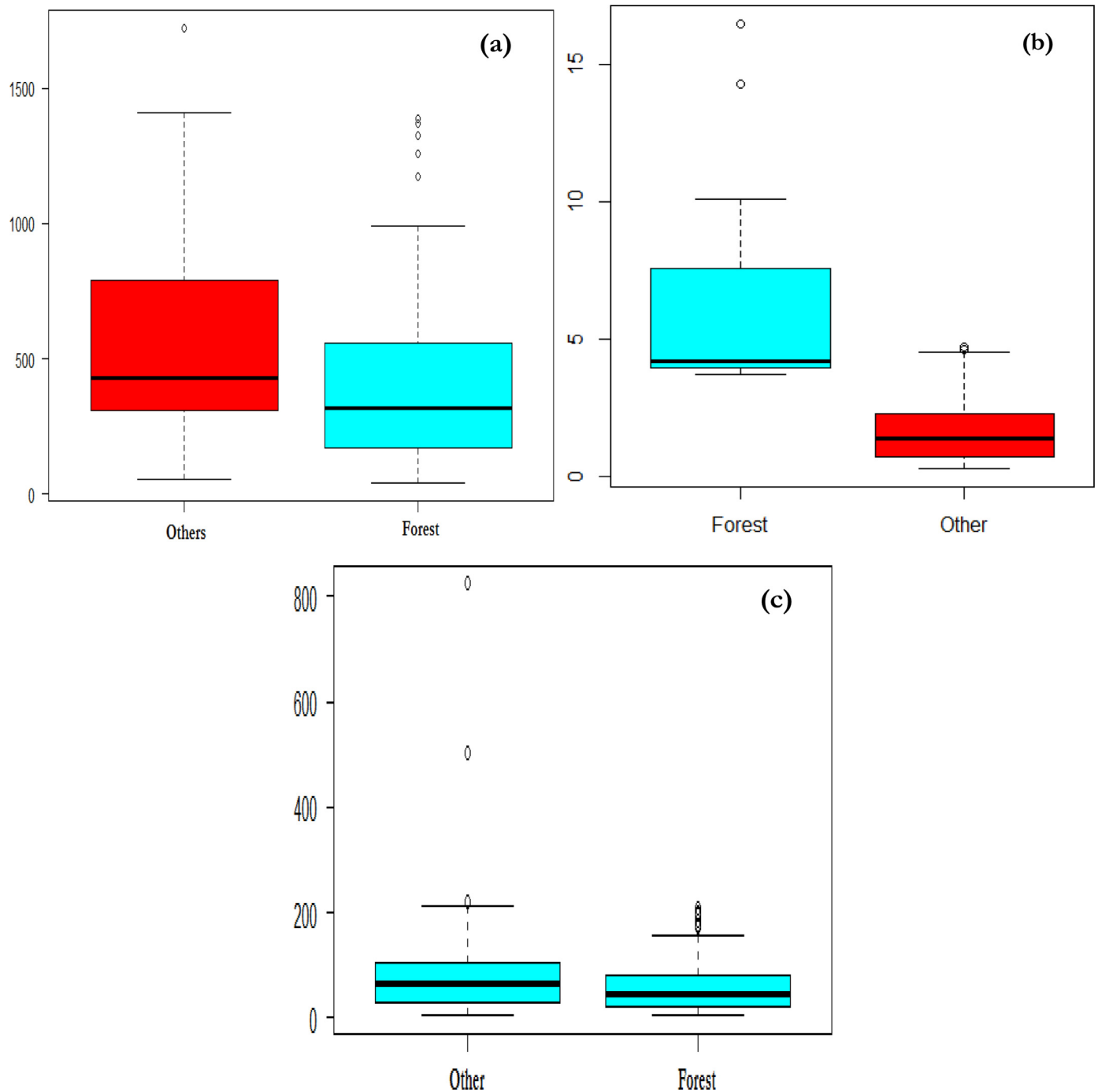


Fig. 14. Variation in terms of volume (m^3) (a), depth (m) (b) and surface (m^2) (c) between gullies headcut located in woodland and forest and other land use types (settlements, savannah and farms). We combined the gully headcut and contributing area cover extracted from land use and land cover map using zonal statistic analysis (Spatial analysis tools in ArcGIS 10.7) of contributing area and validated with field data.

activities contributed to gully development and land degradation and pressure in general. At the watershed scale, integrated recovery policies are required to restore and preserve land and its productivity. Conservative practices may help to prevent and to mitigate gullies' problems in rural areas of eastern DRC. This article can be used as a basis for initiating projects and land use planning, not only for Luzinzi watershed, but for other areas of South-Kivu and eastern DRC that share similar environmental conditions. The adopted methodology which combined different data sources to highlight the land use and land cover change in relation with gully expansion should be expended to other eastern DRC's watersheds. Knowledge of the site through field visits and the use

of VHR images were essential for digitizing and characterizing gullies at the watershed scale.

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Declaration of Competing Interest

No conflict of interest.



Fig. 15. Man activities in gullies in the Luzinzi watershed. Two main activities are practiced in the study area: stones and minerals (gold) mining.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2021.100083.

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