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Assessing the Driving Factors of Deforestation and Afforestation Over Three Decades (1990-2020) in Ngororero District, Rwanda

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Abstract

Deforestation is a critical environmental issue that has far-reaching impacts on biodiversity, ecosystems, and climate change. Monitoring deforestation and Afforestation processes over time is essential for understanding their drivers, patterns, and consequences, as well as informing sustainable land management strategies. This study aims to assess the driving factors of deforestation and afforestation over three decades (1990-2020) in Ngororero District, Rwanda, between 1990 and 2020, using a combination of remote sensing and geographic information system (GIS) techniques. The results indicated approximately 274.4 km^2 (40.45%) of Ngororero District remained unchanged over three decades. Moreover, the findings showed that the district experienced significant deforestation, converting 43.29% of its land to cropland and 8.96% of forested areas to grasslands. This led to a loss of 53.33% of the total land use transformations. Despite this, efforts towards afforestation and reforestation were modest, with only 0.53% of total land use conversions. The study contributed to a deeper understanding of the dynamics of forest cover change in Ngororero District and provide valuable insights for policymakers, land managers, and conservation efforts in Rwanda. The findings inform sustainable land-use planning, forest management strategies, and environmental conservation initiatives aimed at mitigating deforestation and promoting afforestation in the area. By leveraging the capabilities of remote sensing and GIS technologies, this research offers a comprehensive spatiotemporal analysis of deforestation and afforestation patterns, enabling evidence-based decision-making and supporting the sustainable management of forest resources in Ngororero District and potentially other regions of Rwanda.

Keywords: *Afforestation, Deforestation, Forest Cover Change, GIS, Remote Sensing*

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1. Introduction

The historical background of afforestation and deforestation is deeply intertwined with human civilization and the evolution of societies (Swanson et al., 2021). Conservation movements that promoted the preservation and regeneration of forests first appeared in the late 19th and early 20th centuries (Rozas, 2003). In the US, groups like the National Parks Conservation Association and the Sierra Club supported afforestation programs and sustainable forestry techniques.

The world's largest forests are vital ecosystems that play crucial roles in controlling global temperature and supply basic supplies to human cultures. The Amazon Rainforest located in South America with approximately 5.5 million square kilometers is the largest tropical rainforest in the world and one of the most biodiverse ecosystems on the planet. Millions of different kinds of plants, animals, and microbes can be found there, many of which are native to the area. The Amazon also plays a critical role in regulating the Earth's climate by absorbing and storing vast amounts of carbon dioxide (Ruiz-Vásquez et al., 2020).

Africa is home to a diverse range of forest ecosystems, including tropical rainforests and dry forests. The Congo Basin Rainforest, located in Central Africa, is the second-largest tropical rainforest in the world after the Amazon. It covers approximately 2 million square kilometers and is known for its high levels of biodiversity (L. Zhou et al., 2014).Another significant tropical forest zone in Africa is the West African rainforest, which stretches from Guinea and Sierra Leone to Nigeria and Cameroon. However, increased agricultural activity have caused significant deforestation and fragmentation of these woods (Bowman et al., 2011). Africa's relationship with its forests is complex and multifaceted. The continent continues to lose its tree cover at an alarming rate and estimated the average loss of 3.9 million hectares per year between 2010 and 2020 (FAO, 2020). Deforestation has severe consequences for African communities, leading to soil erosion, loss of biodiversity, disruption of natural water cycles, and increased greenhouse gas emissions. Although overshadowed by deforestation, Africa has witnessed a notable rise in afforestation efforts in recent years. Countries like Ethiopia, Rwanda, and Niger have implemented ambitious tree-planting programs aimed at restoring degraded lands and mitigating climate change (WRI, 2022).

In Rwanda forests cover around 724,695 hectares of the total country land (MoE, 2019). In terms of the forest density and tree cover, about 318,434 hectares are very dense forests (44%), 234,004 are moderately dense (32%), 146,222 hectares are sparse (20%) and only 26,035 hectares are much degraded (4%) (MoE, 2019). In the early 2000s, Rwanda's forests faced a rapid decline, losing an estimated 2.3% of its tree cover annually. The rapid deforestation had severe consequences for Rwanda's environment and people. Soil erosion increased, leading to decreased agricultural productivity and land degradation. Biodiversity suffered, with the loss of valuable habitats and species. Recognizing the gravity of the situation, the Rwandan government implemented a series of ambitious policies to combat deforestation and promote afforestation. These included the National Forest Policy (2018),This policy aimed to increase forest cover to 30% by 2030 and established protected areas and community forest (MINILAF, 2018).

Ngororero district is one of the 7 districts of the western province of Rwanda. It has an area of 679 Km². Forests in Western Province cover about 174,199 ha (36% of the total province land) and statistics indicates that 22% of Ngororero district land is covered by forest (MoE, 2020). Ngororero district encapsulates a diverse range of ecosystems, including forests,

wetlands, and agricultural lands (REMA,2015), making it a focal point for studying land use changes such as afforestation and deforestation. Over the past few decades, the district has undergone significant transformations driven by a combination of natural processes and human activities (MoE, 2019). These changes have been particularly pronounced in terms of afforestation, aimed at restoring degraded landscapes and promoting sustainable land management practices, as well as deforestation, often spurred by agricultural expansion, population growth, and infrastructural development (MINILAF, 2018).The western province of Rwanda has proven as high density for both natural and manmade forests except Ngororero which shows remarkable forest degradation. However, reforestation of degraded forest plantations has been identified on 1,183 ha in Ngororero (MoE, 2019). Understanding the dynamics of afforestation and deforestation in Ngororero district is crucial for devising effective strategies to mitigate environmental degradation, promote sustainable development, and enhance resilience to climate change impacts (Khan, 2021). In this regard, A Remote Sensing and GIS-Based Approach has been used for this research to analyzing Deforestation and Afforestation areas over two decades (2000-2020) in Ngororero district, Rwanda.

1.1 Research Objectives

1.1.1 General objective

The general objective of this study was to assess the driving factors of deforestation and afforestation areas over three decades (1990-2020) in Ngororero district of Rwanda.

1.1.2 Specific objectives

The specific objectives of this study are the followings:

(i) To assess deforestation and afforestation hotspots
(ii) To examine possible driving factors leading to deforestation and afforestation
(iii) To determine the relationships between deforestation/afforestation hotspots and their potential driving factors in Ngororero district (1990-2020).

2. Materials and methods

2.1 Profile of Ngororero District

Ngororero District, located in Rwanda's Western Province, spans 679 km² and shares borders with Nyabihu, Gakenke, Karongi, Muhanga, and Rutsiro districts. It is administratively divided into 13 sectors, 73 cells, and 419 villages. The district experiences a tropical climate with four distinct seasons: the short rainy season (October–December), the short dry season (January–February), the long rainy season (March–June), and the long dry season (July–September). Annual rainfall averages 1527.7 mm, though anomalies occur (MoE, 2019).

Ngororero's economy is primarily based on agriculture, with key crops including coffee, tea, bananas, maize, wheat, beans, cassava, and potatoes. The Gishwati region supports cattle farming, but soil degradation due to steep slopes and intensive agriculture necessitates conservation efforts (NgororeroDDS, 2018). The district has several rivers, including Nyabarongo, Mukungwa, and Satinsyi, which support farming in wetland areas, enabling three agricultural seasons annually (REMA, 2015).

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Ngororero's fauna includes various bird species such as eagles, owls, pigeons, and crowned cranes. Vegetation is dominated by eucalyptus and cypress trees, with forests covering 8,000 hectares. The Gishwati and Mukura forests, now national parks, present eco-tourism opportunities. The district's diverse landscapes and biodiversity make it an attractive area for conservation and economic development (Ngororero LED, 2018).

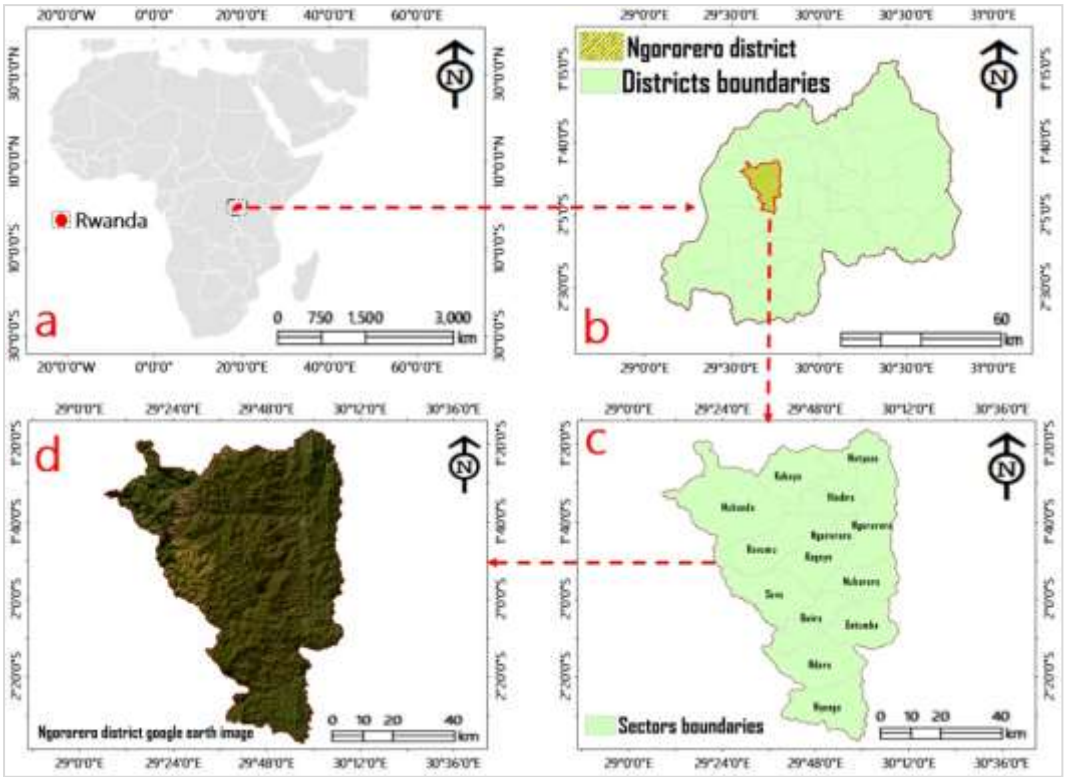

Figure 2.**1: Geographical location map of the study area; (a) location of Rwanda at continent level; (b) location of Ngororero District at national level; (c) the sectors subdivisions in Ngororero District; (d) The google earth map representation of Ngororero district.**

2.2 Research design and data collection methods

This study employed a mixed research design, integrating quantitative and qualitative approaches to assess deforestation and afforestation in Ngororero District. The quantitative component used ArcGIS and remote sensing techniques to analyze Land Use and Land Cover (LULC) changes from 1990 to 2020, utilizing Landsat 7 ETM+ and Landsat 8 OLI imagery. Spatial regression analysis examined relationships between deforestation/afforestation hotspots and driving factors such as population growth, agricultural expansion, and proximity to roads.

Secondary data included satellite imagery from NASA and USGS, historical land cover maps, and policy documents. Primary data involved field observations for ground-truthing and documenting land use changes through photographic and GPS-based surveys. Data collection combined remote sensing and field surveys, with ArcGIS 10.8 used for image processing and change detection analysis. Qualitative data from field visits and document analysis provided additional insights into governance frameworks, offering a comprehensive understanding of deforestation and afforestation trends in Ngororero District.

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Table 1.3: Landsat 7 data bands with their resolution and wavelength

Band	Landsat 7 Operational Land Imagers (OLI) & Thermal Infrared Sensor (TIRS)		
	Band Name	**Wavelength (micrometers)**	**Resolution (meter)**
Band 1	Coastal Blue	0.45 - 0.52	30
Band2	Green	0.52 - 0.60	30
Band 3	Red	0.63 - 0.69	30
Band4	NIR	0.77 - 0.90	30
Band5	SWIR	1.55 - 1.75	30
Band6	Thermal Infrared	10.40 - 12.50	60
Band7	SWIR	2.08 - 2.35	30
Band8	Panchromatic	0.52 - 0.90	15

Table 2.3: Landsat 8 data bands with their resolution and Wavelength

Band	Landsat 8 Operational Land Imagers (OLI) & Thermal Infrared Sensor (TIRS)		
	Band Name	**Wavelength (micrometers)**	**Resolution (meter)**
Band 1	Ultra-Blue	0.435-0.451	30
Band 2	Blue	0.452-0.512	30
Band 3	Green	0.533-0.590	30
Band 4	Red	0.636-0.673	30
Band 5	NIR	0.851-0.879	30
Band 6	SWIR 1	1.566-1.651	30
Band 7	SWIR 2	2.107-2.294	30
Band 8	Panchromatic	0.503-0.676	15
Band 9	Cirrus	1.363-1.384	30
Band 10	TIRS 1	10.60-11.19	100*30
Band 11	TIRS 2	11.50-12.51	100*30

Source: U.S. Geological Survey (https://www.usgs.gov/landsat-missions/landsat-8)

The annual rate of afforestation and deforestation in 1990 and 2020 analyzed and interpreted expressed either in rate(area/time) or in percentage. The following formula applied to compute annual rate of deforestation:

$$R = \frac{A_1 - A_2}{t_2 - t_1} \quad \text{or} \quad R = \frac{A_1 - A_2}{A_1} * 100$$

Where R, is the annual rate of deforestation, A_1 & A_2 refer to area of forest cover at time t_1 and t_2, respectively.

Moreover, for the second objective examining the driving factors of deforestation versus afforestation in Ngororero district, the study focused on detecting changes in land use and

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land cover (LULC) over the Ngororero district. Using remote sensing and GIS analysis, the research assesses the various conversions that have occurred during the study period (1990-2020). The detection of LULC changes provided insights into the driving forces behind the observed patterns of deforestation and afforestation. By identifying and analyzing these conversions, the study aims to reveal the underlying factors influencing the changes in forest cover within the Ngororero district.

2.3 Illustration of research methodology

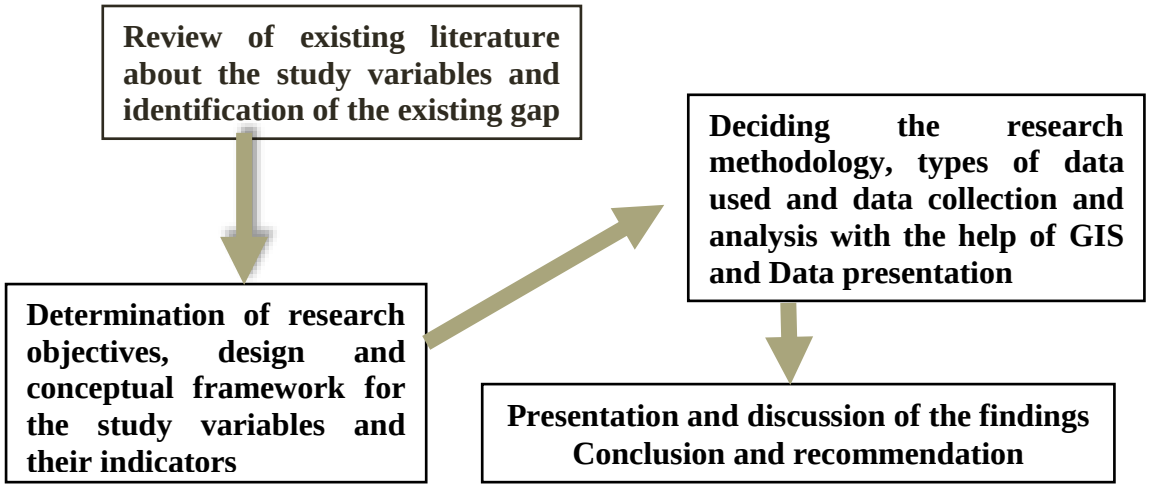

Figure 2.1: Methodology flowchart followed by the researcher

3. Results

3.1 Assessing deforestation and afforestation in Ngororero district over three decades (1990-2020)

The results disclosed various LULC conversions that occurred in Ngororero District between 1990 and 2020 (Figure 4-1). The conversions from forest areas to cropland, grassland, and built-up areas have been categorized as deforestation zones. These deforestation hotspots are widespread across the district, with larger concentrations in the central, western, and northern regions. Conversely, the map also highlights areas where afforestation or reforestation has taken place during this period. These afforested areas are identified by the conversions from grassland and cropland to forest cover (Figure 4-1). The afforestation zones are distributed throughout the district, but appear to be more prevalent in the eastern and central sections. In plain text, the deforestation areas represent the loss of forest cover due to the expansion of cropland, grassland, and built-up areas, likely driven by factors such as agricultural expansion, urbanization, and other land-use changes. On the other hand, the afforested areas indicate efforts to restore or establish new forest cover, either through natural regeneration or intentional reforestation initiatives. These afforestation zones may have been implemented to mitigate the impacts of deforestation, promote biodiversity conservation, or support sustainable land management practices.

When comparing the extent of deforestation and afforestation, it is evident that the deforested areas occupy a larger spatial coverage than the afforested areas. The loss of forest cover due to conversions to cropland, grassland, and built-up areas is more extensive and widespread than the gains in forest cover through afforestation efforts. However, it is important to note that while the afforested areas may be smaller in extent, they represent

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significant efforts to restore or establish new forest cover, potentially mitigating the impacts of deforestation and supporting sustainable land management practices in the district.

Beyond deforestation and afforestation, the results captured a dynamic interplay of other LULC conversions. Some croplands have transitioned to grasslands or grazing lands, while in other areas, grasslands have been converted to croplands, reflecting shifts in agricultural practices or land use priorities. Additionally, certain grassland areas have been replaced by built-up or urban development, indicating urban sprawl and the expansion of residential or commercial areas. The findings also reveal the presence of wetlands, which may have undergone conversions or remained unchanged during this period, underscoring the importance of preserving these ecologically sensitive areas. Amidst these transformations, the findings highlight regions that have remained unconverted, such as persistent forest cover, consistent croplands, or stable grasslands, serving as potential refuges for biodiversity or areas of sustained land use practices.

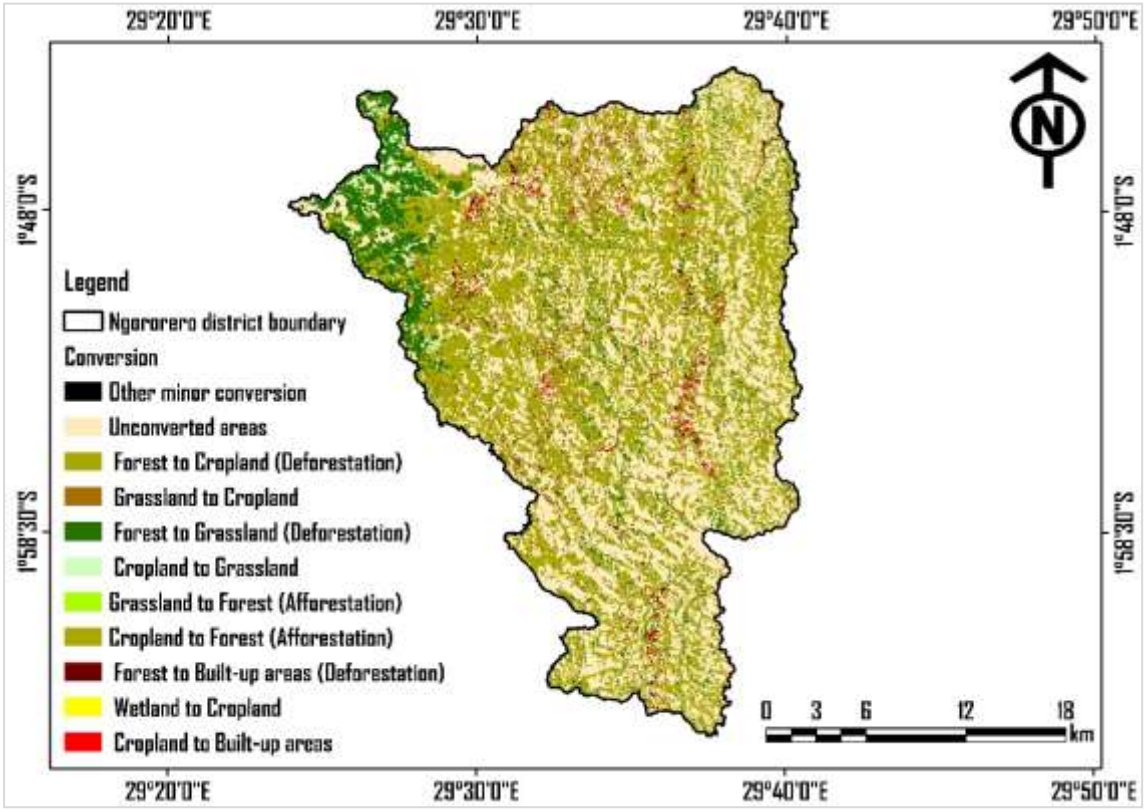

Figure 3**.1: Conversion in LULC Ngororero district (1990-2020)**

The quantitative insights into the land use conversions that occurred in Ngororero District (1990-2020) are given in Table 3.1. The results disclosed that a significant portion of the district, approximately 274.4 km^2 (40.45%), remained unconverted, indicating areas where the land use patterns persisted throughout the three-decade period. However, the findings reveal (Table 3-1) concerning trends of deforestation, which emerged as the most prominent transformation. A staggering 43.29% of the district's total area, spanning 293.7 km^2, and undergone conversion from forest cover to cropland. Additionally, 60.8 km^2 (8.96%) of forested regions transitioned to grasslands. Compounding the issue of deforestation, 7.3 km^2 (1.08%) of forested areas were converted to built-up or urban environments, further exacerbating the strain on the district's ecological resources. These

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conversions, collectively termed deforestation, accounted for a substantial 53.33% of the total land use transformations, highlighting the severe loss of natural forest cover within the district.

In contrast, efforts towards afforestation and reforestation were comparatively modest, with only 1.1 km^2 (0.16%) of grasslands and 2.5 km^2 (0.37%) of croplands transitioning to forest cover (Table 3-1). These afforestation initiatives constitute a mere 0.53% of the total land use conversions, underscoring the need for more comprehensive and extensive reforestation programs to counterbalance the substantial deforestation observed.

The results also highlighted other conversions, such as the expansion of croplands into grasslands (17.1 km^2 or 2.52%) and the conversion of croplands to built-up areas (9.6 km^2 or 1.42%). Additionally, some grasslands reverted to croplands (7.6 km^2 or 1.12%), and minor conversions accounted for 0.57% of the total transformations (Table 4-1).

These quantitative information highlights the significant environmental challenges faced by Ngororero District, with deforestation emerging as the dominant driver of land use conversion, outpacing afforestation efforts by a substantial margin. Addressing this imbalance and promoting sustainable land management practices will be crucial for preserving the district's natural resources and ensuring long-term ecological resilience.

Table 3.1: Quantification of major LULC conversion in Ngororero district (1990-2020)

Converted classes	**Area (km^2)**	**Conversion (%)**
Other minor conversion	3.9	0.57
Unconverted land use	274.4	40.45
Forest to crop (Deforestation)	293.7	43.29
Grass to crop	17.1	2.52
Forest to Grass (Deforestation)	60.8	8.96
Crop to Grass	7.6	1.12
Grass to Forest (Afforestation)	1.1	0.16
Crop to forest (Afforestation)	2.5	0.37
Forest to built-up (Deforestation)	7.3	1.08
Wetland to crop	0.4	0.06
Cropland to Built-up	9.6	1.42
Total deforestation	361.8	53.33
Total afforestation	3.6	0.53
Total other conversions	313	46.14
Overall total	**678.4**	**100**

In summary, the results highlighted the deforested and afforested areas extent in Ngororero District from 1990 to 2020. The deforested areas are depicted in green (Figure 3.2), representing 53.33% of the total land area and regions where forest cover has been lost due to conversions to other land uses like cropland, grassland, or built-up areas. These widespread deforestation hotspots are particularly concentrated in the central, western, and northern part of the district. In contrast, the afforested areas shown in red (Figure 3.2) indicate only 0.53% of the total land area, highlighting zones where new forest cover has been established or existing forests have been restored through afforestation or reforestation

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efforts. These relatively small afforestation hotspots appear more localized and distributed compared to the large deforested areas. Additionally, the areas covering 46.14% of the land have not experienced significant deforestation or afforestation during the study period.

The substantial spatial extent of the deforestation hotspots covering over half the district is visibly much larger compared to the limited afforestation hotspots, implying that the rate of deforestation has vastly outpaced afforestation efforts within the district over the past three decades. This striking imbalance highlights the pressing need for comprehensive conservation strategies and sustainable land management practices to mitigate further deforestation and promote more extensive afforestation initiatives. This is because with a significantly larger deforested area than afforested areas, there is a decrease in the overall forest cover, resulting in loss of biodiversity, disruption of ecosystems, and reduced carbon sequestration. This imbalance exacerbates the impact of climate change, as forests play a crucial role in mitigating carbon dioxide levels. Furthermore, it can lead to soil erosion, loss of habitat for wildlife, and a decrease in the availability of essential resources such as timber and medicinal plants. Ultimately, this imbalance threatens the delicate balance of the environment, affecting not only ecological stability but also human well-being. Therefore, a harmonious equilibrium between deforestation and afforestation is crucial for sustaining a healthy and thriving environment.

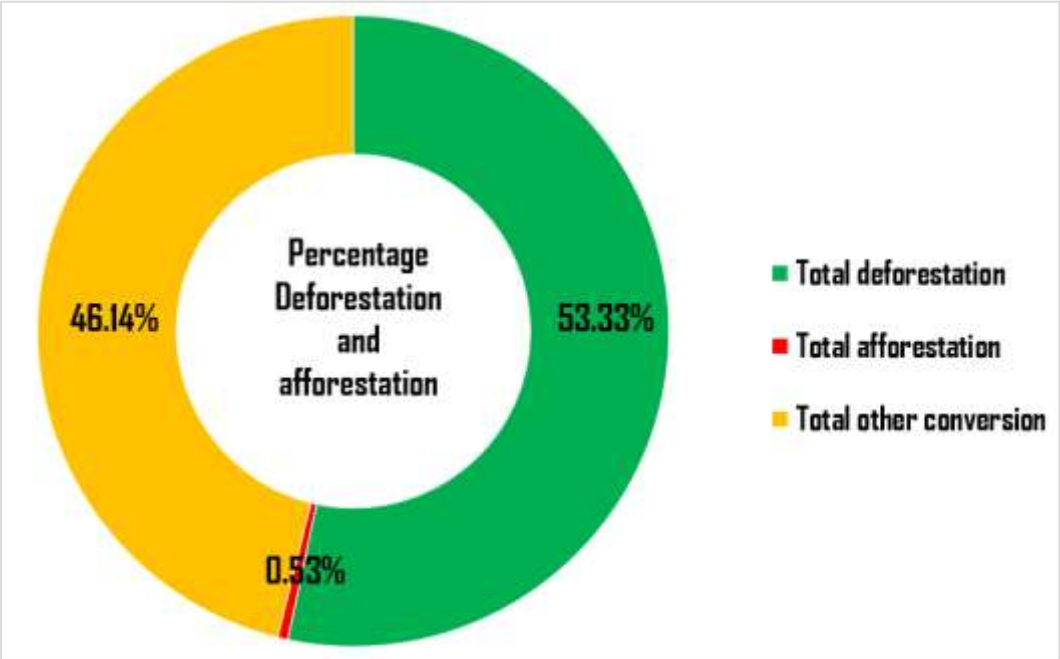

Figure 3.2: Deforestation and afforestation quantification in Ngororero district (1990-2020)

3.2 Possible driving factors of deforestation vs afforestation in Ngororero district

The second objective of the study was to examine possible driving factors of deforestation vs afforestation in Ngororero district. Based on the obtained results (Figure 3.2) comparing the LULC patterns in Ngororero District between 1990 and 2020, the researcher identifies several potential driving factors that contributed to the observed deforestation and afforestation trends. Deforestation appears to have been primarily driven by the expansion of agricultural activities and urban development. The substantial increase in cropland areas, as evident from Figure 3.2 in 2020 compared to 1990, suggests that forest clearing for agricultural purposes was a major driver of deforestation. The growing demand for arable land to support the region's agricultural needs likely led to the conversion of forested areas

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into croplands. Furthermore, the emergence of new built-up or urban areas in 2020, indicated that deforestation also occurred to accommodate urban expansion and infrastructure development. As the district's population grew (Figure 3.2), the demand for residential, commercial, and industrial areas increased, resulting in the clearance of forested lands. Additionally, the transition of forested areas to grasslands in 2020, could be attributed to factors such as overgrazing, unsustainable land management practices, or the conversion of forests for grazing purposes.

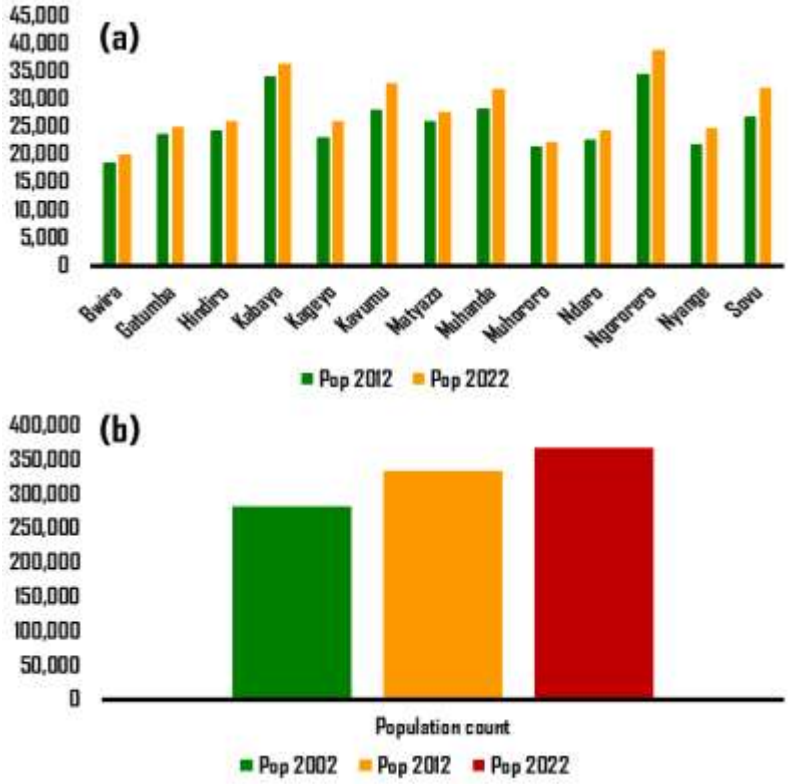

Figure 3.2: Population growth of Ngororero district. (a) Population growth per sector from 2012 -2022, (b) population growth from 2002 – 2022.
Source: National Institute of Statistics Rwanda (NISR).

On the other hand, the afforestation efforts, though limited in extent, can be observed in the areas where new forest cover has emerged, particularly in the eastern and central regions of the district. These afforestation initiatives may have been driven by various factors. Reforestation programs implemented by governmental or non-governmental organizations could have aimed to restore degraded lands or establish new forest areas for conservation purposes. In some areas, the abandonment of agricultural lands or grazing areas may have allowed natural forest regrowth and regeneration, contributing to the afforested zones. Additionally, the integration of trees into agricultural systems, such as in the form of shelter belts or woodlots, may have contributed to the afforestation efforts through agroforestry practices. Increased recognition of the importance of forests for ecological services, biodiversity conservation, and climate change mitigation could have prompted community-driven or government-supported afforestation initiatives within the district. When examining the spatial patterns, it is evident that deforestation has been more widespread and intense in the central, western, and northern regions of the district. These areas show a significant reduction in forest cover between 1990 and 2020 (Figure 3.3), likely driven by the expansion of croplands and urban development. Conversely, the afforestation hotspots, though limited, appear more concentrated in the eastern and central sections of the district, suggesting that these regions may have been targeted for reforestation or agroforestry

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initiatives. It is crucial to note that the driving factors for deforestation and afforestation may vary across different localities within the district, influenced by local socioeconomic conditions, land tenure systems, environmental policies, and cultural practices. Addressing the imbalance between deforestation and afforestation rates will require a multifaceted approach, including sustainable agricultural intensification, promotion of agroforestry systems, urban planning to minimize forest encroachment, and strengthening of environmental protection policies and enforcement mechanisms.

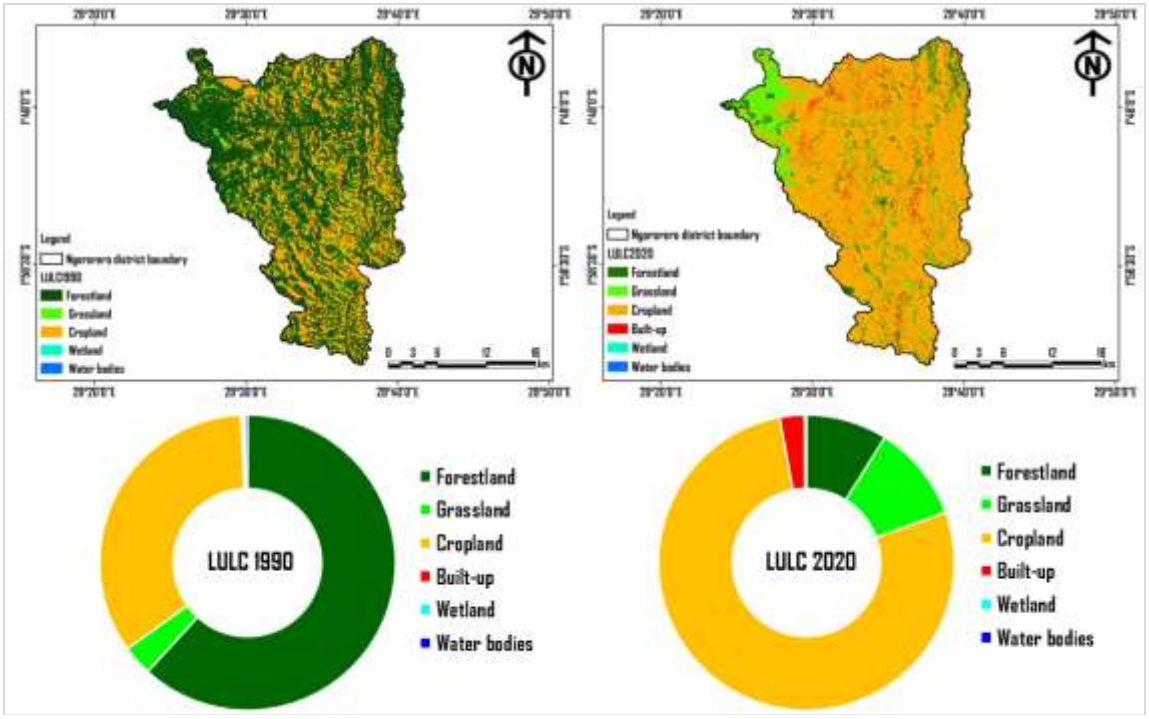

Figure 3.4: Spatio-temporal LULC in Ngororero district (1990-2020)

Table 3.4: Statistics of the spatio-temporal LULC change in Ngororero district (1990-2020)

Classes	1990	Percent	2020	Percent	Change (km^2)	Change (%)
Forestland	419	61.8	60.2	8.9	-358.8	-85.7
Grassland	22.4	3.3	71.8	10.6	49.4	220.5
Cropland	232.7	34.2	526.6	77.6	293.9	125.9
Built-up	1.2	0.2	18.5	2.7	17.3	1441.7
Wetland	1.3	0.2	0.1	0.01	-1.2	-92.3
Water bodies	1.8	0.3	1.2	0.19	-0.6	-33.3
Total	**678.4**	**100**	**678.4**	**100**		

4.3 Relationships between deforestation/afforestation hotspots and their potential driving factors in Ngororero district (1990-2020).

The observed changes in land cover classes within Ngororero district from 1990 to 2020 reveal intricate relationships between deforestation/afforestation dynamics and their driving factors through different gains and losses (Figure 3.3). This has been revealed

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through gains and losses from one LULC type at the expense of another. For instance, the significant gain of 400 Km^2 in forestland compared with a substantial loss of -358.8 Km^2 suggesting a complex interaction between deforestation activities and reforestation efforts over the studied period (Figure 4.5). This relationship underlines the ongoing challenges of deforestation mitigation and the potential success of afforestation initiatives in restoring forest cover within the district.

In contrast, the stagnant trend in grassland with no recorded gains or losses indicates a relative stability in this land cover class, potentially influenced by consistent land management practices or natural preservation efforts. On a positive note, the gain in grassland area (48.4 Km^2) could potentially represent opportunities for afforestation initiatives (Figure 4.5). Afforestation hotspots, such as the conversion of grassland to forest and crop land to forest, indicate positive trends towards forest restoration and reforestation activities. These conversions may result from afforestation initiatives, reforestation projects, or natural regeneration processes facilitated by conservation efforts and community participation. Grasslands may be more easily converted to forested areas compared to built-up or intensively cultivated lands, provided there is sufficient support and incentives for such land use transitions. The relatively small area of afforestation compared to deforestation suggests the need for intensified efforts to promote afforestation and restore degraded ecosystems in the district.

In addition, the increase of 17.3 Km^2 in built-up areas without losses reflects urbanization trends and infrastructural development within the district (Figure 3.4). This relationship emphasizes the urban-rural dynamics shaping land use patterns and presented the importance of land use planning to manage urban sprawl and preserve natural habitats. Moreover, the loss of -12 Km^2 in wetland areas signals wetland degradation, possibly due to urban encroachment, agricultural runoff, or inadequate conservation measures (Figure 3.5). This relationship discloses the vulnerability of wetland ecosystems to human activities and the necessity of targeted conservation efforts to protect these valuable habitats. The findings revealed no significant changes in water bodies with a minimal loss of -0.6 Km^2 implies relatively stable aquatic ecosystems within the district (Figure 3.5). This relationship highlights the interconnectedness of land and water resources, emphasizing the need for integrated watershed management approaches to safeguard water quality and ecosystem health.

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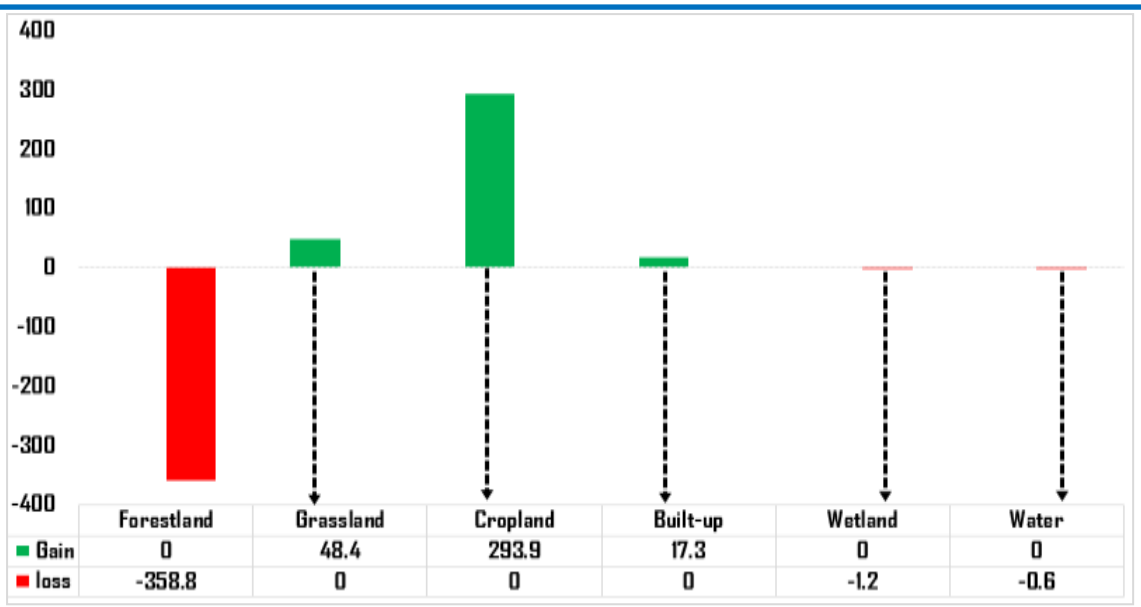

Figure 3.**6: Gain and losses (Km2) in LULC (Increase or decrease at the expense of another class)**

4.4. Discussion of the Results

The research findings demonstrated that there was a huge change in Land use land cover in Ngororero and this is common in developed and developing countries where spatial urban expansion is a common phenomenon (Kasraian et al., 2016; Traore et al., 2021). It is associated with economic progression and land development which are seen as engine of city growth which drive the land use land cover (Traore et al., 2021). However, in developing countries urban land use land cover changes are with negative Impacts. Many researchers claimed that the major driving factors of deforestation in Africa as rapid population growth, agriculture activities and spatial urban development (Nduwayezu et al., 2017). Although agriculture land covers a very small fraction of the world's land surface, rapid agricultural land expansion has significantly changed the landscape of Ngororero district (MININFRA, 2021). Over the last decades, several studies have focused on the field of urban expansion. However, the implications of key driving factors of deforestation and afforestation in Ngororero district have not been sufficiently analysed (Fazal, 2000. Moreover, it was reported that A combination of remotely sensed (RS) data and geographic information systems (GIS) technologies could provide an eminently suitable means of assessing the driving factor of deforestation and afforestation (Hassan et al., 2016).

Doing so in this study, the findings reveal a concerning trend of widespread deforestation in Ngororero District over the past three decades, along with modest efforts towards afforestation. These results align with the broader pattern of deforestation observed across Rwanda and other parts of Sub-Saharan Africa, driven by factors such as agricultural expansion, urbanization, and unsustainable land use practices(Olorunfemi et al., 2022; Uwiringiyimana & Choi, 2022). The substantial loss of 358.8 km^2 (85.7%) of forestland between 1990 and 2020 in Ngororero District is a striking indicator of the severe deforestation pressure experienced in the region. This finding is consistent with previous studies that have documented rapid deforestation rates in Rwanda, with an estimated loss of over 60% of the country's forest cover between 1960 and 2010 (Akinyemi, 2017; Ndayambaje et al., 2014). The conversion of forestland to cropland and built-up areas, accounting for 43.29% and 1.08% of the total land use changes, respectively, highlights the role of agricultural expansion and urbanization as primary drivers of deforestation. This

corroborates the findings of(Bimenyimana et al., 2022; C. Li et al., 2021), who identified similar drivers of deforestation in other regions of Rwanda.

In contrast, the limited afforestation efforts, covering only 0.53% of the total land use conversions, implicate the challenges in restoring forest cover and achieving a balance between deforestation and afforestation rates. This imbalance is a common issue faced by many developing countries, where the need for agricultural land and urban development often takes precedence over environmental conservation efforts(Bondarev et al., 2019; T. Zhou & Ke, 2021). The observed spatial patterns, with deforestation hotspots concentrated in the central, western, and northern regions, while afforestation efforts were more localized in the eastern and central areas, highlight the uneven distribution of these processes within the district. This spatial heterogeneity may be influenced by factors such as proximity to urban centers, accessibility, land tenure systems, and the effectiveness of local conservation initiatives(Tang et al., 2017). The substantial increase in cropland area (293.9 km^2 or 125.9%) and urban built-up areas (17.3 km^2 or 1441.7%) aligns with the findings of (Bimenyimana et al., 2022; Karamage et al., 2016), who documented the expansion of agricultural land and urban areas as major drivers of deforestation in Rwanda. This trend is often driven by population growth, increasing demand for food and land resources, and urbanization pressures(JHA & BAWA, 2006; Oyetunji et al., 2020).

The decline in wetland areas (-1.2 km^2 or 92.3%) is a concerning observation, as wetlands play crucial roles in biodiversity conservation, water regulation, and ecosystem services. This finding accentuates the need for targeted conservation efforts and sustainable management practices to protect these valuable ecosystems, as highlighted by (Suhani et al., 2020; Yi et al., 2024)in their studies on wetland degradation in Rwanda. While the results of this study provide valuable insights into the deforestation and afforestation dynamics in Ngororero District, it is essential to acknowledge the limitations of the research. The study primarily relied on remote sensing data and spatial analysis, which may not fully capture the complex socio-economic and cultural factors driving land use changes. Future research could incorporate field-based data collection, stakeholder interviews, and socio-economic assessments to better understand the underlying drivers and develop more contextualized conservation strategies.

Overall, the findings of this study contribute to the growing body of literature on deforestation and land use change in Rwanda and Sub-Saharan Africa. By quantifying and spatially analyzing the deforestation and afforestation hotspots, as well as their potential driving factors, this research provides valuable insights for policymakers, conservation organizations, and local communities to develop targeted interventions and sustainable land management strategies. Addressing the imbalance between deforestation and afforestation rates is crucial for preserving biodiversity, mitigating climate change impacts, and promoting sustainable development in Ngororero District and beyond.

4. Conclusion

In conclusion, this study sought to assess the driving factors behind deforestation and afforestation in the Ngororero district over a span of three decades (1990 - 2020). The goal was to comprehensively analyze the trends, underlying factors, and implications of deforestation and afforestation dynamics within the district. The findings of this study illuminate the pressing need for sustainable land management strategies and comprehensive conservation efforts to address the significant environmental challenges posed by deforestation and afforestation trends in the Ngororero district. The quantitative analysis

revealed a pronounced imbalance between deforestation and afforestation activities, with deforestation emerging as the dominant driver of land use conversion over the study period. Specifically, the results highlighted those deforested areas represented 53.33% of the total land area, signifying the extensive nature of forest loss due to conversions to other land uses such as cropland, grassland, and built-up areas. In contrast, afforestation efforts accounted for only 0.53% of the total land use conversions, indicating a substantial disparity that warrants urgent attention.

Comparing these results with prior studies highlights the consistency of the identified driving factors, while also elucidating unique local dynamics that influence land use changes within the Ngororero district. The alignment of the study's findings with existing literature underscores the relevance and significance of this research contribution to the field of environmental conservation and land management in the region. The implications of this extend to the development of targeted interventions and policies aimed at mitigating the adverse effects of deforestation, promoting afforestation initiatives, and fostering sustainable land use practices. By understanding the specific drivers of deforestation and afforestation within the Ngororero district, policymakers and conservation practitioners can develop tailored strategies to address these challenges effectively. In conclusion, the findings of this study offer valuable insights into the complex dynamics of deforestation and afforestation in the Ngororero district, with far-reaching implications for environmental sustainability and land use management. These findings contribute to the growing body of knowledge in this field and provide a foundation for developing targeted strategies to address the identified driving factors and achieve a harmonious equilibrium between deforestation and afforestation activities in the region.

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