



Spatio-temporal landscape dynamics in northwestern Virunga National Park amid armed conflicts, urban expansion, and agricultural transition

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Join Doctoral dissertation

**Spatio-temporal landscape dynamics in
northwestern Virunga National Park amid armed
conflicts, urban expansion, and agricultural
transition**

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Cover photo: illustration of agriculture encroachment and forest clearing by local population in the Mayango's area within Virunga National Park (DRC), ©Charles Mumbere Musavandalo

1. Dedication

To my uncle Katembo Mundenga, a victim of terrorism, but whose courage continues to inspire our spirit. This thesis honors your sacrifices and those of the other victim's terrorism in Beni region.

To my parents Kambale Mundenga Dominique and Kavira Kavula Jeanne

To my wife, Kahindo Lukuhi Wivine

*To my children: Mumbere Mundenga Christian, Kambale Mundenga Gaël,
Kasereka Mundenga Jan and Kahindo Mundenga Angela.*

2. Epigraph

*Faced with industrial pollution, the Democratic Republic of the Congo,
formerly Zaïre, will become the last refuge natural nature.*

Joseph MOBUTU SESESEKO

3. Abstract

Protected areas in the Democratic Republic of Congo, especially Virunga National Park, are crucial for biodiversity conservation. Nevertheless, they face significant challenges, such as the human impact on natural ecosystems caused by agricultural expansion, urbanization, and persistent insecurity. Despite increased concern over these human pressures, few studies have simultaneously explored the links between landscape changes, socioeconomic factors, and urban expansion. This thesis investigates these issues by examining territorial dynamics at multiple scales and the socio-economic processes in north-western Virunga, a region marked by high population growth and ongoing insecurity.

The study provides a comprehensive overview of landscape changes, forest disturbance factors, perceptions, and motivations behind agricultural migration, as well as urban growth in Beni and Butembo. Methodologically, it combines satellite image analysis with household surveys, interviews, and landscape ecology indicators. Land-cover changes and urban expansion patterns were quantified through spatial analysis, while socio-economic data helped explain motivations, perceptions, and adaptive strategies linked to human-induced environmental changes.

Regarding the results, several findings emerge: first, the analysis indicates that since 1995, the landscape change in northwestern Virunga has been primarily driven by the expansion of smallholder farms, leading to landscape fragmentation. However, since 2005, this expansion has slowed, which coincides with passive forest restoration, partly associated with insecurity in farming areas. In this regard, a relative increase in forest areas (~2%) has been observed both globally and around military camps. Nevertheless, despite this partial recovery, forests within the landscape remain threatened by various disturbances. In particular, these include the spread of cash and food crops outside the park and timber extraction and charcoal production within the park.

Additionally, the analysis perception of households on shifting cultivation reveals an important transition: it is no longer driven solely by the search for fallow land but reflects a more complex decision-making process involving soil fertility, investment in cash crops, and resilience to face insecurity. Turning to urban dynamics, the result indicated urban expansion is rapid but varies between Beni and Butembo, with security playing a greater role than population growth. While Butembo's growth is more consistent, while Beni, despite rapid population increases, is growing more slowly due to insecurity. Overall, this study emphasizes the key role of Virunga National Park in preventing deforestation in Beni region, highlights the unpredictable impact of insecurity on ecosystems. Therefore, it underscores the need for land-use planning that balances agricultural intensification with forest conservation. It also stresses the importance of anticipating human-environmental interactions in a post-conflict context.

Keywords: Forest disturbance, Landscape fragmentation, Protected area, North Kivu

4. Résumé

En République Démocratique du Congo, les aires protégées, notamment le Parc National des Virunga, jouent un rôle crucial dans la sauvegarde de la biodiversité. Toutefois, elles sont confrontées à de nombreux défis, tels que la pression humaine croissante sur les écosystèmes naturels, due à l'expansion agricole, l'augmentation démographique, l'urbanisation et l'insécurité persistante. Bien que ces enjeux suscitent un vif intérêt, peu d'études ont abordé simultanément les interactions entre les dynamiques paysagères, les facteurs socio-sécuritaires et l'urbanisation. Cette thèse analyse ces différentes dimensions dans le paysage nord-ouest des Virunga en adoptant une approche systémique.

L'étude examine les dynamiques du paysage, les facteurs anthropiques de perturbant les forêts naturelles, les perceptions liées à l'itinérance agricole ainsi que l'expansion urbaine des villes de Beni et Butembo dans un contexte d'insécurité persistante entre 2016 et 2023. Sur le plan méthodologique, elle combine l'analyse d'images satellites Landsat, couvrant 1995 à 2021, pour suivre la dynamique générale de la structure spatiale du paysage, d'images Planet, de 2016 à 2023, pour analyser l'expansion urbaine, ainsi que des enquêtes auprès des ménages, des interviews et des indicateurs écologiques du paysage.

Les résultats indiquent que, depuis 1995, les pertes de couvert naturel ont été causées par l'expansion agricole, qui constitue la matrice du paysage. Cependant, depuis 2005, cette dynamique a ralenti, entraînant une restauration passive partielle des forêts (~2%), en partie due à l'insécurité dans la zone agricole. Malgré cette embellie, les forêts restent vulnérables à diverses formes de perturbation. Parmi celles-ci, l'expansion des cultures de rente, souvent associée aux cultures vivrières, et l'extraction de bois sous diverses formes au sein du parc sont les plus fréquemment recensées dans les zones forestières perturbées du paysage. Par ailleurs, l'analyse des perceptions des ménages sur l'itinérance agricole révèle une évolution notable. Celle-ci ne dépend plus uniquement de la pratique de jachère, mais traduit désormais un processus décisionnel complexe impliquant la recherche de fertilité, l'adaptation aux opportunités économiques agricoles, ainsi que la résilience face à l'insécurité. De plus, l'urbanisation semble influencée par la situation sécuritaire. En effet, l'expansion de Butembo, ville relativement stable sur le plan sécuritaire, se déroule de manière plus régulière et plus rapide, tandis que celle de Beni demeure lente malgré une forte croissance démographique par rapport à Butembo.

Dans l'ensemble, cette étude souligne la nature imprévisible de l'insécurité sur les écosystèmes naturels. Elle met en avant la nécessité d'une planification de l'utilisation des terres et d'une gestion des ressources naturelles adaptées au contexte local, surtout dans un environnement fragilisé par l'insécurité.

Mots clés : Perturbation forestière, Fragmentation du paysage, Aire protégée, Nord Kivu

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9. List of abbreviations and acronyms

ADF:	Allied Democratic Forces
ECOFAC:	Central African Forest Ecosystem (<i>Ecosystème Forestier d’Afrique Central</i>)
GEE:	Google Earth Engine
IUCN:	International Union for Conservation of Nature
NICFI :	International Climate and Forest Initiative (NICFI).
OFAC :	Central African Forest Observation (Observatoire des Forêts d’Afrique Centrale)
UNESCO:	United Nation Educational, Scientific and Cultural Organization
WWF:	World Wide Fund
NALU:	National Army for Liberation of Uganda

Chapter1

1. General introduction

1.1. Context

The Democratic Republic of the Congo, rich in natural resources, plays a central role in the global strategy to preserve biodiversity, combat climate change, and achieve sustainable development goals. The country aims to reduce deforestation-related carbon emissions by 56% by 2035 (Eba'a Atyi et al., 2022). For over a century, the DRC has been engaged in biodiversity conservation, beginning with the creation of Central Africa's first national park, the Virunga (Balole et al., 2015). Since then, it has developed a large network of protected areas, including national parks, nature reserves, hunting grounds, and other legally protected spaces. According to Law 20/24, which amends and supplements Law 014 on nature conservation (Article 26), the Democratic Republic of the Congo has set a goal of protecting 30% of its territory. However, the country faces numerous challenges, including fragile governance, political instability related to armed conflicts, population growth, and rapid urbanization, particularly in intermediate cities (Doumenge et al., 2015; Gillet et al., 2016; Itsoua Madzous et al., 2021). These factors lead to intense intersectoral competition for land use and reduce the capacity of protected area networks to safeguard natural resources (Inogwabini et al., 2005).

Within this context, Virunga National Park, created in 1925 under Belgian colonial administration and located in the eastern DRC, stands as a flagship protected area. It forms part of the “Greater Virunga landscape”, where 56% is covered by protected areas, including the Volcanoes National Park in Rwanda, the Mgahinga Gorilla Park, and the Semuliki Park in Uganda (Lanjouw et al., 2001). This landscape is one of the largest natural habitats in the Albert Rift (Vikanza, 2011), renowned for its biodiversity, including the mountain gorilla, an iconic species. The landscape consists of rainforests, mountains, savannas, tropical glaciers, lakes, and volcanic massifs (Henrard and Huart, 2025). Virunga total economic value is currently estimated at \$48.9 million per year, reflecting its socio-economic and environmental importance (WWF, 2013). However, ongoing instability in the eastern DRC threatens the park's economic and ecological integrity. Virunga National Park remains listed as a World Heritage Site in Danger by UNESCO (UNESCO, 2025). This instability stems from the park's establishment, when the dispossession of land sparked conflicts between managers and local communities. This situation deteriorated further during the 1994 Rwandan genocide and subsequent cycle of wars and armed conflicts from 1996 to the present day, posing numerous challenges not only for landscape monitoring but also, and especially, for the environment and forest ecosystems

that abound in the country (Christensen and Arsanjani, 2020; Henrard and Huart, 2025). Furthermore, amid political instability, North Kivu province has experienced population growth and rapid urbanization, with annual rates of 10% and 7.5%, respectively. Approximately 80% of the population (more than 5 million people) live within the Virunga landscape, where the economy is weakened by ongoing conflicts (Balole et al., 2015). This demographic growth leads to a high demand for resources, including land for cultivation, firewood, and mineral products (Doumenge et al., 2015). Despite conservation efforts implemented by managers, land encroachment, shifting agriculture, loss of lowland humid forest, and habitat destruction continue across the northern, southern, and central parts of the landscape.

This study focuses on the anthropization of the northwestern Virunga landscape. This area provides numerous ecosystem services, notably through its natural humid forests in the Middle Semuliki. Like the entire Virunga landscape, this area is under human pressure, influenced by dynamics in the local economy, within a persistent context of security instability dominated by the activities of the armed group “Alliance Democratic Force” (ADF) since 2014. Security instability may not merely constitute a contextual condition but a major of landscape transformation in the northwestern Virunga landscape. Armed conflicts can reshape population distribution, land-use practice and natural resource exploitation. These processes could result in contrasting landscape trajectories, accelerating forest degradation in some areas while promoting temporary natural regeneration in others. Consequently, understanding the interaction between insecurity and other anthropogenic drivers would be essential for explaining landscape anthropization. While many studies in conflict contexts emphasize the economic, social, political, and ethical ramifications of the conflict (Vikanza., 2011), relatively little attention has been paid to its impact on natural landscapes. Moreover, the expansion of urban centers such as Butembo, Beni, Oicha, and Kasindi has intensified the encroachment of human activities into the region's natural ecosystems. In this regard, previous research indicates that the vulnerability of protected areas increases when they are near densely populated urban centers or when they risk approaching them due to constant land-use changes on the periphery (Hansen and DeFries, 2007). Taken together, these dynamics indicate the growing complexity of conservation in the region. Due to these challenges, conservation managers are forced to revise their protectionist strategies for managing protected areas. The landscape approach is gaining prominence worldwide, including in the DRC, as it seeks solutions that reconcile conservation and local development. Early considerations, focused on the

landscape scale, size, and connectivity, often overlooked society and the population, and have frequently failed (Sayer et al., 2013; Xun et al., 2017). This limit underscores the need to integrate human dimension into landscape management. In the specific context of northwest Virunga, the main challenge of this approach lies in how to meet the needs of five million impoverished inhabitants who depend on natural resources for their livelihoods (NaturAfrica, 2021). Addressing this challenge requires comprehensive information not only on landscape dynamics but also on the relationships between the residents and the natural ecosystems, particularly with abundant forest ecosystems. Addressing this challenge requires comprehensive information not only on landscape dynamics but also on the interaction between local communities, insecurity and forest ecosystems.

Nevertheless, previous research on the northwestern Virunga landscape has often lacked a comprehensive approach to monitoring the dynamics of human impact. For instance, some studies, such as those by (, have examined the conflict between the population and the park primarily from a political standpoint rather than ecological perspective one. Similarly, others studies, like Bweya et al. (2019), have addressed deforestation in Beni, without a direct link to park conservation. In addition, studies by Mulondi et al. (2019) and Kasekete et al. (2023) have mainly focused on the supply of firewood, without integrating the broader human and insincerity impact dimension involved. As a result, important gaps remain regarding the cumulative effect of human activities. Consequently, the cumulative impacts of these interacting drivers remain poorly understood. This knowledge gap is particularly critical because the northwestern Virunga landscape constitute a potential ecological corridor connecting Virunga National Park with Okapi Wildlife Reserve. Adopting a landscape perspective is essential for achieving balanced spatial and resource management. Our analysis considers the protected area as part of a larger ecosystem, where human pressures, even at the edges, can disrupt the entire system. From a management and policy perspective, analyzing the processes at landscape scales is crucial to assess the effectiveness of conservation policies and investments, as well as for developing appropriate management strategies for the northwestern Virunga landscape. This study, therefore, aims to address the existing knowledge gap regarding anthropization in the region in the context of insecurity.

1.2. Research questions

This study questions the anthropization of the northwest landscape of Virunga, which extends beyond the protected area to encompass the entire landscape,

including peripheral spaces. The fundamental question is: 'How do insecurity and urbanization, and agriculture transition influence land cover change and forest pressure in the north-western Virunga landscape? This question thus raises the trade-off between the desire to develop while preserving natural forest ecosystems in a broad sense. From this main question, the following specific questions:

- How has the spatial structure of the Northwestern Virunga landscape evolved over the past three decades of armed conflicts?
- What are the anthropogenic factors disrupting the natural forest habitats of the landscape?
- How do farmers perceive and justify the itinerant nature of farming in mature forest in the Northwestern Virunga landscape?
- What is the recent trend in urbanization of the two major cities, Beni and Butembo, in the Northwestern Virunga landscape within the context of widespread human impact and increasing security instability?

1.3. Hypothesis

This study is based on the main hypothesis: "Insecurity, urbanization, and agricultural transition affected land-cover and increased forest pressure in the northwestern Virunga landscape." Specifically, the study aims to test the four hypotheses formulated as follows:

Hypothesis 1: The spatial dynamics of the landscape in the Northwest of Virunga follow a decrease in forests and savannas, replaced by agricultural and built-up areas, linked to the evolution of security instability. Thus, the significant losses of forests and savannas, both within the protected area and in the periphery, correspond to periods of high instability rather than phases of relative stability.

Hypothesis 2: Given the economic stakes and urbanization, cash crops expansion, mainly cocoa, and the extraction of firewood and timber are the main factors positively associated with the disturbance of natural forests in the northwestern Virunga landscape.

Hypothesis 3: The Shifting cultivation in mature forest are driven by various motivations beyond merely seeking fertile soils. These include economic consideration, land preparation methods and the mode of land access. But the perception of security in agricultural areas drives households' willingness to adopt more sedentary farming practices rather than agricultural innovations.

Hypothesis 4: The security and economic contexts specific to each city play a more decisive role in urbanization than the demographic context alone. Thus,

despite more moderate population growth, Butembo benefits from a commercial function that is a powerful driver of its expansion, compared to Beni. This commercial vocation, by stimulating land investment and residential sprawl (Nuissl et al., 2021) leads to faster urbanization in Butembo than in Beni.

1.4. Objectives

The main objective of this study is to analyze how insecurity, urbanization, and agricultural transition influence land cover change and forest disturbance in the northwestern Virunga landscape. It involves analyzing both the evolution of the landscape's composition and configuration, as well as the various relationships between the factors responsible for its degradation. Specifically, the study aims to:

Objective 1: Map and quantify the dynamics of the spatial structure of the landscape to a better understanding of human-induced landscape change and support landscape management;

Objective 2: Identify and categorize the physical factors of anthropogenic disturbances to the landscape in order to support the understanding of anthropization process and guide conservation action;

Objective 3: Examine farmers' perception and motivation regarding shift farming practices in mature forests to understand the key factors influencing the expansion of their cultivation front within landscape

Objective 4: Map and quantify recent urbanization in the landscape, focusing on the two main urban centers, Beni and Butembo, in order to understand pattern of urban expansion and their implication on the surrounding landscape.

1.5. Structure of thesis

This study is structured around nine chapters, four of which are dedicated to the results corresponding to the four research questions. The first chapter is dedicated to the introduction. It presents the study's problem statement, research questions, hypotheses, and objectives. This chapter concludes with an overview of the thesis structure, summarizing the content, contributions, and the complementarity of the different chapters to the overall reflection. The second chapter presents the study's conceptual framework. It outlines the main themes within which the study is embedded, as well as the concepts, approaches, and disciplines on which it relies to examine the problem of anthropization. The third chapter describes the study environment, the systemic foundation of the scientific approach, and the synthesis of the methodological approaches used to achieve each objective.

The fourth chapter presents the results concerning spatiotemporal dynamics at the global scale of the landscape studied. It describes changes in both the composition and configuration of landscape elements and provides an overview of the impact of preservation on the dynamics of natural landscape components. The fifth chapter complements the fourth by focusing on anthropogenic factors that cause landscape disturbances. It offers an essential contribution to better understanding of the spatial and temporal evolution of the landscape. The sixth chapter, complementary to the fifth, addresses uncontrolled agricultural itinerancy in the landscape, a significant factor in deforestation. It explores the underlying motivation of this agricultural dynamic in forested areas and presents local populations' perceptions regarding the stabilization of agricultural itinerancy. The seventh chapter presents results on recent urbanization in the landscape, focusing on intensity, processes, and trajectory. This chapter focuses on two strategic towns within the landscape, namely Beni and Butembo. The eighth chapter centers on a general discussion that compares the results and approaches obtained with those in existing documentation. It also addresses the implications of these findings for biodiversity conservation in the landscape and the management of the Virunga National Park. The ninth chapter synthesizes the overall conclusions drawn from all the results. The thesis concludes with bibliographic references and some appendices deemed useful for the study (Figure 1-1).

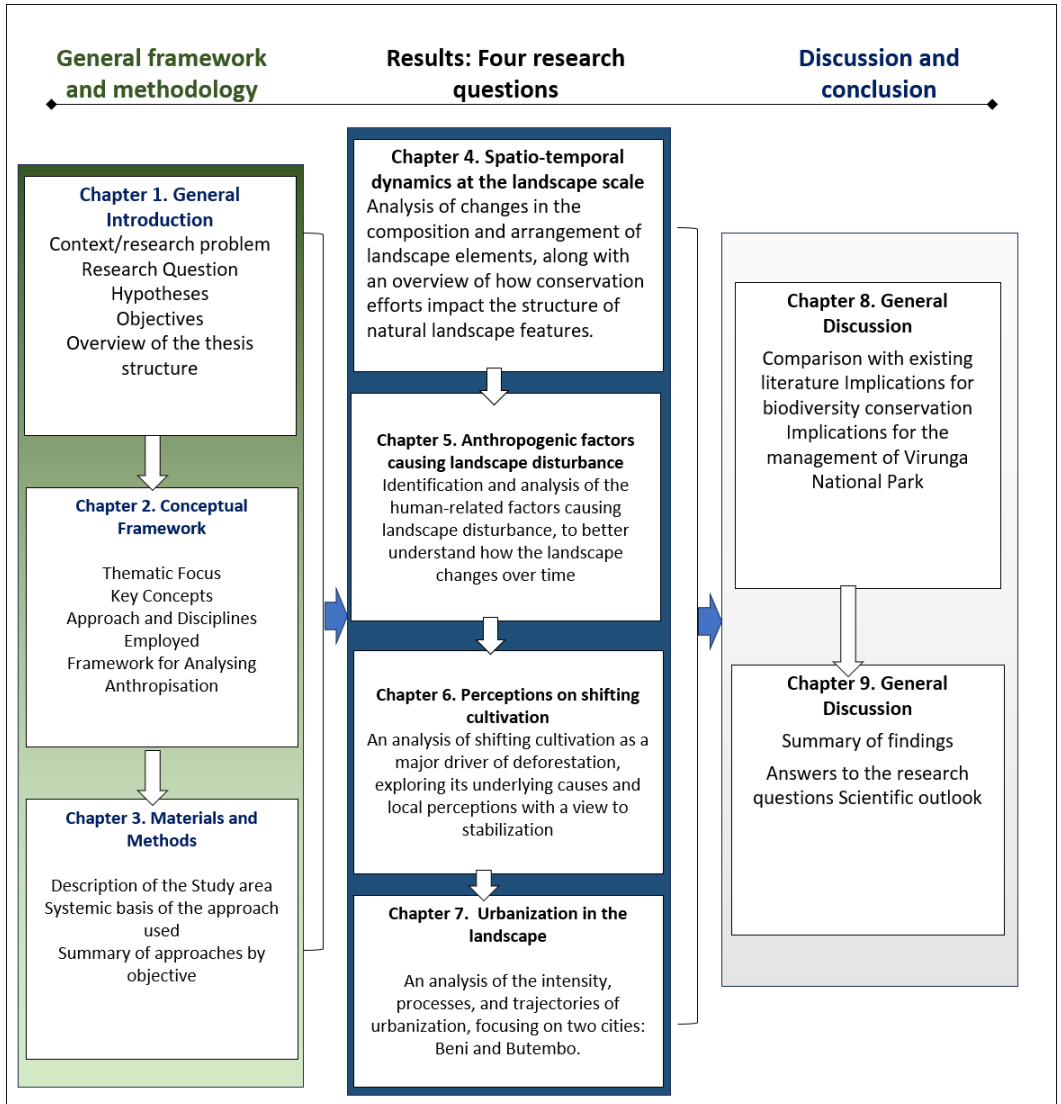


Figure 1-1 Overview of the thesis structure and how chapters complement each other

1.6. Logic behind the framework of the findings

The results chapters of this study address a need for complementary perspectives, thereby strengthening its systemic dimension. Specifically, the characterization of landscape dynamics answers the question: what changes occur in the landscape, and how do these changes evolve over time? The identification of forest disturbance factors based on field observations logically follows this inquiry by asking: which physical and observable processes are disrupting the forest? Subsequently, identifying the perceptions and motivations behind these changes explains why and how households make decisions that lead to the observed spatial dynamics and disturbances. These findings thus connect the observed landscape changes to local decision-making processes. Lastly, the analysis of urbanization offers insight into urban dynamics within the larger context of global urban growth.

Chapter 2

2. Theoretical Basis

2.1. Anthropization of natural landscapes: understanding the cause and taking responsibility

2.1.1. Ecosystem services provided by forests vs. ecosystem services provided by anthropized areas

The issue of the anthropization of tropical forests often raises questions about ecosystem services, defined as the benefits that people can obtain directly or indirectly from forests (Barot et al., 2017). Forests serve both as a resource and a habitat. What distinguishes them from other resources is their multifunctionality. They are simultaneously a reservoir of biodiversity, a land reserve, a source of energy, a regulator of global climate, a source of food for people, and the foundation of culture and civilization (Katrina and David, 1994; Smouts, 2000). According to Katrina & David (1994), the anthropization of tropical forests results from two main causes: first, competition between humans and other species for ecological niches; and second, the lack of ecosystem functions in national and international economic decisions. This interpretation aligns with the distinction between direct and indirect drivers of landscape change. Direct causes involve competition for ecological niche like agriculture. Indirect causes stem from lack of integration of ecosystem functions into economic decision. While ecosystem services support humanity's reliance on natural ecosystems and the organisms they contain, which also underpins conservation efforts, Barot et al. (2017) and Villamagna et al. (2013) suggest understanding this functioning within a global framework that includes capacities, flows, demands, and pressures. This framework conveys the concept of ecosystem management, considering not only ecosystem services but also how human decisions affect them (figure 2-1).

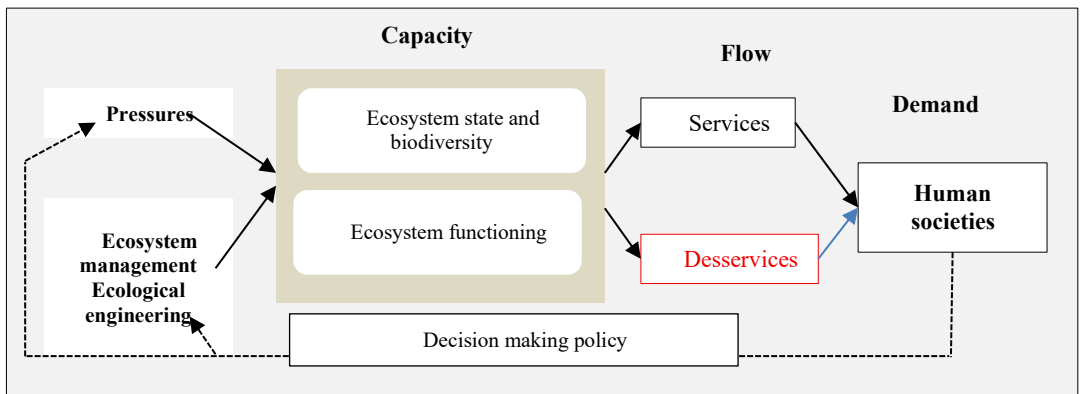


Figure 2-1. Ecosystem service framework according to Barot et al. (2017) and Villamagna et al. (2013)

The initial definition of ecosystem services often considers forest ecosystems in isolation from human impacts. However, for various reasons, humans influence the ecosystems around them, either through ecological engineering or through economic and social factors. Ecological engineering aims to create and restore sustainable ecosystems that benefit both nature and human needs (Mitsch and Jørgensen, 2003). Artificial spaces, such as planted forests, urban green spaces, cultivated land, and fallow land, although created by human activity, also play a significant role in providing ecosystem services. Figure 2-2 presents a framework for assessing the ecosystem services of anthropized ecosystems, as proposed by Barot et al.; (2017).

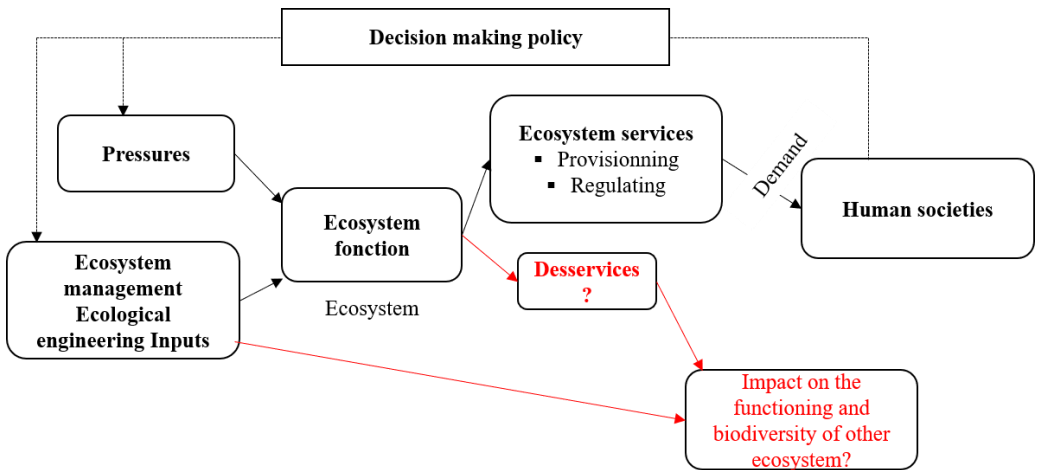


Figure 2-2. Framework for ecosystem services according to Barot et al (2017). This figure shows that the anthropized landscape provides ecosystem services, whose assessment must take into account disservices related to human interventions, changes in the state and functioning of the ecosystem that influence natural capital and the provision of future services.

2.1.2. Deforestation caused by multiple factors

Deforestation refers to the reduction of forest cover caused by human activities. The fight against deforestation, which is the largest form of human-caused alteration of the natural landscape, remains a priority for local, national, and international policies (Mackey et al., 2020). It results from multiple factors, whose importance varies depending on the actors involved, the geographical context, and the period (Smouts, 2000). Specifically, deforestation is caused by land clearing for agriculture, artisanal and industrial logging, fires, the demand for wood energy, the expansion of mining and infrastructure development, and urbanization. These direct causes are driven by complex, indirect factors, such as inadequate land-use policy coordination, poverty, population growth, lack of transparency in governance, and a less regulated, unclear

land-ownership rights system (Gillet et al., 2016). These elements reinforce the direct causes, depending on the social, economic, and political context (Geist and Lambin, 2002; Smouts, 2000; Gillet et al., 2016).

2.1.3. Assessment of human impact in the Congo Basin Ecosystem

2.1.3.1. Importance of the Forest

Before addressing deforestation or degradation, it is essential to understand what this forest represents in the region or within the Congo Basin. Indeed, the Congo Basin is the second-largest area of dense rainforest, whose ecological, economic, social, and even cultural value makes it a critical topic in many international debates (Eba'a Atyi et al., 2022). Congo Basin forests are vital for regulating the climate and also serve as habitat and food sources for thousands of people. Over 30 million people live in this area, with about 75 million people depending on it for their livelihoods (Megevand et al., 2013).

The Democratic Republic of the Congo is located in the core of this extensive forest region, covering approximately 105.8 million hectares of forest. This makes it the second-largest tropical forest country after Brazil (Eba'a Atyi et al., 2022). Other authors estimate the Democratic Republic of the Congo's forest area at around 155 million hectares (Tchatchou et al., 2015). Variations in these estimations usually result from different methods and data sources used in assessments, so they should be taken as a spatial reference rather than an exact number. Figure 2-3 provides an overall overview of forest cover in relation to other key indicators in Congo Bassin, including populations estimations, demographic growth, forest area and proportion of land under protected areas.

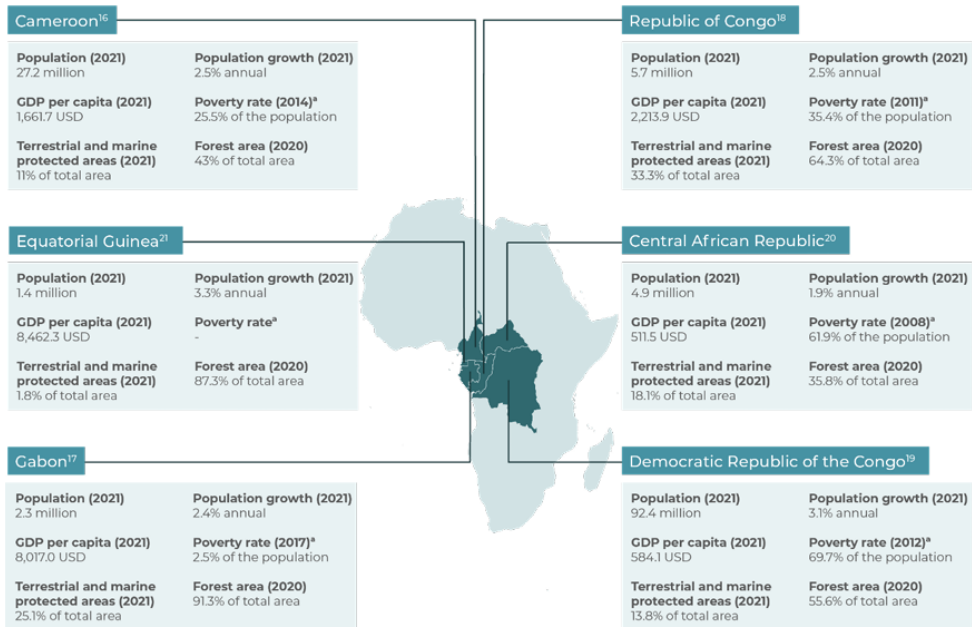


Figure 2-3. Per capita, demographic growth and forested areas estimation formation in the Congo Basin in 2022 (sources: <https://forestdeclaration.org/wp-content>, accessed April 20, 2026)

2.1.3.2. Passive protection of forest in Congo Bassin

For many decades, the Congo Basin forests have experienced passive protection from deforestation due to factors such as low population density, recurring political instability and civil conflicts, an unattractive economic climate for major private investment, and underdeveloped infrastructure, especially the road network (Megevand et al., 2013). However, population growth, averaging 2.4% annually, along with infrastructure expansion, has brought forests closer to population centers, leading to increased human impact (Eba'a Atyi et al., 2022; Ebanyat et al., 2010; Megevand et al., 2013). In 2000, undisturbed forests in the Congo Basin covered approximately 207.2 million hectares, but by 2019, this had decreased to 184.7 million hectares, representing a loss of 22.5 million hectares over 19 years (Vancutsem et al., 2021). It is also important to recognize that different approaches to data collection and analysis can yield differences in annual forest loss estimates. Figure 2-4 illustrates population growth.

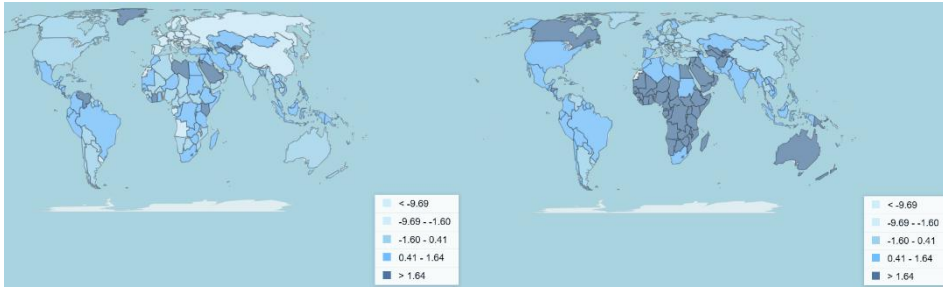


Figure 2-4. Map illustrating population growth (left 1961, right 2024). These two maps show the population increase in the Congo Basin, which is growing over time. (Source: World Bank 2024. <https://donnees.banquemondiale.org/indicateur/SP.POP.GROW> accessed October 12, 2025).

Several studies indicate that the primary existential threat to the forest stems mainly from the development and expansion of small-scale shifting agriculture, especially amid increasing urbanization and demographic growth (Abrell et al., 2024; Barral and Oscar, 2012; Demaze and Manusset, 2008; Eba'a Atyi et al., 2022; Ebanyat et al., 2010; Jouve, 2007; Li et al., 2015; Mertz et al., 2005; Sikuzani et al., 2018; Tegegne et al., 2016) and the insufficiency of the rule of law (Ongolo and Karsenty, 2011). Over 61% of tropical forests are now fragmented by shifting cultivation. These disruptions are often viewed as temporary compared to those caused by urbanization and mining (Zou et al., 2025). Smallholder agriculture has traditionally been seen as having a lower long-term environmental impact, due to its shifting practices and the extended use of fallow land. However, this approach is shifting toward an unsustainable model, driven by population growth and the move from subsistence farming to cash crops (Demaze and Manusset, 2008). The expansion of agricultural land mainly aims to support more profitable crops rather than ensuring local food security (Khan et al., 2025). Shifting cultivation causes significant deforestation even when rural population density exceeds 8.5 inhabitants per km², without considering urban population density (Eba'a Atyi et al., 2022). Besides slash-and-burn agriculture, the extraction of timber, both legal and illegal (Katembera Ciza et al., 2015; Koy and Kabuanga, 2019) and wood energy cause significant losses. These issues are particularly pronounced in the supply basins of major urban centers such as Kinshasa and Kisangani (Tchatchou et al., 2015), as well as in medium-sized cities like Goma and Butembo (Mulondi et al., 2019) within the Democratic Republic of the Congo. Figure 2-5 provides a simplified illustration of the anthropogenic drivers contributing to forest loss.

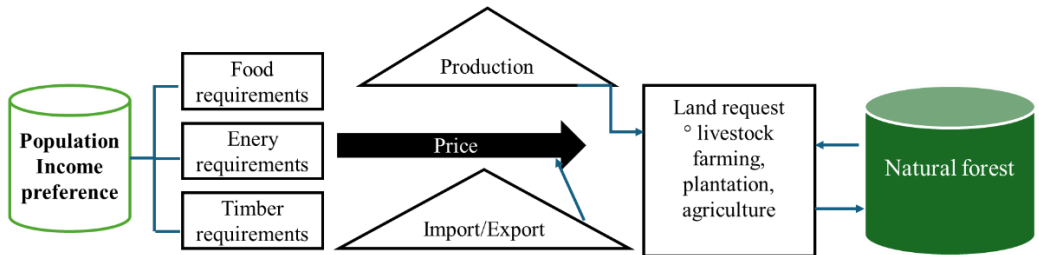


Figure 2-5. Graphical modeling of the influence of food, wood energy, and timber demand on deforestation in the Congo Basin, adapted from the model by OFAC (2015). This model offers a meaningful framework for viewing the anthropization of Virunga not as an isolated event, but as the outcome of interconnected pressures grounded in the basic needs of local communities and resource use practices.

2.1.3.3. Deforestation resulting from institutional failure

In the Congo Basin, the government often acts as an economic player motivated by profit. From this perspective, forest protection and conservation depend on financial gains within national development policies and the common good. The main challenge usually lies in choosing and implementing a shared good. Government discourse and commitments are often torn between environmental protection and economic growth through agricultural value chains that frequently clear mature forests, such as cocoa and palm cultivation (Ongolo & Karsenty, 2011).

2.1.4. Link with result chapters

This concept framework on the anthropization of natural landscape clarifies the observed landscape dynamic in northwestern Virunga, where ecosystems gradually transform under human influence. It also emphasizes the passive nature of forest protection amid armed conflict, as discussed in chapter 4. Additionally, the impact of human activities on Congo Basin ecosystem, detailed in the literature, is placed in context in chapter 5, focusing on forest disturbance in Virunga landscape. Factor like informal harvesting, subsistence farming, and recurring military bases contribute to understanding the landscape change and disturbance factors in northwestern Virunga.

2.2. Protected areas as tools for fighting deforestation

2.2.1. Expanding protected areas

In Central Africa, protected areas are being established as tools for biodiversity conservation within highly dynamic environments. These areas are essential for supporting the resilience of plants and animals under human influence pressure.

Acting as natural barriers, they help maintain the ecological balance, which human activities often disturb (Eba'a Atyi et al., 2022). A protected area refers to “*all geographically delineated regions that are recognized, dedicated, and managed through various effective means, whether legal or otherwise, to ensure the long-term preservation of nature, ecosystem services, and related cultural values associated with it*” (Dudley, 2008). Protected areas are classified by the IUCN according to their conservation objectives and corresponding management approaches, as illustrated in the figure 2-6 from (Doumenge et al., 2021).



Figure 2-6. Categorization of protected areas according to the IUCN (Doumenge et al., 2021)

Since the 1930s, protected areas have continued to expand (Figure 2-7). Initially, these areas were created to conserve resources during periods of wildlife and timber overexploitation. After gaining independence, the new state, asserting sovereignty over resources, increased its protected area network by establishing several new sites (Doumenge et al., 2021, 2015; Scholte et al., 2018). Since the Stockholm Declaration in 1972, which emphasized ecological issues, and the Rio Declaration in 1992, which highlighted sustainable management of forest ecosystems, Central African countries have committed to enlarging their protected areas. The ECOFAC program has also

supported this initiative. Over two decades, the protected area coverage has grown by more than 50%. By 2020, the region included 206 protected areas covering about 799,000 km² (Doumenge et al., 2021).

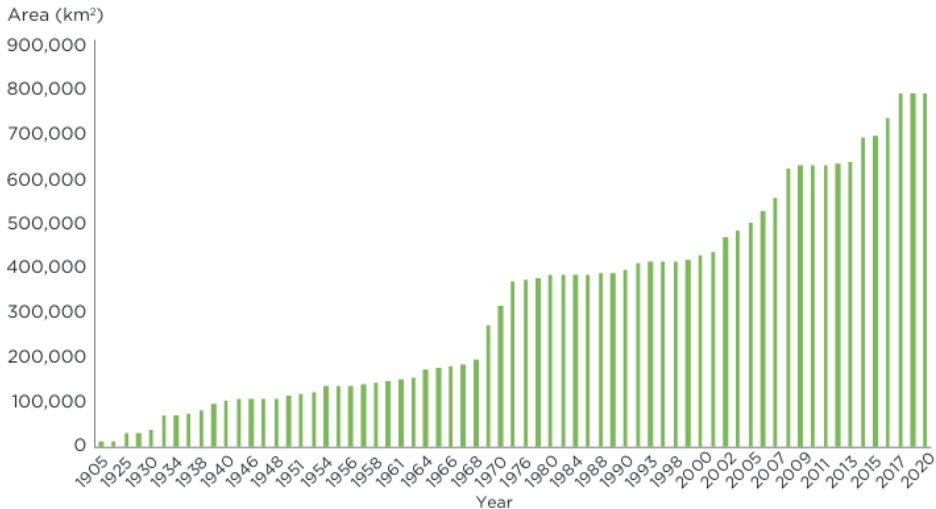


Figure 2-7. Increasing protected areas in Central Africa (Doumenge et al., 2021)

2.2.2. Governance of protected areas: moving towards a transition to public-private partnership approaches

Effective governance is essential for managing protected landscapes, especially when facing human impacts, as it involves accountability and the strategies used. The governance of a protected area depends on cooperation and interaction between private and public stakeholders. The IUCN identifies four main governance styles for protected areas. These can be public, involving government intervention at different levels; shared, involving multiple rights holders; or private or community-based, where indigenous peoples and local communities are key players (Baghai et al., 2018; Phillips, 2002; UNEP-WCMC, 2018).

Most protected areas in Central Africa, including those in the Democratic Republic of the Congo, are managed by governments, agencies, and, to a lesser extent, local communities. Since 2005, however, countries in the region have established management agreements through public-private partnerships, mainly for World Heritage sites. In the Democratic Republic of the Congo, such collaborations include Virunga National Park (Virunga Foundation), Garamba (African Parks Network), the Upemba-Kundelungo complex (Forgotten Parks), and Salonga (WWF) (Baghai et al., 2018; Doumenge et al., 2021; Scholte et al., 2018). The primary challenges of this

approach to sustainable biodiversity conservation are the fragile nature of financial resources. Aside from Akagera in Rwanda, these partnerships depend heavily on international funding, covering about 90%. Management costs vary from USD 640 to USD 800 per km² (Doumenge et al., 2015).

2.2.3. Ecological theory of armed conflict

The impacts of armed conflicts on the environment have been investigated from multiple perspectives. The table 2-1 summarizes the main theoretical frameworks and conceptual approaches, collectively described here as the ecological theories of conflict.

Table 2-1. Ecological theory of armed conflict

Concept	Explanation
Environment as Victim and Vector of Wars	Conflicts degrade ecosystems, which in turn creates new forms of insecurity, leading to a vicious cycle (Dagnicourt and Le Floch, 2020)
Deep ecological footprint of war	Conflicts leave lasting marks on ecosystems (contaminated soil, polluted water, degraded ecosystems) (Lawrence et al., 2015)
Conflict primarily occurs in areas rich in biodiversity	About 80% of conflicts take place in biodiversity hotspots, making these areas vulnerable (Hanson et al., 2009; Ordway, 2015)
Post-conflict demographic pressure	After the conflict, violence persists, and community brutality increases the exploitation of natural resources (Garcia Corrales et al., 2019)

This ecological theory of armed conflicts finds its illustration in protected areas in the DRC, particularly in the northwestern landscapes of Virunga. Subsequently, we present this theory by focusing on protected areas in 2.2.4 section.

2.2.4. Protected areas weakened by civil war crises

Managing protected areas during conflicts is a major challenge in Central Africa, especially in the Democratic Republic of the Congo. War impacts ecosystems in multiple ways: it hampers institutions' ability to enforce sustainable conservation efforts or directly damages ecosystems and their biodiversity (IUCN, 2021). More than 80% of conflicts often occur in areas with high human density and biodiversity (Ordway, 2015; Shapiro et al., 2021).

The impact often depends on several factors, including the nature of the crisis, the ecological condition of the region, the spatial scale, and the duration of the crisis (Stevens et al., 2011). In this study on the anthropization of the Virunga landscapes, understanding how armed conflict affects ecosystems is key to explaining the resulting spatial-temporal processes and human disturbances that drive landscape change. The figure 2-8 shows possible scenarios for how war impacts protected areas.

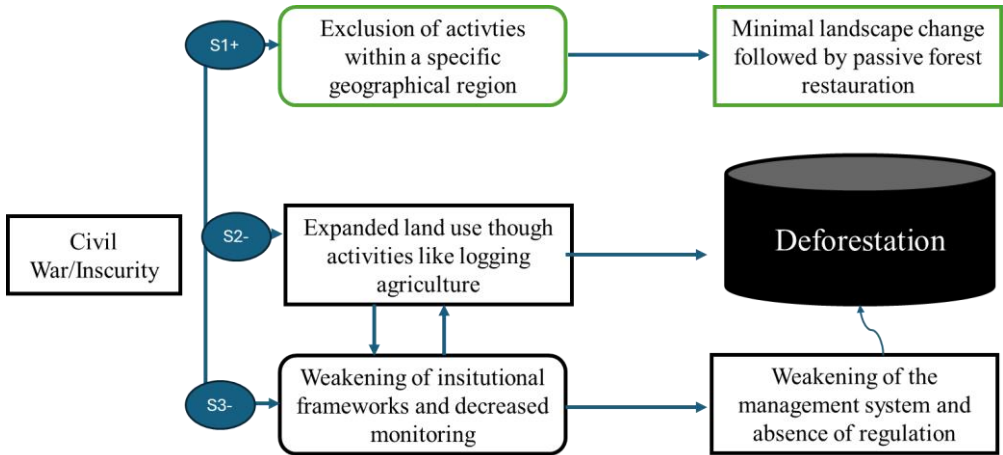


Figure 2-8. A straightforward conceptual showing how war could affect the natural ecosystem of a protected area. S1, S2 and S3 stand different potential effects. The + and – signs indicate positive or negative effects, respectively. Figure adapted from Ordway (2015).

The figure shows that when violence reaches extreme levels, human activities that disturb natural landscapes tend to decrease or even stop (S1+). This pause often encourages forest regeneration in previously degraded ecosystems, as seen in protected areas in western Nicaragua (Lawrence et al., 2015; Stevens et al., 2011). However, this relationship is not always straightforward (S2-, S3-). Extreme violence can also lead to large-scale population movements toward protected areas, increasing pressure on ecosystems. This issue is especially prominent in the Democratic Republic of the Congo, particularly in the Virunga region, where a security crisis in one neighboring country can cause ecosystem damage in another. This was evident in 1994 during the influx of Rwandan refugees (Balole et al., 2015; Shapiro et al., 2021; Vikanza, 2011). Furthermore, Ordway (2015) indicates that during the genocide in Rwanda, the spatial redistribution of inhabitants increased pressure on previously protected areas, such as the Gishwati Forest Reserve. Similarly, De Merode & Cowlishaw (2006) mentioned that, in Garamba, periods of war are accompanied by a surge in the trafficking of protected species and their sale as bush meat in urban markets. Additionally, the post-conflict period is often the most challenging to manage, as it involves redefining development policies, local economies, and, most

importantly, the relationship between populations and nature (Butsic et al., 2015). This is why, even during times of conflict, it is crucial to monitor the condition of natural and human-made habitats to anticipate degradation and adjust management strategies (De Merode and Cowlshaw, 2006; Ordway, 2015).

2.2.5. The Virunga National Park, an example of the complexity of conservation

Virunga National Park is part of the Democratic Republic of the Congo's protected areas network, which covers over 74 categories such as national parks, wildlife and nature reserves, hunting grounds, and botanical and zoological gardens. Five of these are designated as World Heritage Sites, namely Virunga National Park, Kauzi Biega National Park, Garamba National Park, Salonga National Park, and Okapi Wildlife Reserve. Four are listed as in Danger World Heritage Sites, namely Virunga, Kauzi Biega, Garamba, and the Okapi Wildlife Reserve (Henrard & Huart, 2025, Doumenge et al., 2015, <https://cod.forest-atlas.org/pages/dash-ap>). All protected areas are managed by the Congolese Institute for Nature Conservation (ICCN). Their governance is guided by several legal frameworks, including Law 14/002 revised in January 2025 (February 11, 2014) on conservation, and Law 82/002 (May 28, 1982) on hunting regulations (Doumenge et al., 2015). One of these, Virunga National Park, symbolizes the complexity of conservation through its history, exceptional biodiversity, geopolitical position, and social tensions. Describing the socio-political events that have shaped these landscapes and their dynamics is important for better understanding and explaining human influence in northwestern Virunga (Christensen and Arsanjani, 2020; Lanjouw et al., 2001). The park is an ecosystem that lives with socio-political complex realities.

Virunga National Park has been a World Heritage Site since 1979 and has been listed as a World Heritage Site in Danger from 1994 to the present (UNESCO, 2025). Virunga is an area that extends 300 km in length and 23 km in width, covering 784,368 hectares with a perimeter of 1,150 km. It encompasses a range of altitudes from 680 m to 5,109 m. Its origins are linked to exploration efforts and strategic interests among Germany, Great Britain, and Belgium in the 19th century, focusing on control of land rich in economic, ecological, and aesthetic value. Due to its strategic location and resource abundance, Virunga attracted explorers and nations alike. Consequently, in the name of conservation, Virunga National Park was established in 1925, leading to the expropriation and displacement of populations outside the park. This approach, which removed people from their traditional lands, has caused social tensions and ongoing conflicts between park authorities and local communities that continue today (Henrard & Huart, 2025). Vikanza (2011) observes that Virunga National Park is no

longer just a protected area; due to its historical background, it is increasingly contested by local communities, who are selling their customary land rights as the population grows. This crisis is likely to intensify over time because of several factors: modifications to the park's boundaries through eight legal texts, which cause interpretative confusion among stakeholders; the loss of boundary markers during conflict periods; corruption among management during times of state failure; and the ongoing pursuit of fertile land driven by rapid local demographic growth (Henrard & Huart, 2025). Along with social tensions surrounding the park's creation, the Great Lakes region has endured over 30 years of political instability and ongoing conflict, with profound effects on protected areas. The first illegal activities in the park began in 1986, when poaching started affecting the Rwenzori region. For example, in 1990, rebel groups increased pressure on wildlife in northern Virunga National Park, from Watalinga to Mount Hoyo. These events demonstrate that, initially, armed conflict mainly impacted wildlife. It was only after the Rwandan genocide that Virunga National Park experienced significant habitat loss. In July 1994, over 500,000 Rwandan refugees crossed into the Democratic Republic of Congo, then called Zaire. Every day, over 40,000 people entered the park to collect wood in various forms, amounting to 1,000 tons of fuelwood daily (Henrard & Huart, 2025). This activity contributed to widespread deforestation and the poaching of large, protected mammals. Additionally, the war in Ituri from 2002 to 2004 led many displaced people to settle in the Beni area, especially near Ngité on the park's edge. To survive, these war refugees started exploiting local forest resources (Vikanza, 2011; Vikanza, 2018).

Table 2-2. The state of land usurpation within Virunga National Park in 2024, driven not only by historical factors but also by the region's socio-political context (Henrard et Huart, 2025).

Anthropized area	Area in km²
Crops	692,3
Grazing	144,2
Degradation	92,1
Conversion to built-up areas	25
Deforestation	24,4
Total anthropized area	678,1
Ratio relative to the total area of the park	14,2%

Overall, the ongoing political turmoil in the DR Congo since 1996 has substantially contributed to the degradation of the park's landscapes. This protected area has become a battleground amid a series of violent conflicts in the region and, since 2014, has served as a theater of operations related to the hunt for terrorist groups, especially the Allied Democratic Forces, in Beni territory (Figure 2-9).

In certain contexts, military control over parts of the landscape, combined with the isolation and restricted mobility of conservation officers, has severely constrained the monitoring and management of habitats and natural resources. These conflict-related constraints are compounded by other pressures on Virunga National Park. In addition to its exceptional ecological importance, the park overlaps with areas of documented oil potential, generating competing interests between biodiversity conservation and hydrocarbon development. The Democratic Republic of Congo has expressed its intention to explore and potentially exploit these resources as part of its broader strategy to promote national economic development. However, assessments of the park's broader economic value, including the ecosystem services it provides, have not fully prevented continued interest in oil exploration and extraction within or around its boundaries (WWF, 2013).

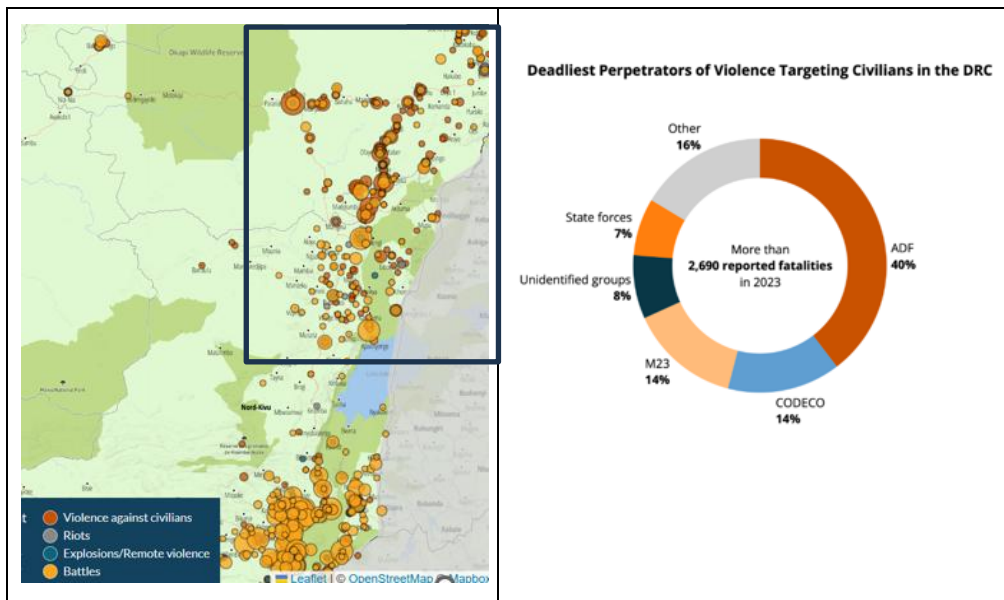


Figure 2-9. Spatial distribution of armed violence in the Virunga landscape, Democratic Republic of the Congo, illustrating areas affected by armed conflict: in the north, violence is mainly linked to the terrorist group ADF, while in the south, it is primarily attributed to the M23. Sources: ACLED 2025. (<https://acleddata.com/> viewed on 16 November 2025)

2.2.6. Link with result chapters

Understanding the IUCN's theory regarding protected areas, such as Virunga National Park, as well as their governance system, provides an essential framework for interpreting the dynamics observed in the northwestern Virunga landscape. The protection status and management of modalities define conservation objectives, the level of restrictions, and the mechanisms challenged by local constraints that influence

governance. In this study, the landscape revolves around protected areas, which constitutes the scientific interest of the thesis. Developing this concept allows to better understand the spatial logic behind the disturbance together with governance support.

2.3. Landscape Ecology as a Multidisciplinary Framework for Spatiotemporal Analysis of Landscape Dynamics

2.3.1. Ecology vs Landscape Ecology

Introduced in 1866 by Ernst Haeckel, ecology is a field that studies the interactions between living organisms and their biotic and abiotic environments. To do this, ecology evaluates the abundance of organisms, their spatial distribution, and how resources are transferred among them (Lee, 1955; Sagoff, 2017). Initially, the focus was on isolated natural elements and understanding the internal processes of living beings, without fully considering the impact of the environment's spatial structure, which is often shaped by human activities (Chouquer and Gérard, 2003). The advancement of remote sensing and mapping technologies has enabled a new approach to studying ecosystems and life's manifestations. In this context, landscape ecology was first developed in Central and Eastern Europe, where biogeographers integrated the landscape into human living space and its interactions with the environment. German biogeographer Carl Troll introduced this concept in 1950. Starting from the 1980s, the discipline expanded to North America, Australia, and China (Turner and Gardner, 2015). In Africa, especially in the DRC, landscape ecology is a more recent development, focusing on understanding spatial structures within more diverse socio-economic settings (Useni Sikuzani and Bogaert, 2025).

Landscape ecology is a science positioned at the intersection of ecology and geography, drawing from various disciplines such as architecture, geography, economics, planning, and forestry (Turner and Gardner, 2015). It aims to describe the functioning, dynamics, and quality of a landscape (Liding et al., 2008). It considers the role of humans in shaping the landscape, given their impact on natural ecosystems. It emphasizes quantifying the structure and functioning of landscapes (Bruno and Jacky, 1995). Landscape ecology is based on studying complex interactions between spatial structure and ecological processes. These interactions include different ways of defining the field (Turner and Simard, 2017). In landscape ecology, two main approaches have developed. The first, European, emphasizes large areas and the human activities that shape them. The second, American and Australian, focuses on understanding the causes and effects of spatial structure, as defined by organisms and relevant processes (Turner, 2005).

Kirchhoff et al. (2013) propose that landscape ecology can be understood through multiple perspectives, leading to a variety of concepts. It may involve an interdisciplinary scientific study of landscape units, topological ecology at the landscape level, or a topological ecology focused on organisms across multiple scales. Additionally, it can refer to the socio-cultural system as applied to the natural and human sciences or be influenced by cultural meanings derived from human experience.

Furthermore, perceptions and even definitions of landscape can differ across disciplines, leading to various ways of understanding it. Seen as a spatially diverse mosaic, the landscape also incorporates human-made imprints. As illustrated by figure 2-10, it occupies an intermediate position in ecological organization, between the ecosystem and regional levels (Bogaert and Mahamane, 2005). It emphasizes the significance of the composition and spatial distribution of landscape elements, which impact the ecological system (Turner & Gardner., 2015). Landscape also plays a crucial role in shaping planning strategies for the sustainable management of the biotic, abiotic, and cultural resources it includes (Ahern, 1999).

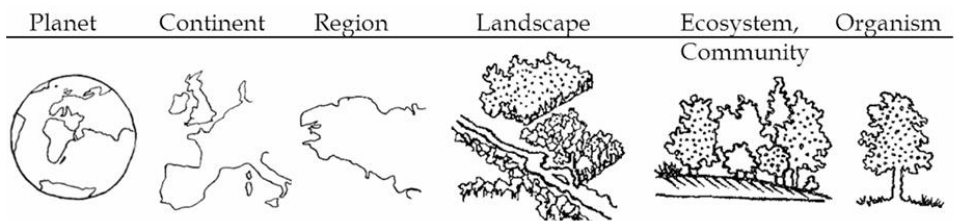


Figure 2-10. Illustration of the landscape as an intermediate organization between the scale of the ecosystem and that of the region (Burel and Baudry, 2003)

2.3.2. Principles of Landscape Ecology

In landscape ecology, the landscape is not simply the sum of its parts but rather the outcome of interactions among its component elements. (Antrop and Van Eetvelde, 2017) note that the landscape is defined by its elements, components, and structure, based on a set of spatial properties. An element is defined as a discrete phenomenon with well-defined and finite boundaries (e.g., a tree, a house). Components are phenomena that change over time (e.g., soil conditions, climatic conditions). Structure refers to the way components or elements are linked, both spatially and functionally.

According to Turner (1989) a landscape is a space that consistently features three key elements: structure, function, and change. The author states that structure refers to the spatial arrangement of ecosystems. It includes how energy, materials, and species are distributed according to their size, shape, and type. Function, meanwhile, describes

the interactions among spatially defined elements. Lastly, change pertains to alterations in structure and function. Traditionally, a landscape is composed of three basic components: patches, corridors, and matrix, as illustrated in Figure 2-11.

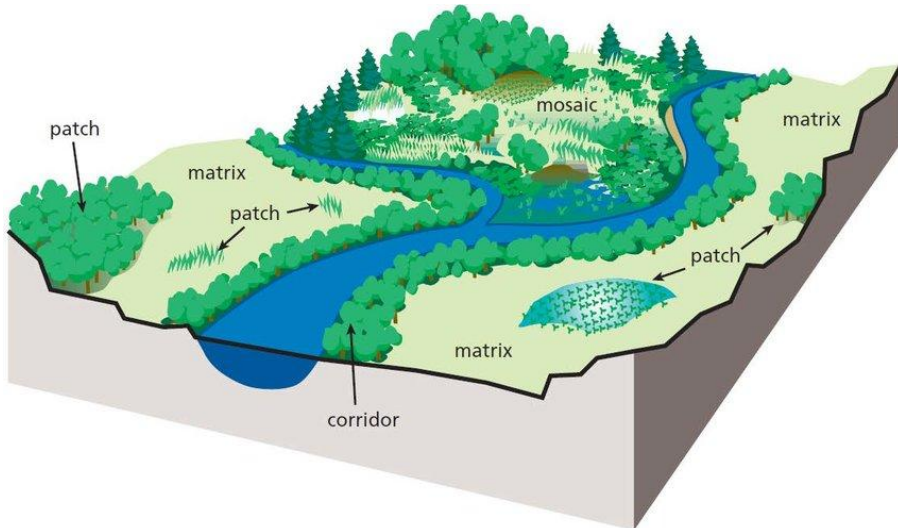


Figure 2-11. Illustrate the main components of a landscape (patch, matrices, and corridor) according to FISRWG, 1998.

Different authors define patches in various ways. They are considered areas of a landscape that are favorable to a specific species (Antrop & Van Eetvelde, 2017). (Lausch et al., 2015) define patches as homogeneous areas within certain land use types in the landscape, with specific characteristics like shape and size. Their spatial arrangement gives the landscape a unique structure. A patch is therefore an area that stands out from its surroundings, characterized by continuity that maintains its biological significance. Its homogeneous nature affects both biotic and abiotic processes, thereby influencing population dynamics (Girvetz et al., 2007).

Corridors are extensive linear features that facilitate species movement by linking fragmented habitats (Antrop & Van Eetvelde, 2017) and promote genetic exchange between populations. According to Butler (2001), corridors differ from matrix and patches due to their linear shape and five key functions: habitat, filter, conduit, source, and sink. Consequently, they support ecological processes within the landscape. As noted above, the landscape is more than just the sum of its parts, and corridors play a crucial role in emphasizing the emergent properties of the landscape. They also help bolster the ecological resilience of fragmented ecosystems within the landscape (Hilty et al., 2007).

The landscape matrix refers to the type of patches that dominate the landscape in terms of surface area and extent (Lausch et al., 2015). When no patch is dominant, the landscape is considered a mosaic (Bogaert et al., 2014). The matrix influences the structure and composition of the landscape and affects its dynamics (Forman and Godron, 1981). Some landscape matrices, such as agricultural matrices, can negatively impact forest fragments and disrupt or even change their specific composition (Assis et al., 2018; Ferrante et al., 2017).

Spatial structure (Figure 2-12) illustrates the interaction between the composition and configuration of patches. Composition describes the number, proportions, and types of land cover, while configuration examines how these patches are arranged or organized within the landscape (Bogaert et al., 2014; Lausch et al., 2015). Landscape structure results from abiotic factors (climate, tectonic relief), biotic factors (interspecific competition), and social and demographic influences (Turner, 2005). In this study, these concepts of composition and configuration have been applied to analyze spatial change at various levels (chapter 4), including global landscape, military camps (chapter 5) and urban areas (chapter 7).

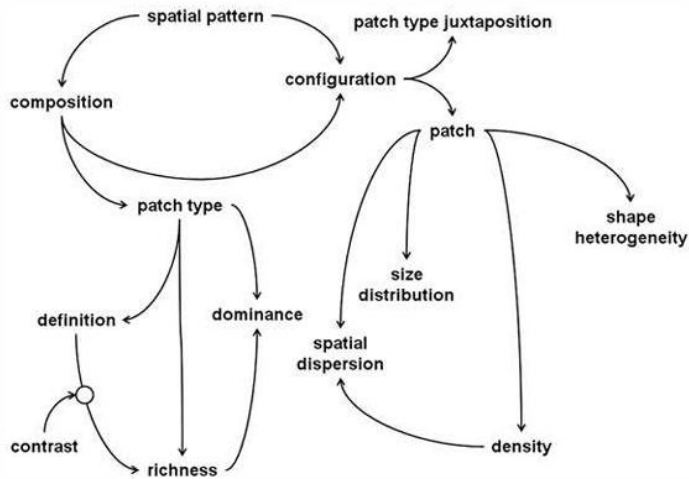


Figure 2-12. Landscape structure determined by the composition and configuration of the landscape (Bogaert et al., 2014)

2.3.3. Landscape disturbances as a driver of landscape heterogeneity

In landscape ecology, disturbances are discrete events that alter ecosystem structure and functions (Farina, 1998; Hüttl and Gerwin, 2024). They play a key role in processes such as fragmentation and animal migration, and may lead to the extinction

of certain species (Farina, 1998). These disturbances can be natural or human-made. Human disturbances are among the primary drivers of significant changes in landscape structure, impacting its composition and layout over short timescales (Huang et al., 2022). Typically, disturbance is characterized by its magnitude, size, and the extent of its spread across the landscape (Farina, 1998; Turner & Simard, 2017). The landscape's diversity increases depending on how often and how severe these disturbances are (Hüttl & Gerwin, 2024).

Additionally, Acil et al. (2025) highlight that the extent of structural damage to landscapes due to disturbances depends on various factors, including the type of disturbing agent, the initial condition of the landscape, and the surrounding environment. The characteristics and intensity of these disturbances produce different landscape forms, from regular shapes like clear-cut forests to irregular patterns such as fires, and linear features such as roads. Turner & Simard (2017) stress the importance of understanding both the disturbances and their causes to better predict their impacts on ecosystems and to formulate effective conservation strategies change.

2.3.4. Use of the transition matrix to measure anthropization

The most common method for monitoring landscape anthropization is the transition matrix. It relies on a diachronic analysis of the landscape. This approach is based on the work of the Russian mathematician Markov, who proposed that the state of a system is always characterized by the probability of transitioning to a specific future state (Dale et al., 2002). This method uses a dynamic cross-tabulation table in which columns and rows represent different landscape components or land-use types. The central part displays information about area transfers between classes. The diagonals show areas that remained unchanged between two observation periods; the values on the diagonals indicate transfers between land cover classes. This matrix helps assess stability of a land cover class, referring to classes whose significant surface remains nearly unchanged over time. The further these values are from the diagonal, the less stable the landscape. It offers insights into the class's loss and gain identifies vulnerable and resilient classes under pressure. The transition matrix reveals also the dominant pressure within the landscape. Anthropization is then understood as areas shifting between natural classes, such as forests and savannahs, and human-made classes, such as agricultural or urban areas (Bogaert et al., 2014). In this study, this matrix was used mainly in the analysis of landscape dynamics (Chapter 4).

Table 2-3. Illustration of the transition matrix adapted from the model by Dale et al., 2002.

		Final state			
		$S_1(t+1)$	$S_2(t+1)$	$S_3(t+1)$	$S_n(t+1)$
Initial state	S_1t	$P_{1,1}$	$P_{1,2}$	$P_{1,3}$	$P_{1,n}$
	S_2t	$P_{2,1}$	$P_{2,2}$	$P_{2,3}$	$P_{2,n}$
	S_3t	$P_{3,1}$	$P_{3,2}$	$P_{3,3}$	$P_{3,n}$
	S_nt	$P_{n,1}$	$P_{n,2}$	$P_{n,3}$	$P_{n,n}$

2.3.5. Use of ecological landscape metrics

To describe and quantify spatial structure, several metrics and indicators have been developed in landscape ecology, mainly based on the Patch-Corridor-Matrix model. These indices are extracted from vector or raster landscape formats using digital methods (Haines-Young & Chopping, 1996; Eldred, 2017). Haines-Young & Chopping (1996) grouped these indices into three categories: the first, called "*areal indices*," measures the surface characteristics of different land cover classes; the second, "*linear indices*," concerns landscape elements with an elongated shape; and finally, the third, "*topological indices*," focuses on landscape connectivity and diversity. These indices are used according to the objectives of the study. As a guide, commonly used indices include: patch area (CA), patch density (PD), number of patches (NP), largest patch index (LPI); landscape shape indices (LSI), landscape type percentage (PLAND), fractal dimension, Shannon diversity index (SHDI), Shannon equitability index (SHEI), and mean patch size (MSP), have been used more extensively in the presentation of the results of this study. The choice of index will depend on the nature of the data, the research hypotheses, and its relevance in explaining the spatial phenomena observed. Figure 2-13 presents a simplified conceptual framework for landscape structure analysis proposed by (Chen et al., 2019).

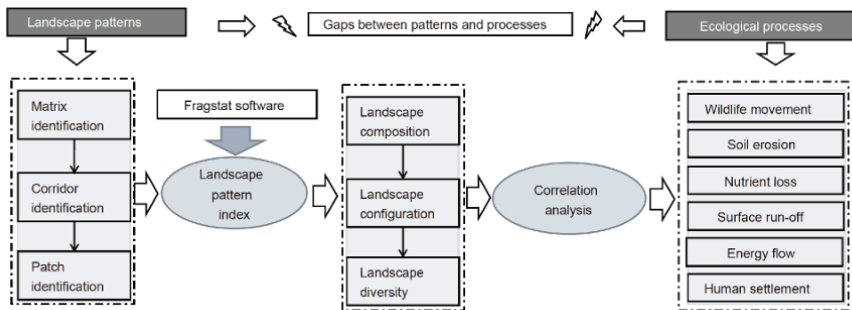


Figure 2-13. Conceptual framework for analyzing the landscape structure of the conventional model based on the 'patch-corridor-matrix' model (Chen et al., 2019)

2.3.6. Note on the process of landscape transformation analysis

The landscape transformation process is identified using the decision tree developed by Bogaert et al. (2004). Many landscape ecology studies in Africa, particularly in the Democratic Republic of the Congo, have employed this method to characterize different types of landscape changes (Sikuzani et al., 2020). Transformation can result in patch creation, aggregation, displacement, erosion, deformation, dissection, fragmentation, perforation, and shrinkage (Bogaert et al., 2004). To differentiate specific processes such as fragmentation and dissection, the concept of observed t is used. It measures the ratio of land cover types at times t and $t + n$. This ratio is usually compared to a threshold value t (50 or 75%). Dissection occurs when the observed t exceeds this threshold, while fragmentation is indicated when it falls below it (Figure 2-14).

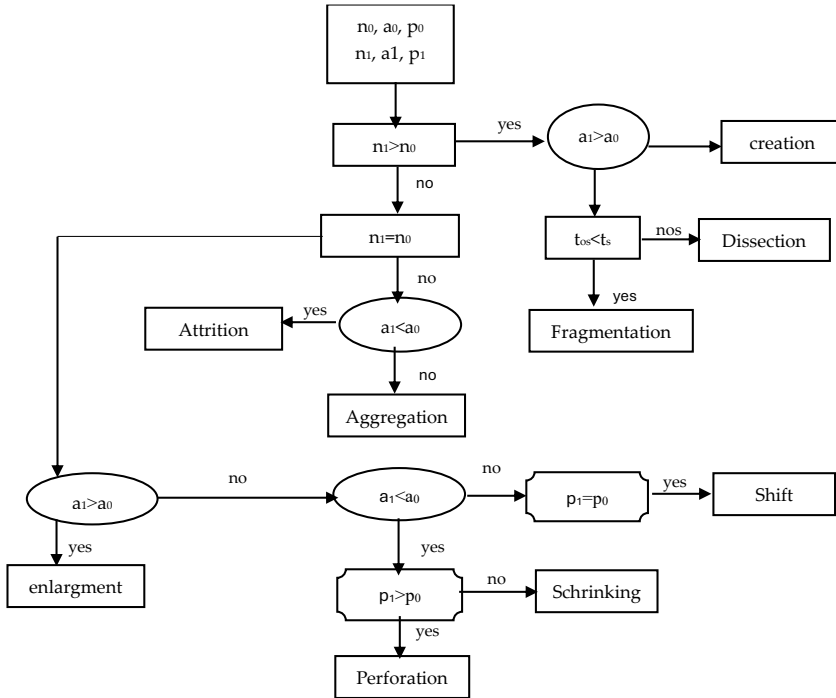


Figure 2-14. A decision tree used to determine the landscape transformation process (Bogaert et al., 2014). a_0 , p_0 , n_0 are respectively the area, perimeter and number of patches before the change. a_1 , p_1 , n_1 are respectively the area, perimeter and number of patches following the transformation.

2.3.7. Remote sensing as the main source of information in landscape ecology

As a reminder, landscape ecology is based on the principle that landscape structure influences ecological processes. Understanding this structure requires quantitative measurements, for which remote sensing appears to be an essential tool (Bruno and Jacky, 1995). Knowledge of landscape heterogeneity and land use has always been linked to technological advances in remote sensing (Pazúr et al., 2021). Groom et al. (2006) emphasize that the close connection between remote sensing and landscape ecology stems from the ability to collect data over large areas, ranging from a few dozen to several hundred kilometers, as well as the high frequency of data collection capture. Foody (2002) also highlights that the promotion of remote sensing in landscape ecology is due to its user-friendly nature and the availability of free or inexpensive spatial data. This open data approach has driven notable progress in landscape ecology research (Pazúr et al., 2021). With remote sensing, various areas such as vegetation analysis, degradation tracking, biotope classification, topography

enhancement, and urbanization have been widely studied at local, national, and global scales (Groom et al., 2006). Moreover, selecting suitable spatial data, especially images in landscape ecology, is purposeful rather than arbitrary. It is influenced by factors such as the study's goals, scope, the spatial and spectral resolution of the images, and access costs (Rogan and Chen, 2004; Shao and Wu, 2008). Consequently, Landsat and Sentinel images have often preferred due to their free availability online and appropriate resolution, making them ideal for studies at local, national, or even international levels (Foody, 2023; Lechner et al., 2012). In our study, we used spatial data like Landsat images to describe anthropization over larger regions, including the entire landscape, protected areas, and surrounding zones. For smaller areas such as armed camps and cities, higher-resolution planet images were employed. The rationale behind selecting these images is detailed in Chapter 3, which focuses on methodological aspects. Figure 1-15 presents a synthesis of the complementarity between remote sensing and landscape ecology.

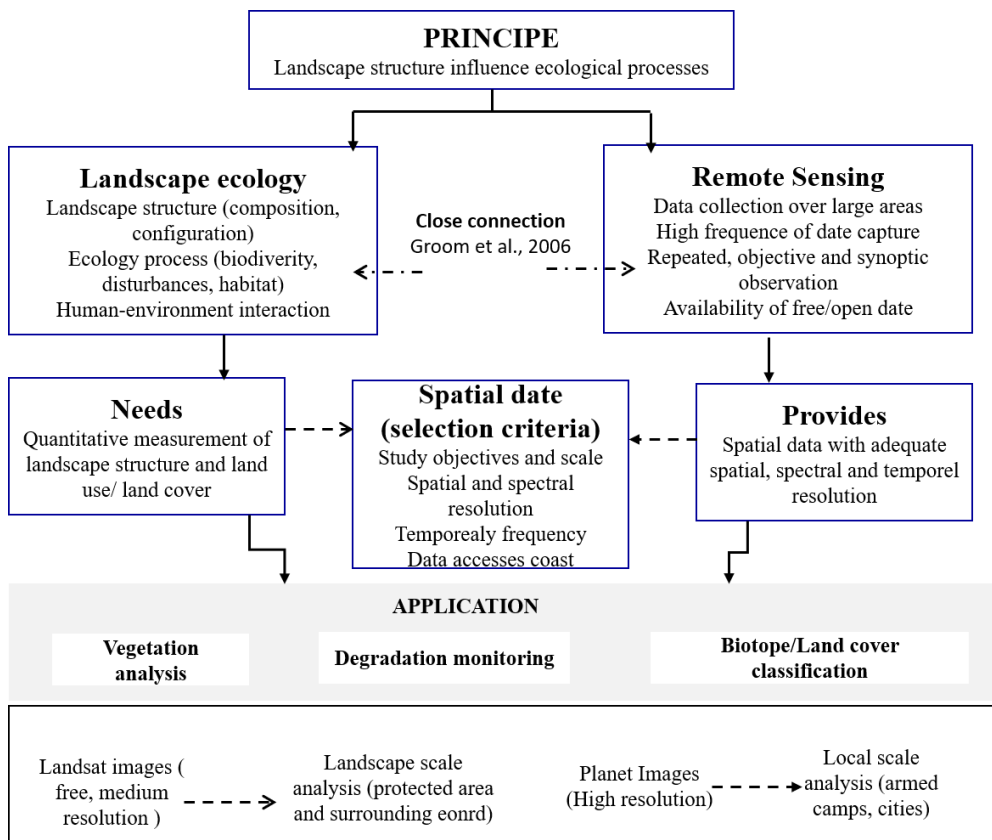


Figure 2-15. Synthesis of the interconnections between landscape ecology and remote sensing

2.3.8. Link with result chapters

The core principles of landscape ecology are vital for analyzing landscape dynamics, disturbance factors and urbanization. Landscape ecology offers robust analytical tools to evaluate spatiotemporal changes at whole landscape, urban, or recently disturbed sites. In this study, understanding the composition and configuration, along with the associated tools, data types, and indices was essential for accurately analyzing anthropization of the northwestern Virunga landscape. Tools and concept were used in chapters 4, 5 and 7.

Chapter 3

3. Study area and methodological framework

3.1. Study area

3.1.1. Rationale for choosing the study area: Ecological, Socio-economic and insecurity context

Our doctoral research employs a multi-scale approach, involving analyses tailored to specific objectives at various scales. The upper zone encompasses the entire northwest region of the Virunga landscape. This geographic area has been selected as the focus of this study based on several key considerations:

- Vegetation gradient: the presence of dense forest cover at low altitudes constituted a primary criterion for the selection of northwestern Virunga landscape (Henrard & Huart, 2025);
- High levels of terrorism- related insecurity: unlike other sector of Virunga landscape, the northwestern part has experienced a prolonged period of instability, largely driven by the activities of ADF armed group. The ecological impact of this insecurity remains less documented;
- Historically agricultural landscape: the northwestern is characterized by a long-standing tradition of agricultural production currently undergoing a gradual shift toward cash crop systems, largely by smallholder farmers (Vikanza, 2011);
- Strategic importance for the green economy: this landscape is of significant importance for achieving the Kivu-Kinshasa Green Corridor objectives (De Meroode and Jérôme, 2025).

A 6,285.11 km² area was extracted from this landscape based on the vegetation gradient of Virunga National Park (Languy et al., 2006) and human concentration patterns described by Vikanza (2011). This area is characterized by dense, humid forests, setting it apart from the central and southern zones of the Virunga landscape. It is part of the 'Butembo region,' as defined by Vikanza (2011), situated between 0°9'S and 0°54'N latitude and 28°57' and 30°9'E longitude. The study area uses the WGS 84/UTM Zone 35N coordinate reference system.

The northwest Virunga has an economy primarily focused on agriculture, especially the cultivation of cocoa, coffee, beans and other food crops. In addition to agriculture, small-scale trade is also a pillar of local economy. However, despite this potential, economic development remains hindered by ongoing insecurity, mainly due to ADF, which hampers farming, people mobility, and disrupts market supplies (Henrard & Huart, 2025). Today, this landscape is within the 'Green Corridor,' a major initiative by the Congolese government aimed at fostering sustainable economic growth, conserving biodiversity, supporting peacebuilding efforts, and addressing climate

change (De Merode and Jérôme, 2025). The landscape dynamics discussed in chapter 4 of the study, which relate to the first thesis objective, focus on the entire landscape.

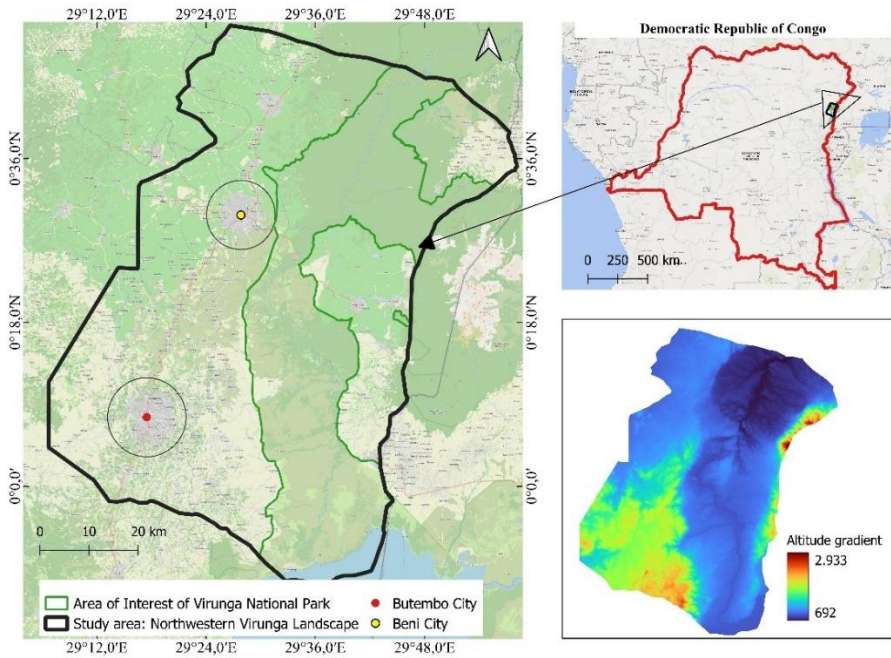


Figure 3-1. Study area. The map on the left illustrates the northwestern landscape of the Virunga, highlighting the area of interest within Virunga National Park as outlined in our study. The maps on the right show, respectively, the study area's location within the Democratic Republic of the Congo and its altitude gradient. The study area uses the WGS 84/UTM Zone 35N coordinate reference system.

Furthermore, Chapter 5, which is dedicated to analyzing the factors of human disturbance and relates to objective 2 of the thesis, focused solely on disturbed areas within Middle Semuliki (Languy et al., 2006). This area is the focus for this chapter because it highlights the factors that disrupt natural forest zones. The savannahs between Middle Semuliki and Lake Edward were not included since the indicators and focus of study were on forest area, which is very strategic for ecological corridor with the Okapi Wildlife Reserve. This underscores the importance of this second level of study sites. Chapter 6, following logically after Chapter 5 and analyzing household perception on shifting cultivation in line with Objective 3 of the thesis, also concentrated on settlements in the Middle Semuliki region.

Chapter 7, dedicated to urbanization and related to objective 4 of the thesis, focuses on two cities located in the northwest part of Virunga, at different altitudes and with varied economic and security conditions. The city of Butembo is situated at a higher

elevation than Beni. These two cities are also at the core of Virunga's sustainable initiatives and the 'Green Corridor' program, which aims to reduce their pressure on natural ecosystems.

3.1.2. Climate variability

The landscape studied has a humid tropical climate of the Af type according to the Köppen classification. Rainfall distribution is uneven, mainly due to the orographic effects of Mount Ruwenzori. Annual precipitation ranges between 1,200 and 1,600 mm. Typically, January, February, March, June, and July see a decrease in rainfall, while from August to December, especially in September and October, rainfall is very high (Posite et al., 2025, 2024).

Amid climate change issues, some zone of the landscape such as Oïcha present a high risk of water shortages, affecting farming. This also leads to forest ecosystem decline as local communities depend more on natural resources due to changing rainfall that affects crops. Conversely, region like Kasindi, influenced by the Rwenzori Mountains 'orographic effects, experience more consistent rainfall. However, this favorable climatic condition could also lead to intensified human activity, as people move in search of better farmland (Posite et al., 2024).. The figure 3-2 does not encompass the entire landscape but is presented for indicative purposes representing a city located near forested zone of Viunga national park.

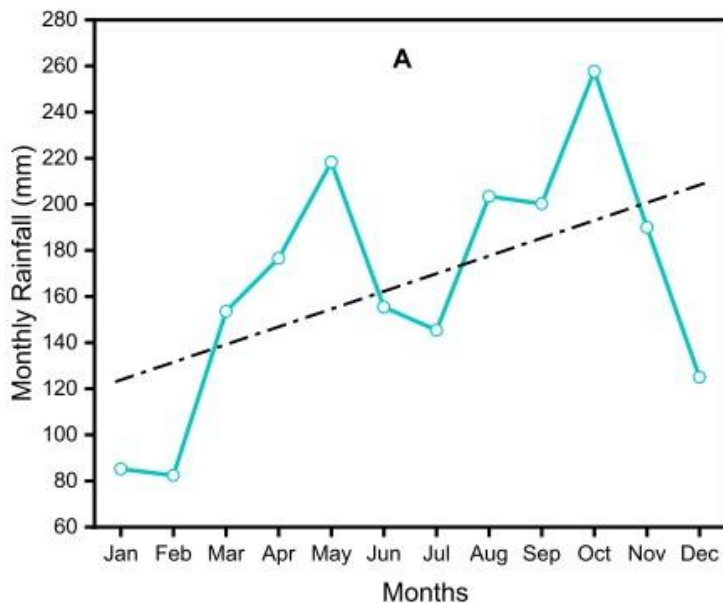


Figure 3-2. Illustration of evolution of monthly precipitation in Beni city (Posite et al., 2024).

3.2. Methodological approach

This thesis used a scientific approach that combined a systemic and multiscale method. This engineering approach helped achieve the thesis's objectives by connecting analysis from the overall landscape level down to the household level.

3.2.1. Systemic approach

The northwest Virunga landscape is viewed as an open system that constantly interacts with its biophysical, socio-economic, and political surroundings. This viewpoint enables analysis through the systemic framework of De Rosnay 1975 model. The system comprises two interconnected dimensions: a structural component and a functional component. Structurally, the landscape includes the protected area, the northern part of Virunga National Park, and the peripheral zone, which has less restricted access and sees increased human activity, including agriculture, resource extraction, and urbanization, including the growth of towns and villages. Analyzing anthropization requires a theoretical framework that accounts for both the complexity and the multiple interactions among factors across different scales. This work's distinctive feature is its explanation of anthropization using a coherent, dynamic, and interconnected framework, in which biophysical and socio-economic factors interact to influence the landscape's spatial structure.

The integrated systemic approach merges various disciplines: remote sensing and GIS for assessing and mapping spatial changes; landscape ecology for studying spatial structure; and economics and social sciences to investigate disturbance causes. It considers five interconnected subsystems: (1) biophysical environment, (2) urbanization, (3) human disturbance factors, (4) perception and motivation affecting land use, and (5) security conditions as transversal factor. Applying this approach reveals that landscape dynamics are closely tied to human society, emphasizing the significance of understanding human-nature interactions (Collange, 1977). Analyzing spatial events based on social event understanding allows for reinterpreting the landscape's composition and configuration within a dynamic context shaped by these influencing factors (Figure 3-3).

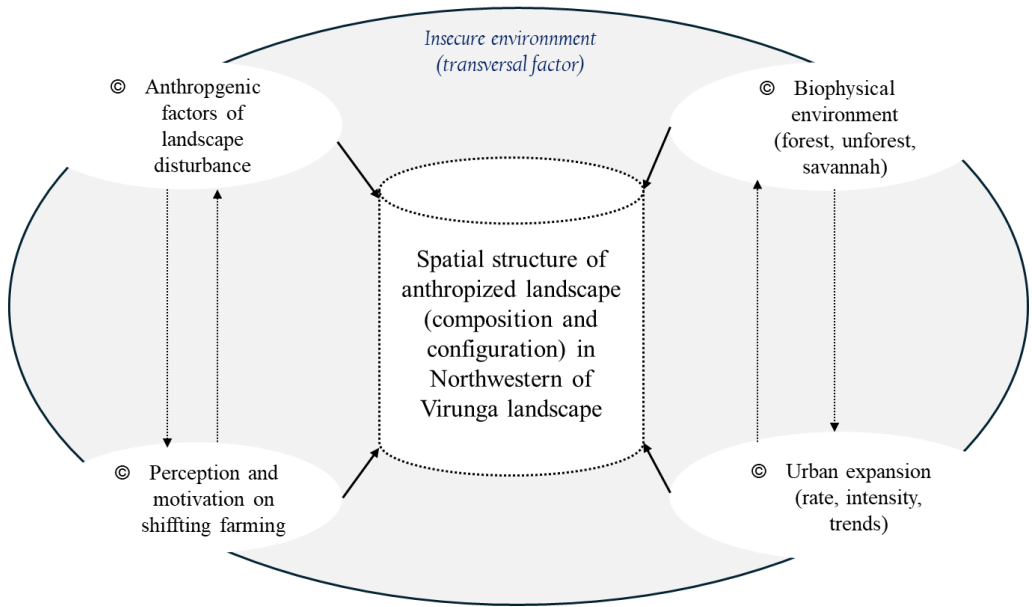


Figure 3-3. Systemic framework for analyzing anthropization in northwestern Virunga landscape.

3.3. Data sources and integrated methodological approach

This thesis adopted an integrated methodological framework combining remote sensing, landscape ecology, spatial analysis, and socioeconomic approaches. Multiple data sources were used, including spatial data, field observations, institutional documents, and local reports. The combination of these complementary allowed the analysis of landscape transformations by considering both their spatial patterns and socioeconomic processes driving them.

The methodological framework was organized according to the four research axes of the thesis. Axis 1 focused on long-term land-cover dynamics and landscape transformation between 1995 and 2021, with particular attention to change occurring under different security context. Axis 2 investigated recent forest disturbances and fragmentation processes associated with anthropogenic pressures and the establishment of military camps. Axis 3 examined household practices and perceptions on socioeconomic factors influencing agricultural expansion and forest conversion. Axis 4 analyzed recent urban growth in Beni and Butembo in relation to demographic pressure and insecurity-related population movements.

3.4. Description and processing of spatial data

3.4.1. Satellite data for long term landscape dynamics (Axis 1)

The analysis of long-term landscape dynamics was based on a multi-temporal series of Landsat satellite images. Landsat data were selected because of their long historical record, radiometric consistency, and suitability for monitoring land cover changes over several decades (Feng et al., 2012; Roy et al., 2016). The datasets included Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 OLI imagery acquired for six reference years: 1995, 2001, 2005, 2010, 2015 and 2021.

These observation dates were selected to represent contrasting socioeconomic and security contexts. The period 1995-2010 was considered relatively stable, whereas 2010-2021 corresponded to increasing insecurity associated with armed groups, particularly the ADF. Surface reflectance data were chosen to minimize atmospheric effects and enhance multi-temporal analysis (Feng et al., 2012; Roy et al., 2016). Images were selected mainly from the dry season, between January and March, with cloud cover below 10%. For each period, cloud-free composite images were generated using the median value of available pixel to reduce seasonal variability. All datasets were harmonized using WGS 84/UTM Zone 35N projection system. The 30 m spatial resolution of Landsat imagery was considered appropriate for analyzing landscape-scale processes.

3.4.2. Planet imagery for recent forest disturbances and urban expansion (Axes 2 and 4)

High-resolution PlanetScope imagery was used to analyze recent and localized landscape transformations. These images, obtained through the Norwegian International Climate and Forests Initiative, provide approximately 3 m spatial resolution. They include blue, green, red and near-infrared spectral bands 5 (Helman et al., 2018; Pickering et al., 2021)

Planet imagery was selected because of its ability to detect fine-scale changes over short temporal intervals that cannot be accurately identified using medium-resolution datasets. For Axis 2, these images were used to evaluate forest-cover changes around military camps established between 2018 and 2019 within and around the northern forest massif of Virunga National Park to track the ADF. The objective was to assess whether these infrastructures contributed to increased forest disturbance through accessibility and human activities. These images were used alongside visual observations of disturbance zones from the interactive maps on the Global Forest Watch platform.

For Axis 4, Planet imagery was used to analyze urban expansion in Beni and Butembo between 2016 and 2023. This period was selected because it corresponds to an important

demographic and security changes, including population displacement from rural affected by insecurity toward urban centers.

Table 3-1. Characteristics of satellite images and related studies

Sensor	Band	Spatial resolution (m)	Year
Landsat 5 TM	0.45-0.52 μm	30	1995
	0.52-0.60 μm		
	0.63-0.69 μm		
	0.76-0.90 μm		
	1.55-1.75 μm		
	10.4-12.5 μm		
	2.08-2.35 μm		
Landsat ETM+	0.45-0.52 μm	30	2001, 2005 and 2010
	0.52-0.60 μm		
	0.63-0.69 μm		
	0.76-0.90 μm		
	1.55-1.75 μm		
	10.4-12.5 μm		
	2.08-2.35 μm		
Landsat 8 OLI	0.43-0.45 μm	30	2015 and 2021
	0.45-0.51 μm		
	0.53-0.59 μm		
	0.64-0.67 μm		
	0.85-0.88 μm		
	1.57-1.65 μm		
	10.60-11.19 μm		
	2.11-2.29 μm		
Planet Imagery	650-680nm	3	2016, 2019 and 2023
	547-585nm		
	465-515nm		
	854-885nm		

3.4.3. Spatial data processing

Satellite image processing was mainly conducted using Google Earth and Engine and ArcGIS 10.5, QGIS 3.26. Google Earth Engine was used for satellite data management, cloud filtering, image compositing, spectral processing and supervised classification. ArcGIS 10.5 and Qgis 3.8 were used for spatial calculation, map production, vector processing and computation of landscape metrics.

3.5. Field data collection and supporting datasets

3.5.1. Training sample and field reference data

Field observation and reference datasets were collected to support image classification, validate spatial analyses and improve interpretation of landscape changes. Field missions conducted between August-September 2022 and September-November 2023. These combined GPS surveys, land-cover observation, forest disturbance inventories, household surveys, and interview with local stakeholders.

Because insecurity limited access to some areas, field observations were complemented by high resolution satellite imagery, particularly Planet and Google Earth images. Training areas were mainly selected from stable locations where landcover characteristics remained unchanged during the observation period, ensuring reliable reference data.

A total of 1902 training points were collected and used according to the objectives of each axis. For landscape-scale analysis (Axis 1), five land cover categories were considered: forest, savannah, field and follow, bare land and built-up areas, and water bodies. For urban analyses (Axis 4), training samples distinguished between built-up areas and green spaces. For forest disturbance analyses (Ax2), a simplified classification distinguishing forest and non-forest areas was adopted to focus on forest loss ad fragmentation processes.

Meanwhile, qualitative data on human disturbance factors was collected through transects. Using the frequency of occurrence for each factor type, this data helped develop axis 2 of the thesis, along with spatiotemporal analyses. It also laid the groundwork for axis 3 of the thesis. This mixed approach is inspired from those used by Barima et al. (2016) and Rakotondrasoa Olivia L et al. (2013).

3.5.2. Validation of the classification results

The classification results were validated using the standard confusion matrix method, built from the field-collected training and validation data. This contingency table allowed each spatial study to assess overall accuracy, user accuracy, and producer accuracy (Olofsson et al., 2013). In addition to these three metrics, the Kappa index (**k**) was used. All these indexes were used to assess the reliability of the classification results. Kappa Index is expressed as function of observed overall accuracy (P_o) and expected accuracy (P_e).

$$k = \frac{P_o - P_e}{1 - P_e},$$

$$P_o = \frac{\sum_{i=1}^r x_{ii}}{N}$$

$$P_e = \frac{\sum_{i=1}^r (x_{i+} * x_{+i})}{N^2}$$

x_{ii} = value of the diagonal of confusion matrix

x_{i+} = total of row i

x_{+i} = total of column i

N = total number of samples

r = number of classes

623 points from field, along with those from image analysis, were used to validate and interpret the classification results.

3.5.3. Identification and inventory of forest disturbance factors

The identification of anthropogenic disturbance factors affecting forest ecosystems was based on a combination of literature review, remote sensing analysis, field observations, and stakeholder consultation. Previous studies on tropical forest degradation provided an initial framework (Rakotondraso et al. (2013), which was adapted to the local context using field observations. Twelve disturbance factors were considered: tree cutting, food crop cultivation, cash crops cultivation, burned areas, charcoal production, artisanal timber harvesting, forest paths, isolated forest settlements, artisanal mining, invasive plant species, exotic plantations and livestock. Each disturbance factor was associated with specific field indicators to ensure consistent identification during inventories. Subsequently, an inventory of these factors was conducted along transects at six study sites: three within Virunga National Park and three at its edge. The systematic collection of observed factors covered 12 transects, each transects of 1000 m divided into plots measuring 100 meters long and 25 meters wide, totaling 30 hectares. In each plot, the data was collected in binary form: presence or absence of disturbance factor. The recorded data were the frequencies of each disturbance type.

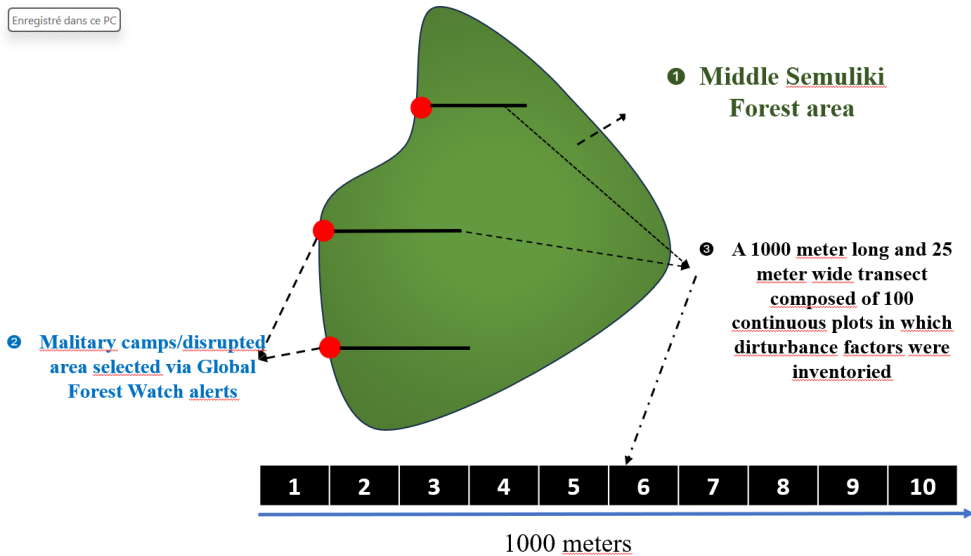


Figure 3-4. Graphical model summarizing the disturbance factor inventory approach

3.5.4. Field survey data

Socioeconomic data were collected to understand the human processes underlying landscape transformations. Axis 2 was based on surveys conducted on 650 households in the Beni region, complemented by focus group discussion and semi-structured interview with local authorities and community representatives. The survey provided valuable information on household profiles, key drivers of the ongoing conversion of agricultural land to forests, and the frequency of forest-to-agricultural land conversion, based on the five-year experience of the surveyed households. The study also identified socioeconomic factors related to land access, types of clearing, and the frequency of natural forests being converted to farmland, along with community perspectives on strategies to support small-scale farming in the area.

3.6. Analysis

3.6.1. Analysis of spatial structures at the whole landscape (Axis 1)

The analysis of landscape dynamics focused on quantifying land-cover changes over the period 1995-2021 and evaluating their relationship with the changing security context. Two main periods were distinguished: a relatively stable period (1995-2010) and a period characterized by increasing insecurity (2010-2021), corresponding to intensification of armed conflicts, particularly activities associated with the ADF group.

Six land-cover maps were produced for the years 1995, 2001, 2005, 2010, 2015 and 2021. Changes in landscape composition were assessed using transition matrices developed for five successive periods (1995-2001, 2001-2005, 2005-2010, 2010-2015 and 2015-2021). These matrices were used to quantify conversion between land-cover classes and identify the dominant transformation pathways, particularly conversion of natural ecosystems (forest and savannah) into anthropogenic classes such as agricultural areas and built-up.

Land-cover stability was evaluated to measure the persistence of each class between observation periods. The stability index was calculated as the ration between unchanged areas and area converted to other land-cover categories. Temporal variations in stability were analyzed to identify periods of increased landscape transformation. In addition, annual rate land-cover change was also calculated.

Landscape structural dynamics were analyzed using spatial metrics, including class area (CA), number of patches (NP), and largest Patch Index (LPI). These indicators provided information on landscape composition, configuration and spatial dominance. Finally, the decision tree approach developed by Bogaert et al. (2004) was applied to identify spatial transformation processes, including fragmentation, dissection, attrition, shrinkage, creation, aggregation, enlargement, and deformation. Analyses were performed at the landscape scale and separately for protected and non-protected areas to evaluate differences related to conservation status. Chapter 4 provide a detailed presentation of this methodological approach.

3.6.2. Analysis of disturbance processes (Axis 2)

Axis 2 focused on recent forest disturbance and the potential influence of military installations on forest fragmentation. Seven study sites located within and around the northern forest massif of Virunga National Park were analyzed: Kinziki, Lahe, Mamundioma, Mikuha, Ngite, Pk25 and PK26. These sites were selected based on forest alert from Global Forest Watch, field observations, and information collected from local stakeholders.

The period 2016-2023 was selected because of availability of high-resolution Planet imagery and because it corresponds to major security-related changes, including the establishment of military camps between 2018 and 2012. A circular analysis zone with a radius of 1 km was defined around each site to evaluate forest changes surrounding military installations.

Forest fragmentation was analyzed through three temporal stages: before camp establishment (2016), during camps installation (2019) and after establishment (2023). Forest structural changes were assessed using three landscape metrics: Percentage of Landscape (PLAND), Largest Patch Index (LPI), and Mean Patch Size.

PLAND quantified the proportion of forest remaining within each analysis zone. LPI evaluated forest patch continuity and Mean patch Size measured changes in fragment dimension. Additionally, the decision tree by Bogaert et al. (2004) was employed, using the theoretical threshold of 0.75 to distinguish between fragmentation and dissection.

According disturbance factors, statistical analyses included frequency analysis, Friedman tests to compare disturbance occurrences, chi-square test to evaluate relationship among disturbance factors and sites, generalized linear models to estimate disturbance promotility according to distance from access roads. Factorial correspondence analysis was used to identify associations between disturbance types and locations.

3.6.3. Analysis of the perception of household on smallholder farmers' expansion in intact forest landscapes

This analysis complements the one about factors disrupting the forest landscape. The scientific method involved surveys of 650 households and interviews with local leaders in the Beni area. It provided valuable information on household profiles, key drivers of the ongoing conversion of agricultural land to forests, and the frequency of forest-to-agricultural land conversion, based on the five-year experience of the surveyed households. The study also identified socioeconomic factors related to land access, types of clearing, and the frequency of natural forests being converted to farmland, along with community perspectives on strategies to support small-scale farming in the area.

The frequency of land conversion served as an indicator of household involvement in active deforestation within the studied area. Different statistical tests were used depending on the parameter being analyzed. This includes calculating means and proportion from both quantitative and qualitative data. Additionally, non-parametric test like Friedman and Wilcoxon were used to evaluate whether households' perception scores for various factors influencing land acquisition decision and recurring expansion of farm plots into forest differ significantly in terms of score distribution. Chi-square test was also used to examine the relationships between land access system and reported frequency extending field in forest area, as well as between land-clearing methods and reported frequency extending field in forest area(Liu and Xu, 2022).

3.6.4. Analysis of urban expansion in the landscape

The recent urbanization trend, set against the backdrop of security instability in rural areas and demographic growth, has been analyzed in two major cities: Beni and Butembo. This study covers the period from 2016 to 2023.

Urban expansion was analyzed through three complementary approaches: overall growth dynamics expansion along the urban-rural gradient and directional expansion patterns. Landscape metrics, particularly PLAND and LPI were used to quantify spatial configuration (Turner & Simard., 2017).

To evaluate peri-urbanization processes, both cities were divided into concentric zones spaced 1 km apart from the city core. PLAND and LPI were calculated within each zone to assess changes in urban density and spatial organization. The Shannon entropy index was used to evaluate spatial diversity and determine whether urban growth followed compact or dispersed patterns (Yang et al., 2018).

Finally, directional expansion was analyzed by dividing each city into four sectors (northeast, northwest, southwest and southeast). PLAND and LPI were calculated for each sector to identify preferential direction of urban growth and assess the influence of spatial constraint on urban expansion.

Chapter 3. Study area and methodological framework

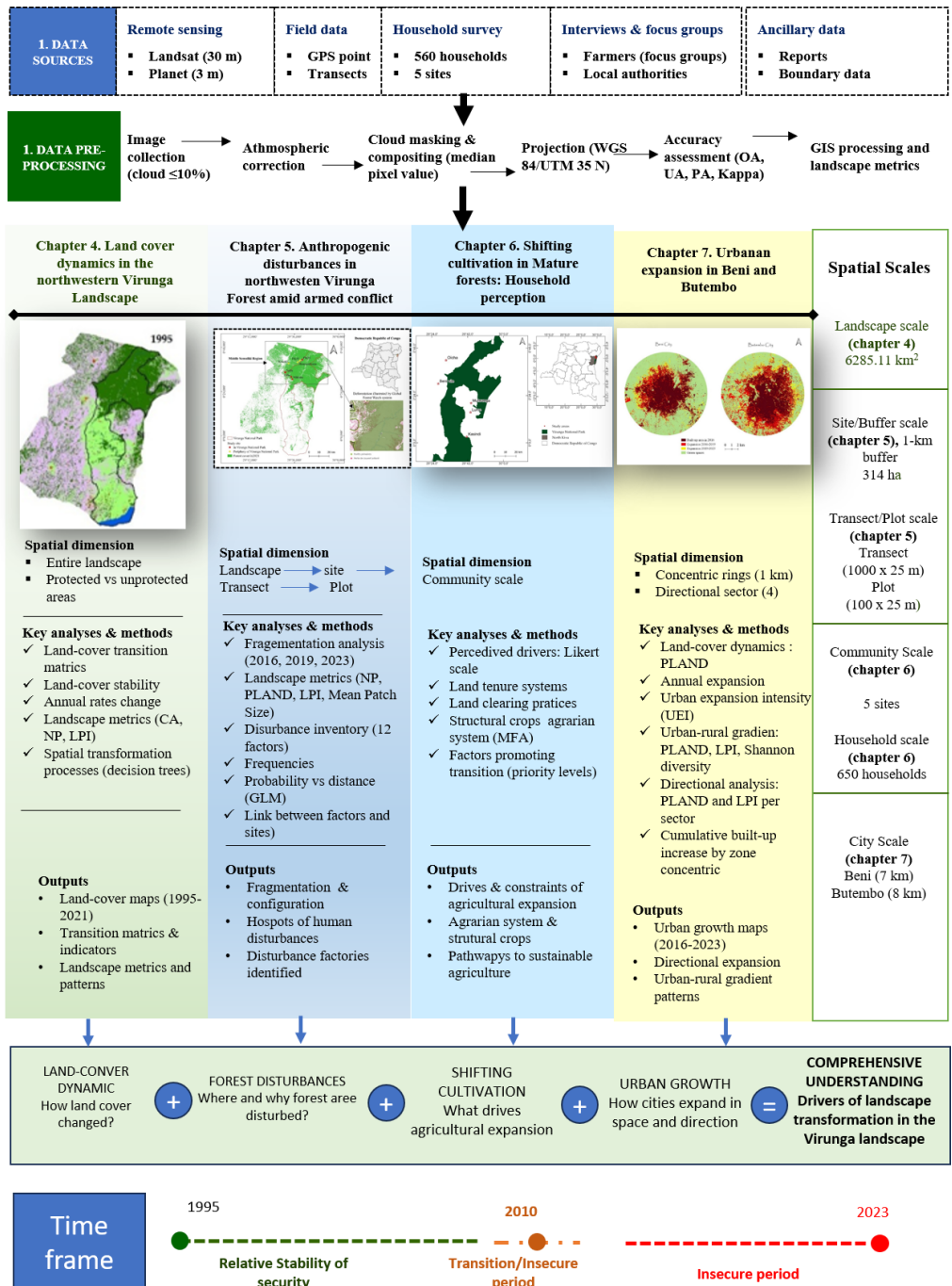


Figure 3-5. Methodological framework of the thesis

Chapter 4

4. Land Cover Dynamics in the Northwestern Virunga Landscape: An Analysis of the Past Two Decades in a Dynamic Economic and Security Context

Reference

Musavandalo, C.M., Sambieni, K.R., Mweru, J-P.M., Bastin, J-F., Ndukura, C.S., Nguba, T.B., Balandi, J.B., Bogaert, J., 2024. 4. Land Cover Dynamics in the Northwestern Virunga Landscape: An Analysis of the Past Two Decades in a Dynamic Economic and Security Context. *Land*, 13(5), 566. <https://doi.org/10.3390/land13050566>

Chapter positioning in the overall analysis

This chapter explores land cover dynamics across the global landscape in northwest Virunga, focusing on key changes and transformation processes from 1995 to 2021. It also highlights the vital role of Virunga National Park in preserving a less fragmented ecosystem.

Abstract

The Beni region in the eastern Democratic Republic of the Congo is grappling with socioeconomic development and security challenges that have affected its natural ecosystems, especially those located in the northern Virunga National Park. This study aims to document the anthropization of the northwestern Virunga landscape from 1995 to 2021 in the context of insecurity. Using a cartographic approach and ecological-landscape-analysis tools, this study delves into the overall landscape changes through a comparative analysis of protected and unprotected areas. These investigations focus on landscape composition, transitions between land-cover classes, and the spatial transformation process. The northwestern Virunga landscape is undergoing significant land cover changes due to the influence of insecurity on socioeconomic activities, primarily agriculture. Agricultural land encompasses a larger area than other land-cover types. However, its expansion has decelerated since the 2000s. The loss of forested area is discontinuous. During relatively stable periods (1995–2005), forests exhibited a reduction of up to 2.90% in area, while in the period of the return of Iturian refugees to their province, followed by terrorist insecurity in Beni (2005–2021), the forested area increased by 2.07%. Savannah areas, which are mainly located in the graben rift valley and near Butembo, have been more heavily affected by human activity than forests. Ultimately, the apparent stability of the landscape can be attributed to its protected areas, especially Virunga National Park.

Key word: Forest loss; Protected area; North Kivu; Land cover; Army faction

4.1. Introduction

The stability of protected areas is important for maintaining ecosystem services and ensuring a high rate of biodiversity conservation. Today, the ecological processes of forest ecosystems and their biological communities in protected areas experience

changes in land cover due to anthropogenic pressure. These anthropogenic changes lead to the conversion, fragmentation, and degradation of natural habitats (Guerra et al., 2019; Newbold et al., 2015).

The protected area network of the Democratic Republic of the Congo is an important tool for conserving biodiversity and preserving natural ecosystems. This network covers 13% of the national territory (Doumenge et al., 2015). However, nearly a century after the establishment of the country's first protected area, Virunga National Park, the context for nature conservation has evolved a great deal. Despite the Congolese government's sustainable conservation efforts and support from several technical and financial partners, many protected areas face increasing anthropization (Megevand, 2013). Although these anthropogenic pressures are complex and difficult to reduce to a few variables, they are generally attributed to the expansion of agricultural activities and the search for energy in the form of wood, exacerbated by demographic growth and decades of insecurity (Doumenge et al., 2015). According to Potapov et al. (2012), the gross loss of forests in Congolese protected areas is a key parameter for assessing the effectiveness of protected-area management. However, it varies among protected areas according to their conservation status and the landscape in which they are located.

Virunga National Park, created in 1925, is one of these protected areas and a world heritage site. It is famous for its outstanding biodiversity of plants and animals, as well as the range of habitats it encompasses, including tropical rainforests, mountain forests, savannah, volcanic mountains, and lakes, making Virunga National Park a beacon of conservation. However, demographic growth and insecurity in North Kivu over the last three decades have been ecologically affecting both Virunga National Park and its surroundings (Bweya et al., 2019; Lanjouw et al., 2001).

The northwestern Virunga landscape, while crucial for biodiversity conservation, has rarely been scientifically studied. This landscape plays a significant stabilizing role through its tropical forest, which also ensures the flow of several rivers that are crucial for the hydrological regime of the Nile River. Unfortunately, over the last three decades, the northwestern Virunga landscape has faced rapid economic development in cities such as Beni and Butembo, based mainly on the exploitation of forest resources. Since 2010, this landscape has also been afflicted by the violent activities of terrorist groups and military operations (Bweya et al., 2019). Developing a rational policy to reduce pressure on natural habitats and restore degraded areas within and around this protected area requires an understanding and quantitative assessment of land-cover-change processes at the landscape scale (Liping et al., 2018).

The development of remote sensing has facilitated the monitoring of land cover at the local, national, and global scales. Remote sensing is used to monitor various types of land cover and use, including forest, savannah, wetland, agricultural areas, and urbanized regions (Aslam et al., 2024, 2023; Muteya et al., 2022). Particularly in the context of armed conflict, when data are often scarce, remote sensing is a powerful tool for monitoring land cover and land use, enabling the anticipation of post-conflict management strategies (Müller et al., 2016; Z. Zhang et al., 2023). While various spatial products for land use and land cover change are available on a global scale, some are being debated for use in the conservation of biodiversity and protected area management (Fritz et al., 2011; Tropek et al., 2014).

This study analyzes the anthropization of the northwestern Virunga landscape in the context of insecurity. It focuses on the composition and configuration of the northwestern Virunga landscape over the last two decades. Two hypotheses were formulated to achieve the study objective. The first hypothesis is that the anthropization of natural forest ecosystems in the northwestern Virunga landscape increases during periods of insecurity compared to stable periods. This manifests as high fragmentation, low stability, and a high loss of forest and savannah areas during insecure periods. The second hypothesis is that Virunga National Park is less disturbed than its peripheral areas regardless of a period's stability or insecurity.

4.2. Materials and methods

4.2.1. Study area

To conduct this study, an area of 6285.11 km² was isolated from the Virunga landscape, mainly in Beni territory in North Kivu province (figure 4-1). This area is geographically part of the “Butembo region”, as defined by Vikanza (2011), located between 0°9'S and 0°54'N latitude and 28°57' and 30°9'E longitude. Referring to the global Landsat data notation system, the northwestern Virunga landscape is located at position 173 and 060 for the “path” and “row,” respectively. This zone is defined based on the population and Virunga National Park interactions.

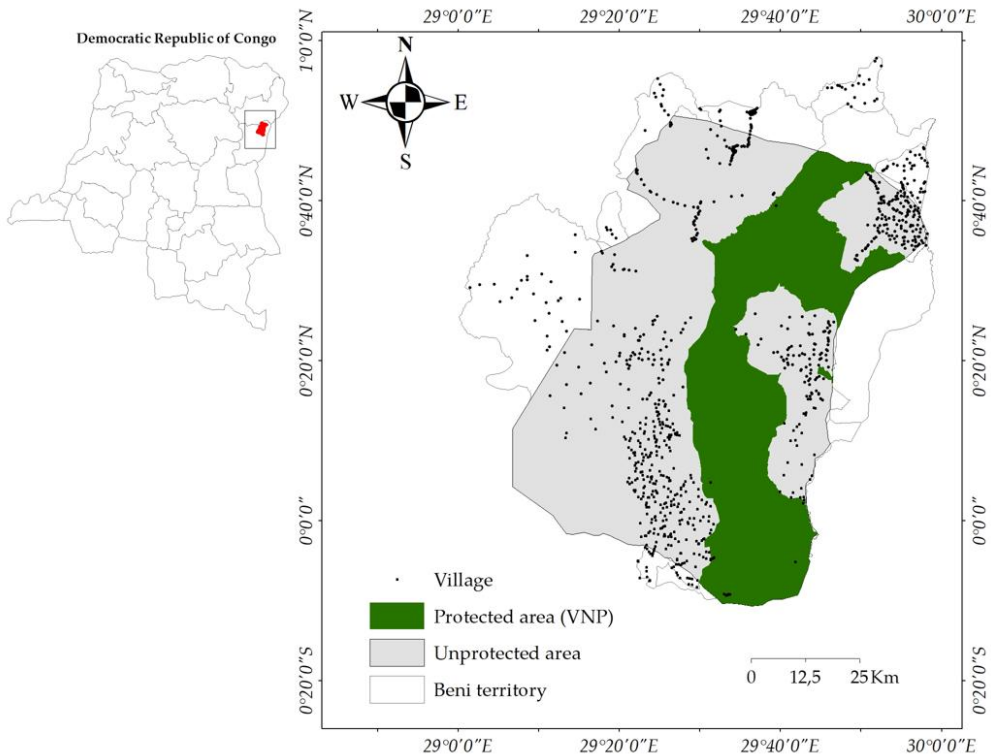


Figure 4-1. Northwestern Virunga landscape as defined in our study

The study area is covered by several types of natural forest ecosystems, including typical Central African rainforest, as well as shrubby and grassy savannah. It experiences a humid tropical climate of the *Af* type according to the Köppen classification, tempered sometimes by the mountains. The study area is characterized by abundant rainfall throughout the year, with a slight decrease between January and March, as well as between June and August. Rainfall in the region varies from 1200 to 2000 mm, with an estimated average of 1600 mm. The temperature ranges from 20 to 30 °C, with an average of 25 °C. The population is estimated at over 2 million and is concentrated mainly in Butembo and Beni cities and the rural communes of Oïcha, Kasindi, and Mangina (Bweya et al., 2019).

4.2.2. Remote sensing data acquisition

The satellite images used in this study were acquired from a multispectral satellite collection including Landsat 5 Thematic Mapper™, Landsat 7 Enhanced Thematic Mapper (ETM), and Landsat 8 Operational Land Imager (OLI). These Landsat data correspond to the observation periods (1995, 2001, 2005, 2010, 2015, and 2021) and indicate the presence of several types of natural forest ecosystems, including the

typical Central African rainforest. The years before 2010 are characterized by relatively more stable security. These images were acquired during the period of low rainfall, between January and March, in order to maintain the uniformity of the vegetation's spectral responses. Landsat data were filtered using two parameters: availability and cloud cover $\leq 10\%$ (Potapov et al., 2012). The selected dates include periods of significant instability (from 2010 to 2021) and periods of apparent peace (between 1995 and 2010). As mentioned by Roy et al. (2010), although the African continent often faces challenges regarding the availability of quality images, most images with low cloud cover are acquired between December and April. Furthermore, we estimate that the effect of seasonality is limited because of the low climatic fluctuation in the study area (Bweya et al., 2019). For each observation period, a composite image was produced by using the median pixel value of cloud-free images acquired during the low rainfall. Each composite image was then projected into the WGS/UTM 35N system (Potapov et al., 2012).

4.2.3. Spatial data processing

Image processing was first conducted on the Google Earth Engine platform, then completed on ArcGIS 10.5. The Google Earth Engine serves as a platform that connects researchers to powerful computational resources, facilitating the virtual and efficient processing of spatial data for research (Gorelick et al., 2017). It is a web-based integrated development code editor that enables users to analyze large-scale spatial data (Al Shogoor et al., 2022). The primary processing operations included radiometric correction, false color composition, supervised classification, and the assessment of classification accuracy.

4.2.3.1. Supervised classification

Supervised classification was employed to achieve a detailed assessment of land cover. We defined five dominant land-cover classes according to the study objectives. These classes comprised forest and savannah, or natural vegetation areas; field and fallow, bare and built-up land, describing the human footprint on the landscape; and, finally, water, encompassing all bodies of water (Table 4-1). A total of 1252 training points covering all types of land cover were collected on the ground using a Garmin 64 GPS between June and September 2022 and through the visual interpretation of Landsat images supported by our field knowledge. This included 271 points for forested land, 536 points for field and fallow land, 165 points for savannah, 250 points for built-up and bare land, and 30 points for water, using Lake Edward and the Semuliki River as reference points for water. The high number of points in the field and fallow class is explained by the diversity of crops. The random forest classification algorithm was chosen for its robustness and high classification accuracy

compared to other classification methods, such as maximum likelihood (Talukdar et al., 2020). Random forest classification operates through multiple decision trees during classification training to offer a final result based on several decision trees (Aslam et al., 2024). Google Earth’s high-resolution images are considered suitable as reference data (Tropek et al., 2014). Only areas with unchanged spatial composition throughout the observation period were selected for training. The subsequent processing in ArcGIS 10.5 involved vectorization and the calculation of the surface areas of the various land-use classes.

4.2.3.2. Accuracy assessment

A total of 393 points were used to test the accuracy of the maps produced. Different confusion matrices were produced for each map (Appendix A-1). Accuracy was assessed using conventional indices, including error of omission (producer accuracy), error of commission (user accuracy), and overall accuracy (Çakir et al., 2007; Olofsson et al., 2013). These indices were calculated using Equations (1)–(3) of Olofsson et al. (2013) (Table 4-2).

Table 4-1. Land-cover descriptions

Land Cover Class	Description
Forest	Primary forest, mature secondary forest, and other forest formations resulting from large-scale afforestation.
Field and fallow	Cultivated land (food crops such as rice, beans, and cassava), perennial crops (coffee, palm, and cocoa), and fallow land less than 4 years old that is likely to be reconverted to agricultural land or disturbed by other anthropogenic factors, such as bush fires.
Savannah	Grassland and shrubland savannah, mainly located within Virunga National Park.
Bare and built-up land	Residential areas, roads, or other surfaces not covered by vegetation at the time of image acquisition.
Water	Permanent or seasonal bodies of water (rivers, lakes).

Table 4-2. Accuracy assessment of land cover based on supervised classification using Random Forest classification (UA: User accuracy, PA: Producer accuracy)

	Forest		Field and Fallow		Savannah		Bare and Built-Up Land		Water		Overall Accuracy
Year	UA	PA	UA	PA	UA	PA	UA	PA	UA	PA	
1995	0.82	0.88	0.81	0.83	0.77	0.82	0.90	0.80	1.00	0.80	0.83
2001	0.86	0.92	0.84	0.82	0.82	0.82	0.88	0.88	1.00	0.89	0.85
2005	0.90	0.89	0.87	0.86	0.81	0.78	0.88	0.93	0.94	0.85	0.87
2010	0.83	0.93	0.90	0.79	0.80	0.80	0.88	0.97	0.95	0.97	0.87
2015	0.86	0.94	0.96	0.81	0.73	0.90	0.92	0.97	1.00	1.00	0.89
2021	0.81	0.90	0.88	0.85	0.89	0.80	0.92	0.93	1.00	0.95	0.88

4.2.4. Spatial analysis

The analyses were conducted in terms of insecurity as the key parameter in land-cover change. The stable period spanned 1995 to 2010, while the period of insecurity covered 2010 to 2021. These timeframes coincided with increased activism by ADF-NALU (Allied Democratic Force) terrorist groups imported from Uganda and other armed factions. Both hypotheses were tested through landscape composition and configuration analysis. This classical approach is based on land-cover analysis, transitions between land-cover classes, land-cover stability, pattern processes, and annual rates of change. These analyses were initially conducted on the entire landscape, followed by separate analyses of protected and unprotected areas within the study landscape.

4.2.3.3. Composition assessment

Six land-cover maps corresponding to the six observation periods were generated. The transition matrix (Çakir et al., 2007; Olofsson et al., 2013; Sikuzani et al., 2020) was used to quantify changes in land cover and evaluate its stability. Five transition matrices were established for the periods of 1995–2001, 2001–2005, 2005–2010, 2010–2015, and 2015–2021. These matrices were utilized to verify our sub-postulate regarding the greater conversion of natural areas (forest and savannah) to anthropogenic areas than the reverse process in the analysis of later transition matrices. The land-cover stability index was calculated as the ratio between unchanged areas and those converted to other forms of land cover between two observation periods. This index varied from 0 to ∞ with values approaching 0 when no areas of land cover remained unchanged over two periods and approaching ∞ when the unchanged areas surpassed the sum of the transferred or received areas from other land-cover classes. Alongside the stability-index value, its evolution over time was emphasized. Annual land-cover change was computed using the following standardized equation (Puyravaud, 2003):

$$R = -\frac{1}{T_1 - T_2} \ln\left(\frac{S_2}{S_1}\right)$$

where S_1 and S_2 represent the land-cover areas at times T_1 and T_2 .

4.2.3.4. Structural dynamics

To elucidate the dynamics of the spatial structure, three indices were calculated: the number of patches (NP), the class area (CA), and the largest patches index (LPI) (Kabanyegye et al., 2021). The following equation were used to determine the values of the LPI.

$$LPI = \frac{Max(aij)}{Ai}$$

where a_{ij} = area (km^2) of the patch ij and A_i = total area land cover i

The LPI tended toward 0 for highly fragmented classes and toward 1 for compact and non-fragmented classes. To identify the spatial transformation processes of the landscape, a decision tree from (Bogaert et al., 2004) was employed (figure 4-2). This method relies on changes in the class area, perimeter, and the number of patches between two periods (Barima et al., 2016, 2009; Bogaert et al., 2004; Gorelick et al., 2017; Kabanyegeye et al., 2021).

The ratio $t_{os} = \frac{At1}{At2}$ was defined to evaluate the loss of surface area for a land-cover class. The obtained ratio was then compared with a theoretical threshold value ($t_s = 0.50$) to differentiate fragmentation from other spatial landscape-transformation processes. Any transformation resulting in $t_{os} < 0.50$ was considered a fragmentation, and other transformations were considered dissections. Our analysis is based on the theoretical proposition that anthropogenic classes are primarily characterized by the aggregation and creation of patches, while natural classes exhibit characteristics such as dissection, fragmentation, attrition, and shrinkage. These indices and analyses were conducted for the entire landscape and the protected and unprotected areas as distinct zones.

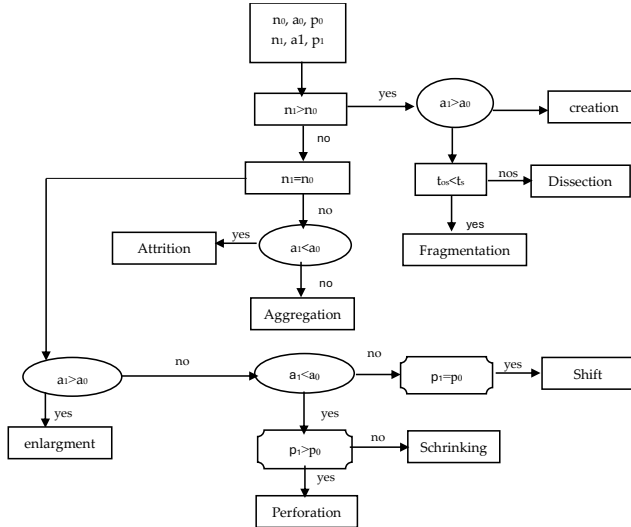


Figure 4-2. Decision tree used to analyze the spatial transformation process. a_0 = class area at initial period, n_0 = number of patches at initial period, and p_0 = class perimeter at initial period. a_1 , n_1 , and p_1 refer to final period (Bogaert et al., 2004)

4.3. Results

4.3.1. Land-cover mapping of Northwestern Virunga Landscape from 1995 to 2021

Six land-use maps were generated for the years 1995, 2001, 2005, 2010, 2015, and 2021 using the operational process described in Section 2.3. A visual analysis of these maps reveals that between 1995 and 2021, none of the land-cover classes remained virtually unchanged. The land-cover classes experienced regression and progression at different times; nevertheless, the spatial distribution of land cover suggests that the Virunga National Park is a significant reserve of forest and savannah. The extent of forest cover and savannah decreases with increasing distance from the park. Field and fallow land also covers more area in unprotected zones than in protected zones (figure 4-3)

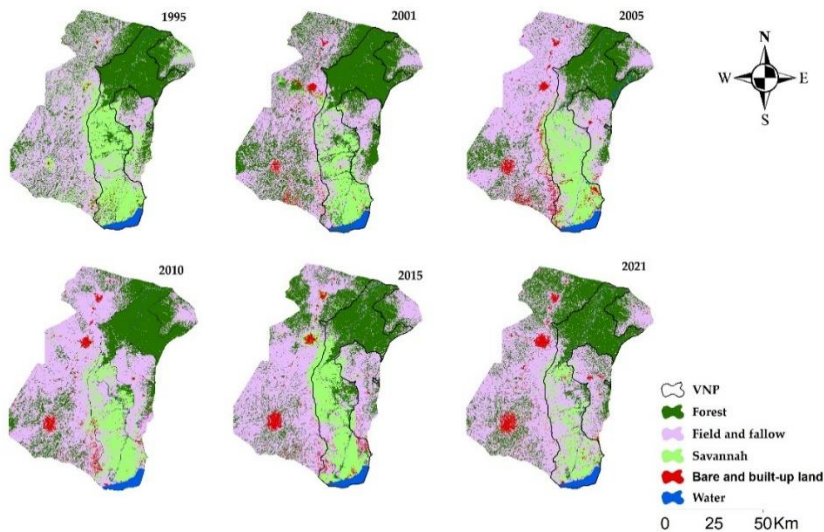


Figure 4-3. Land-cover maps of the northwestern Virunga landscape from 1995 to 2021.

4.3.2. Composition, Stability, and Spatial Pattern Processes of the Northwestern Virunga Landscape

4.3.2.1. Composition and Stability

The results of the landscape-composition and transition analysis are presented in Table 4-3. Overall, from 1995 to 2021, this landscape has been largely characterized by two land-cover classes: field and fallow, and forest. These two land-cover classes alone encompass approximately 80% of the landscape. The other 20% is occupied by savannah, bare and built-up land, and water. Field and fallow areas constitute the

landscape matrix, covering more than half of the area. Between 1995 and 2001, field and fallow area increased by 13%. Forested area decreased from 33.21% to 25.19% between 1995 and 2005, but then increased after 2005 to cover 29.81% of the total landscape area in 2021. Savannah decreased considerably during the observation period, declining from 24.18% in 1995 to 8.96% in 2021. Significant losses of savannah area were recorded between 1995 and 2001 and again between 2015 and 2021. In contrast, bare and built-up area increased significantly over time, rising from 0.82% in 1995 to 3.34% in 2021, representing a 307.31% increase.

Table 4-3. Transition probability matrix at the landscape scale, illustrating the dynamics of the areas of different land-use classes between 1995–2001, 2001–2005, 2005–2010, 2010–2015, and 2015–2021. Values are given as percentages (%); 1% = 62.8511 km². The values in the rows correspond to the first year and the values in the columns to the second year given in the date ranges specified. Values in the bold indicate the class stability.

1995–2001	Forest	Field and Fallow	Savannah	Bare and built-up land	Water	Total
Forest	21.62	9.83	1.33	0.25	0.18	33.21
Field and fallow	4.65	32.43	2.38	1.03	0.02	40.51
Savannah	1.51	11.29	10.00	1.04	0.34	24.18
Bare and built-up land	0.04	0.27	0.23	0.23	0.05	0.82
Water	0.09	0.13	0.11	0.00	0.97	1.29
Total	27.91	53.95	14.04	2.54	1.55	100.00
2001–2005	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	18.84	7.75	0.97	0.09	0.26	27.91
Field and fallow	5.62	41.20	5.28	1.80	0.04	53.95
Savannah	0.44	3.85	9.03	0.66	0.06	14.04
Bare and built-up land	0.23	0.88	0.14	1.29	0.00	2.54
Water	0.05	0.05	0.04	0.00	1.42	1.55
Total	25.19	53.73	15.46	3.84	1.78	100.00
2005–2010	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	18.84	5.91	0.22	0.17	0.05	25.19
Field and fallow	8.15	41.96	2.87	0.74	0.03	53.73
Savannah	0.57	5.46	9.18	0.25	0.01	15.46
Bare and built-up land	0.07	1.59	0.66	1.52	0.00	3.84
Water	0.31	0.03	0.07	0.00	1.38	1.78
Total	27.93	54.94	12.99	2.68	1.47	100.00
2010–2015	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	19.98	7.46	0.39	0.05	0.05	27.93
Field and fallow	8.68	39.33	6.10	0.81	0.01	54.94
Savannah	1.01	3.32	8.23	0.41	0.02	12.99
Bare and built-up land	0.09	0.70	0.39	1.49	0.00	2.68
Water	0.04	0.05	0.00	0.00	1.38	1.47
Total	29.81	50.86	15.11	2.77	1.46	100.00
2015–2021	Forest	Fields and fallow	Savannah	Bare and built-up land	Water	Total
Forest	21.96	7.40	0.32	0.12	0.01	29.81
Field and fallow	10.39	37.86	1.81	0.78	0.01	50.86
Savannah	0.41	7.41	6.45	0.83	0.01	15.11
Bare and built-up land	0.03	0.76	0.37	1.61	0.00	2.77
Water	0.01	0.02	0.02	0.00	1.41	1.46
Total	32.80	53.45	8.96	3.34	1.45	100.00

Overall, the transition matrix indicates that the exchange of areas between natural and anthropogenic classes is higher than that between anthropogenic classes alone. Between 1995 and 2005, the conversion of forest to field and fallow area exceeded the conversion of field and fallow area to forest. However, after 2005, more field and fallow area was transformed into forest than forest to field and fallow area. In addition, there was a greater extent of transformation from savannah to field and fallow area than from field and fallow area into savannah.

Table 4-4 presents a stability index of land cover at the overall landscape level. These findings reveal that none of the five land-cover classes has remained stable over the last 26 years. However, the stability index values for the fields and fallow, forest, and water classes are greater than one. This indicates that, despite transitions between land-cover classes, more than half of the area occupied by these three land-cover classes has remained unchanged at the landscape scale between observation intervals. Conversely, the savannah and bare and built-up land classes have stability index values of less than one. Therefore, during each observation period, more than half of the total area of bare and built-up land and savannah transitioned to and from other land-cover classes.

Table 4-4. Evolution of the stability index of each land-cover class in the northwestern Virunga landscape.

Year	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
1995–2001	1.21	1.39	0.55	0.08	1.06
2001–2005	1.22	2.98	0.79	0.34	2.82
2005–2010	1.22	3.13	0.91	0.44	2.78
2010–2015	1.12	3.27	0.71	0.61	7.93
2015–2021	1.20	2.40	0.58	0.55	16.01

4.3.2.2. Landscape Change Processes

Tables 4-5 and 4-6 provide information on the spatial transformation of the landscape. Between 1995 and 2021, three land-cover classes, water, forest, and field and fallow, exhibited high LPI values compared with the two other classes, savannah and bare and built-up land. While the largest patches index values of field and fallow land and bare and built-up land increased over time, the forest LPI value decreased. The savannah LPI value varied significantly over time. The decrease in LPI values of the natural classes compared to the increase in those of the anthropogenic classes highlights the effect of human activity on the landscape. Overall, forest dissection was observed during the first 10 years, followed by forest aggregation between 2005 and 2010 and again between 2015 and 2021. A few forest patches were created between

2010 and 2015. Savannah dissection occurred between 2005 and 2010 and again between 2015 and 2021. Savannah aggregation was observed between 2001 and 2005 and again between 2010 and 2015. Savannah attrition was only observed before 2001. Bare and built-up land attrition was observed between 2005 and 2010, while bare and built-up areas increased between 1995 and 2005 and between 2010 and 2021. Field and fallow land underwent dissection three times and aggregation twice, indicating a pattern that is likely associated with agricultural itinerancy.

Table 4-5. Synthesis of spatial-pattern indices in the northwestern Virunga landscape between 1995 and 2021. N = Number of patches, CA = Class area (in km²), LPI = Largest-patch index.

Indices	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
N ₁₉₉₅	73,502	86,291	220,987	13,130	5576
CA ₁₉₉₅	2086.98	2545.79	1519.47	51.80	81.05
LPI ₁₉₉₅	0.57	0.69	0.29	0.04	0.47
N ₂₀₀₁	115,120	73,828	59,074	30,334	5583
CA ₂₀₀₁	1754.04	3390.95	882.55	159.92	97.64
LPI ₂₀₀₁	0.52	0.71	0.24	0.10	0.82
N ₂₀₀₅	137,520	100,001	45,611	30,889	5411
CA ₂₀₀₅	1582.91	3377.27	971.61	241.27	112.05
LPI ₂₀₀₅	0.57	0.69	0.50	0.11	0.72
N ₂₀₁₀	91,474	77,794	56,177	15,633	929
CA ₂₀₁₀	1755.40	3453.11	816.15	168.20	92.25
LPI ₂₀₁₀	0.62	0.85	0.35	0.19	0.86
N ₂₀₁₅	121,749	94,648	27,212	31,858	769
CA ₂₀₁₅	1873.35	3196.38	949.69	173.88	91.81
LPI ₂₀₁₅	0.49	0.66	0.52	0.27	0.86
N ₂₀₂₁	83,663	107,678	75,941	34,085	671
CA ₂₀₂₁	2061.79	3359.18	563.36	209.84	90.94
LPI ₂₀₂₁	0.44	0.78	0.11	0.26	0.88

Table 4-6. Identification of spatial transformation processes (STPs) of land-cover classes in the northwestern Virunga landscape between 1995 and 2021. Di = Dissection, Ag = Aggregation, Cr = Creation, At = Attrition.

	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
STP _{1995–2001}	Di	Ag	At	Cr	Cr
STP _{2001–2005}	Di	Di	Ag	Cr	Ag
STP _{2005–2010}	Ag	Ag	Di	At	At
STP _{2010–2015}	Cr	Di	Ag	Cr	At
STP _{2015–2021}	Ag	Di	Di	Cr	At

4.3.2.3. Annual Land-Cover Change Overall in the Northwestern Virunga Landscape between 1995 and 2021

Table 4-7 summarizes the annual rate of change in land cover within the studied landscape. From 1995 to 2005, forests exhibited a net annual loss of area, estimated at over 2%. Subsequently, there was an increase in forested area, ranging between 1.34 and 2.18%, which was observed after 2005 and continued until 2021. The annual loss of savannah from 1995 to 2001, 2005 to 2010, and 2015 to 2021 was considerably greater than the annual gain from 2001 to 2005 and 2010 to 2015. Similarly, field and fallow land showed significant annual increases between 1995 and 2001, followed by low increases from 2005 to 2010 and 2015 to 2021. However, from 2001 to 2005 and 2010 to 2015, field and fallow land experienced a loss in area of 0.10 to 1.48% per year. Except for 2005 to 2010, bare and built-up land area increased. The negative values for water classes are thought to be due to the low discrimination of small watercourses in Landsat images during a certain period.

Table 4-7. Annual rate of land-cover change (percent) in the northwestern Virunga landscape

	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
1995–2001	–2.90	4.58	–9.06	18.79	3.10
2001–2005	–2.57	–0.10	2.40	10.28	3.44
2005–2010	2.07	0.44	–3.49	–7.22	–3.89
2010–2015	1.30	–1.55	3.03	0.66	–0.09
2015–2021	1.60	0.83	–8.70	3.13	–0.16

4.3.3. Comparative Assessment of Stability and Spatial-Pattern Processes between the Protected and Unprotected Areas in the Northwestern Virunga Landscape

Tables 4-8 and 4-9 offer specific, crucial information regarding the spatial transformation of the protected and unprotected areas in the northwestern Virunga landscape. The protected area constitutes the northern reaches of Virunga National Park, surrounded by a vast area that is not subject to any measure restricting access to resources. The natural land-cover classes, forest and savannah, within the protected area are characterized by high stability-index values, reflecting their low conversion to anthropogenic land-cover classes. Furthermore, the stability of forested area is higher than that of savannah.

Conversely, in the unprotected area of the periphery of the Virunga National Park, the natural land-cover classes are characterized by very low stability-index values. Only the anthropogenic class of field and fallow land showed stability-index values greater

than one, with slight variations. However, the conversion of savannah to other land-cover types remains higher than that of forest to other land-cover types. In addition, the bare and built-up land class presented a continuous increase in stability index values, from 0.08 in 1995 to 1.06 in 2021. This continuous increase can be linked to the densification of built-up areas in the landscape, specifically in Beni and Butembo. Finally, the stability-index values for the water class reflect the difficulty of discriminating small waterways in Landsat images in this landscape.

Table 4-8. Stability-index values for each land-cover class in the protected area.

	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
1995–2001	3.17	0.17	1.07	0.04	1.20
2001–2005	2.66	0.38	1.17	0.07	2.35
2005–2010	3.32	0.41	1.27	0.10	3.51
2010–2015	3.09	0.27	1.00	0.10	12.88
2015–2021	2.95	0.33	0.88	0.05	17.88

Table 4-9. Stability-index values for each land-cover class in the unprotected area.

	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
1995–2001	0.67	1.35	0.15	0.08	0.00
2001–2005	0.65	1.95	0.20	0.38	0.00
2005–2010	0.60	2.08	0.23	0.60	0.00
2010–2015	0.57	1.89	0.18	0.69	0.00
2015–2021	0.67	1.73	0.17	1.06	0.00

Tables 4-10 and 4-11 present the characteristics of the spatial transformation processes between the protected and unprotected areas in the study landscape. Within the park, forested areas underwent dissection between 1995 and 2001. In contrast, other land-cover classes revealed various processes during the same period: aggregation followed by dissection for field and fallow land, dissection followed by aggregation for savannah, and attrition followed by creation for bare and built-up land. Between 2025 and 2021, a significant decrease in forested and bare and built-up land occurred. Field and fallow land, as well as savannah, underwent creation and dissection, respectively, during this period. The LPI of forested land was estimated at more than 0.70 from 1995 to 2015, indicating low forest fragmentation in the protected area during this period. However, by 2021, the LPI of the forest had decreased to 47%, suggesting ongoing disturbance and increasing fragmentation. In the unprotected area, between 1995 and 2005, forest and savannah areas underwent patch dissection and attrition, respectively. Field and fallow land underwent patch aggregation from 1995 to 2001, followed by patch creation between 2001 and 2005. The bare and built-up land underwent patch creation between 1995 and 2001, followed by aggregation from

2001 to 2005. From 2005 to 2010, patch aggregation was observed in forested and field and fallow land. During the same period, bare and built-up land experienced attrition, while savannah underwent dissection. From 2010 to 2015, forest patches were created, savannah patches aggregated, and field and fallow land was dissected. The dissection of field and fallow land continued until 2021. Low LPI values indicate disturbance in the forested and savannah areas within the unprotected area. Only field and fallow land recorded LPI values of more than 0.60.

Table 4-10. Land-cover pattern dynamics of protected and unprotected areas of the northwestern Virunga landscape from 1995 to 2021. N = Number of patches, CA = Class area (in km²), LPI = Largest-patch index. The protected area covers 2074.65 km² and the unprotected area, 4210.46 km².

Protected Area (within Virunga National Park)						Unprotected Area (around Virunga National Park)				
Indices	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
N ₁₉₉₅	12,772	33,440	30,333	5907	3754	60,977	52,851	190,564	7223	1822
CA ₁₉₉₅	913.27	187.00	880.74	19.38	74.26	1173.71	2358.94	638.80	32.42	6.79
LPI ₁₉₉₅	0.84	0.21	0.39	0.01	0.60	0.14	0.72	0.09	0.06	0.17
N ₂₀₀₁	18,954	37,041	18,338	3022	3852	96,166	37,335	41,018	27,352	1736
CA ₂₀₀₁	805.17	488.48	670.50	15.00	95.50	948.86	2902.42	212.08	144.89	2.10
LPI ₂₀₀₁	0.85	0.12	0.29	0.16	0.84	0.08	0.76	0.07	0.10	0.05
N ₂₀₀₅	10,362	50,008	19,170	7409	3535	127,510	50,675	26,778	23,592	1886
CA ₂₀₀₅	711.13	416.80	789.91	48.21	108.60	871.76	2960.48	181.72	193.08	3.45
LPI ₂₀₀₅	0.94	0.16	0.57	0.14	0.77	0.15	0.74	0.22	0.14	0.10
N ₂₀₁₀	14,897	40,997	21,704	2776	418	76,868	37,697	34,944	12,941	511
CA ₂₀₁₀	852.15	458.92	656.08	16.86	90.64	903.25	2994.21	160.07	151.34	1.70
LPI ₂₀₁₀	0.90	0.24	0.42	0.08	0.90	0.13	0.75	0.04	0.21	0.10
N ₂₀₁₅	18,206	42,512	12,818	10,622	633	103,863	52,836	14,658	21,341	138
C ₂₀₁₅	854.06	350.96	740.74	37.37	91.52	1019.29	2845.42	208.95	138.56	0.29
LPI ₂₀₁₅	0.77	0.19	0.51	0.10	0.91	0.13	0.71	0.44	0.32	0.10
N ₂₀₂₁	12,824	55,346	27,106	10,200	229	71,210	53,836	49,129	24,045	442
C ₂₀₂₁	850.76	655.22	451.37	27.12	90.18	1211.03	2703.98	112.00	182.71	0.76
LPI ₂₀₂₁	0.47	0.45	0.14	0.07	0.92	0.15	0.67	0.06	0.29	0.06

Table 4-11. Spatial transformation processes (STPs) within and around Virunga National Park. Di = Dissection, Cr = Creation, At = Attrition, Ag = Aggregation.

Protected Area (within Virunga National Park)						Unprotected Area (around Virunga National Park)				
	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water	Forest	Field and Fallow	Savannah	Bare and Built-Up Land	Water
STP ₁₉₉₅₋₂₀₀₁	Di	Cr	At	At	Cr	Di	Ag	At	Cr	At
STP ₂₀₀₁₋₂₀₀₅	At	Di	Cr	Cr	Ag	Di	Cr	At	Ag	Cr
STP ₂₀₀₅₋₂₀₁₀	Cr	Ag	Di	At	At	Ag	Ag	Di	At	At
STP ₂₀₁₀₋₂₀₁₅	Cr	Di	Ag	Cr	Cr	Cr	Di	At	Di	At
SPT ₂₀₁₅₋₂₀₂₁	At	Cr	Di	At	At	Ag	Di	Di	Cr	Cr

4.4. Discussion

4.4.1. Land-Use Dynamics and Deforestation

This study defined five land-use types in the northwestern Virunga landscape: forest, savannah, field and fallow, bare and built-up land, and water. A 26-year observation of the northwestern Virunga landscape reveals that, at the landscape scale, field and fallow areas constitute the landscape matrix. Following a 13% spatial increase between 1995 and 2001, the expansion of agricultural areas slowed between 2001 and 2021. As Bogaert et al. (2014) emphasized, in a landscape under heavy human pressure, natural areas are replaced by dominant agricultural activities characterized by fields, fallow land, pastures, and farm buildings. Likewise, Christensen and Arsanjani (2020) indicated that the conversion of forest areas to farmland is a common and increasingly frequent process around Virunga National Park that is resulting in a net loss of natural ecosystems.

Agricultural practices in the northwestern Virunga landscape, particularly in the Beni lowlands, have historical roots. They are closely linked to the migration of the Nande people starting in the 18th century as they sought new lands to cultivate. This phenomenon was accentuated by the creation of the Virunga National Park, colonial agricultural policies promoting cash crops such as coffee, and the development of urban centers, including Oïcha, Beni, and Butembo (Vikanza, 2011; Vyakuno, 2006). Our cartographic analyses support this narrative, revealing that over 40% of the landscape was converted to farmland many years before the major sociopolitical upheavals in the Beni region began in the 1990s. Human migration has also been documented as a factor in the destruction of natural habitats at the Dosso partial wildlife reserve in Niger due to land saturation and climate change (Abdou et al., 2019). Furthermore, our results partially align with the trends observed by Bweya et al. (2019), who indicated that by 2018, field and fallow land occupied more than half (66.8%) of the Beni region. However, our estimate of field and fallow land differs from those results by more than 30% in 1995, and by a further 10% after that period. These discrepancies primarily stem from the differing accuracy levels of the random forest classification algorithm used in our study and the maximum likelihood method used in Bweya et al. (2019). Furthermore, Talukdar et al. (2020) mentioned that spatial analysis using random forest classification offers better precision when assessing land cover. Therefore, the land-cover trends provided by Bweya et al. (2019). for the overall Beni landscape should be considered in context. Importantly, Bweya et al. (2019), focused their analysis on the unprotected area of the Beni landscape that

extends into the Mambasa Territory forest between 1995 and 2018 without considering intermediate changes.

Forest constitutes the second-most prominent type of land cover in the landscape studied, followed by savannah. After a decrease between 1995 and 2005, forest cover increased from 2005 to 2021. Meanwhile, savannah experienced a continuous decrease throughout the observation period from 24.18% in 1995 to 8.96% in 2021. Simultaneously, bare and built-up land has increased significantly over the 26-year study period, gaining around 307.31%. The forest loss in the initial decade of observation and continuous savannah loss over the entire 26 study years are closely linked to the expansion of the agricultural frontier and urban areas. Our results support those of Molinario et al. (2020) and reinforce the trends observed by Potapov et al. (2012) between 2000 and 2005, which indicate a significant loss of forest near Beni city, primarily due to the cultivation of rice, beans, cassava, coffee, palm, and cocoa, as well as charcoal production, followed by a modest recovery of forests between 2005 and 2010. Agriculture, which employs 80% of the population, remains rudimentary and focused on rice, manioc, and beans, combined with cash crops such as cocoa, palm, and coffee. Lacking institutional support, farmers expand fields in the hope of producing more and earning a higher income (Vikanza, 2011). Our results also align with those of Christensen and Arsanjani (2020) concerning the significant loss of savannah areas north of Lake Edward, but they contextualize the projection these authors made of an intense and continuous loss of forest cover in the Virunga landscape at a rate of 4.21% by 2030. Forest transition to other land cover is discontinuous, as the annual change shows. Between 1995 and 2005, forested area decreased by slightly more than 2% each year. However, after 2005, the forested area increased, with values varying between 1.30% and 2.07%. Only the savannah experienced significant loss rather than gain, up to 9.06%. Potapov et al. (2012) estimated a 2.60% annual rate of forest cover loss across the Virunga landscape between 2000 and 2010, attributing this loss to massive forest clearing in North Kivu. This aligns with our observation of the land-cover pattern between 1995 and 2005, which correlates with the intensification of agricultural activities and the search for wood to use as energy and timber by local populations and refugees from Ituri who were deprived of all means of survival.

From 2002 to 2005, the Beni Territory hosted several thousand refugees fleeing the war in Ituri. Due to a lack of alternatives, these refugees settled in the forested area bordering Virunga National Park, notably in Ngadi, Mavivi, Mbau, and Oïcha (Vikanza, 2011). The influx of refugees led to a rapid increase in the population in northwestern Virunga and an increased the demand for natural resources. The arrival

of so many people into an area that was unprepared for such pressure, coupled with the endogenous demographic growth, indirectly contributed to deforestation. Population growth, economic growth, and weak institutional structures are leading to increased deforestation in the Democratic Republic of the Congo (Ajanaku and Collins, 2021; Indarto and Mutaqin, 2016) and several other developing countries (Ajanaku and Collins, 2021; Indarto and Mutaqin, 2016).

However, contrary to Potapov et al. (2012), our study reveals a forest cover gain of 2.07% per year between 2005 and 2010 and of more than 1% between 2010 and 2021. This difference may reflect the scale of each study: while Potapov et al. (2012) focused on analyses at the national and provincial levels, our study focused exclusively on the northern sector of the Virunga landscape. Therefore, the increase in forest area primarily reflects insecurity in the Beni Territory and the neighboring province of Ituri, resulting in almost continuous population movements. Since the security situation in Ituri stabilized in 2005, refugees have vacated occupied land and have cultivated in the Beni Territory, allowing reforestation to occur in degraded areas. After the departure of the Iturian refugees, the Beni Territory experienced the activity of armed factions and terrorism. Since 2010, this insecurity has prompted a massive movement of rural populations toward major urban centers, such as Beni and Butembo, and into Mambasa Territory and the savannah areas in the Virunga National Park, especially north of Lake Edward. Agricultural abandonment due to insecurity has led to the passive reconstitution of forested land. The activities of armed groups often interfere with agricultural activities and prevent farmers from accessing their fields (Stevens et al., 2011). Therefore, as Opelele et al. (2020) demonstrate, the influx of population from Beni and Butembo into the Mambasa Territory in search of land for cultivation, timber, and charcoal has led to a 12% decline in primary forest in 2019.

The trend of slower deforestation during insecure periods was also reported by Koy and Kabuanga (2019) in the Yangambi Biosphere Reserve from 1995 to 2003. Ordway (2015) noted a forest-restoration rate of more than 4% in the Volcan National Park landscape, another portion of the greater Virunga landscape, in Rwanda during the genocide. Grima and Singh (2019) revealed passive forest restoration during periods of armed conflict in Nepal, Sri Lanka, Peru, and the Republic of Côte d'Ivoire. Stevens et al. (2011) also documented a decrease in deforestation during armed conflicts. Conversely, Salomon et al. (2021) noted a decrease in forested area in protected areas, notably in Macaya National Natural Park, La-Visite National Natural Park, and Pine Forest Unit 2 during a period of political instability in the Republic of Haiti. In addition to economic and demographic factors, this study emphasizes that spatial transitions in the northwestern Virunga landscape are heavily influenced by the

nature and intensity of insecurity. In areas where armed and terrorist groups are more active, forest passively covers the large agricultural areas left by the retreating population. This contradicts our initial hypothesis that anthropization would be more pronounced during wartime than during peacetime.

According to Koy and Kabuanga (2019), the national annual rate of deforestation in the Democratic Republic of the Congo varies from 0.2 to 0.4%. These values are lower than the minimum forest loss rate recorded in our study area (2.57–2.90%). This suggests that, without insecurity or regulatory constraints, annual forest loss in the northwestern Virunga landscape may be higher than the national average. Insecurity is, therefore, not a factor in the widespread destruction of forest ecosystems in the northwestern Virunga landscape, as insecurity, characterized by terrorist activism, reduces the local people's ability to extend their activities into the forest. In addition to insecurity, Virunga National Park, as an integral part of the landscape, appears to be significantly slowing the rapid expansion of the human footprint in forested areas. Nevertheless, the savannah remains permanently vulnerable. Farmers and herders surrounding the park can easily enter savannah areas illegally; these areas are vulnerable to anthropogenic pressure (Tong et al., 2020).

4.4.2. Landscape Stability is Enhanced by Protected Areas

The anthropization of protected areas differs from the pattern observed in unprotected areas. The protected area in the northwestern Virunga landscape displayed a greater stability of natural elements than the unprotected area over the study period. This stability confirms our second hypothesis, that regardless of stability or insecurity, the Virunga National Park is less disturbed than its peripheral areas. The LPI values also indicate that natural land cover remains more contiguous in the protected area than in unprotected areas.

Moreover, the loss of forest area within the park is often attributed to dissection and removal, whereas in the peripheral zone, it mainly occurs through dissection. The forest loss of 2.10% per year between 1995 and 2005 is lower than the 3.40% observed by Sikuzani et al. (2023) during the same period in Kundelungu National Park. The increase in field and fallow land inside the protected area is attributed to creation, while in the peripheral zone, the increase in field and fallow land occurs through both aggregation and the creation of new patches. These results align with global trends in land-use change, which is greater in the vicinity of the protected areas than within them (Guerra et al., 2019). As Bogaert et al. (2014) noted, constraints on access to protected areas contribute significantly to the landscape-transformation process. These may include physical or regulatory measures, as in the case of Virunga National

Park. Virunga, as a national park and World Heritage Site, is governed by national and international laws prohibiting the exploitation of natural resources in any form. Furthermore, as protected areas cover a large area, the “Institut Congolais de Conservation de la Nature (ICCN)” has developed partnerships with organizations and private partners to manage protected areas. This strategy enabled the protected areas sector to be revitalized both technically and financially. In the Virunga National Park, ICCN has signed a public–private partnership with the Virunga Foundation for operational management of the park. The Virunga National Park is also one of four protected areas in the Democratic Republic of the Congo, which accounts for 90% of investment in protected area management, with 85% provided by international partners. The technical and financial resources available to the Virunga Park manager contribute to the preservation of natural areas despite security challenges (Doumenge et al., 2015).

The dissection of forested land within the park can be explained by natural and anthropogenic factors. One natural factor is the local hydrography, which is dominated by the Semuliki River. The primary anthropogenic factor is the rehabilitation of the Beni-Kasindi and Mbau-Kamango roads between Uganda and the Democratic Republic of the Congo and the military roads in Virunga National Park. The highly fragmented residual forest in the periphery of the Virunga National Park is typical of a shifting system. These residual forests serve to regulate soil fertility and provide firewood and building materials for the local population (Tong et al., 2020). Unlike the proposed theoretical process of spatial landscape transformation, the natural classes are characterized by a certain amount of creation and aggregation within both the protected and unprotected areas. Forest and savannah creation within the protected area may be the result of the healing of anthropized areas after the illegal users of the protected area have been removed. Similarly, the dissection of field and fallow land shows the transient nature of local agriculture, in which field continuity over time is interspersed with passive forest restoration through long-term fallowing.

4.4.3. The Usefulness of Local Mapping

Remote sensing imagery currently offers significant potential for monitoring changes in land cover not only on a local scale but also on a global scale. This is crucial in areas with high conservation value that face threats from armed factions and terrorism (Ordway, 2015). Land-cover maps have been made available to the public for decision-making purposes. However, as Tropek et al. (2014) highlighted, some of these maps provide an overly general representation of the local dynamics of a landscape. Comparing our land-cover results for 2021 with those extracted from ESA World Cover 2021 (Zanaga et al., 2021) reveals some disparities. The map by Zanaga

et al. (2021) designates more areas as forest (66.10%) than ours, while our map identified more areas as field and fallow land (53.40%). This variation exists because Zanaga et al. (2021) categorized perennial crops, such as oil palms, as forested land; however, in the context of Virunga, we included multi-annual crops as field and fallow land. Similarly, Potapov et al. (2022) and Buchhorn et al. (2020) have used the same definitions of forest and agricultural land classes to monitor world land-cover trends.

In the context of the Virunga landscape, excluding some perennial crop areas from the farming land class diminishes the trend toward landscape anthropization. Conversely, integrating perennially cultivated areas into the farming category increases the visibility of the trend toward anthropization. As Fritz et al. (2011) noted, the Virunga National Park manager's use of the ESA World Cover maps necessitates agreement on the definition of land-use classes and comparison with maps produced using local knowledge. Another spatial land-cover framework was proposed by Vancutsem et al. (2021), comprising 10 transition classes to monitor forest-cover changes in the humid tropics. The authors considered the absence of tree-foliage cover in a pixel as an indicator of disturbance. However, given the difference in approach and class definition, direct comparison with these results is difficult.

4.4.4. Management Implications for Virunga National Park

This study highlights the process of anthropization and its spatial effects on the natural habitats of the northwestern Virunga landscape in contexts of insecurity. It identifies an important element in the transformation of the landscape that requires particular monitoring by Virunga National Park managers during and after insecurity: despite the unfortunate human and social toll, armed groups' violent extremism since 2010 has improved the overall balance of forest cover in the northwestern Virunga landscape. Meanwhile, this study underlines the vulnerability of savannah areas to anthropogenic pressure due to the ease with which farmers and herders access this habitat (Nagendra et al., 2006; Ndavaro et al., 2021). The restoration of forest cover in degraded areas is only a temporary relationship, as post-conflict development can also threaten restored forests and exert negative pressure on biodiversity (Garcia Corrales et al., 2019). The post-conflict development phase in the Beni Territory is a critical period for protected habitats, due to the potential harm development can cause to conservation strategies (Butsic et al., 2015).

This study also affirmed that the regulatory barrier established by the Virunga National Park significantly protects natural forest land against fragmentation. However, effective protection against forest fragmentation does not necessarily indicate that all biodiversity is preserved (Butsic et al., 2015). The attrition of forest

cover in the Virunga National Park, attributed to illegal armed factions and increased militarization to combat the ADF terrorist group, demonstrates why forest cover should be understood as a partial indicator of conservation-management performance. While insecurity contributes to landscape change, political factors also contribute to habitat degradation, often leading to the deterioration of porous savannah areas. In Kasindi and Mwalika, intrusions into vast areas of land are often reported inside the park. As political instability, corruption, and weak law enforcement lead to environmental degradation (Muteya et al., 2023), conservation efforts need reinforcement in the vulnerable savannah zone, which is susceptible to agricultural encroachment

4.5. Partial Conclusion

This study focused on land-cover changes in the northwestern Virunga landscape via remote sensing data and spatial patterns. These changes were detected and quantified in an insecure context. The data revealed that agricultural activities dominate the landscape matrix, although they are diminishing over time due to several factors, including the highly insecure situation and restricted access to certain areas in Virunga National Park. Forests' transition to other land covers is strongly linked to local stability, which naturally affects economic activities that depend on forest resources. Therefore, on a landscape scale, forested areas shrink during peaceful periods and regenerate during wartime. Furthermore, this study found that forests are less fragmented in protected areas than in unprotected ones, suggesting that Virunga National Park plays a significant role in maintaining the stability of natural ecosystems. This emphasizes the importance of reinforcing conservation measures in this protected area. The intact forest in Virunga National Park plays a vital role in biodiversity conservation, supports local rain-fed agriculture, and maintains the hydrological regime of the Nile Basin. In addition, the highly vulnerable savannah area must be regularly and carefully monitored due to its susceptibility to human pressure.

Chapter 5

5. Anthropogenic Disturbances in Northwestern Virunga Forest Amid Armed Conflict

Reference

Musavandalo, C.M., Essouman, P.F.E., Ndjadi, S.S., Balandi, J.B., Nguba, T.B., Sodalo, C., Mweru, J-P.M., Sambieni, K.R., Bogaert, J., 2025. 5. Anthropogenic Disturbances in Northwestern Virunga Forest Amid Armed Conflict. *Land*, 14(4), 732. <https://doi.org/10.3390/land14040732>

Chapter positioning in the overall analysis

Building on Chapter 4's continuity, this chapter emphasizes the physical disturbance factors observed in forests within and around Virunga National Park. It also enhances the understanding of the land cover spatiotemporal dynamics previously discussed by pinpointing the direct causes.

Abstract

This study focuses on identifying and assessing the extent of anthropogenic disturbance factors directly affecting the forests of northwestern Virunga. It posits that the army camps within the forest are a hotspot for expanding human activities in the context of armed conflict. A multiscale approach was used to examine disturbances across multiple levels to capture their complex interaction and to avoid oversimplified interpretations. This approach included an analysis of the dynamics and spatial structure of the forest cover from 2016 to 2023, along with an inventory of the local disturbance factors. The study focused on seven study sites hosting army camps, namely Mikuha, Lahe, Pk26, and Ngite within Virunga National Park, as well as Mamundioma, PK2, and Kinziki in its periphery. The findings show that the installation of army camps did not lead to significant forest fragmentation. Except for Mamundioma, all the other sites showed an increase in forest areas, due to the aggregation of remaining forest patches during periods of insecurity. However, this trend toward passive forest restoration does not offset disturbances. It merely reflects a slowdown in the conversion of forest areas to other land cover. Nine anthropogenic factors contribute to forest disturbances, with cash crops (74.17%), food crops (72.50%), and trees cut down for energy (61.61%) being the most prominent. Other contributing factors include carbonization (31.67%), fire use (30.00%), sawn timber (26.67%), path creation (17.50%), exotic tree species introduction (10.00%), and the establishment of invasive species (11.67%). Spatial analysis provides a partial explanation for such forest disturbances. Its exhaustive description would require a mix of spatial data and field observations.

Keywords: Virunga National Park; Degradation; Land use; Insecurity; Disturbance inventory

5.1. Introduction

In the Democratic Republic of the Congo, deforestation and forest degradation are significant threats to the carbon balance, biodiversity, and management of protected areas. Forest cover changes have been extensively documented and continue to be studied using the tools and data provided by remote sensing and geographic information systems (Nagendra et al., 2009; Olofsson et al., 2013; Ouattara et al., 2021; Polo-Akpisso et al., 2020; Salomon et al., 2021; Sikuzani et al., 2020; Tyukavina et al., 2018). Many studies have concentrated on deforestation rather than forest ecosystem degradation itself. This is largely due to the simplicity of mapping and quantifying areas of canopy loss using satellite imagery. However, there is often a paucity of information regarding the contribution of other disturbance drivers, which are inherently challenging to represent spatially (Ahrends et al., 2010; Tyukavina et al., 2018).

Slash-and-burn agriculture has traditionally been documented as the main driver of forest cover change in both the DRC and Congo Basin (Curtis et al., 2018; Molinario et al., 2020). However, despite this evidence, other factors also contribute to forest cover change. These include artisanal and/or industrial mining, the search for fuelwood, and artisanal and/or industrial timber extraction (Hosonuma et al., 2012). These factors vary across regions and change over time, shaped by the specific socio-economic dynamics of each region (Rudel et al., 2009). For example, Curtis et al. (2018), noted that, unlike other tropical regions, deforestation in Africa is driven by cash crops and mining. This type of deforestation is often difficult to spatially separate from deforestation driven by shifting agriculture, which is characterized by small-scale clearing and anthropogenic fire. Similarly, Molinario et al. (2020) indicated that, in the Congolese forest ecosystem, resource extractions and land use with minimal spatial footprints are not directly detectable, even in high spatial resolution images. Thus, the relationship between forest disturbance fractions and specific anthropogenic or natural drivers remains poorly documented (Hosonuma et al., 2012). Identifying the inferred human pressures around protected areas, such as Virunga National Park, is important for understanding authorization. It is also important for the preservation of park resources (Grantham et al., 2020).

The northwestern Virunga landscape is distinguished by robust endogenous economic dynamism and a climate of insecurity characterized by significant unpredictability. This landscape is home to Virunga National Park, a World Heritage site with important ecological, economic, and climatic functions (Languy and De Wasseige, 2008). Its total economic value is estimated at over USD 48 million (WWF, 2013). The northwestern Virunga landscape requires scientific attention due to its potential as an

ecological corridor between the Ituri forest massif and Virunga National Park. For over two decades, this landscape has been subjected to anthropogenic pressures from many sources. Its population experiences an annual growth rate exceeding the national average. It remains predominantly reliant on the exploitation of natural forest ecosystems for sustenance and energy. This reliance extends to all activities contributing to local economic development (Vikanza, 2018).

Since 1997, the northwestern Virunga landscape has faced insecurity due to the presence of national and foreign armed groups, notably the Alliance of Democratic Forces (ADF). Since 2010, the security situation in the region has deteriorated further with the activism of the ADF terrorist group from Ugandan. The Global Forest Watch system warns of deforestation and the degradation of forests in and around Virunga National Park despite ongoing insecurity, as well as its impact on farming activities. In theory, these disturbances would be associated with the reinforcement of security arrangements, particularly establishing military camps in the forest zone. This would enable the local population to carry out their activities during the war period. The presence of military camps would first lead to localized deforestation, which would then spread because of the concentration of human activities within a radius considered secure by the army. However, the relationship between forest transitions and armed conflict is intricate and multifaceted (Ordway, 2015). A more comprehensive grasp of these elements, particularly in the context of the ongoing armed conflict, is vital for the formulation of post-conflict forest management strategies within this landscape (Molinario et al., 2020; Stevens et al., 2011).

The following four fundamental questions were formulated to understand the forest disturbances in northwestern Virunga: (1) In the context of the ongoing armed conflict, is the establishment of military camps within and around Virunga National Park contributing to the deforestation and subsequent disruption of forest ecosystems? (2) What key local anthropogenic factors drive forest disturbances? (3) How are local disturbance factors spatially distributed within Virunga National Park under protection and in its periphery, which is free of access? (4) How does access to different disturbed regions within and surrounding Virunga National Park affect the frequency of the disturbance factors?

The following four hypotheses were defined based on the four research questions: (1) In the current context of insecurity in northwestern Virunga, forest disintegration intensified after the creation of the security infrastructure compared with the period preceding its installation. This may be due to the possibility of intensification of agricultural and resource extraction activities by the local people, who benefit from the security provided by the presence of the security forces. (2) Given the economic

stakes and urbanization, cash crops, mainly cocoa, and the exploitation of firewood and timber are the main factors disturbing the natural forests in the northwestern Virunga landscape. (3) Given the diversity and dispersion of human activities across the landscape, human disturbance of natural forest ecosystems in this landscape is randomly distributed and has no discernible correlation with distance from access roads. (4) Access to specific disturbed areas in and around Virunga National Park affects both the frequency and nature of human disturbance. Thus, timber extraction is a greater source of disturbance than cash crops in Virunga National Park, due to resource availability and the monitoring of agricultural activities in the park.

This study proposes a global framework to better understand the relationship between forest cover changes and local root factors in northwestern Virunga. Firstly, it uses spatial data to assess the impact of security measures on forest dynamics, particularly in the Middle Semuliki forest region. Secondly, it aims to identify, categorize, and analyze the prevalence of human-induced factors contributing to forest disturbances, with an emphasis on the direct factors of deforestation and forest degradation as defined by DeFries et al. (2010).

5.2. Materials and Methods

5.2.1. Study Area and Data Collection Sites

The present study concentrated primarily on the Middle Semuliki forest region of the northwest Virunga landscape, as delineated by Languy et al. (2006). The Beni–Kasindi and Beni–Bunia roads circumscribe this forest region. The Middle Semuliki region was selected based on the vegetation gradient that characterizes the northern part of Virunga National Park in the Beni region. This gradient is reflected in the distribution of the forest cover, which is dominant in the extreme north (Figure 5-1). The study area is characterized by year-round rainfall, with slight decreases between January and March and between June and August. It receives between 1200 and 2000 mm of rainfall annually, with an estimated average of 1600 mm. The temperature ranges from 20 to 30 °C, with an average of 25 °C. The population of the region is estimated at over 2 million, concentrated in the urban centers of Beni and Butembo, as well as the rural communes of Oïcha, Kasindi, and Mangina (Bweya et al., 2019). Data collection sites were identified using a combination of methods, including reviewing the relevant literature, informal interviews with local stakeholders in Beni (farmers and authorities of sectors and territory), and deforestation alerts provided by the Global Forest Watch system (<https://www.globalforestwatch.org>, accessed on 2 March 2024). The literature review provided an overview of the anthropogenic factors affecting tropical forest ecosystems. The Global Forest Watch system was used to pre-identify potential study sites based on deforestation alerts. The interviews were

conducted to assess whether the areas targeted by the study would be easily accessible to the population amid insecurity, and to determine whether accessibility and related activities would be linked to the presence of security forces. They also provided an opportunity for a general discussion on the various activities carried out in the target areas, which would be subject to verification in the field. These interviews were also used to assess the region's security level. Security was identified in this study as a key indicator of the intensification of human activities in a forest area. As a result of these discussions, the seven pre-identified sites were validated (see Figure 5-1). These sites also house military camps within the forest.

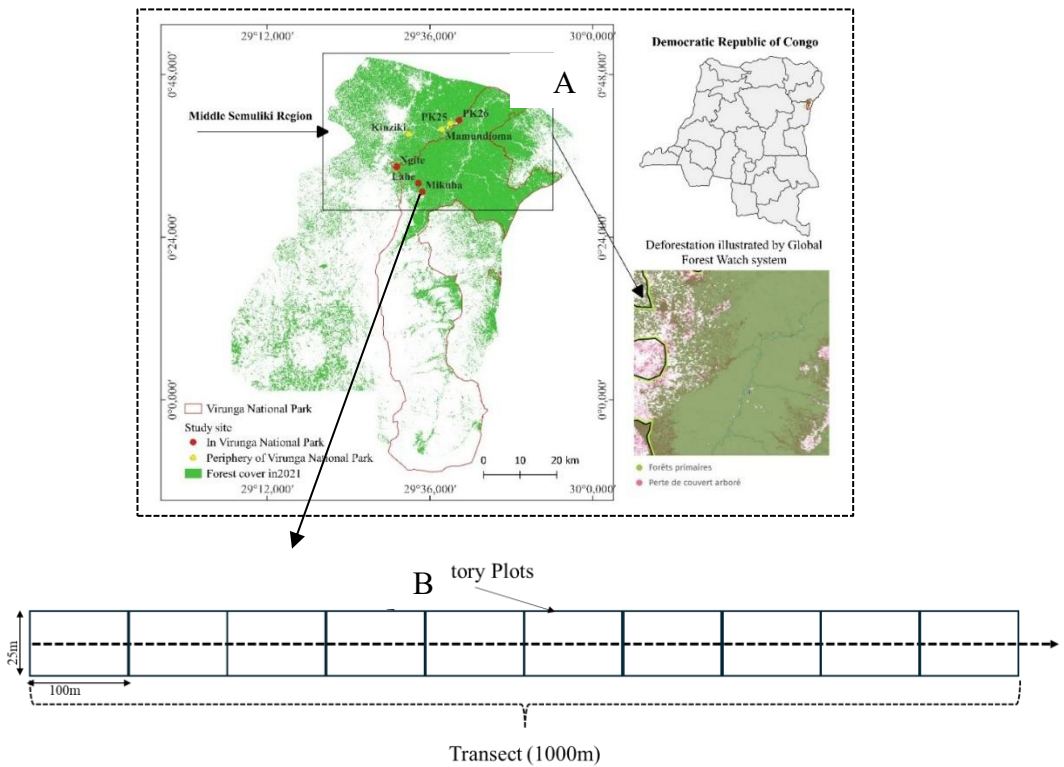


Figure 5-1. (A) Study sites in the Middle Semuliki region in the northwestern Virunga landscape: Kinziki (0.649292–29.548510°), Mamundioma (0.666242–29.630453°), PK25 (0.679734–29.650058°) in Virunga National Park; Mikuha (0.511841–29.581330°), Lahe (0.532963–29.572107°), PK26 (0.688012–29.672113°), Ngite (0.573233–29.518436°) in periphery of Virunga National Park; **(B)** illustration of the sample plots for the inventory of disturbance factors on a transect adapted from Barima et al. (2016)

5.2.2. Method

This study used a multiscale approach drawing on the following two key global observations: the dynamics of the northwestern landscape described by (Guittet and Le Dû-Blayo, 2013; Musavandalo et al., 2024) and the deforestation warnings often provided by the Global Forest Watch system. It examined the fragmentation of forest landscapes due to army installations and the local factors contributing to the observed disturbances (Guittet and Le Dû-Blayo, 2013). A diachronic analysis was used to map and quantify changes in forest cover and assess forest configuration and spatial transformation processes. Furthermore, the study employed a transect approach (Rakotondrasoa Olivia L et al., 2013), to identify local disturbance factors impacting the forest landscape, including those less detectable through spatial imagery. The analysis of forest dynamics focused on seven sites, while the analysis of disturbance factors was conducted across six sites. This difference is attributed to the insecurity of one PK26 during data collection on disturbance factors.

5.2.2.1. Forest Cover Fragmentation Analysis Around the Study Sites

Landscape fragmentation was analyzed in Lahe, Mikuha, Mamundioma, PK25, PK26, Ngite, and Kinziki (Figure 5-1) from 2016 to 2023 to test the first hypothesis. This observation period was chosen because of the significant deployment of the Democratic Republic of the Congo Armed Forces (FARDC) in the region to combat the Alliance of Democratic Forces (ADF) terrorist group. Additionally, the availability of high-resolution geospatial imagery was another criterion for selecting this period. Informal discussions with the residents revealed that several security force installations had been established in the remote forest region between 2015 and 2021. For this analysis, only the main camps established between 2018 and 2019, located in and around the northern forest massif of Virunga National Park, were considered. Landscape fragmentation was carried out over the following three periods: before the establishment of the camps (with 2016 as the reference period), during the approximate period of camp establishment (with 2019 as the reference period), and after camp establishment in 2023. A circular area, with a radius of one kilometer corresponding to 314 hectares, was defined around each study site by adapting the approach previously used by Bernard et al. (2022); Hagenlocher et al. (2012); Salemi (2021). This radius was determined based on two reasons. Firstly, discussions with local people indicated that this distance would be optimal for carrying out agricultural work or safely extracting forest resources. Secondly, the Euclidean distance between the army camps ranged from 2 to 3 km (Helman et al., 2018; Pickering et al., 2021).

Processing spatial reference data

All the images used in this study were obtained from the Planet collection. Planet is a commercial company that operates a constellation of more than 175 standardized nanosatellites, collectively known as PlanetScope. The satellites provide daily high-spatial-resolution (3 m) images in four spectral bands, including three in the visible (red, green, and blue) and one in the near-infrared (NIR) (Helman et al., 2018; Pickering et al., 2021). Planet images detect small changes more effectively than Landsat images with 30 m spatial resolution, which are often used to analyze deforestation (Pickering et al., 2021). Due to their high resolution, Planet images were used in our study. Spatial processing was performed using the Google Earth Engine. For each period of investigation, a false-color composite image was created using the median pixel values of all images available throughout the year of observation and supervised classification (Gorelick et al., 2017). A supervised classification was then used to map land cover at each site, distinguishing between the forest and non-forest categories. The “forest” category included mature and secondary forests in this classification. In contrast, the “non-forest” category included fields with food crops and areas lacking tree cover. The Random Forest algorithm was used because of its high classification accuracy. A total of 300 training points were used. Of these, 220 points were used to train the classification model, with 120 points for the forest class and 100 points for the non-forest class. These training points were collected in the field and by visually analyzing Planet images using our knowledge of the land.

Classification accuracy

A random sample of 80 points, 40 per land-use class, was selected from a set of 300 control points collected in the field. This sample was used as a reference to assess the accuracy of the land cover maps produced for each site. The accuracy of the land cover maps was determined by conventional indices, including overall accuracy, user accuracy, and producer accuracy. The indices were calculated using Equations (1) and (2) from Olofsson et al. (2014). Table 5-1 and Table A-2 present the overall classification accuracy for each site.

Table 5-1. Accuracy of land cover based on supervised classification (refer to Table A-2 in the Appendix for details pertaining to user and producer accuracy)

Overall Accuracy							
Year	Kinziki	Lahe	Mamundioma	Mikuha	Nite	PK25	PK26
2016	0.85	0.93	0.95	0.81	0.89	0.99	0.88
2019	0.84	0.80	0.98	0.85	0.93	0.96	0.94
2023	0.88	0.91	0.98	0.90	0.88	0.94	0.90

Structural analysis of the forest landscape on disturbed sites

The spatial data analysis primarily focused on assessing changes in the composition and configuration of the forest class using several spatial structure indices. The selection of these indices was based on the principles of providing a coherent representation of landscape characteristics over time and the minimization of information redundancy (Šímová and Gdulová, 2012). In this regard, McGarigal et al. (2002) proposed a classification of indices for the study of landscape structure, including the following categories: (1) area/density/edge metrics; (2) shape metrics; (3) core area metrics; (4) isolation and proximity metrics; (5) diversity metrics; and (6) interception metrics. This study used three indices derived from the “area/density/edge” classification primarily because of their enhanced ability to represent landscape structure in composition and configuration (Table 5-2). Additionally, three indices derived from the “area/density/edge” classification area, number of patches, and perimeter—were used to examine the landscape transformation processes.

Table 5-2. Landscape parameters, description, unit of measurement, and landscape pattern facet.

Equation	Description	Unit	Landscape Pattern Facet
$PLAND = \frac{\sum_i^n ai}{A}$	The proportion of landscape occupied by each class. Measure the dominance. A = total area of landscape	Percent	Composition
$Largest\ Patch\ Index(LPI) = \frac{MAX(aij)}{A}$	The ratio of the area of the largest patch of forest to the total area of the landscape	–	Configuration
$Mean\ Patch\ Size = \frac{\sum ai}{n}$	The average forest patches into the landscape. n = total number of forest patches, ai = area of the individual patches.	–	Configuration

The spatial transformation process of the forest cover was determined by applying the decision tree method of Bogaert et al (2004), based on the analysis of the variation in surface area, perimeter, and number of patches within a given class between two observation periods. This decision tree defines the following ten spatial transformation processes: aggregation, attrition, creation, deformation, dissection, enlargement, fragmentation, perforation, displacement, and shrinkage. The ratio of the total area of the forest class in different periods was obtained from Equation (1) (tabs)

in Bogaert et al. (2004). This ratio was used to distinguish fragmentation from other spatial transformation processes. A theoretical threshold of 0.75 was applied to facilitate this distinction. A ratio above 0.75 indicated fragmentation, whereas a ratio below this threshold indicated dissection.

5.2.2.2. Identification and Inventory of Disturbance Factors in Natural Forest Ecosystems

A list of potential disturbance factors for forest ecosystems within and around protected areas was developed in several stages. The initial compilation of the list was based on the existing literature (Barima et al., 2016; Heink and Kowarik, 2010; Sadaoui et al., 2016). Particular attention was paid to categorizing the factors related to deforestation and forest degradation provided by Hosonuma et al. (2012). To complete the list, direct field observations and interviews with local stakeholders were conducted during the field exploration mission in September 2022. Thus, 12 potential disturbance factors and their characteristic indicators in the field were defined (Table 5-3).

Table 5-3. Factors and indicators of disturbance.

Disturbance Factors	On-Site Indicators
Cut trees	A stump and/or trunk of a felled tree is present, with evidence of previous use for firewood or construction material rather than timber.
Food crops	Crops such as rice, beans, maize, and ground nuts or other crops for direct consumption by the local population are present.
Cash crops	Cash crops, in particular cocoa, coffee, palm, and papaya, have been introduced into the landscape, and their produce is intended for export or for local industry to make a profit.
Burn area	A tree trunk with evidence of fire or ash, showing that a fire has spread locally or widely, is present.
Carbonization	A charcoal kiln is present, either actively producing charcoal or already in use with charcoal residues.
Sawn timber	The presence of a tree being sawn or sawdust indicates the production of boards and rafters, which is synonymous with artisanal timber harvesting.
Path	There is access for local people through the forest.
Isolated bush dwelling	There is an isolated building in the forest.
Artisanal mining	Artisanal mining quarries are present, either abandoned or in the process of being exploited.
Invasive species	<i>Chromolaena odorata</i> is present.
Exotic tree	An exotic tree species (<i>Eucalyptus</i> sp., <i>Grevillea robusta</i> , etc.) is present, which was introduced into the natural ecosystem by the local people.
Livestock	A grazing area and livestock facilities are present.

An inventory of disturbance factors was carried out at Mikuha, Lahe, Kinziki, Pk25, Mamundioma, and Ngite. It was carried out by adapting the transect method initially used by Rakotondrasoa Olivia L et al. (2013) in the Tapia forest of Madagascar and subsequently used by Kabanyegeye et al. (2023) and Sadaïou et al. (2016) in Côte d'Ivoire and Burundi, respectively. In each site, two transects were established, each 1000 m in length and 25 m in width (see Figure 5-1). The transect was oriented perpendicularly to the access road and was subdivided into ten contiguous 100 m plots, i.e., 0.25 hectare per plot. In total, 12 transects were established, covering 30 hectares. Human disturbances were observed, categorized, and recorded in each plot. The data were recorded as binary data, where 1 represented the presence of a particular form of disturbance and 0 its absence (Kabanyegeye et al., 2023; Sadaïou et al., 2016). The data collected allowed us to test the second, third, and fourth hypotheses. Only factors recorded in the field based on indicators were analyzed. Factors with zero frequency of occurrence were excluded in the analysis, as they would not provide any relevant information on the perturbations observed.

The second hypothesis was therefore evaluated by analyzing the relative frequencies of occurrence of the disturbance factors to highlight each factor's prevalence. The Friedman test was used to determine whether there were differences in the frequencies of occurrence of the observed disturbance factors. Friedman's post hoc test was used to compare the different factors in pairs and assess their statistical similarity. Finally, the χ^2 test for independence of variables (Rakotondrasoa Olivia L et al., 2013) was used to examine the interaction between the disturbance factors.

In addition, the generalized linear model with Bernoulli distribution was used to test the third hypothesis, i.e., to determine the probability of the occurrence of a disturbance as a function of the distance from the access roads, using the following equation: $Y = 1/(1 + e^{-(b_0 + b_1X)})$, where Y is the probability of the occurrence of a disturbance on a plot at distance X, b_0 is the intercept, and b_1 is the coefficient associated with the distance variable. The fourth hypothesis was assessed through a two-step approach. First, a chi-squared test of independence was performed to assess associations between disturbed sites and disturbance factors. Secondly, a factorial correspondence analysis (FCA) was used to analyze the relationships between the disturbance factors and the sites. In our case, the FAC emphasized the proximity or distance between the various modalities of two variables, the type of disturbance, and the sites. A factorial map was generated to facilitate the interpretation of the results.

5.3. Results

5.3.1. Forest Cover Change and Spatial Transformation Processes

Figures 5-2 and 5-3 illustrate the spatial and temporal changes in the forest and non-forest areas across the seven study sites in Virunga National Park and its periphery. Over the eight years of observation, a general trend of increasing forest cover was observed in six of the sites, with a notable disparity between them (p -value < 0.05).

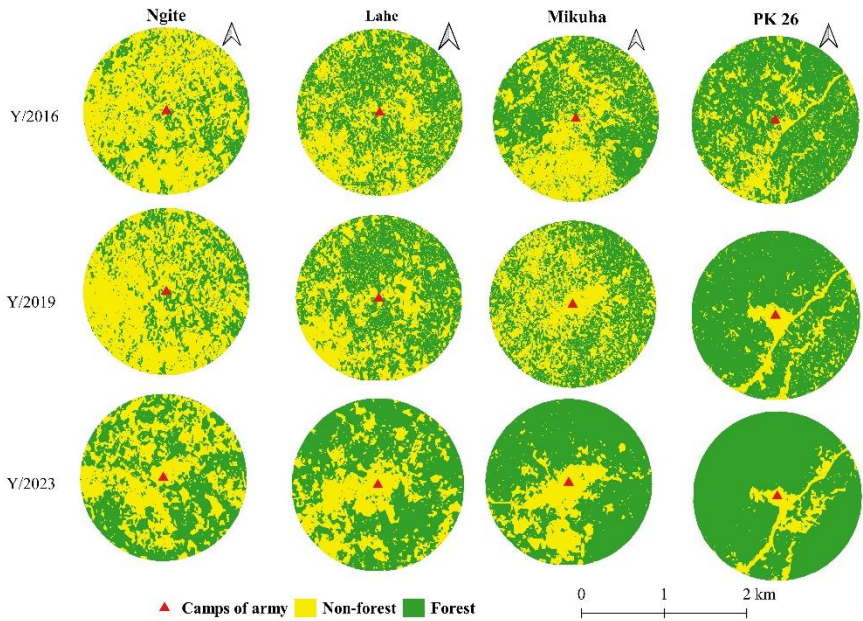


Figure 5-2.Land cover around security force camps in Virunga National Park (Y = year).

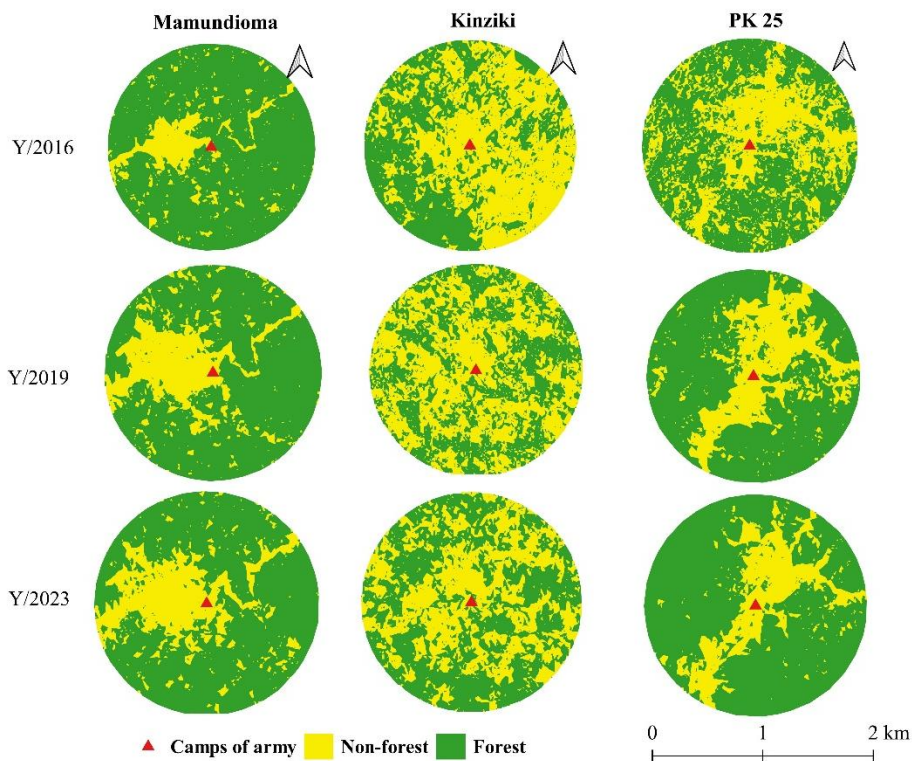


Figure 5-3. Land cover around security force camps on outskirts of Virunga National Park (Y = year).

The forest area trend reveals a significant shift prior to the establishment of the armed camps. Except for Mamundioma, all the other sites show an increasing trend in forest cover. This suggests that fewer forests have been converted into farmland since the beginning of the security crisis in Beni (see Figure 5-4 and Table A-5). However, Ngite has a lower forest cover rate than the other sites.

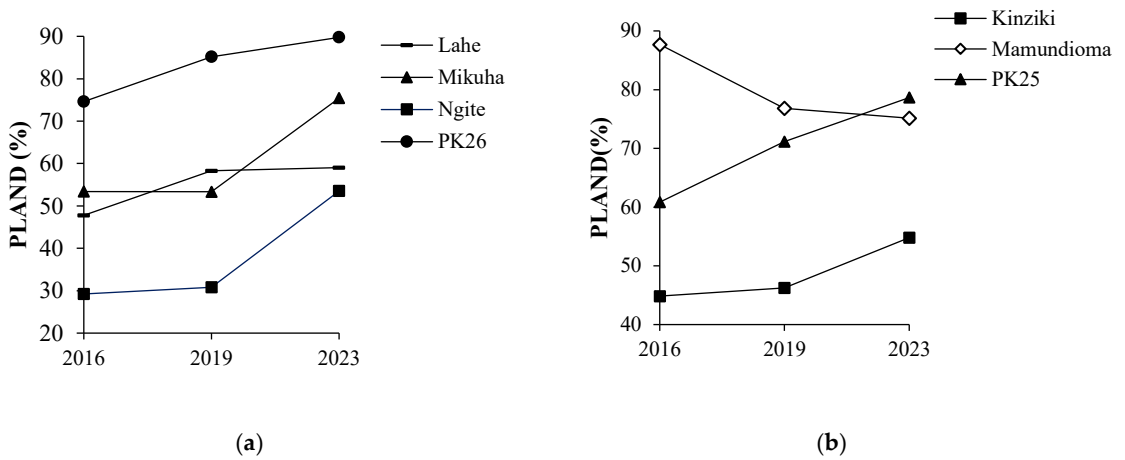


Figure 5-4. Forest cover: (a) represents the sites located in the park, and (b) represents the sites situated on the periphery of the park. Each site has an area of 314 hectares. The year 2016 represents the situation before the camp's establishment, while 2020 corresponds to the camp's operational period. The situation in 2023 illustrates the situation after the camp's establishment.

Figures 5-5 and 5-6 visually represent the landscape structure observed at each study site. The largest patch index (LPI) increased at all the disturbed sites within Virunga National Park, as well as Kinziki and PK25 in the park's periphery. However, the LPI decreased in Mamundioma. A similar trend was observed for the mean patch size index, which increased at all sites in the park, as well as in Kinziki and PK25 situated in the park's periphery.

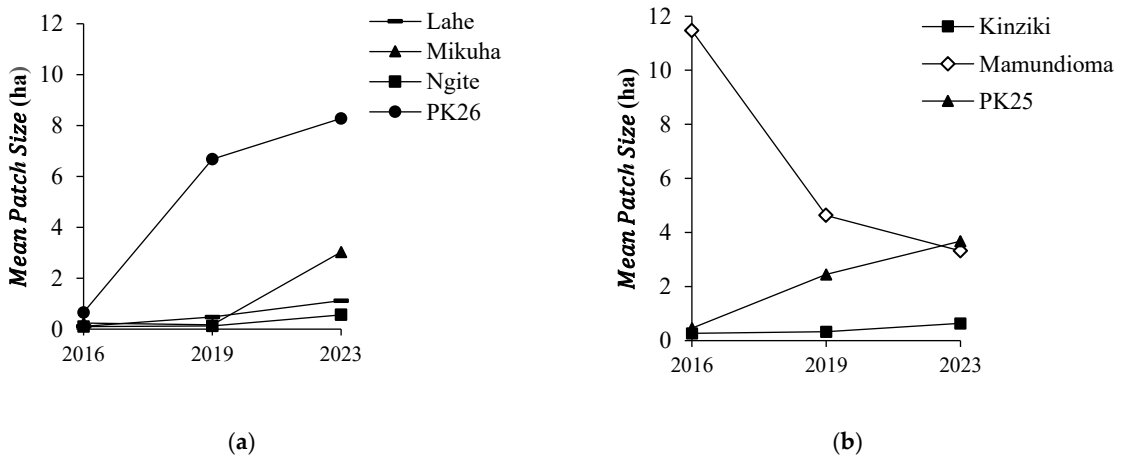


Figure 5-5. Trend of the Mean Patch Size from 2016 to 2023: (a) the disturbed sites in the park and (b) the disturbed sites on the park's periphery. Each site has a surface area of 314 hectares.

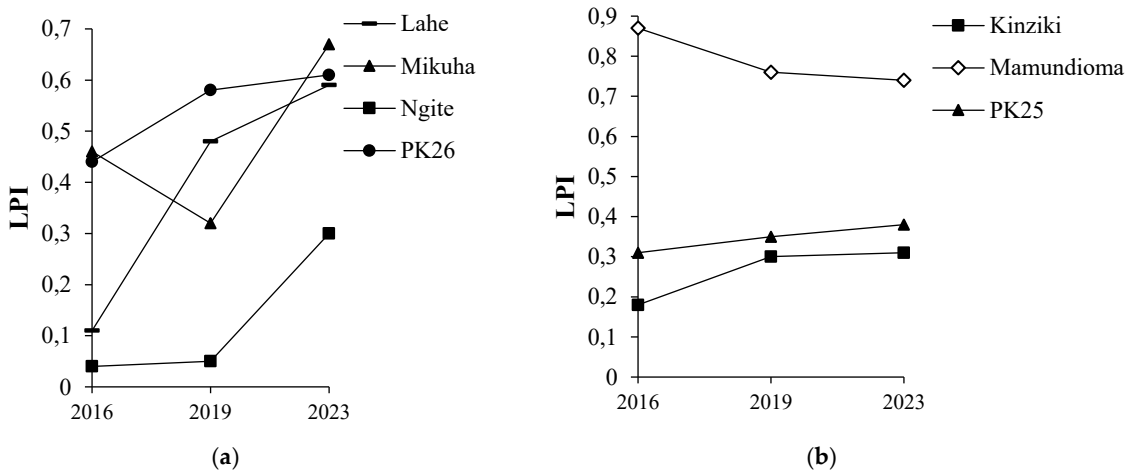


Figure 5-6. Trend of the Largest Patch Index (LPI) from 2016 to 2023: (a) the disturbed sites in the park and (b) the disturbed sites in the park's periphery. Each site has a surface area of 314 hectares. Each site has a surface area of 314 hectares.

From 2016 to 2019, the decrease in forest cover observed in Mamundioma was due to a spatial process known as attrition, which refers to a reduction in the size and number of forest patches. The forest cover in Mamundima continued to decrease due to attrition from 2019 to 2023. In contrast, the forest cover increases in Lahe, Ngite, PK25, Kinziki, Mikuha, and PK26 was mainly due to patch aggregation (Table 5-4). The aggregation of forest patches was more dominant after the installation of army camps. This trend can be attributed to the security measures taken to limit the expansion of farming activities into the newly accessible forest areas.

Table 5-4. Spatial transformation processes of forest class

	Kinziki	Lahe	Mamundioma	Mikuha	Ngite	PK25	PK26
STP ₂₀₁₆₋₂₀₁₉	Di	Ag	At	Di	Ag	Ag	Ag
STP ₂₀₁₉₋₂₀₂₁	Ag	Ag	Dis	Ag	Ag	Ag	Ag

5.3.2. Forest Landscape Disturbance Factors

Nine disturbance factors were identified in the Middle Semuliki region of northwestern Virunga. These included food crops, cash crops, cut trees, carbonization (charcoal production), burn area, sawn timber (artisanal timber harvesting), paths, exotic tree introduction, and invasive species establishment. Food crops, cash crops, and cut trees occur at a frequency of over 50%. Carbonization, burn area, sawn timber, and paths exhibited intermediate occurrence frequencies ranging from 20% to 50%. Finally, exotic trees and the establishment of invasive species exhibited occurrence

frequencies below 20%. However, artisanal mining and livestock farming, which are likely to cause significant alterations to large natural areas, were not observed within the study area (Table 5-5).

Table 5-5. Frequency of occurrence of each disturbance factor (N = 120 plots)

Factors of Disturbance	Frequency of Occurrence (%)
Cash crops	74.17
Food crops	72.50
Cut trees	61.61
Carbonization	31.67
Burn areas	30.00
Sawn timber	26.67
Path	17.50
Invasive species	11.67
Exotic tree	10.00

Moreover, the results of the Friedman test ($\chi^2 = 303.35$ with a p -value $< 2.2 \times 10^{-16}$) indicated a significant difference in the frequency of occurrence between the disturbance factors. The post hoc test, which was used to conduct pairwise comparisons of the frequencies of the various types of disturbances, indicated no significant differences in the rates of occurrence among cut trees, food crops, and cash crops (p -value > 0.05). Similarly, carbonization, burn area, sawn timber, and path frequencies were similar (p -value > 0.05) while remaining distinct from those of the invasive species and exotic trees (Table A-2). The Friedman post hoc test thus demonstrated the existence of three different groups of disturbance factors characterized by their respective frequencies of occurrence.

5.3.3. Association Between Disturbance Factors

Table 5-6 presents the results of the Chi-squared (χ^2) test of independence between the distribution of different types of disturbances, as proposed in our second hypothesis. This hypothesis is based on the sub-hypothesis that disturbances are not caused by isolated factors, which reflect the intensity of anthropogenic pressure per unit of forest area. The results show a statistically significant association between cut trees and other variables, notably the cultivation of cash and food crops, the use of fire, and artisanal timber harvesting. The association between artisanal wood harvesting and charcoal production also remained statistically significant. This can be explained by the fact that low-value trees, which are felled during artisanal harvesting, are directly used for charcoal production.

Furthermore, a statistically significant association was found between food and cash crops. This suggests that the plots disturbed by food crop production were also widely used for cash crop production during the survey. Moreover, artisanal timber harvesting, cash crops, and areas disturbed by burning were also associated. The results showed that fire occurrence was significantly associated with other forms of disturbances, except for exotic species, invasive species, and paths. The presence of exotic species, invasive species and paths was not found to be directly correlated with other forms of disturbances. This suggests that these disturbances occur as isolated events.

Table 5-6. Association between factors of disturbance in the northwestern Virunga region (values in the table represent the results of chi-squared tests for disturbance independence)

	Cash Crops	Food Crops	Carbonization	Path	Burn Areas	Sawn Timber	Invasive Species	Exotic Tree
Cut trees	5.33 *	24.28 **	8.13 *	3.07 Ns	17.80 *	17.19 *	1.19 Ns	1.96 ns
Cash crops	-	5.50 *	1.44 Ns	0.44 Ns	21.54 **	38.94 **	1.23 Ns	1.28 ns
Food crops	-	-	3.01 Ns	1.49 Ns	5.08 *	2.32 Ns	1.18 Ns	0.58 ns
Carbonization	-	-	-	1.05 Ns	26.84 **	10.68 **	2.71 Ns	3.69 ns
Path	-	-	-	-	1.10 Ns	1.22	2.90 Ns	1.96 ns
Burn area	-	-	-	-	-	28.73 **	1.96 Ns	1.18 ns
Sawn timber	-	-	-	-	-	-	0.10 Ns	2.73 ns
Invasive species	-	-	-	-	-	-	-	1.20 ns

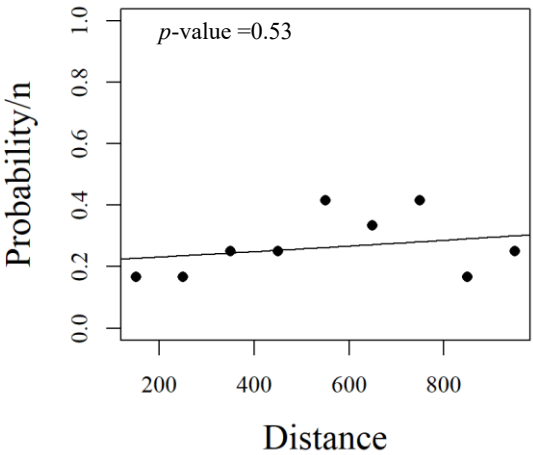
Legend: * = significant p -value < 0.05; ** = significant p -value < 0.001, ns = non-significant p -value > 0.05.

5.3.4. Probability of Occurrence of Disturbance Factors in Relation to Distance from an Access Road

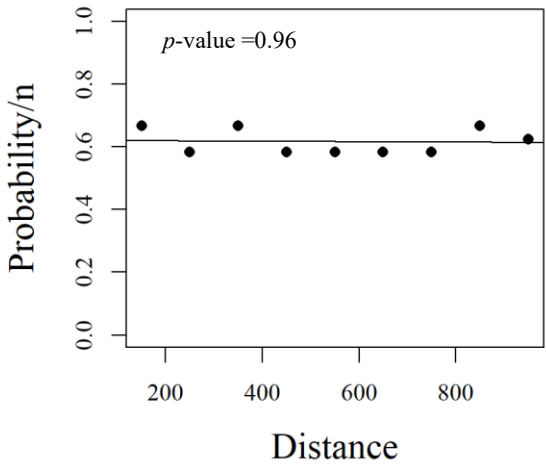
Figure 5-7 and Table A-4 in the appendix refer to the third hypothesis of the study, which predicts the probability of a disturbance factor occurring as a function of distance from the forest access road (forest track). The figure shows that the probability of a plot being affected by the expansion of invasive species, especially *Chromolaena odorata* (L.) R.M. King & H. Rob decrease significantly with distance from the forest access road (p -value = 0.03). The same trend is observed for food crops (p -value = 0.01). This pattern can be explained by the security situation in Beni, where farmers feel safer developing their agricultural activities closer to the access roads than deeper within the forest zone. This explains the more significant development of food crops near the access roads, which require human presence. No statistically significant effect of the distance gradient from the forest access road was observed on the probability of a plot being affected by the cutting of trees for wood energy (p -value = 0.96), cash crops (p -value = 0.46), fire use (p -value = 0.32), or the production of charcoal (p -value = 0.38), although a slight decrease in these three disturbance

factors was observed as the distance from the forest access road increased. However, the distance from the forest access road did not significantly affect the probability.

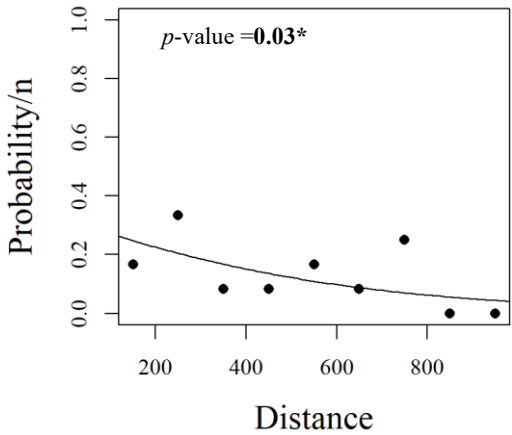
Sawn timber vs. distance



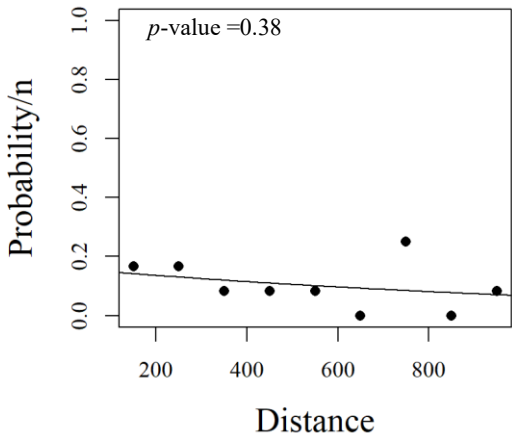
Cut trees vs. distance



Invasive species vs. distance



Exotic trees vs. distance



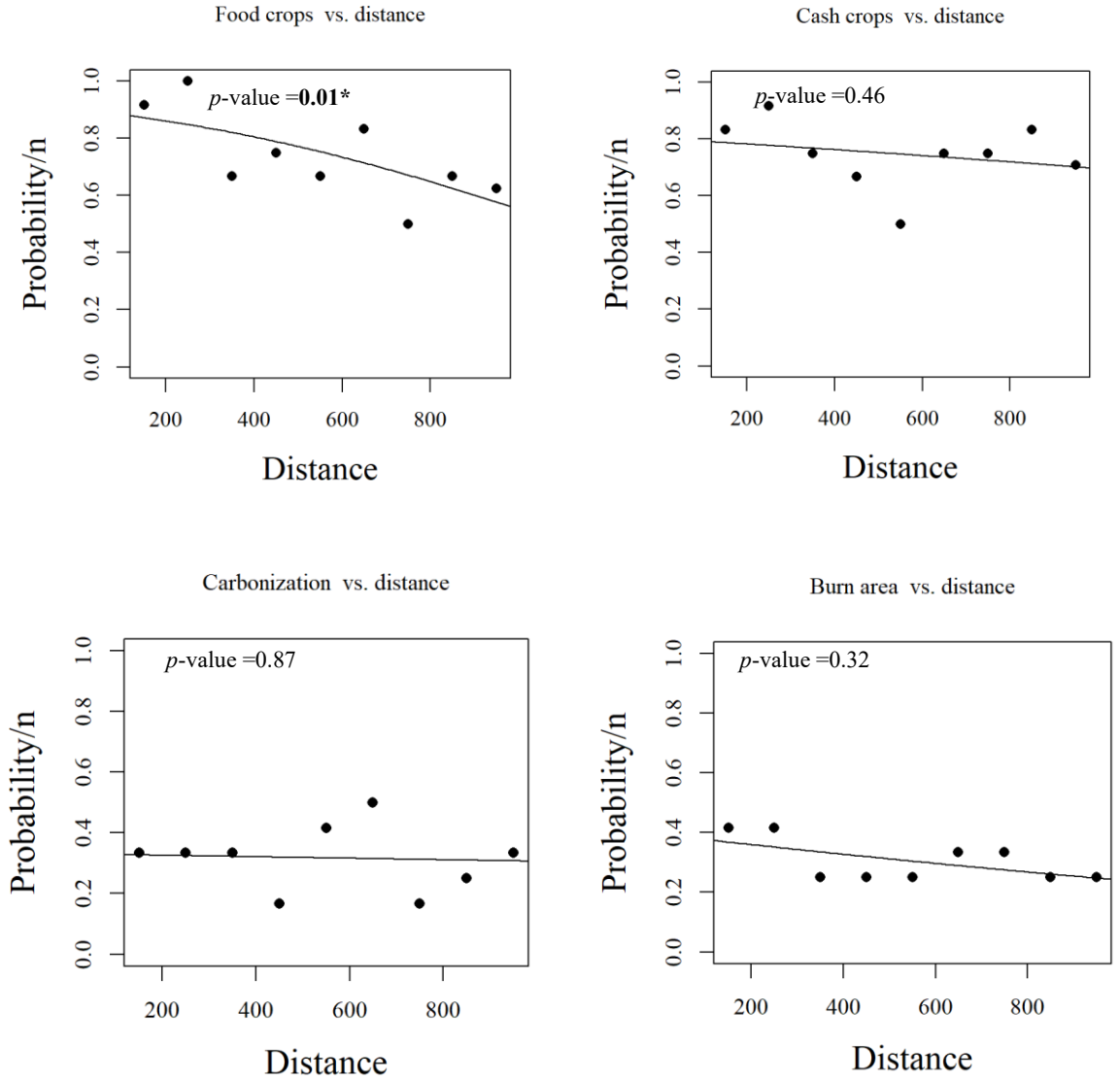


Figure 5-7. Evolution of the probability of occurrence of disturbance factors as a function of distance from forest access road. The X-axis represents the distance in meters, and the Y-axis represents the probability of occurrence, distance in m (* = significant p -value < 0.05)

5.3.5. Association Between Disturbance Factors and Degraded Sites

Figure 5-8 provides an overview of the disturbance factors most significantly associated with each disturbed site. Dimension 1 accounts for 69.37% of the total variability, with cash crops, food crops, the expansion of invasive species, and the introduction of exotic trees on the left, followed by artisanal wood harvesting, fire use, charcoal production, cut trees, and the path on the right. The central position of food crops indicates that this disturbance shows minimal variation across the sites. In contrast, charcoal production, fire use, and artisanal wood harvesting are associated with the Mikuha site in Virunga National Park. The cut trees are associated with the Lahe site, which is also located in the park. This disturbance is also found in PK25, at the park gateway on the Mbau–Kamango road. The expansion of cash crops is a distinctive feature of the Mamundioma and Kinziki sites. The introduction of exotic trees is most closely associated with Ngite in the park.

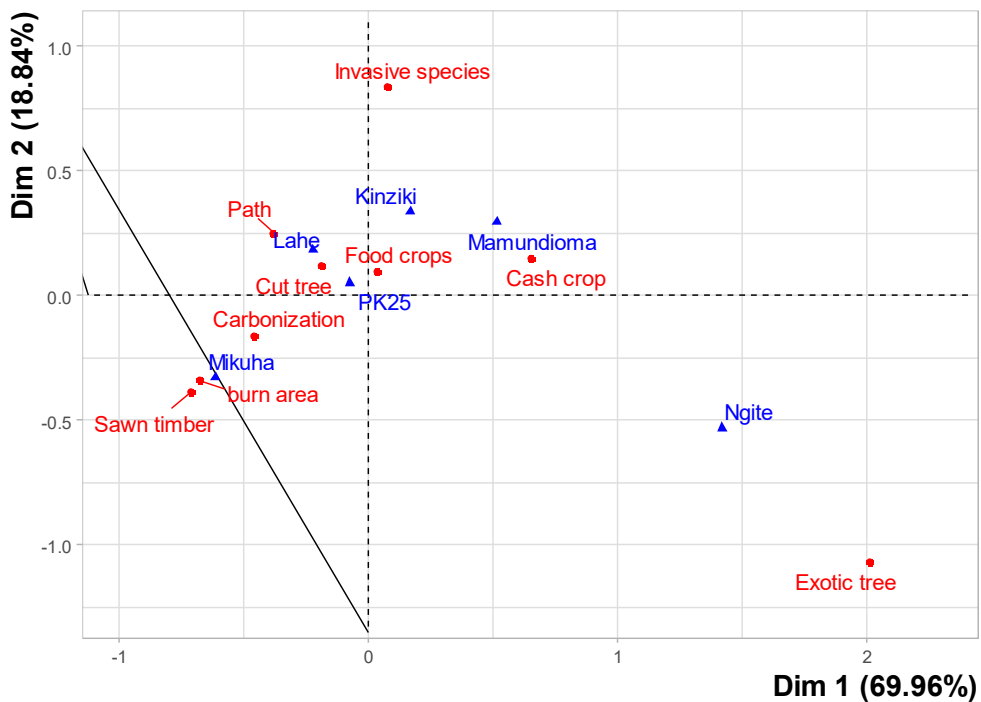


Figure 5-8. Associations between the disturbed sites and the distinctive disturbance factors. Red represents the local disturbance factors, while blue corresponds to the sites. This figure also illustrates the expected result of hypothesis 4 of this study. Dimensions 1 and 2 explain the variability of the data and the oppositions between the variables. The variables nearest to each other on the graph have similar profiles and are therefore significantly associated.

5.4. Discussion

5.4.1. Effects of Security Measures on Forest Disintegration of the Middle Semuliki Region

The impact of war on ecosystems is not limited to events directly linked to the armed conflict. It can be related to the defense infrastructure and the fluidity of the exchanges it involves. The base's size and the operations' nature can give rise to a series of anthropogenic impacts. The establishment of a military base typically requires the clearance of tree vegetation, thereby altering the natural landscape (Dunlap and Brock, 2022; Lawrence et al., 2015). Mishra et al. (2006), in their study of Arunachal Pradesh, identified military bases as the primary source of disturbance in ecologically sensitive regions with high biodiversity. Contrary to these findings, the most significant forest disturbance in the Middle Semuliki region occurred before the establishment of defense infrastructures. This is reflected in the gradual increase in the forest cover observed around these sites. One explanation of this trend of increasing forest area is that the access and activities in the northwestern forest region of the Virunga landscape are restricted and/or regulated by the army for security reasons (Lawrence et al., 2015). Another explanation is that agricultural and resource extraction activities ceased in sites located in remote distances from villages or towns, motivated by the fear of the risk of violence from armed groups on the way (Stevens et al., 2011). The first hypothesis, which posited that forest disintegration would be more significant after installing security devices than before, is only corroborated by the findings at Mamundioma. The aggregation of forest patches in the other sites results from natural regeneration and ecological succession, limiting the dispersal of forest patches.

Moreover, the increase in forest cover within the various study sites does not necessarily indicate the absence of disturbances in northwestern Virunga. Forest regeneration indicates a slowdown in extensive land conversion areas observed since 2010, following the activities of the armed terrorist group ADF (Musavandalo et al., 2024). Exploration beneath the canopy reveals indications of prior human activity. This finding is also consistent with the conclusions of Zalles et al. (2024), which indicate that shifting cultivation often results in temporary tree loss if the environmental and socio-economic conditions allow for forest regeneration. In our case, forest regeneration leads to a natural succession of vegetation, which remains highly vulnerable to the resumption of post-conflict human activity. Remote sensing offers a partial view of forest disturbances. However, combining transect surveys with remote sensing provides a more comprehensive understanding of the nature and persistence of disturbances, including those that may be less visible spatially.

5.4.2. Hierarchy and Association of Disturbance Factors

This study identifies three categories of disturbance factors, classified based on their frequency of occurrence and highlights their interactions. The first category includes agricultural-related factors, such as cash crops, food crops, and cut trees. The second category encompasses the use of fire, sawn timber, and charcoal production. The third category, which occurs less frequently, comprises forest paths, the expansion of invasive species, and the introduction of exotic trees into a natural ecosystem. Artisanal mining and large-scale livestock farming were not observed in the study area.

The prevalence of agricultural disturbance factors in the forest of northwestern Virunga, particularly in the Middle Semuliki region, can be attributed to two main factors. Firstly, subsistence farming is a prominent feature of the region's socio-economic landscape in the Congo Basin (Tchatchou et al., 2015). Secondly, the attraction of the local population to cash crops further intensifies this preponderance. Cash crops are seen as a crucial economic resource in Beni region. Overall, agriculture remains the most important economic activity in the Democratic Republic of the Congo, accounting for 69% of the population in 2022 (Aquilas et al., 2022). Therefore, agriculture is the main factor driving the disruption of natural landscapes in tropical regions, although its geographical distribution varies depending on whether it is commercial or subsistence farming (Hosonuma et al., 2012; Zvobgo and Tsoka, 2021). The preponderance of cash crops reinforces the assertion made by Hosonuma et al. (2012) that commercial agriculture is further transforming the forest landscape in the east of the Democratic Republic of the Congo. The findings of the public opinion analyses conducted by Bweya et al. (2019) also indicate that shifting cultivation on unburnt slash, reinforced by cocoa, coffee, and oil palm, significantly contributes to deforestation in the western region of Beni. While these agricultural practices have substantial economic benefits, they also have considerable ecological impacts. Our findings, based on inventory and observation techniques, corroborate these conclusions. The economic value of cash crops, which began to rise significantly in the 1970s, explains their cultivation in forested areas. Since 2000, the Beni region has attracted several companies involved in the promotion of cash crops, including Esco Kivu, which is involved in the exportation of cocoa and vanilla; Virunga Coffee, which is engaged in the transformation of coffee; and the Enzyme Refiners Association (ENRA), which is involved in the production of papaya. These crops, primarily intended for markets in both developed and developing countries, show that the disruption of forest ecosystems is closely associated with increased agricultural exports (Rautner et al., 2013). The adoption of cash crops, which require a less

permanent farmer presence, represents a strategy developed by local populations to adapt agriculture to the ongoing security crisis. These findings align with those of (Jassogne et al., 2014), who noted that cocoa cultivation is emerging as a new driver of deforestation in the eastern Democratic Republic of the Congo. Other researchers in sub-Saharan Africa have reported similar findings. For example, Ouattara et al. (2021) also emphasized the impact of cash crops on the forests of southeastern Côte d'Ivoire. Furthermore, studies by Annie et al. (2016) and Barima et al. (2016) have shown that the prevalence of cash crops, including cocoa, significantly contributes to the degradation of the Haut Sassandra forest reserve in Côte d'Ivoire. Our findings highlight the central role of cash crops alongside food crops in driving the degradation of the natural landscape of the Beni region.

Furthermore, the association between cash crops and food crops reflects the local population's decision to intensify food and commercial production on a per-unit-of-land basis. It emphasizes the need for sustainable agricultural practices to reduce the pressure on forests. As posited by Tyukavina et al. (2018) the expansion of the agri-food industry in the northwestern Virunga landscape could pose new challenges in the post-conflict management of intact forests.

In addition, unlike Bweya et al. (2019), this study shows that tree extraction, mainly for fuelwood and timber, is also one of the main drivers of natural landscape disturbance. The disparity between these results, provided by field observations, and those of Bweya et al. (2019), as suggested by surveys, people's perceptions may not always align with certain realities on the ground. This divergence highlights the importance of combining multiple approaches to better identify the causes of forest ecosystem disturbances in the Beni region. Kouassi et al. (2021) made the same observation about the differences between the stakeholders' perceptions of deforestation and the results of field inventories in southeastern Côte d'Ivoire. Timber harvesting is not limited to the northwestern Virunga landscape. It has been documented in other parts of the Democratic Republic of the Congo. In the Isangi region, Katembera Ciza et al. (2015) noted that the decrease in forest cover was also due to the cutting of trees for firewood and construction use but could nevertheless be compensated for by natural regeneration.

Although fire occurred in less than 50% of cases, it remains a significant factor in the disturbance of forests in northwestern Virunga. As Shapiro et al. (2021) noted, anthropogenic fires, often associated with agricultural expansion, are a primary cause of forest disturbances in the Democratic Republic of the Congo. This is consistent with the present results, which show that burned areas are not isolated but are associated with various other disturbance factors. Rakotondrasoa Olivia L et al. (2013)

made similar observations in the Tapia Forest in Madagascar. Repeated burning in a tropical biome can weaken ecosystem resilience and lead to biodiversity loss. However, the frequency of burned areas is approximately half that of cultivated plots, suggesting that no-burn agricultural practices remain dominant in the region (Bweya et al., 2019). In addition, fire is often localized rather than applied to whole plots to support specific, targeted agricultural intervention.

The expansion of exotic tree species into the natural environment was one of the disturbances identified in the northwestern Virunga landscape. Since the colonial period, plantations of *Eucalyptus* sp. and *Grevillea robusta* A. Cunn have been established in North Kivu province. *Eucalyptus* sp. and *Grevillea robusta* A. Cunn have spread into natural areas because of the catalytic effect of urbanization and the scarcity of wood resources on the local market (Kasekete et al., 2023). The expansion of *Eucalyptus* sp. has also been recognized by (Zerga et al., 2021)] as a contributing factor in the degradation of natural forest covers in the Ethiopian region, linked to the economic opportunities that the environment provides. However, in the northwestern Virunga landscape, the planting of *Eucalyptus* sp. aligns with economic considerations and a long-term investment strategy that is more resilient to the disruption caused by armed conflict. It provides its owners with two key advantages, specifically long-term security of tenure despite ongoing security challenges and the sustained economic viability of the area. However, the expansion of these exotic species can result in a long-term ecological disaster for natural forests, biodiversity, and soil quality (Kataka et al., 2023). The loss of soil fertility can exacerbate the expansion of agricultural activities in natural forests that are reputed to be fertile (Hochleithner, 2017).

The presence of *Chromolaena odorata* (L.) R.M. King & H. Rob. in disturbed sites, albeit at a low frequency, indicate the extent of anthropogenic activity. This invasive species originated in tropical America and is particularly problematic due to its rapid spread and significant impact on biodiversity and agricultural production (Gbètoho et al., 2018; Mavimbela et al., 2018; Shackleton et al., 2017). It results in biodiversity loss and contributes to the spread of fires during the dry season. The species is often influenced by environmental conditions linked to the level of the canopy (Mavimbela et al., 2018) and can alter the landscape in *Chromolaena odorata* (L.) R.M. King & H. Rob (Gautier, 1994). Consequently, the risk of its spread to Virunga must be considered when developing conservation strategies.

The frequency of cash crops, food crops, and fuelwood extraction exceeding 50% confirms our second hypothesis that these are the primary factors in the disruption of the forest landscape in the northwestern part of Virunga. The disruption of the natural

landscape in northwestern Virunga cannot be attributed to subsistence farming alone; rather, it results from a complex interplay of factors. This finding aligns with the conclusions of Shapiro et al. (2021), which argued that attributing forest disturbances in sub-Saharan Africa to a single factor is challenging. Similarly, Rakotondrasoa Olivia L et al. (2013) reached conclusions regarding the combination of factors contributing to forest degradation in Madagascar, with agriculture remaining the primary factor. This finding demonstrates the necessity to develop strategies that consider the existing associations between disturbances (Shapiro et al., 2021).

The probability of a plot being disturbed by food crops and the expansion of *Chromoleana odorata* (L.) R.M. King & H. Rob decreased with the distance from the forest access road (p -value < 0.05). This high probability was because the food crops and *Chomoleana odoata* (L.) R.M. King & H. Rob expanded best in sufficiently open areas that allowed access to light. Disturbed areas around a forest matrix and fallow land are more vulnerable to the spread of *Chromoleana odorata* (L.) R.M. King & H. Rob (Mandal and Joshi, 2014). In addition, the probability of occupancy of cash crops, the extraction of wood for energy and timber, carbonization, fire use, and the introduction of exotic species did not follow a distance gradient relative to the access road. These factors showed a random dispersal that depended on stakeholders' decisions and resource availability. The random spatial dispersal of carbonization and fires has also been documented by Rakotondrasoa Olivia L et al. (2013).

These results allow us to partially accept our third hypothesis concerning the random nature of the distribution of forest disturbance factors to the access route. The food crop and the expansion of *Chromoleana odorata* (L.) R.M. King & H. Rob oppose this hypothesis.

5.4.3. Implications for Forest Conservation in Virunga National Park

As noted above, the northwestern Virunga landscape has been facing a severe security crisis, leading to the deployment of large security forces. The results show a trend towards an increase in the forest area near army camps. This process represents a phase of passive forest restoration. The canopy cover often masks the ongoing human impact and the forest's daily vulnerability.

Of the nine disturbance types identified, cut trees, fire use, sawn timber, and charcoal production are the most prevalent in the disturbed sites within Virunga National Park, particularly in Mikuha and Lahe. These four disturbance factors, typically associated with forest degradation rather than deforestation, illustrate how the population from the Beni region illegally enters the protected area. Forest degradation leads to changes in forest structure, notably in the structure of commercially valuable trees and in the

forest composition, characterized by the presence of secondary species of low commercial value (Vásquez-Grandón et al., 2018). Damnyag et al. (2013) reported similar findings in the Ankasa Conservation Area in Ghana. As stated by Tranquilli et al. (2014), the illegal logging activities observed in protected areas in Central Africa appeared to follow an economic-value model, whereby the extraction of any tree followed the initial removal of the most valuable tree species, without regard to monetary value. Furthermore, Gross et al. (2013) noted that specific regions of protected areas near local populations remained susceptible to direct human disturbance, including subsistence or commercial farming, tree felling, and poacher fire use. The proximity and access roads between Mikuha and Lahe in Mayango's and Beni city can explain the strong association between wood extraction and these two sites (Hochleithner, 2017). Only the forest in Virunga National Park can provide the precious wood sought by local and regional markets. The peripheral zone has been impoverished by unsustainable logging.

Other studies have also identified improved road infrastructure and proximity to urban centers as key drivers of natural forest disturbances in the Democratic Republic of the Congo (Chervier et al., 2024; Tyukavina et al., 2018). Gillet et al. (2016) also highlighted that improvements in transport infrastructure can reduce production costs and enhance the competitiveness of extracted resources in the local market, while also increasing deforestation. Furthermore, the enhanced security of goods and personnel provided by a large military presence in the region probably explains the close link between timber extraction and Virunga National Park. Nevertheless, this situation may be limited through increased monitoring by state authorities within the region and the restoration of security in other timber supply basins, particularly in Ituri (Mulondi et al., 2019). In contrast to poaching and human-wildlife conflict, fire use, timber harvesting, and charcoal production have long-term impacts on biodiversity and its habitat. Regardless of their scale, these factors increase the vulnerability of protected areas in Central Africa to the effects of climate change (Itsoua et al., 2021). It is also important to note that the small-scale logging and farming observed in Mayango, although illegal, reflects a form of resilience by the local population in response to the food crisis exacerbated by insecurity in the Beni region (Hochleithner, 2017). Figure 5-8 shows a high degree of proximity between the wood extraction factors and the sites located within Virunga National Park, confirming this study's fourth hypothesis.

Sustainable alternatives to forest disturbances in northwestern Virunga involve reconciling the restoration of security, local development, and conservation. This requires continued support for income-generating crops in an agroforestry system, exclusively in the degraded areas within the park's periphery. Agroforestry based on

cocoa and coffee in the disturbed areas would reduce people's dependence on forest resources. This system could improve the connectivity of forests in fragmented landscapes and thus facilitate biodiversity movement across the landscape (Asare et al., 2014). This system will also help to restore soil fertility in degraded areas (Suárez et al., 2021) and thus reduce the practice of itinerant subsistence farming in the northwestern part of Virunga. Economic incentives for sustainable agricultural practices, i.e., those not extending into intact forest areas, are important. This would involve mapping producers and production sites. Another alternative would be to improve access to electricity in the Beni, Oïcha, and Butembo urban areas, which would act as a catalyst for relieving pressure on the resources. In addition, urban and peri-urban agriculture development is crucial in the region to enable the population to meet the city's needs without resorting to rural forest areas (Ghosh, 2021; Newell et al., 2022; Pribadi and Pauleit, 2015).

5.5. Partial Conclusion

This study combined remote sensing and field observation to provide a comprehensive view of the factors disturbing the forest landscape in the northwestern Virunga region. It examined the impact of army camps on forest fragmentation over the past eight years. The study shows that the creation of army camps did not significantly increase forest fragmentation during periods of insecurity. Forest regeneration and aggregation were observed in almost all the sites, except Mamundioma. However, aggregation should not be taken as evidence of the complete lack of disturbance. Some disturbances are not always spatially quantifiable and require continuous field monitoring.

The forest ecosystem of northwestern Virunga faces nine disturbance factors. The most prominent are food crops, cash crops, and timber extraction. Timber extraction remains a significant disturbance factor within the park compared to the surrounding area. Mitigating disturbances in northwestern Virunga requires the involvement of both state and non-state actors in landscape management initiatives. These actors include the Institut Congolais pour la Conservation de la Nature, the regional government of the Beni territory, the customary authorities of Mayango, development partners, and the Congolese armed forces. Promoting agroforestry in the degraded areas could be the key solution to mitigating forest disturbance in the northwestern Virunga. Cocoa-based agroforestry in the disturbed areas is expected to reduce itinerant subsistence farming and logging in intact forest areas.

However, the success of this strategy depends on strengthening stakeholders' capacity to select the appropriate agroforestry species. This will help limit the adoption of exotic species that could disrupt the balance of the natural ecosystem. Further research is needed on the residual trees in disturbed areas and on the endogenous knowledge of forest management. Additionally, future studies should investigate whether forest regeneration also contributes to the restoration of wildlife biodiversity in previously degraded areas. Research on soil fertility in areas affected by various disturbance factors is also essential.

Chapter 6

6. Shifting cultivation in Mature Forests: Understanding Farmers' Perceptions in the Northwestern Virunga Landscape

Chapter positioning in the overall analysis

Chapter 6 analyzes farmers' perceptions of agricultural itinerancy. Building on chapters 4 and 5, it links spatial dynamics and disturbance factors to household decision-making. The chapter shows how local actors' choices and strategies lead to actions that impact landscape disturbances.

Abstract

This study examines shifting agriculture in mature forest through the lens of community perceptions and local land use practices in the northwestern part of the Virunga landscape. It aims to explain how farmers perceive and justify agricultural expansion into forest areas, and how these perceptions shape land-use decisions amid increasing pressure on forest ecosystems. To address these issues, the study adopts a mixed-methods approach, drawing on surveys of 560 farming households, as well as focus group discussions and semi-structured interviews. Data collected were analyzed using descriptive statistics, test of association, and multiple factor analysis.

The results indicate that local populations view shifting cultivation in mature forests as driven by multiple simultaneous constraints, including soil fertility degradation in the former field and economic opportunities for cash crops as the main ($p\text{-value} < 2.2 \times 10^{-16}$). Farmers view land acquisition as essential for investing in cash crops and enhancing household resilience to insecurity. Access to land mainly occurs through informal arrangements mediated by customary authorities. Contrary to common beliefs in the Congo Basin, the findings show that households rarely practice slash-and-burn and seldom convert land to farmland, in contrast to the widespread slash-and-burn practices typically documented in the region. Land control and consolidation for planting fields focus on cash crops such as cocoa, coffee, vanilla, papaya, and oil palm, reflecting a gradual shift toward market-oriented agriculture. Among these, cocoa, coffee, and oil palm are most favored, with 50% of farmers planning to expand. The result also shows that reconciling agricultural development with the stability of forest areas primarily involves securing property and people in former agricultural zones, land-use planning and control by provincial and territorial administrations, promoting urban agriculture, and investing in improving agricultural productivity per spatial unit. The study shows that shifting cultivation should be understood as a complex outcome. It is not merely a consequence of repeated burning system. Shifting cultivation is rather the result of farmers' decision influenced by physical, ecological and socio-economic context.

Keyword: Virunga, sustainable agriculture, land access, protected area, burn farming

6.1. Introduction

Shifting agriculture is a common farming practice in tropical regions, particularly in the Democratic Republic of the Congo. It involves clearing small forest patches, temporarily farming the land, and then leaving it unused for a long period to allow soil nutrients to regenerate. (Demaze and Manusset, 2008) estimate that as long as extended fallow periods are maintained to restore soil fertility and population density remains low, this form of agriculture exerts minimal impact on mature forests. However, with demographic growth and no advances in agricultural technology in the tropics, the delicate balance between land use and fallow period decreases. To increase food production, people must clear new areas in untouched forests (Demaze and Manusset, 2008; Gillet et al., 2016). Additionally, the impact of shifting cultivation varies not only with fallow periods and population density but also depends on factors such as territorial governance, land ownership, infrastructure, and security conditions for goods and people (Temgoua et al., 2026).

Today, shifting agriculture is recognized as the primary driver of deforestation in both the Congo Basin and particularly in the Democratic Republic of the Congo, posing a significant challenge to forest conservation (Curtis et al., 2018). Approximately 61% of forest fragmentation in the tropics is attributed to shifting cultivation. While initially causing temporary disturbances, unlike mining, this activity often becomes a permanent problem due to economic motivations (Zou et al., 2025). According to the 2025 Global Forest Watch, shifting agriculture accounts for 82,00% of all disturbances observed in natural forests. Despite this dominant role in forest dynamics, several studies have examined shifting agriculture, mainly by focusing on its impacts on biodiversity, soil quality, landscape fragmentation, and innovations in family farming. However, few investigations in the Democratic Republic of the Congo have explored the complex factors underlying agricultural itinerancy. In the context of global environmental upheaval, an important question therefore remains how to sustain peasant agriculture while preserving more forested areas, which are crucial for regulating the climate. Addressing this challenge first requires a better understanding of the factors that facilitate the expansion of shifting agriculture into forested areas (Rasul and Thapa, 2003).

Traditionally, shifting cultivation is commonly interpreted as a response to the decline in soil fertility caused by slash-and-burn practices. Nevertheless, this simplistic explanation does not fully capture the complexity of farmers' decisions. Repeated agricultural expansion within natural forests can also stem from socioeconomic

constraints (Stone, 2001), land-access mechanisms (Khatun et al., 2020; Kwapong et al., 2021), household survival strategies and local consideration (Mellon-Bedi et al., 2020). These dimensions remain insufficiently documented, particularly in the context of North-West Virunga, an area strongly affected by insecurity and socio-political instability. Consequently, understanding shifting cultivation can therefore be approached either through explanatory quantitative mechanisms or through the analysis of the social logic underlying farmers' practices and decisions. This study adopts the latter perspective, aiming to better understand the motivations behind repeated agricultural expansion into these forest areas.

This study is motivated by the situation in the northwestern Virunga Landscape, a high biodiversity forested area currently under human pressure. In this landscape, degradation of mature forests, often called primary forests, results from socio-territorial processes that are even less documented. The cross-border situation, characterized by ongoing insecurity, weak land governance, and increasing market incentives, is driving rapid, uncontrolled land acquisition, secured through use, which in turn fuels expansion and agricultural itinerancy (Vikanza, 2018). Previous research by Musavandalo et al (2025) indicates that small-scale farming oriented toward subsistence and cash crops is one of the primary drivers of natural forest degradation, accounting for more than 70% of degraded areas. This agricultural expansion poses a significant challenge to the conservation of Virunga National Park, particularly amid rapid population growth. It is also a challenge for implementing the vision of the Green Corridor initiative launched by the Congolese government in January 2025, to boost agricultural production while protecting the forest.

Faced with this challenge, an important yet insufficiently documented question emerges: how to stabilize agriculture in already cultivated areas without further encroaching on forested lands? Addressing this issue requires understanding several critical dimensions. This includes motivations or constraints behind new land acquisitions, mechanisms of access to land, land preparation practices, the typology of farming systems, which also serves as an indicator of land use diversity, and community views on sustainable strategies for maintaining agricultural activities in areas influenced by humans. This issue can be translated into the following question: What motivates households to acquire new farmland in mature forested areas, and through which mechanisms are those lands acquired? Is the slash-and-burn method a determining factor in the repeated conversion of mature forest to farmland? What are the types of structural cultures in farming systems? What strategies could be used to

stabilize existing agricultural land use and limit further agricultural expansion into the forest?

Based on these questions, the study aims to test the following hypotheses: (1) Household expansion of new farmland into mature forest is driven more by economic incentives tied to cash crop production than by ecological constraints related to declining soil fertility on existing farmland; (2) Households engaged in informal, non-binding land agreements tend to clear mature forest land more frequently than those with more secure access to agricultural land; (3) The predominance of slash and burn clearing practices is positively associated with more frequent agricultural expansion into mature forest; (4) In the northern region of the Virunga landscape, new agricultural land is primarily used for cultivating cash crops, whose dominant crops differ by zone, indicating a process of territorialization of the agricultural system centered around Virunga National Park; (5) The perception of security in agricultural areas drives households' willingness to adopt more sedentary farming practices rather than agricultural innovations.

This study aims to examine agricultural mobility from a social perspective, integrating community perceptions and land-use practices to complement purely environmental or ecological impact-focused perspectives.

6.2. Materials and Methods

6.2.1. Study area

The study focused on five peripheral entities of the Virunga National Park: Beni and Oïcha, located to the west, and Mutwanga, Lume, and Kasindi, situated to the east. These study areas were chosen based on specific criteria: their closeness to Virunga National Park, indicating possible pressure on the park; the participation of local residents in cash crop farming, which notably changes the landscape; safety and ease of access during data collection; and a history of conflict with the park over encroachment caused by expanding agricultural land. The search for agricultural land by local communities frequently encroaches on the park's boundaries, contributing to cycles of conflict over natural resource exploitation in the region.

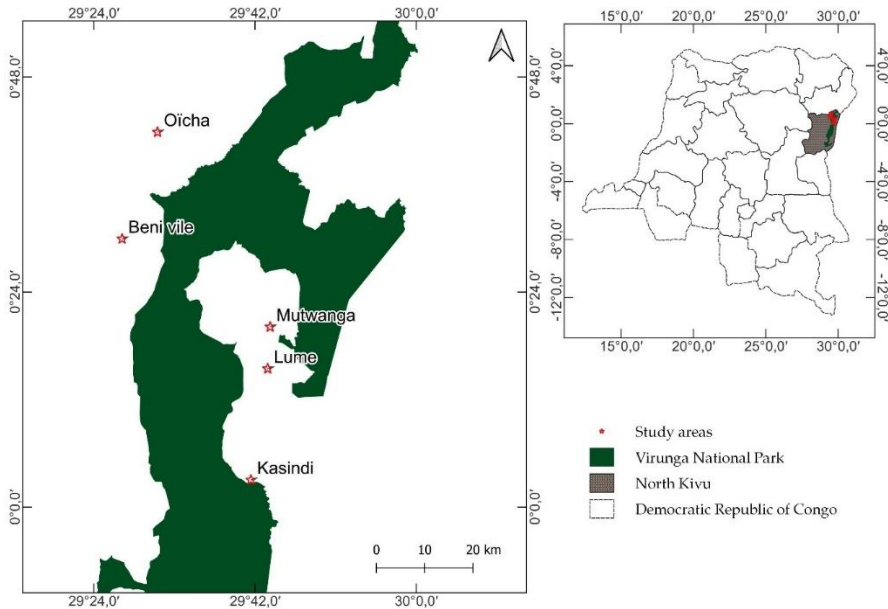


Figure 6-1. Study area. The map shows the five sites where surveys were carried out

6.2.2. Methods

6.2.2.1. Data collection

This study did not aim to find causal factors of deforestation using predictive models. Instead, it focused on understanding local farmers' perceptions, motivations, and practices related to shifting cultivation to guide context-specific management and policy decisions. The study used a mixed-methods approach combining quantitative and qualitative data to understand household perceptions of shift agriculture and institutional viewpoints. Using multiple data sources aimed to improve data credibility, validity, and complementarity through triangulation of information (Lucungu et al., 2022). Quantitative data were gathered through a structured household survey conducted from June 2024 to January 2025. A total of 560 agricultural households participated in the survey across five locations: 200 in Beni, 100 in Oicha, 100 in Mutwanga, 100 in Kasindi, and 60 in Lume. The choice of these sites is primarily based on their close spatial proximity to the intact forest massif of Virunga Park. This area has seen increased interest from the local population, who are seeking permanent farmland along the forest edge to support and expand their livelihoods. This trend is historically rooted in cash crop cultivation. Only households for whom agriculture was their primary livelihood were included. East-west and north-south transects were

employed to diversify the surveyed households, minimizing bias from over-representation of a single area within the study site. Along each axis, households were chosen systematically by sequentially identifying agricultural households along the transect. The sample size of respondent at each study site was determined based on the study area's spatial extent and the response saturation provided, given the absence of a household list. Interviews were conducted solely with household heads to ensure data accuracy, following methods used in similar studies by Kwapong et al. (2021) and (Magugu et al. (2018)). The study's objectives were clearly explained to respondents, and all ethical protocols were followed. Additionally, during field visits, two focus groups of 10 farmers were organized, each to better understand the relationship between people and mature forests in the landscape. Moreover, semi-structured interviews were conducted with two traditional leaders, the burgomasters of the rural communes of Oïcha and Kasindi. The interview was used to investigate land management challenges arising from increasing demand for agricultural land and the strategy of standardizing agriculture. The insights collected offered a more comprehensive view of how households perceive these issues.

The questionnaire, with closed-ended question, was designed to ensure consistent responses and support statistical analysis. It aligns with households' decision-making processes regarding land use and includes five key sections. The first section gathers socio-economic data, household size, education level, income range, farm size, number of fields, and labor distribution, factors that influence investment capacity and land-use strategies within forest landscapes (Zabala et al., 2025).

The second section explored the factors affecting the acquisition of new agricultural land in mature forests. Households rated seven economic, environmental, and security factors on a five-point scale from 0 (no influence) to 5 (very influential), allowing for a quantitative analysis of the pressures contributing to agricultural expansion in forest ecosystems. The third section examined land tenure regimes related to shifting cultivation. The data emphasized the access mechanisms, the stakeholders involved, and the acquisition costs. The fourth section explained the land-clearing practices used to establish new farms in forested areas. Based on earlier research and field observations (Bweya et al., 2019; Musavandalo et al., 2025), three methods were distinguished: total burning, partial burning, and non-burning. These distinctions are relevant because of their differing implications for soil condition, biodiversity, and forest regeneration. Note that the issue of shifting cultivation does not rely on spatially localized frequencies. Instead, we measure how many times households report opening new farming land in natural forest. This approach better captures the behaviors

contributing to deforestation and reflects households' perceptions on their own impact on the environment.

The fifth component focused on identifying the local farming system and defining the structural crops that allow farmers to strengthen their control over natural spaces. Crops were classified into four categories: abundant, moderate, rare, and absent based on their spatial cover across the cultivated plot. A crop was classified as abundant if it was present in all fields and covered over 50% of the area under cultivation by households, moderate if it was present in all fields and covered between 10% and 50%, rare if it was present in one field and covered less than 10%, and absent if it was not cultivated by the respondent. This classification facilitated consistent assessment of crop importance across households. Finally, households were asked to express their perceptions of the key factors likely to promote a transition to sustainable and spatially stable agriculture, including improved security, increased yields, land governance reforms, agroforestry and the promotion of urban agriculture (Zabala et al., 2025).

Qualitative data complemented the household survey through group discussions and semi-structured interviews with traditional authorities and officials in Beni territory and the rural communes of Oïcha and Kasindi. These discussions explored the institutional challenges linked to small-scale forest clearing and how local governance could support biodiversity conservation within and around Virunga National Park.

6.2.2.2. Data analysis

The collected data were compiled and analyzed using R. Descriptive statistics, including absolute and relative frequencies, means, minimums, maximums, and measures of dispersion, were used to present the socio-economic profiles of respondents, as well as the frequency of land acquisition systems and agricultural land clearing methods. The study also used nonparametric tests (Kruskal-Wallis, Friedman, and Wilcoxon) and chi-square independence tests. To test the first hypothesis, the respondents' perception was assessed using Likert type scale from 1 (least important) to 5 (most important). Mean scores were calculated for descriptive purposes to assess general trends. Additionally, non-parametric Kruskal-Wallis, Friedman, and Wilcoxon tests was used to compare the importance levels assigned to various factors statistically. the motivation and constraints determining the decision to acquire new agricultural land in mature forest areas were ranked by respondents' average scores, reflecting the perceived importance of each factor. The Friedman test was used to determine whether these factors presented significant differences in terms of importance, followed by a Wilcoxon post hoc test to identify pairs with significant differences (Liu and Xu, 2022).

To evaluate the second hypothesis, a Chi2 test was conducted to examine the relationship between land acquisition methods and the frequency of agricultural expansion into mature forested areas. This analysis pinpointed land tenure systems that are likely to promote agricultural migration and increase pressure on natural forests. Due to a lack of consensus and a gap in quantitative household data on land acquisition costs, only qualitative information on these costs has been summarized and analyzed, along with informative trends from focus groups.

Additionally, a Chi2 test was used to explore the association between practices of clearing forest land and the reported rate of farming expansion in forest areas. Standardized residual analysis identified the practices most responsible for differences between observed and expected values. This process underscored the effect of land-clearing practices on agricultural expansion in forest areas, thereby addressing the study's third hypothesis.

To test the fourth hypothesis concerning the territorialization of the agrarian system based on structural crops, multiple factor analysis (MFA) was applied to establish the links between agricultural terroirs, structural crops and their relative importance within the agrarian system. Indeed, AFM is an extension of principal component analysis used for variables derived from the same sets of observations. It helps us understand the agreement between subjects or subject groups (Abdi et al., 2013). A factorial map was thus produced to illustrate, for each study site, the relative place of different crops in the local agricultural system. Crops classified as abundant were considered the most fundamental and, therefore, the truly structural crops of the agrarian system. This analysis highlighted the spatial organization of cash crops and offered an original interpretation of their distribution across the Virunga landscape. Spatialization here is expressed as an individual perception that contributes to a collective spatial motif.

Finally, to test the fifth hypothesis, the factors likely to promote the transition to spatially stable smallholder agriculture were identified. For each factor, the level of priority was assessed in three categories: high, medium, and low. The results obtained were then enriched and validated by contributions from experts and local authorities, thereby strengthening the overall interpretation and robustness of the conclusions.

6.3. Result

6.3.1. Profile of household

Table 6-1 presents the profile of the respondents. Indeed, men accounted for more than half of the respondents. The low representation of women is largely due to the traditional reservation of the role of head of household for men. The respondents'

educational level is generally higher. More than half hold at least a secondary school diploma, compared to 17.86% who have not attended school. Each household has an average of 7 people. For half of the respondents, their monthly income ranges between \$ 50 and \$ 100, and for 40%, it is between \$ 100 and \$ 500. On average, each household has between two and six fields, each of which is at least one hectare in size. Each year, agricultural activity covers between 0.50 hectares and 4 hectares, with an estimated average of 1.77 hectares.

Table 6-1. Profile of survey respondents

Variable	Items	Mean	SD	%
Gender	Male			71.79
	Female			21.21
Educational level	None			17.86
	Primary			29.29
	Secondary			41.43
	University			11.43
Origine	Alloctone			20.00
	Autochtone			80.00
Income (\$ USD)	<50			6.79
	50-100			50.89
	100-500			39.82
	500-1000			2.14
	>1000			0.36
Total field	Min	1.00		
	Mean	2.00		
	Max	6.00		
Area farmed per year (ha)	Min	0.50		
	Mean	1,77		
	Max	4.00		
Field activity day	Min	1.00		
	Mean	3.00		
	Max	5.00		
Household size	Min	2.00		
	Mean	7.00		
	Mediane	7.00	2.55	
	Max	15.00		
Age (year)	Min	18.00		
	Mean	48.00	13.87	
	Max	87.00		

6.3.2. Household motivation regarding the acquisition and expansion of farmland in mature forests

Figure 6-2 and Table 6-2 present the motivations and constraints reported by households regarding the acquisition and expansion of agricultural land in mature forests. Based on households' self-reported perception scores, seven factors were identified. These include the price of agricultural products, perceived soil fertility degradation, access to financial resources, security/safety conditions, availability of improved seeds, availability of land, and road accessibility. Rather than causal determinants, these factors reflect households' reported consideration and constraints associated with decisions related to agricultural land expansion. The diversity of reported motivations highlights the complexity of land-use dynamics in mature forests, where land acquisition is shaped by multiple interacting socio-economic and contextual factors beyond yield consideration alone. Households need to navigate multiple constraints simultaneously.

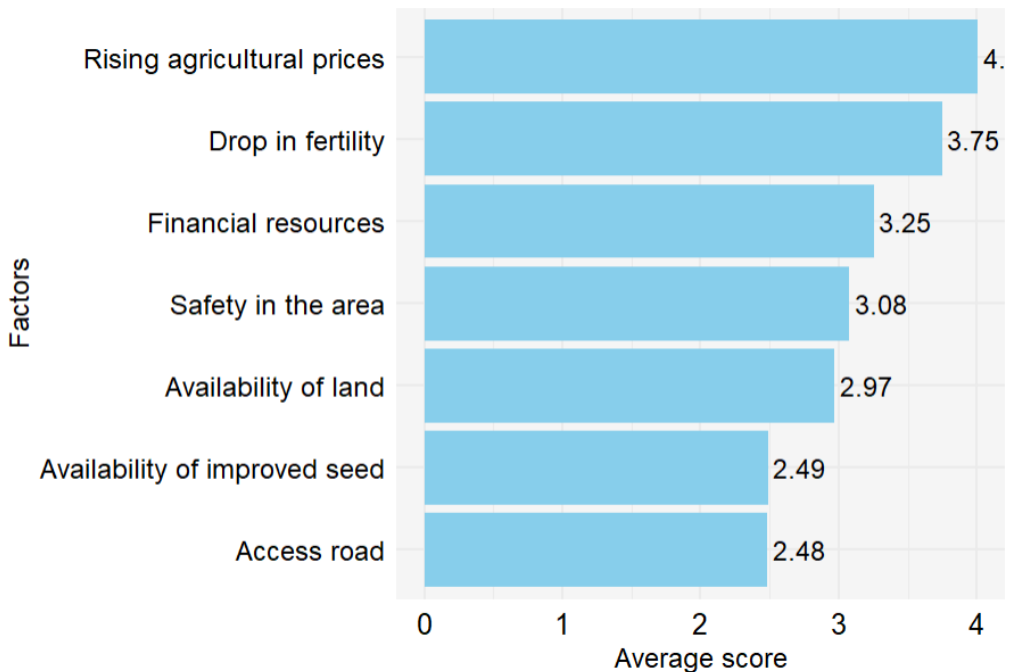


Figure 6-2. Factors of farmland acquisition and expansion in the intact forest

The ranking of factors by importance, based on their scores and the Friedman test ($\chi^2 = 289.34$, $df = 6$, $p\text{-value} < 2.2 \times 10^{-16}$), reveals that the prices of agricultural products on

the market and soil fertility degradation are the most decisive. The Financial resources, security in the area, and the availability of land (vacant land) are considered intermediate factors. Farmers in the Northwest Virunga landscape place less importance on the availability of improved seeds and road access. These results indicate that agricultural itinerancy results not only from a strategy of spatial occupation but also from a direct response to environmental constraints and socio-economic opportunities.

Table 6-2. Pairwise comparison of factors involved in acquiring farmland in intact forest areas (Values in the table represent the p-value for pairwise comparison of variables)

Variable	Access road	Availability of improved seed	Availability of land	Drop in fertility	Financial resources	Rising agricultural prices
Availability of improved seed	1.00	-	-	-	-	-
Availability of land	2.5×10^{-6}	4.0×10^{-7}	-	-	-	-
Drop in fertility	2.0×10^{-16}	2.0×10^{-16}	3.0×10^{-8}	-	-	-
Financial resources	3.1×10^{-14}	1.3×10^{-13}	0.136	0.028	-	-
Rising agricultural prices	2.0×10^{-16}	2.0×10^{-116}	4.9×10^{-15}	0.482	7.7×10^{-06}	-
Safety in the area	7.0×10^{-08}	7.5×10^{-8}	1.000	1.8×10^{-8}	1.00	2.8×10^{-07}

6.3.3. Household-reported frequency of natural forest clearing

This study uses the number of self-reported mature forest conversion events into agricultural land by each household over the past five years as a proxy indicator of their involvement in forest cover change in the Northwest of the Virunga. Households with no forest conversion are seen as stable and less involved in deforestation, while those with at least one conversion are considered active. Table 6-3 below shows that less than half of the surveyed households cleared mature forest land for agriculture over a five-year period. Meanwhile, over half reported at least one instance of clearing natural forest land. Furthermore, the non-parametric Kruskal-Wallis test reveals a link between residence location and household clearing frequency (chi-squared p-value = 11.457, df = 4, p-value = 0.021). The proportions of households by clearing frequency are similar between Beni and Kasindi, and between Oïcha, Mutwanga, and Lume (p-value > 0.05).

Table 6-3. Frequency of natural forest clearing over a five-year period reported by households surveyed (*Codes : '*' 0.05*)

Study area	Number of forests to agricultural conversion				<i>p-Value</i>
	Zero time	One	Twice	Three times	
Beni city (<i>n</i> = 200)	41.00	33.00	17.00	9.00	0.02*
Kasindi (<i>n</i> = 100)	46.00	18.00	25.00	11.00	
Lume (<i>n</i> = 60)	60.00	21.67	10.00	8.33	
Mutwanga (<i>n</i> = 100)	51.00	39.00	5.00	5.00	
Oïcha (<i>n</i> = 100)	48.00	36.00	10.00	6.00	

6.3.4. Land access patterns and frequency of forest conversion events reported by households

In the northwestern Virunga landscape, access to agricultural land follows three modes: inheritance of existing agricultural plot, purchase from customary chiefs, and purchase from the first acquirer. The first acquirer refers to an individual who initially obtained land access from customary authorities and subsequently subdivided and informally transferred portions of the land to other households, without formal registration.

Among the households surveyed (*n*=560), 251 households (41.25%) reported cultivating land bought from a first acquirer; 199 households (35.54%) cultivated land directly acquired directly from a customary chief; and 130 households (23.21%) cultivated inherited farmland. Statistical analysis indicates that the mode of land acquisition is not significantly associated with the frequency of reported forest conversion events over the past five years ($\chi^2 = 8.90$, *df* = 9, *p-value* = 0.4458). It has not been a catalyst for the expansion of agricultural land into mature forest land over the past five years.

Land access expenses are influenced by factors such as vegetation type, proximity to residential areas, and the parties involved. The presence of species such as *Cynometra alexandri* affects land prices because they produce highly sought-after charcoal in urban areas. Interviews suggest that land from indigenous people costs about ten times less than land bought from a Bantu customary chief or a first-time buyer. The purchase price per hectare ranges from \$100 to \$1,000, but these figures are meant as rough qualitative estimates rather than exact values, reflecting informal market conditions.

Table 6-4. Relationship between the land acquisition system and the frequency of natural forest clearing (the data in the table are relative proportions calculated by type of land acquisition and expressed as a percentage)

Land acquisition system	Number of forests to agricultural conversion				<i>p-Value</i>
	Zero time	One	Twice	Three times	
Customary purchase	43.72	31.16	16.58	8.54	0.44
Purchase from the first buyer	45.45	32.03	13.85	8.66	
Inheritance	54.62	27.69	11.54	6.15	

6.3.5. Agricultural clearing and frequency of forest conversion events reported by households

Table 6-5 presents the frequency of agricultural land extension according to the three main methods of land preparation in the north-west landscape of the Virunga over the past five years. In the north-west landscape of the Virunga, more than half of the households surveyed (79.82%) practice non-burning as a method of agricultural land clearing; 8.93% practice partial burning; and 11.93% practice full burning. Non-burning is a traditional method of preparing agricultural land in forested areas, involving the clearing of forests, primarily by felling trees that could shade crops, and allowing organic matter to decompose naturally without the use of fire. Partial-burning clearing is a variant where fire is mainly used to facilitate sowing in difficult areas (such as regions with spruces). Total burning involves clearing the land and then accelerating mineralization by fire across the entire field. The Chi-squared test ($\chi^2 = 13.39$, $df = 6$, $p\text{-value} = 0.03$) reveals a significant relationship between land-clearing methods and the frequency with which households expand their agricultural operations into forested areas. The analysis of standardized residuals of Chi-squared (Figure A-1) shows that households practicing total-burning have positive residuals exceeding +2 at the two- to three-frequency levels of mature forest clearing.

Table 6-5. Relationship between the agricultural clearing system vs. frequency of natural forest clearing (the data in the table are relative proportions calculated by study area and expressed as a percentage)

Clearing system	Number of forests to agricultural conversion				<i>p-Value</i>
	Zero time	One	Twice	Three times	
Total burning	42.86	19.05	25.40	12.70	0.03
Partial burning	44.00	28.00	18.00	10.00	
No- burning	47.87	32.66	12.30	7.16	

6.3.6. Territorialization of the agricultural system based on structural cash crops

Figure 6-3 below links each perennial crop to the respondent's agricultural land based on the extent to which it is currently cultivated on the farming units. Respondents identified five types of cash crops commonly grown alongside food crops. These are coffee, cocoa, vanilla, papaya, and oil palm. These crops are often combined with food crops such as beans, cassava, ground nuts, and, to a lesser extent, rain-fed rice. Furthermore, the importance of these crops in the local farming system varies from one area to another. Respondents reported that cocoa is very abundant and is a key crop for most households in Beni, Oicha, and Mutwanga. Oil palm is also a very abundant crop for households in Oicha and is moderate for those in Beni and Mutwanga fields. Coffee remains very abundant in Lume and is moderate in Mutwanga and Kasindi fields. Vanilla is a very abundant crop in Mutwanga and Lume field, whereas in Beni, Oicha, and Kasindi, it is nearly absent from the farming system. Papaya cultivation is more developed among households in Mutwanga and Kasindi.

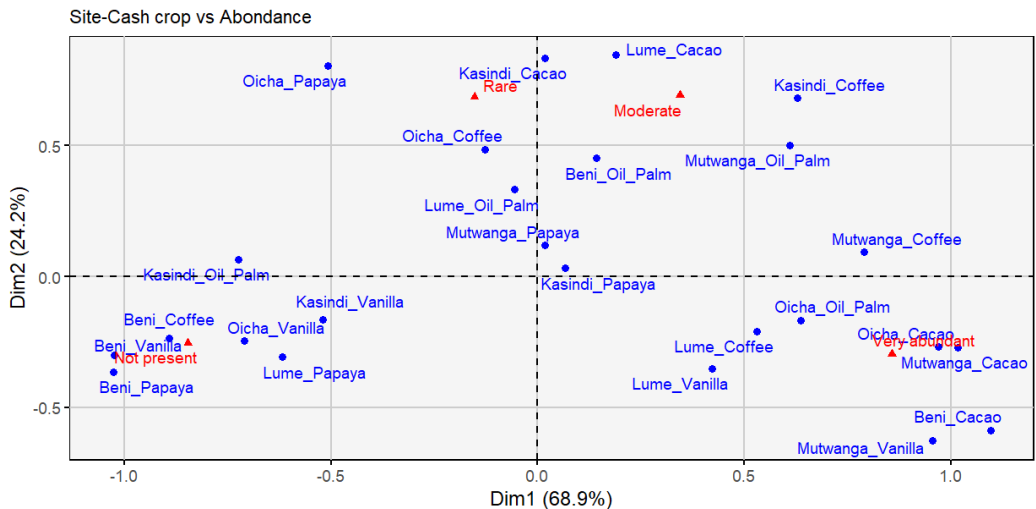


Figure 6-3. Summary on the territorialization of perennial crops according to their importance in local farming systems

6.3.7. Respondents' perceptions of the prospects for areas dedicated to cash crops

Figure 6-4 below shows respondents' perceptions of changes in the area under cultivation for the main cash crops over the next ten years. These perceptions vary by crop. The intention to increase the area under cultivation is mainly observed for cocoa,

followed by oil palm and coffee. In contrast, there is little intention to expand papaya and vanilla cultivation in the near future. This trend can be explained by the development of the cocoa and oil palm value chains, facilitated by the Virunga Initiative's gradual establishment of industrial processing facilities for these crops. Expanding perennial crops can strengthen land claims, particularly in Virunga's protected areas, which are the site of conflicts between local communities and park authorities. Without measures to stabilize forest land, this expansion may further threaten mature forests.

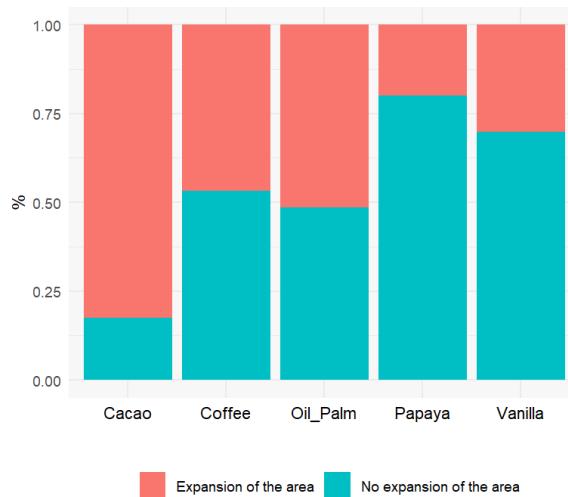


Figure 6-4. Perceptions of farming households on the widespread cultivation of major cash crops around Virunga

6.3.8. Key factors influencing the transition to permanent agriculture

The central question here is: what are the key factors that can keep agriculture stable and sustainable in areas already under cultivation, thereby limiting expansion into forested regions of the landscape? According to respondents, maintaining permanent, sustainable agriculture on existing farmland requires concrete actions across the following factors: improving security in agricultural zones, promoting urban farming, enforcing legal land-use controls (legal obligation in land use), and providing technical support to farmers to increase productivity per land unit. Regarding priorities, about 68.4% of respondents consider improving security in agricultural zones a high priority; 44.3% also prioritize promoting urban farming highly. Conversely, legal control in land use planning is seen as secondary by 65.00% of respondents, while only 19.00% view it as a high priority. Additionally, increasing crop yields is perceived less important in the community's strategies to stabilize agriculture on existing farmland (Figure 6-5).

Furthermore, the location of residence significantly influences key factors that are prioritized for maintaining stable agricultural activities in non-forest zones. In Kasindi, legal control over land use is deemed more important than other considerations. This aligns with the study site's position on the outskirts of Virunga National Park, where residents value the savannah area for farming. In Beni, Mutwange, and Oicha, the top priorities are enhancing security in agricultural zones and encouraging urban agriculture, followed by strengthening land-use regulations. This population stance reflects their recent experiences with insecurity and their development of resilience in urban environments. Conversely, in Lume, increasing crop yields is viewed as the most critical step toward establishing agriculture in a clearly defined area (Figure 6-6).

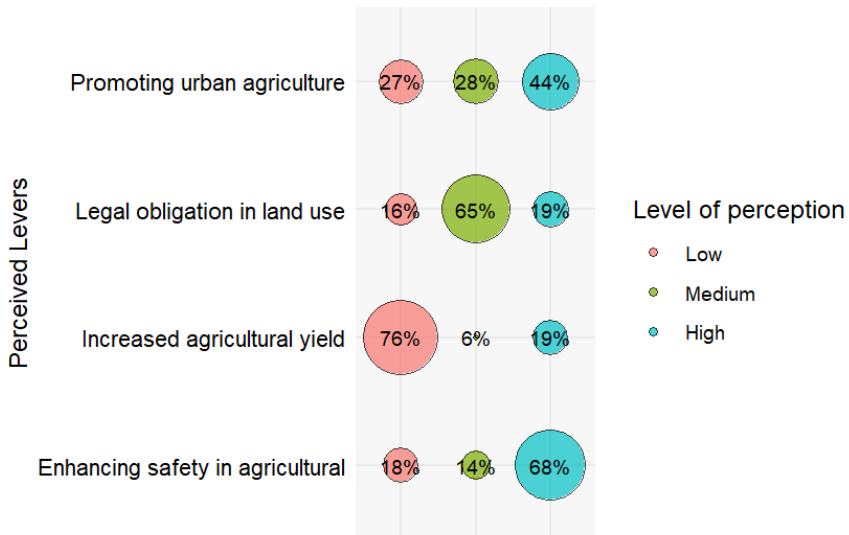


Figure 6-5. Farming households' perceptions of strategies to reduce shifting cultivation

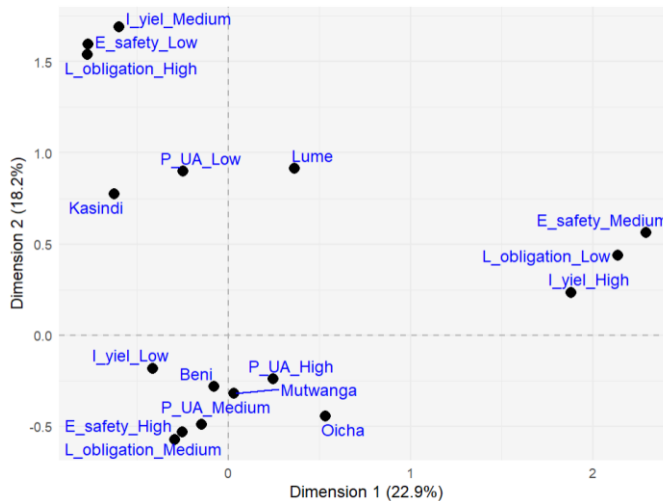


Figure 6-6. Effect of respondents' residence location on their views of priority agricultural stabilization strategies in current areas. (L_obligation: Legal obligation in land use, I_Yield: Encrased crop yield, E_Safety: Enhancing safety in the area, P_UA: Promoting Urban Agriculture).

6.4. Discussion

6.4.1. Economic incentive for agricultural land expansion in intact forest

This study finds that the primary motivation for acquiring agricultural land in natural forest environments is speculation on rising agricultural product prices and the declining fertility of existing farmland. Moderate factors include financial considerations, local security, and land availability, while weak influences involve the adoption of improved seeds and better road infrastructure. Notably, the surge in local cocoa prices, surpassing those of coffee and palm oil during the survey, prompted an increase in farmland searches in the region. This finding contrasts with those of Bweya et al. (2019), which suggested that rising prices of agricultural and forestry products would only minimally impact deforestation in Beni. According to that study, population growth and better roads mainly drive the pursuit of new agricultural land in forests. This difference is due to our research taking place when cocoa prices were high over \$5 per kilogram and the sector was thriving (Jassogne et al., 2014). As a result, farmers' perceptions were heavily influenced by this economic factor, especially relevant in North Kivu. Bweya et al. (2019) conducted their study when the cash crop market was less profitable. Furthermore, Barral and Oscar (2012) note that in agricultural regions, land use generally prioritizes economic gains while neglecting the broader ecosystem

services that the landscape provides to humans. Mertz et al. (2005) indicate that the strategy of using local lands adapts to the economic opportunities offered by the natural and social environment in which the population lives, often in connection with globalization processes. Stone (2001) states that market incentives can drive farmers to intensify production on new lands, even without land shortages. In Nigeria, Khan et al. (2025) observed that expanded agriculture aims to support export income rather than local food security. These findings suggest that economic motives outweigh subsistence, with traditional rudimentary agriculture increasingly shifting toward cash crop cultivation. Vikanza (2018) also notes that demographic growth and low yields of fallow lands led Beni populations to seek new, fertile areas, often within Virunga National Park (*Mayangos*).

6.4.2. Ecological constraints and declining land productivity

Ecological constraints remain a key explanatory factor. The perceived soil fertility, combined with pest and disease outbreaks, contributes to the abandonment of cultivated plots and the search for new fertile land. Soil degradation is exacerbated by very short fallow periods of no more than one growing season (i.e., one year) (Bweya et al. 2019). This aligns with Lim and Douglas (1998), who emphasize the role of shortened fallow cycles in reducing agricultural sustainability. Demichelis et al. (2022) indicate that in the Bolobo territory, the presence of ferns, resulting from short fallow periods, leads to the complete abandonment of the agricultural area. This also causes farmers to seek new land in the forest, even those protected by law. The duration of the fallow period is a key aspect of shifting agriculture cycles. A long and well-managed fallow helps regulate pests and diseases while restoring soil fertility. Forest lands, free from the high risks of pathogen attacks, have become a less costly alternative to support agricultural activities in Beni.

6.4.3. Security pressures and territorial displacement

Insecurity, primarily caused by the terrorist group ADF, plays a major role in the migration of agricultural activities in the northwest of Virunga. Since 2014, these agricultural areas have become a refuge for armed groups. Their strategy, involving massacres of civilians with blades and firearms, has forced peaceful populations to seek arable land further away or even to illegally enter certain zones of Virunga National Park, particularly in Mayango's and Lubirihya (Musavandalo et al., 2025). Opelele et al. (2020) have shown that in Mambasa territory, located near the northwest region of Virunga, significant deforestation coincides with worsening security disturbances in Beni.

Li et al. (2015) demonstrated that road improvements impact deforestation in the Democratic Republic of the Congo by enabling better transportation of intra-agricultural goods and facilitating farmers' evacuation of their products. Shapiro et al. (2021) also considers that the physical access of populations into the forest is one of the important indicators of deforestation. However, households surveyed in the northwest of Virunga assign less importance to upgrading agricultural service roads when considering factors influencing their mobility for agricultural activities. This likely stems from the fact that most farming areas can still be accessed by motorcycles, which are the primary means of transporting agricultural goods in the region. Additionally, the existence of agricultural desert roads has diminished the distance between production zones and the main trading centers located in forested areas, possibly influencing this perception. This study confirms the first hypothesis that the primary factors driving agricultural land expansion are economic incentives, declining fertility, and the search for secure areas.

6.4.4. Role of the land acquisition system and clearing method on the frequency of forest encroachment by agriculture

The acquisition of agricultural land is mainly through inheritance, purchase from the customer, or from the first buyer (Table 6-4). In the local relational order, land constitutes the foundation of social order. The land lease system, which grants farmers the right to use the land, promotes loyalty to the customary chief, who plays a central role in regulating land use (Vikanza, 2018). Regardless of the mode of acquisition, customary authority remains at the heart of regulation. No association has been observed between modes of acquisition and the frequency of agricultural encroachment into intact forests. No mode of acquisition obliges farmers to limit deforestation in agricultural areas. Rasul & Thapa (2003) emphasize that non-binding access modes favor unlimited expansion of agriculture into intact forest zones. This corresponds exactly to the system in the northwest of Virunga. Conversely, Kwapong et al. (2021) indicate that buying, renting, or sharing agricultural harvests influences the scale of exploitation to maximize profits shared with landowners. Gillet et al. (2016) also demonstrated a relationship between sharecropping and deforestation on the Batéké Plateau in the Democratic Republic of the Congo. The second hypothesis of the study is partially accepted, because no significant statistical evidence shows that a particular mode of acquisition is associated with an increased frequency of forest encroachment by agriculture, as reported by the respondents. The sale of forest lands to small-scale farmers outside the legal framework poses a major challenge for the Virunga National

Park. In protected areas, it often occurs under the pretext of humanitarian action to allow populations fleeing the atrocities of the ADF group to meet their basic needs. However, it also rekindles old land claims within the park.

Regarding the method of agricultural clearing, the study revealed that the no-burning farming system predominates in the area. Farmers rarely use partial or total field burning. This is a distinctive feature of the North-West Virunga region, in contrast to the widespread burning in the Congo Basin farming system. The no-burning practice seems linked to a non-restrictive access mode to land, often permitted by customary authority, since it requires more time for soil preparation to mineralize organic matter without the use of fire. It is therefore a method that indicates the farmer's long-term settlement. In the same context, Rahman et al. (2012) note that land rights, regardless of their form, are the primary prerequisite for investment in sustainable agricultural practices. Additionally, the results indicate a relationship between the clearing system and the frequency of forest encroachment by agricultural activities. These frequencies are higher among households practicing burning than those practicing non-burning methods (see Appendix Figure A-1). Indeed, the use of fire is well documented as a factor promoting agricultural itinerancy in tropical forests, especially in the Congo Basin. Within the North-West Virunga landscape, most households using this system reside close to Virunga National Park, where illegal farming happens in protected areas (see Appendix Figure A-2). This approach allows for rapid agricultural output before any possible expulsion. These findings partially support the study's fourth hypothesis.

6.4.5. New agricultural land for cash crop investment: a local logic of forest conversion in northwest Virunga

Our study showed that the coffee plant, cacao tree, papaya, vanilla, and oil palm are the main pillars of the farming system around Virunga National Park. These cash crops are often grown alongside food crops for self-consumption. The choice of commercial crops as the pillars of the agricultural system indicates a shift in the Virunga region from subsistence farming to market-oriented agriculture, without industrial connotations. It is small-scale artisanal agriculture, as described by Temgoua et al. (2026), which bridges subsistence and commercial farming.

However, their relative importance, as expressed by farmers, varies across the landscape, indicating a territorial distribution of these so-called structural elements of crops (Figure 6-3). Thus, cacao and oil palm mainly dominate the agricultural areas of Beni, Oicha, and Mutwanga, while coffee is more prominent in Lume, papaya around Kasindi, and vanilla mainly in Lume and Mutwanga. The oil palm also remains strongly represented in Oicha, Beni, and Mutwanga. This distribution of structural crops, as

reported by the farmers, confirms our fourth hypothesis regarding the territorialization of the agricultural system around Virunga. The expansion of cash crops around protected areas poses a significant challenge in a context marked by population growth, economic incentives, and particularly acute governance issues. Furthermore, Du et al. (2024) highlight that understanding the processes of territorialization in the expansion of structural crops enables the development of more effective policies, particularly for evaluating and reducing their impact on natural ecosystems.

Additionally, this territorialization of cash crops reveals a spatial reorganization of the agricultural system around Virunga National Park, where some crops play a more essential role in land-use changes than others. These crops can help stabilize agricultural systems when integrated into agroforestry systems (Tschardt et al., 2012), but they can also put more pressure on natural landscapes when combined with new land acquisitions in forested areas. This is especially true for cocoa, whose expansion is both continuous and rapid, around Virunga National Park and throughout tropical forests, as highlighted by Ordway et al. (2017). This warrants careful consideration, as the community still strongly desires to expand cacao cultivation, motivated by economic concerns. Ngouhouo-Poufoun et al. (2024) highlights that when a household switches from subsistence farming to commercial cacao farming, each dollar earned results in seven times more deforestation compared to the same amount earned through subsistence farming.

6.4.6. Towards a systemic view of agricultural homelessness in the northwestern landscape of the Virunga

Agricultural itinerancy and its effects on deforestation and forest ecosystem degradation in northwestern Virunga stem from a combination of agronomic, economic, cultural, land, and security challenges unique to the region. This issue extends beyond slash-and-burn farming. More specifically, farmers' perceptions of stabilizing agricultural activities in existing farming areas are based on four prioritized pillars as follows: improving safety in agricultural zones, promoting urban agriculture that can value undeveloped spaces, strict regulation of the use of forest land, and enhancing the farmers' agricultural productivity (Figure 6-5). These findings confirm our fifth hypothesis. These factors aim to balance increased production with the preservation of forests and ecosystem services (Khan et al., 2025). However, agroforestry is not explicitly presented as an alternative to maintaining the spatial stability of agriculture around Virunga. This can be explained by the fact that local populations perceive non-burning technique, applicated in the landscape, as a comprehensive agroforestry method (De Merode and Jérôme, 2025), thereby creating

a mosaic landscape of forests alongside fields. This approach aligns with the FAO's definition of conservation agriculture, emphasizing the integrated management of soil, water, and biodiversity (Giller et al., 2009).

Beyond the local context, experiences from other regions provide useful insights. Kilawe et al. (2018) note that land policy reforms in Tanzania have helped farmers shift to permanent agriculture. Similarly, Rasul & Thapa (2003) add that in Nepal, the introduction of a shifting agriculture tax has motivated people to settle their farming activities. Furthermore, Austin et al. (2017) emphasize that an obstacle to the uncontrolled expansion of crop areas in the forest is the spatial agricultural development plan, which designates areas for specific crops and defines stakeholders' responsibilities regarding forests. In the northwest of Virunga, new initiatives are emerging to control unregulated agricultural growth. One such initiative is "Green Agriculture, Peace, and Non-Violent," launched by the Virunga Alliance. By geolocating farmers, the Alliance helps prevent deforestation linked to agriculture and promotes environmentally sustainable practices. This also enhances product traceability and fights smuggling and armed conflicts, especially since the northwest of Virunga, a vital part of the Congolese government's "aggressive agriculture" policy, is a hotspot for cash crop production, particularly cocoa (Henrard and Huart, 2025). Furthermore, some authors argue that the stability of agricultural expansion also requires integrated landscape management and improvements in agricultural seeds (Fenta et al., 2020). In northwest Virunga, the integrated spatial organization of agricultural lands must necessarily limit spatial competition between cash and subsistence crops. For example, a zoning system that combines cash crops, subsistence farming, and fallow areas would promote an agricultural cycle grounded in fallow periods. Without balanced land use management, and given that economic incentives mainly favor cocoa cultivation, subsistence crops could lead to an increase in land demand. Additionally, it would be useful to link crop type to household field sizes (Slariya, 2014). For smaller plots, priority should be on subsistence crops. More broadly, strengthening small farmers' ability to make wise decisions about how to use their agricultural land is crucial (Tegegne et al., 2016).

6.4.7. Potential biases of study

It is essential to note that the study took place in a specific setting marked by insecurity in northwest Virunga. This environment can shape how actors perceive certain phenomena, influencing the interpretation of results within a particular sociopolitical context. Rather than undermining the validity of the findings, this situation underscores the need to consider agricultural itinerancy within its territorial and sociopolitical framework when analyzing farmers' decision-making. Similarly, Yang et al. (2015)

highlights that the challenging environment, characterized by conflicts and limited access, affects how the local population perceives priorities in natural resource management.

6.5. Partial Conclusion

The present study examined shifting cultivation, identified as the primary driver of forest degradation in the northwest Virunga landscape. The results show that the decision to acquire new agricultural land in mature forests considers several factors simultaneously, rather than focusing solely on the observation of fallow land. This mainly involves households' perceptions of opportunities in cash crop markets, soil fertility, available financial resources to invest, and the resilience of agricultural activity in the face of insecure conditions. While newly acquired lands are often highly vulnerable to deforestation, this perspective clarifies both the underlying motivation for land expansion and the mechanisms by which pressure is exerted on natural forests. When aggregated spatially, individual perceptions reveal a strategy for consolidating control over land in the natural landscape through cash crops. It reveals differentiated patterns of cash crop dominance across the landscape. This suggests an ongoing transformation of the farming system, situated at the crossroads of sustainable agriculture and industrial agriculture. Although land acquisition remains informal and poorly regulated, the findings indicate that no-burning practices are associated with lower reported frequencies of mature forest conversion compared to slash-and-burn systems, highlighting a potential pathway toward more sustainable land-use transitions.

In the northwest Virunga landscape, stabilizing agriculture in the non-forested area requires a balance between households' socio-economic perceptions and environmental considerations. Policy implications emerging from the results include promoting the no-burning land preparation system across the landscape. Additional key measures for the overall strategy include enhancing safety in former agricultural areas and establishing land-use regulations that reflect domestic and environmental priorities, progressing from park to village. In this framework, cash crop plantations would serve as an impenetrable barrier at the perimeter, while also preserving ecosystem services in both natural and agricultural zones. It is also critical to improve land tenure to facilitate a transition from informal to formal legal status. Any proposals to stabilize agriculture on current land must include investment in an interactive geographic information system (GIS) to support necessary land-use reforms.

Chapter 7

7. Assessing Urban Expansion in Beni and Butembo (DRC) using Planet Imagery and Landscape Metrics amid Demographic Growth and Insecurity

Reference

Musavandalo, C.M., Sikuzani, Y.U., Mweru, J-P.M., Mobunda, J.T., Ndukura, C.M., Bogaert, J., 2026. Assessing urban expansion in Beni and Butembo (DRC) using planet imagery and landscape metrics amid demographic growth and insecurity. *Discov Cities* **3**, 83 (2026). <https://doi.org/10.1007/s44327-026-00265-5>

Chapter positioning in the overall analysis

Chapter 7, which focuses on the analysis of urbanization, complements other sections by adding a structural perspective to landscape dynamics. It emphasizes urban expansion as a key driver of resource pressure and landscape transformations. Urbanization drives the dynamics of peripheral agricultural areas and leads to the loss of green, wooded areas.

Abstract

This study examines the urbanization of Beni and Butembo, two urban centers located on the outskirts of Virunga National Park, facing intense demographic pressure amid insecurity. Understanding urban expansion in this region, amid insecurity, is important because it directly affects land-use planning and the management of Virunag National Park. It evaluates urban growth from 2016 to 2023 using high-resolution Planet satellite imagery and quantitative landscape structure metrics, including the Shannon index, to capture the spatial patterns and elucidate the trajectory.

The results reveal a substantial difference in urban growth between Beni and Butembo. Although Beni's population is growing at four times the rate of Butembo, its annual urbanization rate is lower. Butembo's urbanization averages 11.85% annually, ranking it among the fastest-growing cities in the North-West Virunga region. Its urban area has doubled in size over the past 7 years, with 42.54 km² of green space converted to built-up land. In contrast, Beni's rate is 7.20%, with 17.36 km² transformed. These differences are largely explained by the relative stability of security in Butembo compared to Beni. Analyzing landscape indicators alongside the Shannon entropy index highlights varying degrees and patterns of peri-urbanization across the cities. Urban expansion is anisotropic, influenced mainly by security concerns and partly by topography, with growth toward the north-east and south-east in Butembo, and toward the north-west and south-west in Beni.

These results provide a decision-making tool for local authorities, offering a detailed understanding of the spatial dynamics of urbanization. All stakeholders must take ownership of these results to strengthen territorial planning and promote sustainable urbanization in Beni and Butembo.

Keywords: Virunga, urban sprawl, land cover change, armed conflict, urban-rural gradient

7.1. Introduction

Urbanization is a global concern that increasingly captures the attention of both scientists and policymakers. It represents a major pathway of change in forest and agricultural areas, involving city growth, spatial expansion, and densification (Wei et al., 2024). This process is especially rapid in developing countries, where natural landscapes are often converted into urban areas with less planning. By 2050, driven by economic incentives and the pursuit of better living conditions, more than half of Africa's population is projected to reside in urban areas, a significant increase from just 10% in the 1950s, often in vulnerable environments or near biodiversity hotspots (Güneralp et al., 2018; Olfato-Parojinog et al., 2024).

The Democratic Republic of the Congo faces numerous development challenges and is experiencing rapid urbanization. According to the 2018 World Bank report, the urbanization rate stands at 4.1%, impacting both large cities, such as Kinshasa, Lubumbashi, and Kisangani, as well as smaller urban areas, including Butembo and Beni. Many studies have explored the effects of urbanization on green spaces in large cities by combining remote sensing with spatial structure metrics, using a point observation approach over extended time periods (Balandi et al., 2024; Kabanyegeye et al., 2024; Sikuzani, 2019). However, the unique situation of small towns, particularly those affected by armed conflicts in North Kivu, is less thoroughly documented. Additionally, the topic of urbanization gradients and anisotropy, examined through high-resolution spatial images, is less documented in northwest Virunga. This creates challenges for urban planning, both inside the city and in relation to existing protected areas. This study seeks to address this gap context.

This study is situated within the context of rapid urbanization and increasing land pressure surrounding Virunga National Park. It focuses on Beni and Butembo, two key cities in the North-West of Virunga, due to their economic development in a fragile security environment. These cities represent a typical case of African cities facing land pressure, security instability, and ecological challenges. Like many cities in North Kivu, Butembo and especially Beni are suffering the consequences of the ongoing war environment in the DRC since 1997, worsened since 2014 by the activism of the Ugandan terrorist group Allied Democratic Forces (ADF) and other local armed groups, leading to a massive rural exodus (Musavandalo et al., 2024; Posite et al., 2025). This insecurity has led to a significant exodus from rural areas to urban centers. From 2016 to 2023, the city of Beni grew from 363,964 to 1,144,134 inhabitants, recording a 215.00% increase in just seven years, a typical pattern for a city at war. During the same period, Butembo increased from 799,641 to 1,188,183 inhabitants, a 48.00% rise. Theoretically, the spatial growth of urban centers is

characterized by two processes: diffusion and coalescence (Dietzel et al., 2005). However, in the context of armed conflict, the urbanization process remains unpredictable and highly dynamic (Baumann and Kuemmerle, 2016).

Sustainable urbanization in Beni and Butembo has become crucial for reducing human impact on natural resources in the Democratic Republic of the Congo's eastern region. These cities are part of the Kivu Kinshasa Green Corridor's six key urban centers. This green corridor covers 544,270 km² and serves as a protected area dedicated to conserving nature, fostering a green, integrated economy, and combating climate change (De Merode and Jérôme, 2025). Given their close location to Virunga National Park, monitoring their urban development is especially important. The growth of these cities offers economic opportunities but also presents ecological challenges, both directly and indirectly (Follmann et al., 2021). It necessitates careful monitoring to align with the Sustainable Development Goals outlined in Agenda 2030 (Estoque et al., 2021). Unfortunately, like many other cities, Beni and Butembo lack formal urban development plans. Critical data, such as the rate and pattern of urbanization, vital for sustainable planning, are insufficiently documented. Nonetheless, most research has concentrated on how the surrounding landscape has been transformed by human activity (Bweya et al., 2019; Posite et al., 2025), often neglecting the urbanization process itself. Gaining deeper insight into the urban dynamics of Beni and Butembo is vital for developing sustainable strategies tailored to the regional context. This study aims to contribute to a more detailed and up-to-date analysis of the recent urban expansion of these cities in the context of security instability. It uses Planet images with a 3-meter resolution to accurately map the evolution of the urban matrix (Pickering et al., 2021). This study provides an optimal understanding of urban space use. It serves as a diagnostic tool to help decision-makers identify areas for densification and control of urban sprawl. By comparing Butembo, a commercial city relatively unaffected by recent security instability, with Beni, a city heavily impacted by significant security upheavals over the past decade, this study seeks to understand how these factors influence urban growth and development patterns.

The central hypothesis is that the security and economic contexts specific to each city play a more decisive role in urbanization than the demographic context alone. Thus, despite more moderate population growth, Butembo benefits from a commercial function that is a powerful driver of its expansion, compared to Beni. This commercial vocation, by stimulating land investment and residential sprawl (Nuisl et al., 2021) leads to faster urbanization in Butembo than in Beni. This hypothesis has been subdivided into three sub-hypotheses: (1) From 2016 to 2023, Butembo experienced a faster rate of urban expansion due to its relatively calm economic and security

context compared to Beni, which doubled the built-up areas over eight years. (2) Urbanization in both cities follows a monocentric spatial gradient, with dense, compact city centers characterized by high Largest Patch Index (LPI) and Percentage of Landscape (PLAND) values, as well as low spatial diversity. Meanwhile, the peri-urban area shows increasing fragmentation, with significant decreases in LPI and PLAND and an increase in spatial diversity. Additionally, the built-up areas added annually are significantly greater in the peri-urban area than in the center, reflecting a more intense urban growth dynamic spreading across the peri-urban area than in an already saturated central urban core (3) Butembo extends more to the east than to the west due to land constraints, security issues, and the steep terrain to the west, while Beni extends more to the west, considering the steep terrain, the proximity to Virunga National Park, and the hotspot of insecurity in the East..

7.2. Materials and Methods

7.2.1. Study area and limit of the interest area

Beni and Butembo are two cities located in the northern part of North Kivu Province, in the Democratic Republic of the Congo. Approximately 2,000 km from Kinshasa, Butembo and Beni, together with Goma, are the primary urban centers near Virunga National Park. The region's climate is tropical equatorial, moderated by the Butembo Mountains. In Beni, the average temperature is approximately 23.52°C, with annual rainfall averaging 1,988mm (Posite et al., 2025). In Butembo, the mean temperature is approximately 18°C, with an average annual rainfall of around 1,400mm (Mahamba et al., 2022). The economies of these cities rely mainly on agriculture and commerce (Bweya et al., 2019; Sahani Muhindo, 2011). Since 2014, however, security issues caused by various illegal armed groups have disrupted these activities (Musavandalo et al., 2024).

The study did not account for each city's administrative boundaries, as these do not accurately represent the extent of urbanized areas. Instead, a circular zone was created around each city center, using the farthest built-up point from the core as a reference. This choice is justified because the current expansion of both cities goes well beyond their administrative boundaries and into areas belonging to other territorial entities. Limiting the study to administrative boundaries could therefore underestimate the real extent of urbanization by excluding areas already part of urban dynamics. Additionally, the circular approach enables a more effective analysis of the urbanization gradient, considering the gradual transition between the urban core, peri-urban zones, and surrounding rural areas. For example, a circle with an 8 km radius, covering 176.49 km², was drawn for Butembo, while a circle with a 7 km radius,

covering 132.53 km², was used for Beni. It is important to note that in Beni, the upper limit of the buffer zone was defined by the Virunga National Park, located 7 km from the city center. That is why there was approximately a 1 km shift in the gradient between Beni and Butembo.

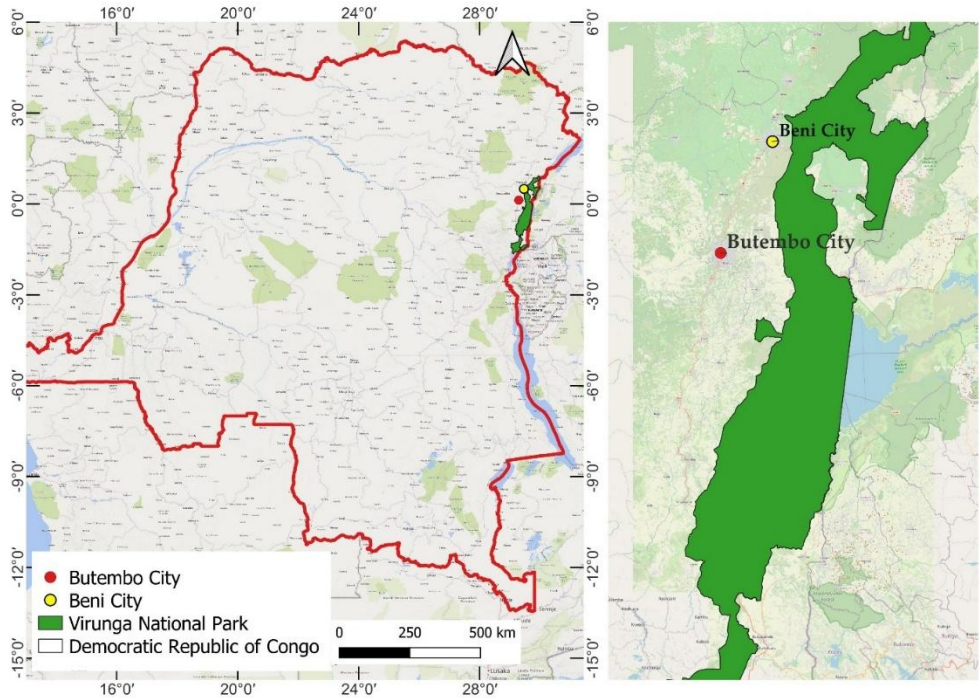


Figure 7-1. Study area location in the eastern part of the DRC. The map on the right shows the study areas near Virunga National Park on an OpenStreetMap background.

7.2.2. Method

7.2.2.1. Acquisition of spatial data

This study spans from 2016 to 2023. The chosen timeframe is based on the availability of high-resolution Planet images, which are freely provided through the Norway International Climate and Forest Initiative (NICFI). The Planet images, with a spatial resolution of 3 meters, include four spectral bands: red (650-680nm), green (547-585nm), blue (465-515nm), and near-infrared (854-885nm). These cloud-free images have allowed overcoming the limitations of urban expansion analysis with Landsat sensors (Helman et al., 2018; Obi-Ani and Isiani, 2020; Pickering et al., 2021). Additionally, this period aligns with a significant movement of rural populations fleeing insecurity and seeking safety, especially in the areas surrounding the two cities

and Beni. Consequently, the study is divided into two main phases: 2016–2019, characterized by high instability in rural regions around Beni and Butembo cities, and 2019–2023, marked by decreasing security tensions, particularly near Beni's outskirts.

7.2.2.2. Image Processing and Classification

The acquisition and processing of Planet images were conducted using the Google Earth Engine platform by using a code editor (Gorelick et al., 2017; Pouya and Aghlmand, 2022). For each observation period, a composite image was generated by calculating the median values of all available monthly images, which helps to minimize seasonal effects on the results (Gxokwe et al., 2022). Two primary land cover categories were identified as the main urban elements in the two cities: built-up areas, including residential zones and artificial surfaces (grey space), and green spaces, which encompass all types of vegetation within the city (Fomba et al., 2024). Supervised classification was performed using the Random Forest algorithm, chosen for its robustness and ability to identify complex spatial and spectral patterns. The classification model was trained with 100 decision trees and 350 training points, distributed as follows: 130 points for built-up areas, 130 for meadows and agricultural lands, and 90 for forested areas. These points are derived from field data and the visual interpretation of Google Earth and Planet images. Only surfaces that remained stable over the past 8 years were retained as references for training. Training points were gathered and used for each analysis period to maintain consistency in the classification process. Additionally, 150 points (50 per land cover class) were used to independently assess the classification quality. The classification performance was measured using standard indices, including the Kappa coefficient and overall accuracy. As indicated in Table A-6 in the appendix, the overall accuracy ranges from 0.88 to 0.97 in Beni, then from 0.86 to 0.97 in Butembo.

7.2.2.3. Landscape metrics used

This study examines urbanization from three perspectives: land cover dynamics, focusing on urban expansion, its variation along an urban-rural gradient, and its geographic progression. These aspects are mainly analyzed through the development of spatial structure indices. The main landscape structure indices used are listed in Table 7-1. These indices are used to understand land cover changes and to characterize the ongoing urbanization process (Nong et al., 2018). They were derived from land cover classification data and can be applied at the scale of a patch, a class, or the entire landscape (Carvalho et al., 2009; Dietzel et al., 2005). The Largest Patch index was used at the built-up class scale to assess fragmentation within this class.

Table 7-1. Landscape metrics used in this study

Indice	Equation	Description	Diffusion	Coalescence
Percentage of landscape (PLAND)	$PLAND_i = \frac{\sum_{i=1}^n a_{ij}}{A}$	a_{ij} = area (km ²) of the patch ij A = total area of land space Interval: 0 ≤ PLAND ≤ 100	Increase	Increase
Large Patch Index (LPI)	$LPI = \frac{Max_{a_{ij}}}{A} \times 100$	a_{ij} = area (km ²) of the patch ij A = total area of class Range: 0 ≤ LPI ≤ 100	Decrease	Increase

7.2.2.3. Land cover change analysis

For each urban center, urban expansion was primarily assessed using three parameters: changes in surface area of built-up and green spaces, the annual urbanization rate, and the intensity of urbanization. The annual rate measures relative growth compared to existing urban areas. Analyzing urbanization intensity helped connect urban growth to the total urban surface, illustrating the speed of urbanization and the pressure on undeveloped green spaces (Yang et al., 2018). The formula below was used to calculate urbanization intensity:

$$UEI = \frac{U_{i+n} - U_i}{A} \times \frac{1}{n} \times 100$$

With UEI defined as Urban Expansion Intensity, U_{i+n} and U_i represent the urbanized areas at times $i+n$ and i ; n is the time interval, and A is the total area of the study zone. To define the level of urban expansion intensity, the study used the standard classification proposed by HU et al. (2007). The urban expansion intensity was divided into 5 levels: high-speed expansion ($UEI \geq 1.92$), fast-speed expansion ($1.05 \leq UEI < 1.92$), medium-speed expansion ($0.59 \leq UEI < 1.05$), and slow expansion ($0 \leq UEI < 0.59$). The overall results obtained allowed testing the first hypothesis of this study, which assumes a faster urbanization rate in Butembo than in Beni.

7.2.2.4. Analysis of urban expansion along urban-rural gradient

Urban expansion often occurs across multiple spatial scales and can take various forms. The city may grow outward from the core to create a concentric pattern or expand around multiple centers (Nkeki, 2016). To evaluate the study's second hypothesis, which proposes a monocentric expansion toward the outskirts, each city was divided into concentric circular zones spaced 1 kilometer apart from the city center. Beni was divided into seven concentric zones, while Butembo was divided into eight. This method enabled tracking urbanization progress along the urban-rural

gradient and highlighted zones of active urban growth (Ramachandra et al., 2015). Landscape indices, such as the PLAND and Largest Patch Index, were computed within each concentric zone, based on the concept of urban land density (Jiao, 2015; Xu et al., 2019), which indicates a gradual decrease in these indices in the city center (urban core), a steep decrease in the peri-urban zone, and another gradual decrease in the rural areas. Furthermore, the analysis of monocentric urban expansion was enhanced by evaluating the Largest Patch Index using the cumulative aggregation method of temporal zones with different surface areas. The goal was to study how the built-up area configuration evolves with the size of the circular zone around the city center. The sub-hypothesis assumes that analysis focused solely on a concentric center effectively distinguishes the gradient of urban fabrics, whereas aggregating concentric circles diminishes spatial contrast during peri-urbanization. These two approaches, studying each concentric zone in isolation and aggregating them, highlighted the metric's sensitivity to the size of the analysis window.

The Shannon entropy index was used to assess spatial diversity along the urban-rural gradient, with the hypothesis that it decreases in central zones, rises in peri-urban areas, and then falls again in rural regions (Nkeki, 2016).

$$H_n = -\sum_{i=1}^n P_i \ln(P_i)$$

P_i represents the proportion of built-up areas within the concentric zone i , and n the number of land cover (2). This index approaches zero when either built-up areas or green spaces dominate, and it approaches $\ln(2)$, or approximately 0.69, when there is a balance between the two. Analyzing these three indices together enables the identification of compact urban zones, peri-urban tendency zones, and rural areas (Yang et al., 2018).

In addition to assessing the spatial diversity in each concentric zone, the Shannon entropy index was used to complement the evaluation of the degree of urban sprawl (Dhanaraj and Angadi, 2021).

$$H_m = -\sum_{j=1}^j P_j \ln(P_j)$$

With P_i representing the proportion of built-up areas and m the number of concentric circles (8 in Butembo and 7 in Beni), the value of H_m tending towards $\ln(j)$ indicates the dispersion of the urban area. Conversely, when it tends toward 0, it indicates the compaction of the urban area. The overall dispersion, measured by H_m , allows us to evaluate the trend of peri-urbanization or densification, while the local diversity H_n within each concentric zone helps identify regions where peri-urbanization is active. Finally, the most active urbanization areas were identified based on the ratio between the built-up area added within the concentric zone i and the total built-up area added across the landscape during the same period. For each concentric zone, the

built-up area added between 2016 and 2019 and then between 2019 and 2023 was calculated in absolute value (km²). A cumulative distribution of the additions to built-up areas as one moves away from the city center was created to track the spatial progression of urbanization (Yang et al., 2018).

7.2.2.5. Directional analysis of urban expansion

The city's growth varies depending on direction. Recognizing active urbanization zones is crucial for sustainable development. To analyze the anisotropic expansion trend, which is the third hypothesis of this study, Beni and Butembo were divided into four equal-area sectors: Northeast (0°-90 °), Northwest (90°-180 °), Southwest (180°-270 °), and Southeast (270°-360 °). This segmentation originates from the central business district (CBD), considered the historical starting point of built-up area expansion (Nkeki, 2016). The initial step involved overlaying three built-up layers on a digital terrain model to visually assess expansion, while accounting for topography. The next step quantified expansion in each sector using two metrics: PLAND and the largest patch index. While PLAND highlighted preferred expansion zones, the largest patch index provided deeper insights into the spatial configuration changes in built-up areas within each zone.

7.3. Results

7.3.1. Spatial dynamics of landscape and urban expansion intensity in Beni and Butembo

Figure 7-2 shows urban expansion in Beni and Butembo from 2016 to 2023. The visual analysis indicates that these two cities are growing in a monocentric pattern, expanding outward from their existing urban cores. Built-up areas experienced significant growth between 2016 and 2019, compared to the period from 2019 to 2023. Additionally, Beni, as a crossroads, primarily shows urban expansion in the eastern part, driven by major roadways connecting it to Uganda and Kisangani.

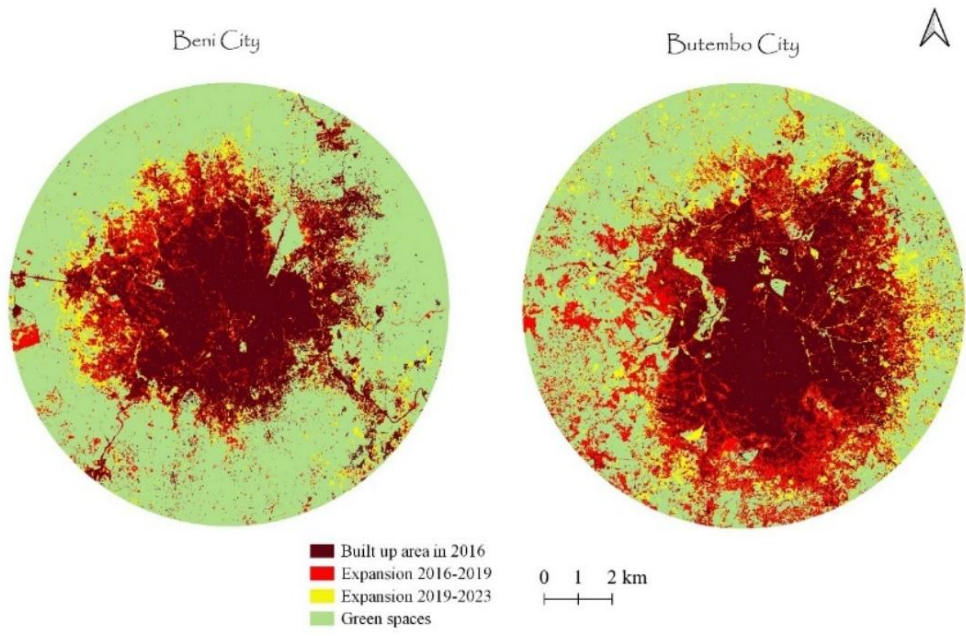


Figure 7-2. Map of urban expansion in Beni and Butembo cities

Table 7-2 presents the quantified urban changes between 2016 and 2023. During this period, built-up areas in Butembo nearly doubled, showing a more pronounced growth compared to Beni. By 2023, more than half of the urban landscape in Butembo was covered by built-up areas, whereas in Beni they accounted for 39.11%.

Table 7-2. Land cover dynamics in Beni and Butembo Cities from 2016 to 2023. The proportion of was calculated based on the total area of each city, namely 176.49km² for Butembo and 132.53km² for Beni

City	Year	Built-up area		Green spaces	
		Km ²	%	Km ²	%
Butembo	2016	51.48	29.17	125.01	70.83
	2019	84.43	47.84	92.06	52.16
	2023	94.18	53.36	82.31	46.64
Beni	2016	34.46	26.00	98.07	74.00
	2019	44.85	33.84	87.68	66.16
	2023	51.83	39.11	80.70	60.89

7.3.2. Annual urban growth rate and expansion intensity

Table 7-3 presents two complementary indices: the annual urbanization rate, which measures relative growth compared to existing urbanization, and the urbanization intensity, which assesses growth across the entire studied landscape. These results show that both cities experienced significant urban expansion during two key periods. A high annual urbanization rate and strong expansion intensity mark the period from 2016 to 2019. During these years, both cities grew rapidly. It is important to note that this period also coincides with a significant wave of displacement related to terrorist attacks by the ADF group in rural areas. After 2019, expansion slowed slightly compared to the previous period. However, overall, Butembo has a higher average annual urbanization rate than Beni. Throughout the entire period, the study indicates that Butembo experienced high-speed expansion, while Beni experienced fast-speed expansion. In terms of area, this translates to 47.70 km² of Butembo's landscape being transformed into built-up areas, compared to 17.36 km² in Beni.

Table 7-3. Annual growth and Expansion Intensity of urban areas in Beni and Butembo Cities. (The annual growth indicates a relative increase in built-up areas, while the intensity of urban expansion represents the annual expansion relative to the total extent of the landscape)

City	Annual Growth rate (%)			Urban Expansion Intensity (%)		
	2016-2019	2019-2023	2016-2023	2016-2019	2016-2019	2016-2023
Butembo	21.34	2.89	11.85	6.22	1.38	3.46
Beni	10.05	3.89	7.20	2.61	1.32	1.87

7.3.3. Degree of sprawl and spatial configuration of built-up area across buffer zones

Overall, Shannon's anthropic index (H_m), which measures the dispersion of built-up areas, shows values close to $\ln(m)$ for each valley. In Butembo, these values were 1.72 in 2016, 1.70 in 2019, and 1.60 in 2023, approaching 2.08. In Beni, they increased from 1.20 in 2016 to 1.09 in 2019, then to 1.16 in 2023. These minor fluctuations indicate a gradual pattern of urban sprawl, with coexistence between expanding and densifying zones. Additionally, figure 7-3 provides an overview of the built-up area configuration from 2016 to 2023. It shows a gradual decrease in the dominance of the large built-up patch as the buffer zone radius around the city center increases, although it remains above 80.00%. These high values of the Largest Patch Index reflect a trend of monocentric urbanization, characterized by the expansion of built-up areas mainly around the existing urban core.

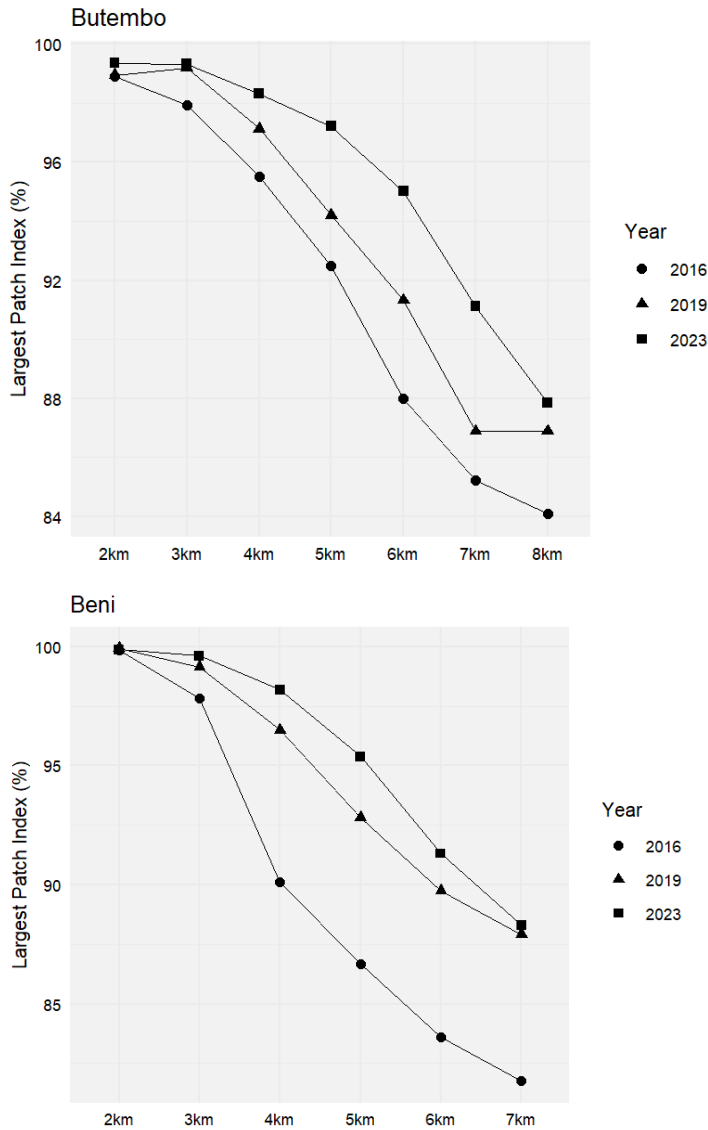


Figure 7-3. Illustration of the monocentric nature of urban expansion in Beni and Butembo, highlighted by the evolution of the largest patch index as the buffer zone increases. It illustrates the evolution of urban fabric's overall structure. It shows the aggregation of built-up patches over time.

7.3.4. Variation of urban structure and diversity along concentric urban gradient

Figures 7-4 and 7-5 depict how the composition and spatial configuration vary along the urban-rural gradient. Generally, the proportion of built-up areas decreases with increasing distance from the city center. The cities are divided into three segments: densely built-up zones, extending up to 4 km in Butembo and 3 km in Beni; transition areas, stretching from 4 to 6 km in Butembo and 3 to 5 km in Beni; and rural zones, beyond 6 km in Butembo and 5 km in Beni. The spatial patterns show an aggregated urban expansion up to 5 km in Butembo and 4 km in Beni, followed by a slight spread between 5 and 6 km in Butembo and 4 to 5 km in Beni. Past these distances, built-up areas become more scattered. A minor rise in the Largest Patch Index at 6 and 7 km in Beni may be due to industrialization, such as the BRASIMBA brewery and toll zones, which are attracting residents to the outskirts.

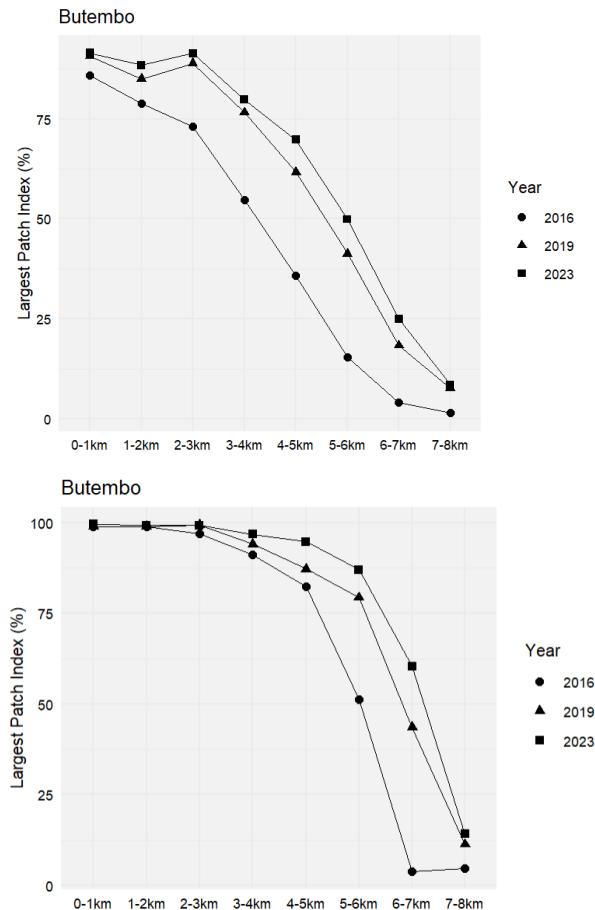


Figure 7-4. Urban Expansion Trends Along the Urban-Rural Gradient in Butembo. The proportion of landscape and the largest patch index represent the values in concentric zones. The largest patch index indicates the dominance of the built-up class.

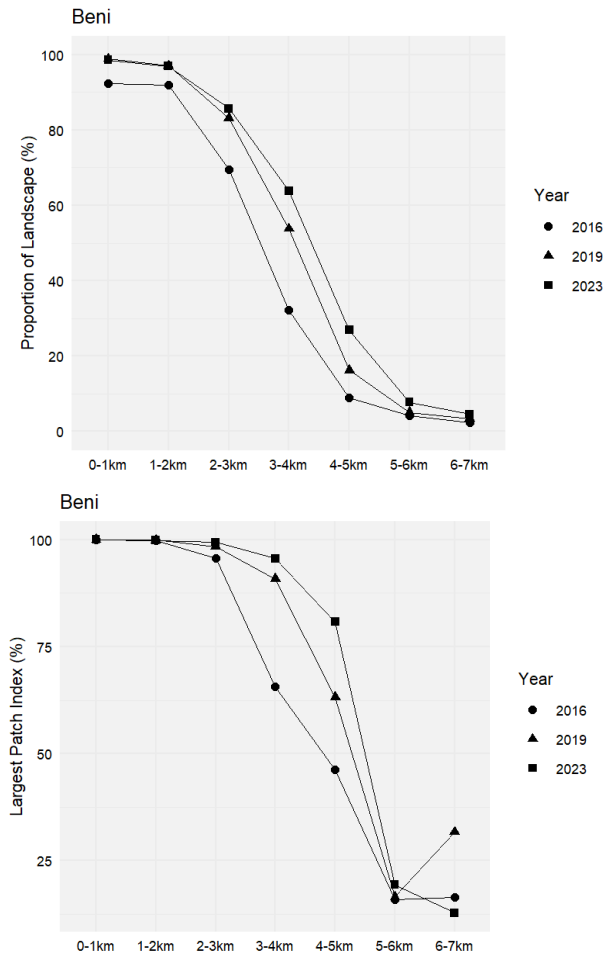


Figure 7-5. Urban Expansion Trends Along the Urban-Rural Gradient in Beni. The proportion of landscape and the largest patch index represent the values in concentric zones. The largest patch index indicates the dominance of the built-up class.

Figure 7-6 illustrates how spatial diversity changes along the urban-rural gradient. The Shannon index H_n forms an inverted U-shape, with low diversity in the urban core, which is mainly built-up. It then peaks in the peri-urban zone, where built-up areas and green spaces coexist, before declining in rural areas, which are mainly covered by green spaces. In Butembo, this diversity decreases over time within the first four gradients due to the densification of built-up zones. The maximum spatial diversity was observed between 4 km and 5 km from the city center in 2016, shifting to 5-6 km

in 2019 and 2023. In Beni, diversity diminishes within the first three kilometers, reflecting the dominance of built-up areas. The highest diversity was reached between 3 km and 4 km.

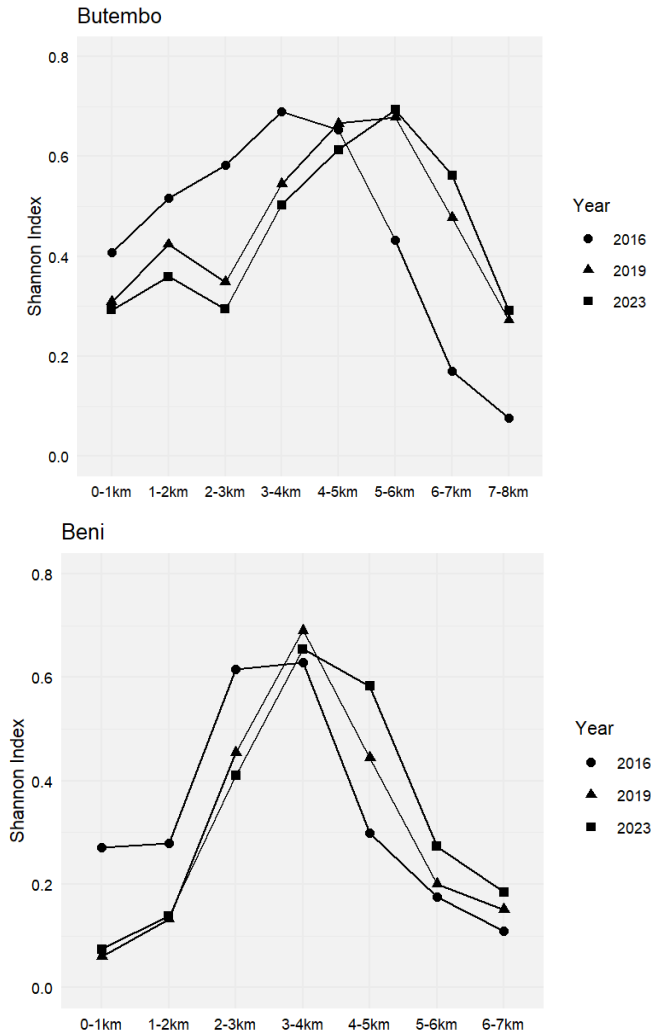


Figure 7-6. Trends in spatial diversity along the urban–rural gradient. Low values indicate dominance by a single patch, while high values indicate a diverse set of patches and a balance between built and green spaces. A low value in the center shows the dominance of built-up areas, whereas a low value in the periphery reflects the dominance of green spaces.

7.3.5. Built-up area added by concentric zones in the urban-rural gradient

Figure 7-7 shows how each distance gradient contributes to urban growth in each city. It highlights areas of active urbanization, where green spaces are notably converted to built-up areas. In Beni, from 2016 to 2023, more than 80.00% of green space conversions occurred within a 3- to 5-km radius of the city center, indicating a trend of outward expansion and inward retreat. Similarly, in Butembo, the major transformations into built-up areas are mainly between 4 and 7 km from the center. This pattern, supported by spatial diversity and the Largest Patch Index, suggests that the transition zone between urban and rural areas is broader in Butembo than in Beni

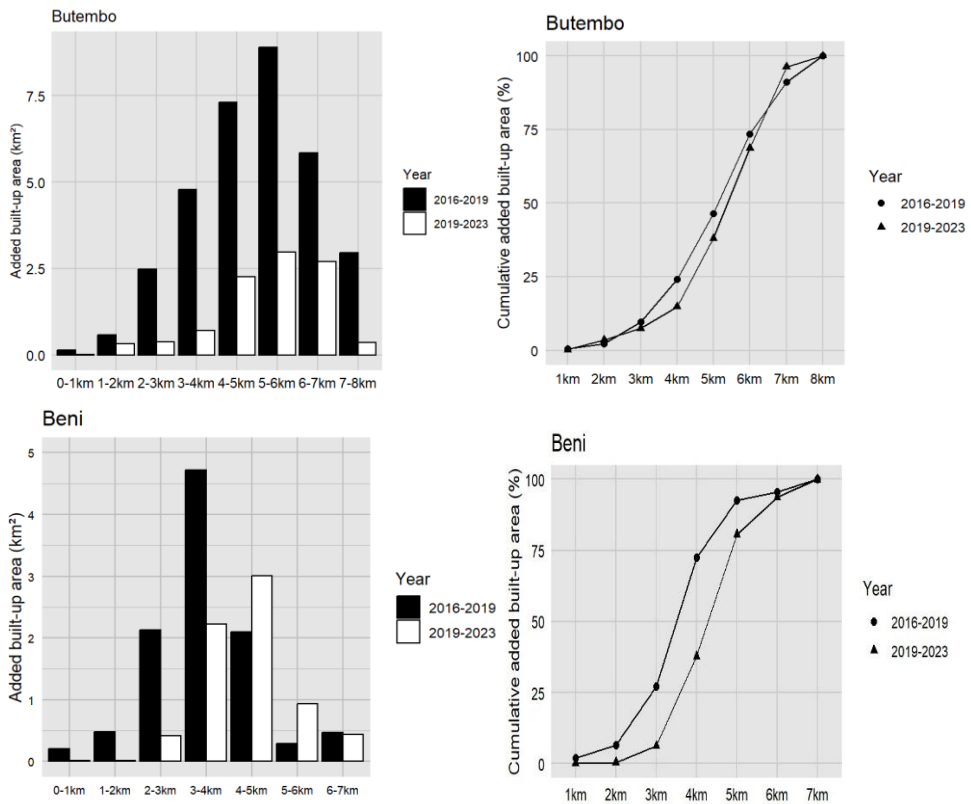


Figure 7-7. Trends of the contribution of each distance gradient to the total Urban expansion. On the left, the absolute values of the built-up areas added in each concentric zone, and on the right, the cumulative proportional values of these areas.

7.3.6. Urban expansion in the fourth anisotropic sector in Beni et and Butembo

Figure 7-8 shows urban expansion relative to terrain constraints, assuming higher built-up density favors hilly areas over steep terrain, protected areas, or land tenure constraints. The map reveals that the built-up area in Butembo is denser to the north and southeast compared to the northwest and southwest, where the terrain is steeper. In Beni, urban growth mainly occurs to the north and southwest, with limited expansion to the northeast due to Virunga National Park, and to the southeast due to steep terrain.

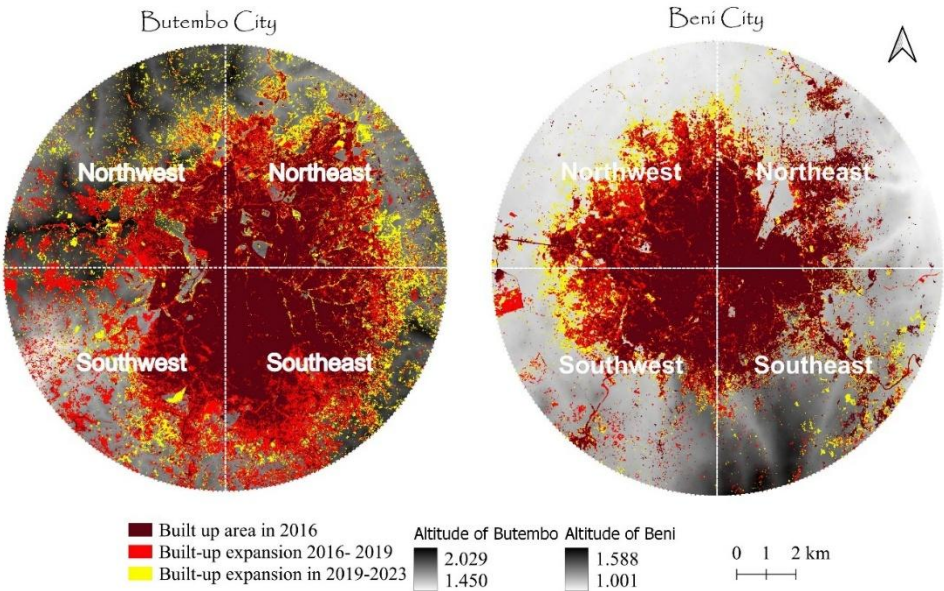


Figure 7-8. Map of urban expansion in the fourth anisotropic sector in relation to relief constraints

Tables 7-4 and 7-5 illustrate the anisotropic patterns of urbanization. In Beni, the extent of urban expansion varied more across the four sectors, both in terms of composition and configuration. The built-up area grew by 22.8% in the Northwest and 15.41% in the Southwest, whereas in the North and Southeast, the increases were 6.60% and 7.45%, respectively. By 2023, almost half of the Northwest and Southwest regions had already undergone urbanization. Regarding configuration, differences between the four sectors remained minimal. The Largest Patch Index consistently stayed above 79.00%. In Butembo, urban growth varies across the four sectors in

terms of composition and landscape structure. In 2023, over 60.00% of the territory in the North and Southeast sectors was urbanized, compared to less than 50.00% in the North and Southwest sectors. Built-up areas expanded by 29.04% in the Northeast, 25.24% in the Southeast, 20.38% in the Northwest, and 21.41% in the Southwest. The Largest Patch Index has consistently grown in the East sectors and decreased in the West sectors.

Table 7-4. Anisotropic expansion of urban areas in Butembo

North East	PLAND	LPI
2016	32.12	78.64
2019	47.56	92.06
2023	61.16	91.98
North West		
2016	14.46	78.31
2019	28.59	70.61
2023	35.38	78.70
South East		
2016	47.48	87.84
2019	67.71	92.61
2023	72.72	93.93
South West		
2016	22.51	87.61
2019	47.34	70.17
2023	44.00	79.36

Table 7-5. Anisotropic expansion of urban areas in Beni

North East	PLAND	LPI
2016	26.45	82.30
2019	30.20	85.38
2023	33.05	86.25
North West		
2016	25.16	84.91
2019	39.43	94.62
2023	47.24	94.79
Sud East		
2016	26.70	79.41
2019	28.06	82.99
2023	34.15	81.61
South West		
2016	25.59	80.52
2019	37.55	86.60
2023	41.82	88.09

7.4. Discussion

7.4.1. Methodological approach

The study shows that, in cities facing growing population pressure and security issues, spatial monitoring of urbanization is an effective way to identify changes over time and space, helping to shape sustainable development policies. Using high-resolution satellite imagery, such as that from Planet, provides accurate, up-to-date maps of urban change in vulnerable regions, such as Beni and Butembo. These images capture small landscape shifts, like expansion or contraction, that medium-resolution sensors like Landsat might miss. Weng (2012) notes that satellite image resolution should match the size of the area being studied. In urban areas, high-resolution images are particularly useful for detailed land cover analysis and help minimize errors from pixel mixing, which are common with lower-resolution images and can make interpretation more difficult (Wang and Gong, 2024).

Many researchers use landscape indices to study urbanization. They provide valuable insights into spatial changes and the resulting spatial configurations (Cengiz et al., 2022; Fang and Zhao, 2018; K and Angadi, 2021; Steurer and Bayr, 2020). Often, these indices are combined with the concentric circle method and geographic direction analysis to gain a deeper understanding of the urbanization process and its impact on the natural landscape (Dhanaraj and Angadi, 2021). In this study, various indices (see Table 7-1) were employed to analyze land-use dynamics and, more importantly, the urbanization process within the urban-rural continuum, using a cross-approach to identify trends from 2016 to 2023. Our approach differs from previous studies by using high-resolution spatial imagery, creating an annual composite to minimize seasonal effects, and using short diachronic analysis step to identify changes in rapidly urbanizing environment (Table 6-1).

Chapter 7. Urbanization Patterns of Beni and Butembo

Table 7-6. Comparison of the methodologies and data employed in previous studies on urbanization in Beni and Butembo.

Author	Analysis Focus	Sensor	Delimitation of the study area	Time frame of the diachronic analysis	Methodology for image processing	Main topic addressed
Our study	A comparison between Beni and Butembo	Planet Satellite image	Circular zone	4 years	- Classification using Google earth engine and Forest Classification - Creation of an annual composite image based on the median pixel values of all available images from January to December to reduce the effect of seasonality - Analysis of the spatial pattern of urbanisation: Yes	Urban expansion
Bweya et al., 2018	Exclusively in the Beni region	Landsat	Undefined	23 years	- Classification using maximum likelihood - Creation of a composite image and reduction of the seasonal effect: Not defined - Analysis of the spatial pattern of urbanisation: No	Deforestation
Posite et al., 2025	Exclusively in Beni city	Landsat	Administrative limits non-official	10 years	- Classification using maximum likelihood - Creation of a composite image and reduction of the seasonal effect: Not defined - Analysis of the spatial pattern of urbanization: No	Deforestation
Sahani., 2011	Exclusively in Butembo city	Landsat	Administrative limits	Variable intervals: 18 years, 14 years, 12 years, 2 years and one year	- The undefined classification algorithm - Creation of a composite image and reduction of the seasonal effect: Not defined - Analysis of the spatial pattern of urbanization: No	Managing risks related to natural disasters

7.4.2. Urban sprawl and intensity

Urban expansion and its impact on green spaces are influenced by various physical, social, and societal factors (Rahim Aguejdad, 2009). According to Lwasa (2014), the main drivers of urbanization in African countries include industrialization, population increase, commercial development, and security challenges. The study identifies two primary phases of urbanization in these cities. From 2016 to 2019, urban growth was rapid and intense, mainly due to the activities of the rebel group ADF, which led to increased displacement toward safer urban centers. Subsequently, from 2019 to 2023, the growth rate slowed down. A comparative analysis shows that Butembo experienced faster urban growth than Beni. Its built-up area nearly doubled between 2016 and 2023, with an average annual urbanization rate of 11.85%, meaning about 3.46% of the landscape was transformed into built-up areas each year (see Tables 7-2 and 7-3). Investment in housing is likely to be higher in the city of Butembo, as it presents fewer risks compared to Beni, where frequent attacks and vandalism in the northeast and southeast have often led to property abandonment. Meanwhile, despite higher population growth, Beni's built-up area did not double during the same period. In Beni, despite frequent attacks by armed groups, the town's physical boundaries haven't expanded significantly. This is mainly due to a sudden influx of rural residents displaced by insecurity in surrounding areas. These households, often without sufficient funds to buy land or build new homes, tend to settle within the existing urban space, often with relatives or in already occupied dwellings. As a result, this leads to increased densification inside the town, exacerbating overcrowding and putting more pressure on urban infrastructure.

These findings support the first hypothesis of the study, which states that urban growth is quicker in Butembo due to its economic benefits and relatively stable security situation compared to Beni. In this regard, Butembo is classified under high-speed expansion, whereas Beni falls into the fast-speed expansion category (HU et al., 2007). Persistent attacks by armed groups on the outskirts significantly slow urbanization in Beni. Residents, fearing for their safety, tend to evacuate peripheral neighborhoods for the city center, hindering urban expansion outward (Posite et al., 2025). Similar effects have been observed in Bunia experienced civil war (Büscher and Mathys, 2019). These impacts can be temporary or persistent, depending on each city's specific context (Baumann and Kuemmerle, 2016). Conversely, the fast urban growth in the northwest of Virunga is typical of many medium-sized cities in eastern Democratic Republic of the Congo, such as Kasumbalesa, where economic opportunities lead to expansion (Useni Sikuzani et al., 2024).

The overall analysis of the evolution of the built-up area configuration, based on changes in the buffer zone size, shows a monocentric urban expansion, with new built-up patches often connected to the large existing built-up patch (Figure 7-3). However, this overall analysis reduces the index's sensitivity to local variations. The analysis of the urbanization gradient indicates that both cities are experiencing monocentric growth, with the urban core expanding outward toward the suburbs (see Figure 7-5). This supports the study's second hypothesis. The values of PLAND, the Largest Patch Index, and Shannon entropy reveal three landscape zones: the dense urban area, which extends from the center to 4 km in Butembo and 3 km in Beni; the transition or peri-urban zone, broader in Butembo (from 4 to 7 km) than in Beni (3-5 km); and the rural zone, characterized by dispersed buildings within a vegetated matrix, located after 7 km in Butembo and 5 km in Beni. Sikuzani et al. (2018) conclusion on urbanization in Lubumbashi supports this trend, showing a compact urban core extending between 0 and 4 km. The expansive concentric transition zone indicates rapid urban growth, a characteristic of many small African cities (Xu et al., 2019). In these areas, where 80% of green space has been converted into built-up areas, Shannon entropy reaches its peak, while the largest patch index decreases as one approaches the periphery (see figures 7-4, 7-5, and 7-6). Additionally, in Beni, a slight rise in the Largest Patch Index was observed in rural areas, mainly due to economic infrastructure such as the toll road, Mavivi Airport, and BRASIMBA Brewery, which are gradually drawing residents to the outskirts. Ecologically, the abundance of green spaces, more common in Beni than in Butembo, stems from the high promotion of *Eucalyptus sp* planting by residents and the growth of urban agriculture. These efforts help restore abandoned land, provide economic benefits, and ensure long-term land security (Posite et al., 2025). Investing in these plantations adds economic value and secures land ownership (Kataka et al., 2023), helping owners endure urbanity issues. Pribadi and Pauleit (2015) highlights that, in this context, peri-urban agricultural and forest green spaces are better equipped to withstand urbanization, even during severe economic crises.

7.4.3. Urban expansion trajectories in Beni and Butembo

The pattern of urban growth is shaped by various factors such as terrain features, accessibility, and the location of businesses (Woldeamayrat and Genovese, 2021). Igugu et al. (2024) highlight that, aside from terrain, factors such as security, the local economy, and cross-border trade also influence urban expansion to the east of the Democratic Republic of the Congo. Findings (see Table 7-4 and Figure 7-8) show that in Beni, the built-up area mainly expands toward the northwest and southwest, with limited growth to the northeast and southeast. This directional preference of built-up areas is associated with improved security and early signs of industrial activity,

especially with the establishment of BRASIMBA to the west. Nonetheless, topography, security issues, and the presence of Virunga National Park significantly restrict urban growth toward the northeast and southeast. In Butembo, urban expansion and densification are more prominent in the northeast and southeast sectors than in the southwest and northwest, as shown in Table 7-5 and Figure 7-8. This difference is due to several factors, including rugged terrain, clayey soils, and large wooded areas that stop both individuals' construction in the western part of the city. Additionally, the western sectors have historically faced security issues, which have hindered the development of new residential neighborhoods. These observations support Sahani Muhindo (2011) findings and complete that physical and security constraints influence urban growth patterns.

7.4.4. Implication for sustainable urbanization and nature conservation

Each year, approximately 3.46% of the urban area in Butembo and 1.87% in Beni are converted into built-up zones. Simultaneously, the built-up area per resident grows in Butembo, from 64.39 m² to 79.26 m², while it declines in Beni, from 94.95 m² to 45.30 m². This suggests increased densification in Beni, with more inhabitants per unit of built-up space. From 2016 to 2023, 42.67 km² of land in Butembo has been urbanized compared to 17.36 km² in Beni. These rapid changes present serious challenges, as both cities lack comprehensive urban planning. In the absence of development strategies or land management policies, rapid expansion often pushes farmers into less suitable zones or informal public areas, particularly into agricultural or forested lands (Kuusaana and Eledi, 2015; Sumbo et al., 2023). This uncontrolled peri-urban growth can spark land conflicts, foster land speculation, and disrupt rural land administration, affecting both individuals and institutions (Mudapakati et al., 2024).

Urban expansion guided by effective urban policy can create opportunities to develop and protect green spaces, along with the ecosystem services they offer (Ghosh, 2021). These large, undeveloped areas can support urban agroforestry practices that provide residents with environmental benefits such as food, firewood, and construction timber, reducing their reliance on natural areas outside the city. Sustainable management methods, including urban agriculture and tree planting, are vital, with careful selection of crops and species that suit local conditions. Encouraging diverse urban agriculture can also generate income for city residents (Pribadi and Pauleit, 2015). This process requires authorities to take initial steps, like conducting stakeholder censuses, analyzing land-related power dynamics, and formulating urban planning policies that incorporate green spaces. Additionally, evaluating the economic value of green spaces amid urban growth is essential to measure their contribution to economic and social well-being, which can support their conservation as part of nature preservation efforts

(Ngulani and Shackleton, 2022). In urban space planning, it would be beneficial to establish a green belt in the northeast of Beni, intended to be valued by city residents as green spaces. Managed by the city administration, this belt could act as a barrier to uncontrolled housing growth towards the park. These green zones should support recreation and environmental education, helping to preserve ecological balance for both the park and the city. In Butembo, emphasis could be placed on converting steep, sloped areas, especially to the west, into forestry zones to prevent erosion and ensure the sustainability of urban spaces. While beneficial, the perceived success of all its actions depends on identifying and engaging the owners of undeveloped urban spaces.

7.5. Partial Conclusion

This study enhances understanding of urban growth in Beni and Butembo from 2016 to 2023, in the context of high demographic pressure and unstable security conditions. Urban expansion in both cities occurs in a monocentric pattern, with the existing core expanding outward toward the periphery. The compact urban area predominantly occupies the concentric zones extending from the city center up to 4 km in Butembo and 3 km in Beni. The transition zone, or peri-urban area, is wider in Butembo (from 4 to 7 km) than in Beni (3 to 5 km). Both cities exhibit high average annual urbanization rates, surpassing the national average of 4.00% and typical of most medium-sized African cities.

Overall, the average urbanization rates were 11.85% in Butembo and 7.20% in Beni, with rates varying depending on security conditions. Urbanization increased between 2016 and 2019 during major security crises and slowed from 2019 to 2023 when security was more stable. Over seven years, Butembo nearly doubled its urbanized area, making it the fastest urbanizing city in northwest Virunga, compared to Beni. This rapid growth is primarily driven by security and economic stability in Butembo rather than population growth. Factors such as security issues, topography, and land constraints heavily influence the spatial development of these cities. Areas facing insecurity and refugee zones, such as the east of Beni and the west of Butembo, tend to be less urbanized than other sectors.

These findings offer researchers, policymakers, and local officials a detailed and precise view of urban dynamics in Beni and Butembo. Understanding this complexity and ensuring that all stakeholders feel a sense of ownership over the results would be valuable for planning and sustainably managing the urbanization phenomenon. Efforts must be made to control urban sprawl while safeguarding green spaces, especially natural areas with rich biodiversity, on which urban populations rely. Future studies should examine the links between land governance and urbanization, as well as how the artificialization of urban landscapes impacts land available for

agriculture in natural environments. This would help develop better decision-making tools for managing urbanization. Furthermore, it would be relevant to analyze the socioeconomic characteristics of the newcomers to the city and their housing choices to better connect these elements to the spatial motif discussed in this study. Finally, since Planet images are currently paid and may limit public access, conducting a comparative study would be beneficial. This research should combine data from Planet sensors with data from other sources, like Landsat and Sentinel, for the same area and time frame. This approach would allow an assessment of the error margin caused by differences in spatial resolution, which could affect measurement accuracy.

Chapter 8

8. General discussion

8.1. Methodological approach

8.1.1. Choosing study areas and combining disciplines

Our scientific approach combines multiple spatial scales and disciplines to better interpret landscape anthropization in the northwest of Virunga. By doing so, this methodology minimizes biases from overly broad analyses and enhances understanding of the complex spatial interactions among landscape components, producing results tailored to specific contexts. The focus of our doctoral research is on Virunga National Park and its surroundings, particularly a strategically located zone within the Virunga landscape that holds significance for conservation and development, shared by the Democratic Republic of the Congo, Rwanda, and Uganda. The selected area of interest is the Northwest Virunga Landscape; chosen due to its ecological importance and the socio-ecological challenges it faces. Virunga National Park exhibits a vegetation gradient, with the northern area characterized by dense, humid forests under significant human pressure.

Regarding the study area, the landscape boundary studied is unofficial but based on research by Balole et al. (2015) and Vikanza (2011), who identify this area as a densely populated zone in northern North Kivu Province. This region holds strategic conservation value, as ICCN aims to promote local agriculture and develop value chains to reduce pressure on Virunga. Additionally, the northwest part of Virunga faces security issues stemming from terrorist activities linked to the ADF group, which significantly impacts human activities and resource use patterns. Therefore, the landscape boundary is defined by three criteria security concerns, vegetation gradients, and conservation importance beyond geographic location alone. Multiple analysis scales are considered within the landscape, from major urban centers like Beni and Butembo, to surrounding villages, and down to armed camps, which serve as the smallest observation units. At each level, specific observations contribute to a broader understanding of how humans interact with and alter natural settings and ecosystems.

The study examines anthropization through a multidisciplinary approach that combines landscape ecology, remote sensing, geographic information systems, and socio-ecological, socio-economic, and governance aspects. It is this integration of disciplines that has added value and a certain originality to our doctoral research, especially in presenting the anthropization of natural ecosystems in the Virunga landscape. This approach combines methodologies to understand the complexity of the causes of anthropization. Since effective management of protected areas depends

on a comprehensive understanding of the factors driving deforestation or degradation (Siegel et al., 2022) our analysis, which considers both the physical and social dimensions of anthropization, helps clarify issues related to managing natural ecosystems in and around Virunga National Park. This is in line with Useni Sikuzani and Bogaert (2025), who suggest that landscape ecology studies in the Democratic Republic of the Congo should go beyond physical aspects and include socio-economic and cultural dimensions to better understand the territory's dynamics.

8.1.2. Quantitative analysis

Gathering and analyzing spatial data require substantial computing capacity and mythological choices that may influence the interpretation of landscape dynamic. In this research, Google Earth Engine (GEE) was used as the main platform for spatial data processing. GEE offers several advantages for environmental monitoring, particularly through access to extensive historical datasets such as satellite images. It facilitates near-real-time monitoring of Earth's surface and tracking forest and hydrological conditions (Amani et al., 2020; Tamiminia et al., 2020). GEE integrates extensive image catalog, notably Landsat images being the most common, followed by Sentinel images (Velasgui-Montoya et al., 2023). Its cloud-based infrastructure provides researchers with opportunities for high-speed data processing using machine learning algorithms that need minimal computing resources (Gorelick et al., 2017; Tamiminia et al., 2020). GEE also provides efficiency in data management and storage (Gorelick et al., 2017). Besides its technical effectiveness, employing GEE in this study enhanced understanding of spatial dynamics link to human pressure and urbanization in the northwestern Virunga landscape.

Additionally, it helps generate large volumes of training data for classification models, supplementing field data. Velastegui-Montoya et al. (2023) highlights that GEE is commonly used in five key areas: monitoring agricultural land and vegetation, land occupation and use, climate change, GIS and mapping, and flood monitoring. Our doctoral research on human impact and urbanization in the north-western Virunga landscape also investigates these topics using GEE (Amani et al., 2020).

However, despite these advantages GEE faces some critical limitations, such as restricted access to high-resolution images and dependence on an internet connection, which can impede data access in remote areas. Support for high-resolution images from the Planet collection is not yet consistently available on the platform (Amani et al., 2020). In our study, limited access to high-resolution images, particularly from the Planet Scope collection (3 meters resolution), hindered urbanization monitoring beyond the period when NICFI provided free data from 2016 to 2023. However, this time restriction did not compromise the study's objectives (see Chapter 4) for two

reasons: first, the period coincided with major security upheavals, serving as a key indicator of urban expansion; second, the high spatial resolution enabled the detection of small changes that might have been obscured when using Landsat images over a shorter timeframe (Posite et al., 2025). Additionally, the study benefited from other advantages, such as aggregating spatial data using the median pixel value to reduce seasonal effects in the analysis, and utilizing the Random Forest model, known for its robustness in supervised classification (Aslam et al., 2024).

8.1.3. Selection of satellite images and the classification approach

The precision of landscape change assessment relies on the availability, quality, and integration of images within a spatial analysis framework. Image selection depends on factors such as the size of the study area, the observation period, how well the spatial resolution aligns with the study goals, the required level of accuracy, and the cloud cover rate (Simón et al., 2023). Woodcock and Strahler (1987) also emphasize that when key landscape features are clearly visible in images, they can be considered essential data for further spatial analyses. Spatial resolution needs careful consideration because it affects the detection of important spatial details. Moreover, landscape structure is influenced by spatial scale, requiring adjustments in the analysis approach (Lechner et al., 2012).

In our doctoral research, images were selected based on the objectives of each sub-study, the area of interest, and the required level of quantification detail. For the landscape scale of the Northwestern Virunga region, we used Landsat images from different sensors: 'Thematic MapperTM' (1995-2000), 'Enhanced Thematic Mapper ETM+' (2000-2013), and 'Operational Land Imager OLI' (2013-2021). These 30-meter-resolution images enabled monitoring of land cover change across the entire landscape. Their 185 x 185 km coverage minimized mosaicking needs and provided a historical landscape record. For finer-scale monitoring, particularly to detect forest disturbances near military camps and urbanization in Beni and Butembo, we employed Planet images, which offer higher resolution and precision. This approach enables rapid urbanization assessment, especially in conflict zones, and reduces bias associated with coarser images (Posite et al., 2025). This makes a difference with the Landsat images used by several studies on urbanization in the Democratic Republic of the Congo (Balandi et al., 2023; Bweya et al., 2019; Muteya et al., 2022; Posite et al., 2025). Combining these data sources improves our understanding of anthropization at both broad and local scales. Our method aligns with Lechner et al. (2012) recommendations to minimize spatial quantification uncertainty by using the highest feasible resolution and extending beyond the ecological process zone. Because seasonal variability and lighting changes can bias spatial analysis (Zhu and Li, 2025),

we created composite images based on the median pixel values of all images with less than 10% cloud cover throughout the year. This technique reduces seasonal effects and accurately captures landscape transitions over time.

The observation period was chosen based on historical events, mainly related to security instability in North Kivu and nearby Ituri. From 1995 to 2010, the North-West remained relatively stable, with strong community interest in cash crops such as oil palms, cotton, and cocoa, which replaced coffee on farms. During this period, Beni also saw many internally displaced persons fleeing ethnic conflicts in Ituri (Vikanza, 2011). After 2010, the region faced a security crisis affecting both rural and urban areas, mainly due to activities of the Ugandan terrorist group ADF operating in the Democratic Republic of the Congo. Taking these social, political, and agronomic crises into account when choosing the dates is crucial, as it helps examine spatial changes in relation to key events.

Furthermore, it should be noted that in addition to Landsat and Planet images, our study also uses the 'Global Forest Watch' platform to, on the one hand, visually explore the level of human impact and, on the other hand, to select sites of interest for analyses related to identifying the anthropogenic factors responsible for disturbances in natural forest ecosystems. Rossi et al. (2019) also utilized data from the 'Global Forest Watch' platform to track logging activities in the boreal forests of Gurbandsdalen, given its ability to provide information on yearly tree cover loss. Moffette et al. (2021) highlighted the importance of Global Forest Watch deforestation alerts in supporting conservation efforts by improving landscape monitoring and contributing to emission reduction strategies within protected areas. In the present study, these alerts were systematically used to identify sites of interest, thereby reducing potential sampling bias associated with subjective of incomplete site selection during data collection.

Selecting the land cover class is a crucial step in land cover analysis, although it remains controversial due to its effects on classification accuracy, result interpretation, and landscape management. The varying definitions of land-use types, the landscape's heterogeneity, and the changing nature of land use make it challenging to develop a universal land-cover classification system (Lechner et al., 2012; Nedd et al., 2021). Additionally, heterogeneity can cause significant differences in maps, even in spatially integrated areas (T. Zhang et al., 2023), mainly because of spectral confusion of land cover (Al-Doski et al., 2024; Zhu and Li, 2025). These challenges can affect the accuracy and reliability of the results. In our study, land cover classes were defined using an approach aimed at reducing class ambiguity. Thus, on a global scale, the study grouped classes into two subgroups: natural classes (forests, savannas,

and waters) and anthropogenic classes (agricultural areas, including fallows that could be transformed over a five-year observation period, and built-up areas). This grouping allowed for a clear description of landscape anthropization and helped reduce bias related to landscape heterogeneity. At a finer scale, such as in urbanization analysis, the study favored a binary classification focused on the expansion of built-up areas as a key indicator to monitor. Additionally, around military camps located in forested areas identified as centers of forest disturbance through alerts from “Global Forest Watch,” the study employed a binary classification (forest or non-forest) to track surface area changes within these areas of interest.

Supervised classification has been used at various spatial analysis scales due to its ability to provide higher accuracy than the unsupervised approach (Alrababah and Alhamad, 2006; Foody, 2002). The choice of this classification-oriented approach is based on several factors, including good knowledge of the terrain, the reliability of field-collected training data, their completeness on GEE using very high spatial resolution images, and their completeness on Collect Earth. However, some studies suggest that when the landscape is highly heterogeneous, classification accuracy improves with a hybrid approach combining supervised and unsupervised classification (Foody, 2002). Furthermore, beyond defining the land cover class and the classification method, the performance of the classification algorithm plays a significant role in the accuracy and reliability of the results. In our study, the Random Forest algorithm embedded in GEE was used for spatial classification. Random Forest classification, which combines multiple decision trees, has been widely used in many studies for its ability to achieve high accuracy compared to other algorithms such as SVM, maximum likelihood, and K-NN. This algorithm reduces variance through the use of multiple decision trees (Al-Doski et al., 2024). These limitations highlight the importance of interpreting quantitative remote-sensing outputs in combination with fields observation and contextual socio-environmental.

The Kappa index and overall accuracy served as performance indicators for the analysis, the accuracy, and the reliability of the spatial results obtained. Although subject to scientific controversy due to its sensitivity to class imbalance in land cover (Huang and Lees, 2007) and its vulnerability to overlap (Verma et al., 2020), the Kappa index remains a widely used statistical measure for assessing classification accuracy in many landscape ecology studies. The Kappa index offers the advantage of standardization and comparison across studies thanks to its versatility in different ecological analysis contexts (Verma et al., 2020), its ability to provide numerical values on the agreement and disagreement between observed classification results and ground truths (Carvalho et al., 2009). The limitations of the Kappa index raise the

desire to seek alternatives to improve classification, particularly to reduce sensitivity to asymmetric distributions (Zvoleff and An, 2013). Thus, approaches quantifying the level of disagreement between classification results and reference maps are also proposed (Feizizadeh et al., 2022).

Nevertheless, despite the relevance of combining Landsat, Planet imagery, and Global Forest watch alert, this methodological framework is subject to some inherent constraints. These should be regarded as opportunities for future methodological refinement rather than as limitation that undermine the validity or scientific relevance of the findings. Optical satellite imagery remains affected by persistent cloud cover, atmospheric conditions, which reduce the availability of usable observations in humid tropical forest. Furthermore, optical tree cover loss products mainly capture changes in canopy cover and may fail to detect more subtle forms of forest degradation, such as selective logging.

Future studies could further strengthen this framework by integrating complementary remote sensing datasets within a multi-sensor approach. In particular, Synthetic Aperture Radar (SAR) data (e.g., Sentinel-1 or ALOS PALSAR) would provide year-round observations independent of cloud cover and enhance the detection of forest degradation and recovery. Likewise, biomass-sensitive missions such as ESA Biomass could improve the assessment of aboveground biomass loss and forest structural changes. Finally, exploiting dense satellite time series and seasonal trajectories of vegetation indices would strengthen disturbance detection by distinguishing temporary seasonal variability from long-term anthropogenic changes.

8.1.4. Complementary use of landscape metrics

The landscape metrics used in this study (PLAN, LPI, MPS, NP) are widely recognized indicators for quantifying landscape composition and spatial configuration. However, their application is subject to several methodological limitations that should be considered when interpreting the results. Previous studies have shown that these metrics may be influenced by the spatial resolution of the input data, the extent of the study area, the scale of analysis and classification errors in remotely sensed imagery (Altamirano et al., 2012; Saura, 2004; Wu, 2012). Saura (2004) demonstrated that LPI is relatively insensitive to changes in spatial resolution compared with other landscape metrics. While this property provides greater stability across datasets of different resolutions, it may reduce the ability of the metric to detect subtle structural changes in highly fragmented landscapes. Conversely, Altamirano et al. (2012) reported that LPI is less affected by land cover classification errors than several other landscape metrics. In contrast PLAND accurately quantifies the

proportional area occupied by each landcover class but provides limited information on the spatial configuration.

In this study, these methodological limitations were mitigated through several analytical choices. PLAND was used to quantify landscape composition, LPI to assess the dominance of the largest patches, MPS to evaluate changes in average patch size. The combined interpretation of these metrics minimizes the limitations associated with any individual metric and provides a more robust assessment of spatial dynamics and fragmentation processes.

8.1.5. Use of qualitative approaches in addition to the quantitative approach

A major limitation in interpreting land cover change results within an anthropogenic context is the empirical reliance on historical relationships between human factors and a static view of the environment. However, the economic and social conditions underlying the observed changes are also dynamic (T. Zhang et al., 2023). Therefore, integrating qualitative and quantitative approaches adds significant value in understanding the components of the landscape and their dynamics over time (Zvoleff and An, 2013). Furthermore, in a context where approaches to mitigating ecosystem degradation rely more on landscape-based strategies, the mixed method offers a major advantage in capturing the complex interactions between the human and natural dimensions of the landscape (Reed et al., 2016). In the specific context of northwest Virunga, the mixed approach has been extremely useful. By combining ground observations, surveys, discussion groups, and interviews with experts and local authorities, it has helped anchor the observed landscape changes within the area's economic and social realities. It was not simply about presenting isolated social facts but about understanding, through causal logic, the spatial phenomena, including landscape heterogeneity.

In addition to conducting surveys and interviews, the study employed participatory observations to identify key factors affecting the landscape. The qualitative data collected enabled linking spatial effects to their underlying anthropogenic causes. This mixed-methods approach to landscape research has been utilized by other scholars as well. For instance, Cortés-Capano et al. (2025) applied this method to analyze landscape homogenization across Ethiopia, central Finland, Germany's Altmühltal, Iran's Arasbaran, and Uruguay's Laureles-Cañas. Nix et al. (2022) used the same approach to investigate historical changes in tree cover within protected urban areas of Pennsylvania. Similarly, Sutherland et al. (2018) employed this method to explore land management's spatial dynamics and regulatory actions by institutional structures, highlighting the importance of focus groups and semi-structured interviews.

8.2. Discussion of the main results and their implications.

8.2.1. Anthropization of the landscape and evolutionary trend

The anthropization of the landscape in northwest Virunga originated with the Nande people's migration, beginning in the 18th century, as they sought fertile land to build their economy. This historic event involved several key incidents prompting migration to lower altitude regions, including the loss of land in southern Lubero due to the establishment of Virunga National Park, the colonial boundary adjustments of ethnic territories in Kivu, which led to land losses in Walikale and Rutshuru, and the creation of Maiko National Park in the southwest. These territorial changes, influenced by ecological and political factors, caused the overpopulated Nande to migrate northwest, which was seen as the only feasible option for expanding agricultural activities (Vyakuno, 2006). This migration initiated a widespread transformation of forests into farmland. Analyzing land cover changes using spatial data since 1995 supports the idea of ancient, gradual deforestation. The data show that in 1995, agricultural land covered 40% of the landscape. After that, agricultural expansion took place in both forested areas and savannah zones, eventually covering more than half of the landscape and forming its main matrix. This growth was particularly rapid from 1995 to 2005, then slowed in subsequent years. Vyakuno (2006) points out that, due to different morpho-climatic zones, export-oriented agriculture mainly developed in low-altitude regions within Beni, whereas high-altitude zones like Lubero are mainly focused on subsistence farming crops.

The difficult trade-off between deforestation and economic development becomes more complex when efforts to improve the cash crop value chain led to urban exodus. Beyond the need for agricultural production, land clearing of forested areas also results from the desire to secure land rights within customary systems (Unruh et al., 2005). Moreover, various policies established by governments since colonial times, focused on boosting the agricultural sector to promote economic growth, have contributed to the expansion of agricultural land (Martiniello and Azambuja, 2019). In Northwestern Virunga, colonial policies aimed at encouraging cash crops, particularly coffee, significantly shaped agricultural organization and the early transformation of the natural landscape (Vikanza, 2011). This land cover pattern, driven by integration into international markets, has led to the conversion of natural spaces, especially where crops like coffee, oil palm, and peanuts thrive. Considering internal migration's role in expanding agricultural land, Ignaciuk et al. (2023) highlight similar patterns in Uganda, where forest conversion into farmland is linked to people migrating toward areas with more favorable agro-ecological conditions for cash crops.

The conversion of forest and savannah lands under agricultural pressure exhibited contrasting trends across the different observation periods. Between 1995 and 2005, the loss of forest area was significantly greater than the natural regeneration gains. During this time, the estimated deforestation rate ranged from 2.26% to 2.90%. After 2005, forest area losses decreased and were much lower than gains, indicating gradual forest recovery in disturbed areas. At the landscape scale, forest cover should be regarded as a dynamic system undergoing continuous ecological change rather than as a static land-cover category. The increase in forest area observed after 2005 is indicative of ongoing natural regeneration and secondary succession in previously disturbed areas, with recovering stands progressively increasing in structural complexity and advancing toward more mature forest conditions.

Additionally, savannah zones were the most vulnerable to human pressure, experiencing episodic losses of up to 9.06%, compared to episodic gains of 3.49%. The vulnerability of the savannah, located mainly within the park, stems from the ease with which residents, both within and nearby, can access these areas. The intermittent process of converting forests and savannahs into human-affected areas is connected to the region's economic and security conditions. As previously mentioned, deforestation from 1995 to 2005 continued the land expansion driven by the Nande people's movement into the area and was intensified by the arrival of war-displaced people from Ituri (Vikanza, 2011). The recovery of forests after 2005 is partly explained by the large-scale return of displaced populations to their villages and hometowns, which reduced human pressure on the buffer zones of Virunga National Park. Additionally, this trend is also linked to the slowdown of agricultural activities, caused by ongoing insecurity due to the activity of the ADF terrorist group since 2014.

At the national level, conventional armed conflicts typically lead to increased deforestation, mainly because of weakened state authority and a rise in illegal resource extraction activities. However, in the northwestern part of Virunga, the observed dynamics differs slightly. Communities affected by armed-group violence often abandon their agricultural activities for several years. In the absence of further external disturbances, forest vegetation gradually regrows and recolonizes previously disturbed land, thereby initiating a process of secondary succession. Insecurity significantly limits access to agricultural land (Stevens et al., 2011) and deters the rapid expansion of natural resource extraction (Prem et al., 2020). Similar patterns have been observed in other countries experiencing ongoing insecurity, such as Colombia and Syria. In Colombia's Magdalena Forest region, Landholm et al. (2019) observed an increase in forested areas during the conflict, mainly due to large-scale population displacements. Prem et al. (2020) noted that after peace agreements were

signed, deforestation rose in former rebel-controlled zones, driven by the rapid growth of grazing areas. Conversely, Panagopoulos et al. (2023) identified an opposite trend in northwest Virunga, showing that from 2010 to 2019, the Syrian Republic lost 19.3% of its land mainly due to armed conflicts, illegal logging, refugee camp proximity, and fires caused by impoverished populations in forests. The conflict dynamics such as armed groups like the ADF, which are not motivated by territorial control or resource theft, have significantly hindered large-scale agriculture and commercial extraction, causing the deforestation front to advance toward Mambasa in Ituri province (Opelele et al., 2020).

This situation indicates a more complex relationship between conflicts and deforestation. Traditional wars, motivated by territorial, political, and economic goals, often cause significant forest degradation and loss, even in areas such as the Virunga landscape (Potapov et al., 2012). Conversely, asymmetric conflicts initiated by terrorist groups driven by ideological or religious motives can sometimes temporarily reduce pressure on forests, supporting short-term regeneration. Although such abandonment can initiate natural regeneration and secondary succession, it does not necessarily imply the recovery of the original forest structure, composition or ecological functions. Consequently, the observed increase in forest cover should be interpreted as evidence of vegetation recovery rather than as unequivocal evidence of ecological restoration. Long-term monitoring of floristic composition, vegetation structure, biomass would be required in the future.

In addition, forest recovery in tropical protected area can result from the interaction between socio-political dynamics and ecological resilience. The success of passive forest regeneration can also be influenced by ecosystem resilience, which is shaped by environmental characteristic such as climate, soil fertility, seed availability and landscape connectivity. Accordingly, our findings should be interpreted within the ecological context of study area and should not be directly extrapolated to other protected areas with different environmental characteristics.

8.2.2. Virunga National Park as a tool for the stability of the natural landscape

The comparative analysis of landscape structure between the park's interior and its periphery shows a clear stability of forests and savannas inside the park compared to outside its boundaries. Despite differences in socio-economic conditions, these natural habitats maintain large, connected patches with little fragmentation. For instance, the largest patch index (LPI) of forest areas ranges from 13% to 15% in the peripheral zones, whereas within the park, the LPI ranges from 47% to 97%, highlighting the park's key role in maintaining large, intact ecosystems. These results are consistent

with the findings of Zou et al. (2025) in the tropical zone. According to these authors, although more than half of tropical forests are fragmented, 80% of the reduction in fragmentation is mainly due to protected areas. Similar patterns were observed by Sousa et al. (2023) in their comparative study of two landscapes, Baixo Munim and Pindare. In their analysis, the authors state that the forest and savanna areas of Boixo Munim have resisted human pressure due to protected areas, unlike the landscape of Pindare.

However, some studies have reported the opposite pattern. For example, Suttidate (2022) found that establishing the Om Koi wild station did not reduce habitat fragmentation, either within or outside the protected zone. Likewise, Muteya et al. (2024) suggest that setting up the Kiziba-Baluba hunting domain in the Democratic Republic of the Congo did not prevent deforestation, fragmentation, or the isolation of forest patches. Maintaining intact forest ecosystems remains crucial for regulatory function, including the precipitation cycle upon which local agricultural activities depend (WWF, 2013). Additionally, in terms of landscape dynamics, the national park is not a fixed barrier to forest fragmentation. Instead, it functions as a dynamic element within a broader socio-ecological system. The conservation activities et livelihood strategies are continually interacting. Although the park contributes to safeguarding core habitats, it can also inadvertently intensify land use pressures and fragmentation in the surrounding peripheral zones.

The effectiveness of protected areas in combating deforestation and landscape fragmentation depends on various factors, including governance, technical expertise, and financial support from public authorities and managers. However, many African protected areas suffer from underfunding, limiting their capacity for effective ecosystem management (Doumenge et al., 2015; Lindsey et al., 2018). In this context, the governance and investment strategies in Virunga National Park contribute to its ecological resilience, even as ongoing conflicts destabilize the country. Since 2005, Virunga has been managed through a public-private partnership in which decision-making and management responsibilities are assigned to the Virunga Foundation. Together with Kahuzi-Biéga National Park, Garamba, and the Okapi Wildlife Reserve, Virunga accounts for over 90% of protected area investments, with 85% funded by international donors. In 2020, Virunga's operational budget reached 12 million US dollars, complemented by a 22-million-dollar investment to enhance management (IUCN, 2021).

However, it is also important to recognize that the minimal fragmentation observed in the forest of central Semuliki represents an exception and does not reflect the overall situation across Virunga National Park. Ongoing armed conflicts involving rebel

groups, including the M23, Mai-Mai and FDLR particularly in the central and southern sectors, may contribute to substantial forest degradation and deforestation through illegal logging. Given the security constraints that limit field-based investigation in these areas, extending the spatial scope of the study to conflict-affected sectors through remote sensing and systematic spatial monitoring would be particularly relevant. Such an approach would help assess the extent, spatial distribution and temporal dynamics of forest-cover changes in areas where direct field observations remain difficult or unsafe. Moreover, security forces occasionally harm forest ecosystems during military operations when ICCN oversight is lacking. As in other regional conflicts, corruption and weak state control facilitate extensive exploitation of forest resources, with displaced populations and armed groups competing to extract resources for survival or to finance activities (Crawford and Bernstein, 2008).

8.2.3. Anthropogenic factors of recent disturbances in the forest landscape of Northwestern Virunga

Recent disturbances in the humid forests of the middle Semuliki in the northwest Virunga landscape result from multiple interacting factors rather than isolated pressures that alter the landscape's composition and structure. These disturbances are mainly concentrated around the camps of armed forces operating against ADF armed groups and are driven by eight key factors: the expansion of cash crops, food crops, exploitation of small wood for domestic energy and construction, use of firewood, artisanal timber logging, trail degradation in natural areas, spread of invasive species (*Chromolaena odorata* (L.) R.M. King & H. Rob), and introduction of exotic species into natural ecosystems. Cash crops, mainly cocoa, are grown by smallholders. Beche et al. (2022) adopted similar methods to inventory disturbance factors by plot, reaching similar conclusions and highlighting the negative impact of cash crop expansion on liana resource availability. Moreover, Dubiez et al. (2016) highlight that in the Congo Basin, particularly in the Democratic Republic of the Congo, the development of cash crops depends on national economic conditions and policies.

In this context, the Democratic Republic of the Congo's government has launched a policy called 'land revenge on the subsoil,' designed to position the country as a major producer of cash crops, particularly cocoa. This policy forms part of the ambitious program called the 'Green Corridor,' which covers 540,000 km² from North Kivu to Kinshasa and focuses on nature conservation and a transition to a green economy. This program also aligns with a landscape-based approach to biodiversity conservation developed around Virunga. This approach involves preserving biodiversity while reducing local poverty by promoting income-generating cash crops

such as cacao, coffee, and oil palm (Balole et al., 2015; Henrard and Huart, 2025). Historically, Cocoa has been cultivated in the eastern Democratic Republic of the Congo since the 1930s. Today, the expansion of cocoa cultivation is not a random agricultural coincidence for the farmers. The northwest of Virunga, which forms a continuum with the landscape of the Okapi Wildlife Reserve, is among the regions with high compatibility for cocoa cultivation mapped in the Congo Basin (Kamath et al., 2024). According to these authors, the outskirts of Virunga National Park are among the areas most suitable for sustainable cocoa production. Consequently, the current enthusiasm among farmers for growing cocoa is supported by global demand and the fact that it provides an alternative to coffee farming. In practice, this value chain employs up to 65,000 cocoa farmers in the northwest of Virunga (De Merode and Jérôme, 2025). However, without appropriate land-use regulations, the expansion of cash crops could further degrade forests (Dubiez et al., 2016).

While disturbances in the studied landscape are confined to specific areas, the expansion of cocoa cultivation in Mambasa, an adjacent region of the Beni landscape, represents a significant environmental disaster in the short term. This expansion leads to extensive deforestation of the dense, humid forest (De Merode and Jérôme, 2025; Opelele et al., 2020) and signal a shift in the deforestation frontier as farmers seek new lands for cocoa cultivation. However, it is important to recognize that cacao expansion is not solely destructive. Jagoret et al. (2014) highlight that expanding agroforestry system focused on cash crops, especially cocoa, can constitute an ecologically sustainable strategy in fragmented landscapes. Such a system not only facilitates wildlife movement but also provides long-term stability for farmers and their families over areas that can last up to 50 years (Gama-Rodrigues et al., 2021). In this context, developing cacao agroforestry between Virunga National Park and the Okapi Wildlife Reserve could help create an ecological corridor connecting these protected areas. Nevertheless, in the current context of security instability affecting former production zones, cacao cultivation is increasingly directed toward intact, dense, and humid forests. Because cacao cultivation requires limited preparation and low annual maintenance, it is perceived as a resilience, agricultural adaptation, and land security strategy in new forest areas, particularly under unstable security conditions (Belsky and Siebert, 2003). It should also be noted that the dominance of cash crops in the region, which initially contributed to forest disturbance, can serve as a strategy to stabilize agricultural activities on fixed land, provided these crops are integrated into an agroforestry system (Kamath et al., 2024). This contributes to a mosaic cultivated landscape that preserves certain ecological functions of the forest and facilitates natural regeneration when human activities slow down due to external factors (Vyakuno, 2025) as demonstrated in chapter 4.

In addition to agricultural drivers, disturbances related to the resource extraction system, including timber harvesting, fuelwood collection, and construction wood intended for charcoal production mainly. These activities are strongly to urban demand, notably in Beni and Butembo, as well as other surrounding settlements. These dynamics interact create feedback with agricultural expansion: when lands are saturated or secured, particularly, through cocoa plantation, pressure increase on forest resources for energy and construction. These activities are primarily concentrated within the park, thereby increasing the degradation of this protected area. The timber resource overexploited during the rebellion of “*Rassemblement congolais pour la Democratie (RCD)*”, have left forests depleted of high-value commercial species. Today, the Moyenne Semuliki forest block, under complete protection, constitutes the last source of high-value timber near urban centers in this landscape. Given the area’s urbanization rate of 7-11% (see Chapter 7), wood consumption in these centers remains extremely high. Mulondi et al. (2019) show that the charcoal supply basin for the city of Butembo extends over 150 km. To address this rising demand for wood, the REDD+ program has promoted Eucalyptus plantations around Virunga to restore degraded landscapes, adopting an economic approach (Kasekete et al., 2023). While economically justified in the region, the introduction of eucalyptus into natural forests leads to the homogenization of plant communities and may result in the loss of endemic or threatened species (Iglesias-Carrasco et al., 2025). Similar findings have been reported at the Kilimanjaro World Heritage site in Tanzania (Enoguanbhor et al., 2023). Finally, unplanned expansion of eucalyptus plantations, often replacing agricultural land at the edges of Virunga National Park, contributes indirectly to deforestation. Landless farmers or those lacking land rights on these plantation concessions frequently search for new land in natural forests as compensation (Vikanza, 2018).

8.2.4. Shifting cultivation under the influence of economic, security, and environmental incentives

In the northwest Virunga landscape, landscape transformation through shifting cultivation should not be understood solely as agronomic practices, but rather as adaptive livelihood strategies shaped by multiple interacting constraint, including market opportunities, ecological conditions and insecurity instability. These factors influence both the acquisition of natural forest lands and their actual conversion into agricultural areas. Households remain on their previous farming sites unless they observe a significant change in the factors below.

Among these factors, the expansion of cacao cultivation constitutes the main economic incentive structuring shifting cultivation. Fluctuations in the price of this commodity serve as an indirect driver of large-scale forest changes in the Beni and Ituri regions (average score >4/5), often linked to development in the international market for cash crops. Moreover, the area is currently experiencing agricultural industrialization led by the Virunga Foundation and several local economic actors. The price stagnation since the coffee crisis has been revived by the cocoa crisis, which has become a key benchmark for households.

However, economic incentives alone do not explain agriculture itineracy. Ecological constraints also play a central role in farmers' decisions. The search for healthy, pest-free land suitable for crops such as cassava, beans, and bananas remain important. The presence of pests like banana wilt or cassava mosaic helps farmers evaluate whether to move their cultivation to new natural lands. More importantly, the study shows that insecurity has become a structuring factor in agricultural decision making. The recent encroachment into protected zones (Mayango's and Lubirihya's) reflects this idea of resilience. After armed groups restricted access to previous farms, households turned to protected areas to establish new farms, supported by policies and civil society pressure groups. Furthermore, easier access to land through purchases from customary landowners enables the use of land outside formal channels. Clearing part of the land helps lower expropriation risks and preserves land rights (Vyakuno, 2006).

8.2.5. Sustainable farming practices slow down the rapid repeated expansion of agricultural in forest area

The results of our study (chapter 6) indicate that the non-burned slash-and-mulch system is widely practiced across the landscape. Seven out of ten households use this technique. This traditional method, passed down through generations, likely plays a key role in preserving forested areas both inside and around the park, despite regional demographic growth and weak government management of forest lands. Furthermore, analyses based on five years of household experience show that the non-burned slash-and-mulch system reduces the likelihood of converting forest land into agricultural land compared to partial or complete burned slash-and-mulch. This practice aligns with a form of conservation agriculture defined by the FAO, based on principles of integrated management of soil, water, and biological resources. It depends on minimal mechanical disturbance, permanent organic cover, and diversified crop rotation. It enables both short- and long-term yields per unit of land, possibly for up to 10 years (Giller et al., 2009).

Moreover, our surveys support these findings, confirming that nearly half of the farmers practicing the non-burned slash method confirm remained on their

agricultural land over the past five years. In contrast, at equal frequency, more households practicing burning have resorted to forest lands two or three times within the same period. Erenstein Olaf et al. (2002) note that maintaining residues in agricultural fields reduces temperature fluctuations and improves the inherent fertility of tropical soils, where plant nutrients are more concentrated in the topsoil. In addition, the adoption of non-burning practice, considered an agroforestry system by De Merode and Jérôme (2025), is not an isolated factor. It is also linked to the land access system, which allows long-term land use without restrictions. Furthermore, given that pedoclimatic conditions support three planting seasons per year for crops such as beans, maize, and peanuts (Vyakuno, 2025), pressure on natural ecosystems would be significantly higher if slash-and-burn practices were more widespread than non-burning methods.



Photo 8-1. Bean production in a non-burnt fallow system in the northwest of Virunga. The seeds are directly planted while maintaining the decomposing biomass. ©Charles Mumbere Musavandalo, 2023.

8.2.6. Understand urbanization to valorize undeveloped potential effectively

Recognizing urbanized areas as ecological landscapes is crucial for maintaining their sustainable dynamics (Kundu, 2020). In this context, understanding how cities in the northwestern Virunga landscape are spatially transforming is key to guiding inclusive development. Beni and Butembo, two major cities in this region and part of the Green Corridor strategy in the Democratic Republic of the Congo, are experiencing rapid urbanization due to high annual expansion rates (7% and 11%, respectively), which can even reach 20% in some instances, combined with growing security instability in rural areas.

This growth is undoubtedly a result of demographic expansion, but also reflects the unique social, economic, and political characteristics of each city. Such rapid expansion may present economic opportunities for green investments in the landscape (Ghosh, 2021) or, conversely, pose serious ecological challenges. The outcome largely depends on how local populations and actors respond to this phenomenon. For example, developing tree plantations on the outskirts of these cities could benefit from urbanization, creating higher demand for firewood and construction timber (Kasekete et al., 2023). These woodlands, driven by urban growth, play a vital role in maintaining a microclimate essential for local farming. However, another less obvious aspect of this urban expansion is that establishing multiple tree plantations involves converting agricultural land, raising land prices, and seeking land in remote areas, including protected zones within the landscape. On the other hand, urban expansion can also trigger deforestation due to lifestyle changes and population growth. This can lead to increased charcoal production (Mulondi et al., 2019) and the destruction of protected forest areas, including sacred sites and green spaces (Vikanza, 2011).

The main challenge facing these two urban centers is the lack of a comprehensive urban development plan to guide policymakers' land-use decisions, which are influenced by the influx of rural populations or internal demographic growth. This unregulated growth may cause ecological harm, such as the loss of wetlands, degradation or disappearance of valuable green spaces, and a decrease in areas suitable for urban agriculture, an effective way to promote biodiversity within cities (Kundu, 2020). Additionally, the creation of economic centers, especially economic interest zones, appears to contribute to urban expansion. For instance, in Beni, building density is gradually increasing around the production units of the BRASIMBA brewery, the airport, and the highway toll station (Chapter 7, Figure 7-5). While this trend remains modest, it is a crucial indicator for this city, located directly beside Virunga National Park. Looking ahead, the development of special

economic zones (to the south of Butembo, specifically in Musienne) and industrial zones (to the west of Beni) will be vital to the future growth plans of these cities, as has been the case for many cities worldwide (Alhosani, 2017).

▪ Positioning the findings within existing literature

Compared to previous studies conducted in DRC (Useni et al., 2018; Bwazani et al., 2023; Posite et al., 2025), our study makes three major contributions. First, it proposes an integrated methodological approach combining very high resolution PlanetScope images and landscape ecology metrics. This approach allows for analyzing not only the intensity of urban expansion but also its spatial configuration and landscape fragmentation. Second, it demonstrates that two cities with similar demographic and security challenges can experience different paths of urban growth, emphasizing the role of local factors. Lastly, it offers valuable insights for sustainable urban planning by pinpointing the sectors most vulnerable to green space reduction and landscape fragmentation, especially in a high ecological value area near Virunga National Park.

Table 8-1. Positioning the present study within previous urban expansion studies in DRC

Autor	Study area	Period	Spatial Data and Methodology	Urban growth indicator
Useni et al., 2018	Lubumbashi	1989-2014	Spot Image	Annual rate of urban expansion: 8.7%
Bwazani et al., 2023	Kisangani	1987-2021	Landsat time series, landscape metrics, urban growth typology	Diffusion and coalescence indices of urban growth Urban core expansion: 8,2%
Posite et al., 2025	Beni	1993-2023	Landsat imagery, LULC change analysis	Annual rate of change of land-use classes Settlement/Bare soil class: - 4.8/year over the entire period +4.4/year during 2013-2023
Present study	Butembo and Beni	2016-2023	PlanetScope(3 m), Landscape metrics	Annual urban expansion: 7% (Beni) and 11% (Butembo)

8.2.7. Territorial and political involvement on the Kivu-Kinshasa Green Corridor

The northwest landscape of the Virunga is part of the Kivu-Kinshasa green corridor, which the DRC government supports to balance conservation, the green economy, and climate change mitigation. In this region, its implementation should be seen as a comprehensive tool for stabilizing areas where security is a key prerequisite for any economic and environmental efforts. In zones affected by insecurity, it is important to recognize and value the spontaneous reforestation processes that occur during periods of instability. This calls for the development of sustainable ecological monitoring systems to capture these phases of natural regeneration and secure their growth in the post-conflict period.

Furthermore, the local socioeconomic context indicates that the population is shifting from subsistence farming to small-scale commercial farming, seen as a means of achieving upward mobility into the middle class. An effective approach to combating deforestation is to develop a middle class within the population, which can help ensure that future generations are less reliant on natural resources. In this context, public policies should encourage this shift rather than hinder it, by supporting profitable agricultural methods based on local knowledge, such as no-burn agriculture.

Additionally, the development of the green corridor in the northwestern part of the Virunga requires participatory agricultural zoning, incorporating planning tailored to different production types based on local needs and export opportunities, to maintain a balance between food security and participation in regional and local markets. These zoning efforts must account for the distance to consumption centers, the ecological functions of crops, especially their potential to reduce edge effects between protected and farmed areas, the nature of the soil, and previous agricultural activities. For example, we might suggest implementing a differentiated agricultural zoning system that integrates agroforestry practices centered around cocoa and coffee, especially near Virunga National Park. This system should feature a gradient of tree density, with denser planting closer to the park's edge to boost ecological benefits such as soil protection, connectivity, and microclimate regulation. As the distance from the park increases, tree density would gradually decrease, facilitating better integration of food crops near inhabited areas and optimizing agricultural yields. The selection of species in these agroforestry systems should favor native trees, which are better suited to local ecological conditions and help conserve biodiversity. This contrasts with some exotic species like eucalyptus, which can disturb natural forest ecosystems.

At the same time, strengthening territorial environmental governance in the lower Beni valley involves establishing a Geographic Information System (GIS) to manage agricultural lands. This tool will help accurately track land cover changes, guide development policies, and prevent conflicts between conservation and agriculture. Furthermore, urban growth in the green corridor requires integrated urban planning, taking into account population movements induced by insecurity.

Chapter 9

9. General conclusion

This thesis conducted a systemic analysis of landscape anthropization in northwestern Virunga, an area facing significant security challenges. Its main goal was to establish a scientific basis for understanding how the natural landscape is being degraded in and around Virunga National Park, considering both direct and indirect causes. The study also aimed to identify opportunities for sustainable ecosystem management. To achieve this, it examined changes in landscape composition and configuration, along with the interconnected factors contributing to degradation. Using a multidimensional approach that integrates spatial analysis of landscape structure, field observation, disturbance transects, and socio-economic surveys, the research offers three key insights into landscape transformation in tropical forest areas experiencing insecurity.

Firstly, the study makes an important contribution by demonstrating that forest dynamics in the northwestern Virunga are strongly condition by fluctuation in security conditions. During times of heightened security instability, forest cover often expands, whereas it declines during more peaceful periods. This result challenges linear interpretation of deforestation processes by showing that conflict does not simply destroy ecosystem directly, but rather reorganizes human access to land and resources across space and time. Furthermore, the analysis underscores Virunga National Park's crucial role in conserving local forests, with fragmentation levels notably lower within the park than in neighboring regions.

Secondly, the study focused on identifying anthropogenic factors behind recent disturbances in forest ecosystems, combining spatial analyses of recently degraded areas, mainly around a military camp, with observations of disturbance factors. Spatial analyses did not show a direct link between these camps and increased changes in forest cover. The study, reveals that recent forest disturbances are produced through the interaction of multiple spatially connected pressure. Within the park, disturbances are mainly associated with timber extraction activities, such as artisanal logging, charcoal production. On the outskirts, the primary factors are the expansion of food and cash crops and the proliferation of invasive species. Additionally, the introduction of exotic tree species into natural forests, especially in conflict zones between the park and its periphery, is a concerning trend that could lead to significant spatial changes in the future. Rather than operating independently, these pressures interact within a dynamic system where agriculture expansion, extraction activities, and ecological substitution processes mutually reinforce landscape degradation.

Thirdly, the study examined the perception on the expansion of smallholder farming in forest landscapes. The findings indicate that acquiring a field in a forested areas is driven by multiple motivation, including the seeking of profits from cash crops, access

to more fertile soils with fewer pathogens, the need for resilience in the context of insecurity in previous agricultural zone and the reinvestment agricultural gains. The frequency of establishing new plots is more influenced by land clearing methods than by land access modes. Although household use of fire is rare, it is associated with intensified forest area clearing over five years.

Fourthly, the study focused on urbanization around Virunga National Park, with attention to Beni and Butembo cities. The expansion of these cities is rapid and strongly influenced by security conditions. The annual rate of urban expansion increases during periods marked by intensified attacks by ADF armed groups and slows down when the situation stabilizes in rural areas. However, this rapid expansion, occurring in the context of very limited urban planning, presents significant challenges for organization and sustainable management of urban green areas.

Overall, this study emphasizes that landscape dynamics in northwest Virunga are part of a complex system where land composition and configuration are shaped by closely interconnected direct and indirect factors. It highlights the need for an integrated approach to understanding these processes, which helps in grasping human impacts on the landscape. Regarding landscape conservation through the 'Green corridor' program, it offers opportunities to improve forest management and develop policies tailored to local conditions and realities. The decline of forests in this region is closely linked to the security situation. Park managers at Virunga National Park, like other stakeholders, should include this understanding in their planning. Temporary stability in forest cover often only reflects a short-term shift of agricultural activity away from tense areas. True security stabilization, although still uncertain, will require bringing decision-makers' focus to preempt ecological risks.

The most delicate period is the upcoming one that ushers in relative peace, similar to what was experienced in the years before 2010. Such times require adjustments in managing both human-modified and natural landscapes. As communities aim to recover agricultural investments lost dramatically during times of insecurity in farming areas, large-scale landscape exploitation, driven by the creation of economic and industrial hubs in Beni, Mbau, Mangina, Butembo, and Mutwanga, becomes increasingly likely. Currently, agricultural activities mainly focus on income-generating cash crops, especially cacao cultivation. The experience gained during the period of terrorist violence has fostered a form of resilience among communities that favors food production on small plots near their homes. Therefore, promoting cacao and coffee cultivation, though initially disruptive, may serve as a practical economic strategy to ease pressure on natural forests. If security measures are strengthened on

non-forest agricultural land, supporting these value chains, which are effectively integrated into agroforestry systems and have been historically adopted by the local community, can boost household incomes while preserving ecological connectivity between Virunga National Park and Okapi Wildlife Reserve. The income generated can then be used to improve children's education and encourage them to pursue entrepreneurial opportunities beyond agriculture or forestry.

The ecological model already established in the area, based on the slash-and-mulch system, should be disseminated more widely and monitored by the relevant authorities. Furthermore, replacing Eucalyptus, often introduced into farming systems and even natural ecosystems, with native species such as *Terminalia superba* or *Maesopsis Eminii* is encouraged. Preliminary experiments in Beni and Oicha indicate that these species exhibit promising ecological adaptability. Such strategic ecological engineering is likely to be more effective than sporadic ecosystem restoration initiatives.

However, without proper local land-use planning and organized access to land, efforts to promote sustainable cash crops to boost household income and reduce reliance on the forest are likely to fail. Essential steps include identifying farmers, mapping farms, improving security in agricultural areas, and establishing legal restrictions on access to forest land to help stabilize farming in existing cultivated zones. Developing a geographic system that links farmers to their fields is crucial for certifying sustainable agricultural value chains. This system should be open access and interactive, incorporating not only spatial locations, crops, and farming techniques but also land governance systems and household profiles.

Regarding urban expansion, the priority should be the development and implementation of urban planning and development schemes that consider both general and intermediate rates and intensities of urbanization, as well as the urbanization processes and orientations shown in this study. This planning is especially urgent in Beni, where administrative boundaries remain contested between urban authorities and managers of Virunga National Park. The growth of these cities can be geographically guided by establishing an economic growth hub, as demonstrated by the trend in Beni with the development of Brassimba, the road toll, and Mavivi Airport.

Beyond the Virunga landscape, these findings contribute to broader international debates on tropical forest governance in conflict-affected regions. The study suggests that armed conflict should not be understood only as a direct driver of environmental degradation, but also as a force that restructures socio-ecological interactions through displacement, land abandonment, adaptive agricultural mobility. The thesis contributes to emerging discussions on socio-ecological resilience and landscape governance in fragile tropical environments.

- Limit and potential for future research

This study suggests several research priorities that could advance our understanding of landscape anthropization and support more effective conservation planning in the northwestern Virunga landscape, particularly as security conditions improve and facilitate field investigations. Future research should investigate the influence of urban expansion on woodland dynamics in Beni and Lubero by identifying the principal sources of construction timber and assessing their implication for forest conservation.

Greater attention should also be given to the governance of forest resources across urban, peri-urban and rural landscape, with particular emphasis on the roles, interactions and institution arrangements of the stakeholders involved in restoration initiatives. In addition, examine soil fertility gradients from the park periphery towards its interior would provide valuable insights into how agricultural practices, influence agricultural expansion and forest conservation. The ecological consequences of passive forest regeneration also deserve further investigation, especially regarding wildlife recolonization and biodiversity recovery, using complementary approach such as wildlife inventories, camera trapping and socio-ecological surveys.

Future studies should also further evaluate the long-term effectiveness of community development and livelihood support programs implemented by ICCN and its partners. Although these interventions are intended to reduce dependence on protected area resources and improve local livelihoods, their ecological outcomes remain insufficiently understood.

From a methodological perspective, future remote sensing research should investigate the influence of seasonal variability on the spectral characteristics of tropical forests to improve the discrimination between undisturbed and disturbed forest stands. These methodological advances would strengthen long-term ecological monitoring and provide more reliable information to support evidence-based conservation planning in the Virunga landscape.

Overall, this thesis demonstrates that mitigating anthropogenic pressures on natural ecosystems requires an integrated landscape approach that explicitly considers ecological, socio-economic and security dimensions. Sustainable natural resource management in the northwestern Virunga landscape will therefore depend on stronger coordination among policies related to biodiversity conservation, agriculture, urban planning and territorial security.

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Scientific papers published during the PHD

1. *Papers published*

Musavandalo, C. M., Sambieni, K. R., Mweru, J.-P. M., Bastin, J.-F., Ndukura, C. S., Nguba, T. B., Balandi, J. B., & Bogaert, J. (2024). Land Cover Dynamics in the Northwestern Virunga Landscape: An Analysis of the Past Two Decades in a Dynamic Economic and Security Context. *Land*, 13(5), 566. <https://doi.org/10.3390/land13050566>

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Musavandalo, C.M., Sikuzani, Y.U., Mweru, J.-P.M., Mobunda, J.T., Ndukura, C.M., Bogaert, J., 2026. Assessing urban expansion in Beni and Butembo (DRC) using planet imagery and landscape metrics amid demographic growth and insecurity. *Discov Cities* 3, 83 (2026). <https://doi.org/10.1007/s44327-026-00265-5>

2. *Co-authored publication*

Balandi, J. B., To Hulu, J.-P. P. M., Sambieni, K. R., Sikuzani, Y. U., Bastin, J.-F., **Musavandalo, C. M.**, Nguba, T. B., Jesuka, R., Sodalo, C., Pika, L. M., & Bogaert, J. (2024). Anthropogenic Effects on Green Infrastructure Spatial Patterns in Kisangani City and Its Urban–Rural Gradient. *Land*, 13(11), 1794. <https://doi.org/10.3390/land13111794>

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Balandi, J. B., To Hulu, J. P. P. M., Sambieni, K. R., Sikuzani, Y. U., Bastin, J.-F., **Musavandalo, C. M.**, Nguba, T. B., Molo, J. E. L., Selemani, T. M., Mweru, J.-P. M., & Bogaert, J. (2023). Urban Sprawl and Changes in Landscape Patterns: The Case of Kisangani City and Its Periphery (DR Congo). *Land*, 12(11), 2066. <https://doi.org/10.3390/land12112066>

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3. Book

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Other Appendix

Table A-1. Error matrix determined from 393 validation points

1995	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	79	17	0	0	0	96
Field and fallow	11	132	6	13	0	162
Savannah	0	8	41	2	2	53
Bare and built-up land	0	2	3	60	2	67
Water	0	0	0	0	15	15
Total	90	159	50	75	19	393
2001	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	83	13	0	0	0	96
Field and fallow	7	130	9	9	0	155
Savannah	0	9	41	0	0	50
Bare and built-up land	0	7	0	66	2	75
Water	0	0	0	0	17	17
Total	90	159	50	75	19	393
2005	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	80	9	0	0	0	89
Field and fallow	10	137	7	4	0	158
Savannah	0	8	39	0	1	48
Bare and built-up land	0	5	4	70	1	80
Water	0	0	0	1	17	18

Total	90	159	50	75	19	393
2010	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	84	17	0	0	0	101
Field and fallow	6	126	7	1	0	140
Savannah	0	10	40	0	0	50
Bare and built-up land	0	6	3	73	1	83
Water	0	0	0	1	18	19
Total	90	159	50	75	19	393
2015	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	85	14	0	0	0	99
Field and fallow	5	128	0	1	0	134
Savannah	0	16	45	1	0	62
Bare and built-up land	0	1	5	73	0	79
Water	0	0	0	0	19	19
Total	90	159	50	75	19	393
2021	Forest	Field and fallow	Savannah	Bare and built-up land	Water	Total
Forest	81	19	0	0	0	100
Field and fallow	9	135	7	3	0	154
Savannah	0	3	40	2	0	45
Bare and built-up land	0	2	3	70	1	76
Water	0	0	0	0	18	18
Total	90	159	50	75	19	393

Table A-2. Producer precision (PA) and User precision (UP).

Site	Forest			Non_Forest		Overall Accuracy
	Year	AU	PA	AU	PA	
Kinziki	2016	0.79	0.94	0.94	0.75	0.85
	2019	0.80	0.90	0.89	0.78	0.84
	2023	0.83	0.95	0.94	0.80	0.88
Lahe	2016	0.90	0.95	0.95	0.90	0.93
	2019	0.80	0.82	0.82	0.78	0.80
	2023	0.88	0.95	0.95	0.88	0.91
Mamundioma	2016	0.95	0.95	0.95	0.95	0.95
	2019	0.98	0.98	0.98	0.98	0.98
	2023	0.98	0.98	0.98	0.98	0.98
Mikuha	2016	0.77	0.90	0.88	0.73	0.81
	2019	0.80	0.93	0.91	0.78	0.85
	2023	0.85	0.98	0.97	0.83	0.90
Ngite	2016	0.83	0.98	0.97	0.80	0.89
	2019	0.92	0.90	0.90	0.93	0.93
	2023	0.92	0.83	0.85	0.93	0.88
PK25	2016	1.00	0.98	0.98	1.00	0.99
	2019	1.00	0.93	0.93	1.00	0.96
	2023	0.93	0.95	0.95	0.93	0.94
PK26	2016	0.84	0.93	0.92	0.83	0.88
	2019	0.91	0.98	0.97	0.90	0.94
	2023	0.85	0.98	0.97	0.83	0.90

Table A-3. Pairwise comparison of disturbance types (Prc = Cash crops, Fcr = Food crops, Tcu = Tree cutting, Ba = burn area, AtiH: Artisanal timber harvesting, Car: Carbonization, Pat = Path, Isp = Invasive species, Et: Exotic tree).

	Tcu	Prc	Fcr	Car	Pat	Ba	AtiH	Isp
Prc	0.09896	-	-	-	-	-	-	-
Fcr	0.05551	0.71399	-	-	-	-	-	-
Car	9.0×10^{-8}	8.6×10^{-9}	2.5×10^{-10}	-	-	-	-	-
Pat	2.5×10^{-10}	5.1×10^{-13}	7.6×10^{-12}	0.10860	-	-	-	-
Ba	1.3×10^{-9}	1.1×10^{-8}	5.2×10^{-12}	0.70546	0.18926	-	-	-
Alog	3.9×10^{-10}	5.6×10^{-9}	3.3×10^{-12}	0.30348	0.45606	0.43277	-	-
Isp	2.0×10^{-14}	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	0.00069	0.04233	0.00036	0.00350	-
Et	1.6×10^{-13}	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	0.00011	0.00607	0.00014	0.00136	0.51269

Table A-4. Probability of Disturbance Occurrence with Increasing Distance from Forest Access.

Factors of Disturbance		Estimate	Std. Error	z Value	Pr(> z)
Invasive species	Intercept	-0.739504	0.595725	-1.241	0.2145
	Distance	-0.002466	0.001141	-2.161	0.0307 *
Exotic trees	Intercept	-1.6525684	0.6712824	-2.462	0.0138 *
	Distance	-0.0009707	0.0011231	-0.864	0.3874
Food crops	Intercept	2.2274938	0.5747891	3.875	0.000106 ***
	Distance	-0.0020174	0.0008148	-2.476	0.013288 *
Cash crops	Intercept	1.3943664	0.5158197	2.703	0.00687 **
	Distance	-0.0005660	0.0007726	-0.733	0.46379
Swan timber	Intercept	-1.2943817	0.5066460	-2.555	0.0106 *
	Distance	0.0004727	0.0007627	0.620	0.5354
Cut trees	Intercept	4.922×10^{-1}	4.478×10^{-1}	1.099	0.272
	Distance	-2.843×10^{-5}	6.884×10^{-4}	-0.041	0.967
Carbonization	Intercept	-0.7021615	0.4654388	-1.509	0.131
	Distance	-0.0001138	0.0007191	-0.158	0.874
Burn area	Intercept	-0.4328143	0.4625662	-0.936	0.349
	Distance	-0.0007153	0.0007331	-0.976	0.329

Table A-5. Forest Cover Changes Around Army Camps (%). Each site covers 314ha. F: forest, Nf: Non-Forest.

	Kinziki		Lahe		Mamundioma		Mikuha		Ngite		PK25		PK26	
	F	Nf	F	Nf	F	Nf	F	Nf	F	Nf	F	Nf	F	Nf
2016	44.85	55.26	46.51	53.49	86.48	13.66	53.38	46.70	29.23	70.77	59.54	40.46	73.33	26.67
2019	46.25	53.86	57.02	42.98	75.65	24.49	52.07	48.01	30.83	69.17	69.87	30.13	83.91	16.12
2023	45.32	54.80	63.12	36.88	75.15	24.99	74.18	25.90	52.20	47.80	77.28	22.72	88.48	11.59

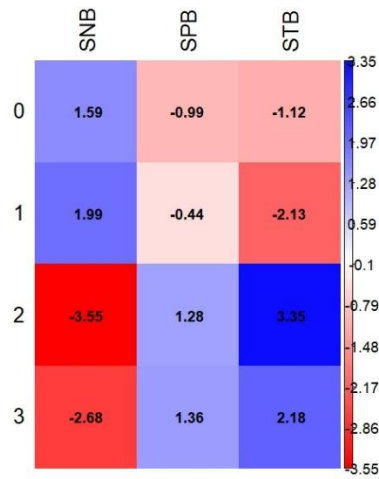


Figure A-1. Standardized residuals of Chi-squared test

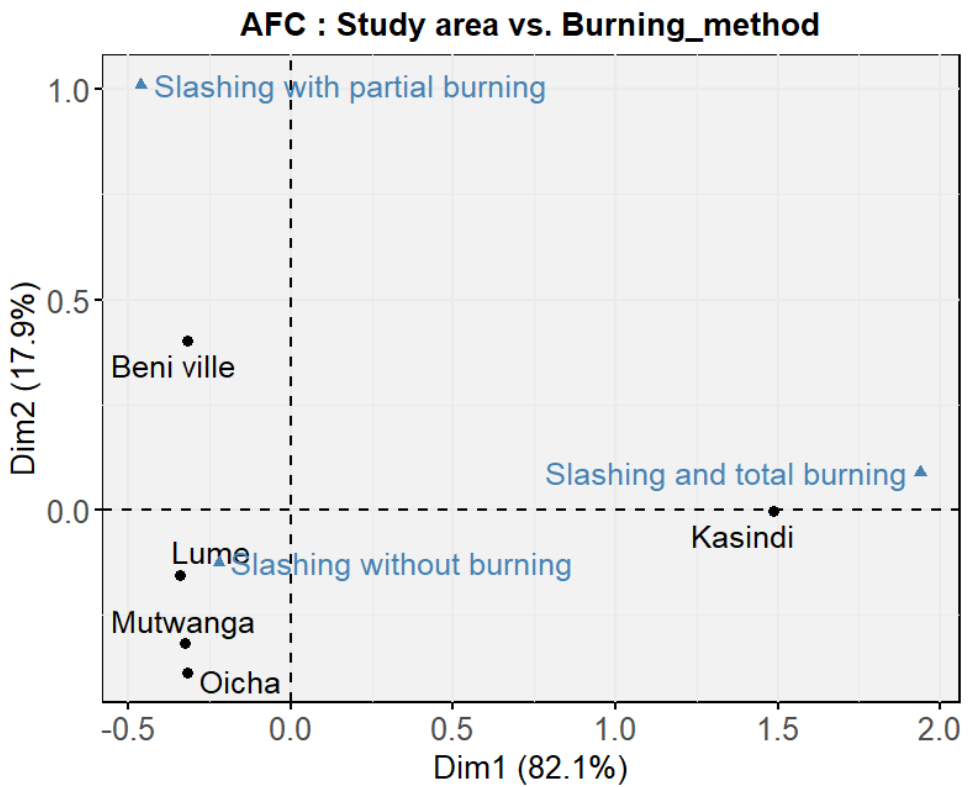


Figure A-2. Distribution of burned and unburned systems around the Virunga site

Table A-6. Kappa Coefficient and Overall Accuracy of Classification.

Year	Ville de Beni		Ville de Butembo	
	Kappa	Overall accuracy	Kappa	Overall accuracy
2016	0,83	0,88	0,82	0,86
2019	0,83	0,88	0,84	0,89
2023	0,96	0,97	0,96	0,97

Survey questionnaire/questionnaire d'enquête

Identification du répondant

Entité

Statut du milieu:

- *Rural*
- *Urbain*

Caractéristiques socio-économiques du répondant

- *Age du répondant*
- *Sexe (Homme/Femme)*
- *Origine (allochtone ou autochtone)*
- *Niveau d'instruction (Aucune, primaire, secondaire et universitaire)*
- *Taille du ménage du répondant*
- *Niveau de revenue (par fourchette)*

Activités agricoles

- *Nombre de champs exploités*
- *Superficie cultivée chaque année*
- *Distance entre le lieu de résidence et le champs (en Km)*

Facteurs motivants l'acquisitions répétée de nouvelles terres agricoles en milieu forestier

- *Selon vous, quels facteurs vous poussent à acquérir de manière répétée et rapide de nouvelles terres en milieu forestiers (donnée à chaque facteur un score allant de 0 (faible influence) à 5 (forte influence)*

Accès à la terre

- *Par quel moyen avez-vous obtenu vos champs agricoles ? (Achat auprès de chef coutumier, achat auprès des premiers acquéreurs, Heritage, location, Don, autre à préciser)*

Pratique culturelle

- *Quel est le mode de préparation des champs pratiquez-vous ? (Abatis sur brulis total, Abatis sur brulis partiel, Abatis sur non brulis)*

Extension des champs en milieu forestier

- *Combien de fois avez-vous ouverts un champ de culture dans une zone forestière mature depuis 2020*

- Dans quelle mesure l'extension des champs vers les zones forestières constitue-t-elle une stratégie pour augmenter la production agricole ?

Territorialisation de l'agriculture

- *A l'ouverture de champs, quels sont les cultures qui occupent l'espace les plus importantes (à classer selon absent, rare, abondant, très abondant)*
- *Quelle culture pensez-vous encore étendre dans les cinq prochaines années ?*

Vers la stabilisation de l'agriculture

- Selon vous, quelles sont les mesures importantes susceptibles de stabiliser l'itinérance de l'agriculture autour de Virunga (classé en fonction de faible, moyen et très important).