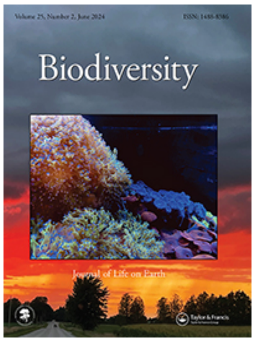

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Spatiotemporal dynamics of land use and land cover change around Volcanoes National Park and their implications for biodiversity conservation

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ABSTRACT

This study comprehensively analyses spatiotemporal land use/land cover (LULC) dynamics within a 10-km buffer zone surrounding Volcanoes National Park (VNP), Rwanda, from 2000 to 2019, integrating biophysical and socio-economic drivers. It aims to quantify LULC change extent, rate, and type around VNP and inside the park; identify socio-economic, demographic, and policy drivers of LULC change; and evaluate the impact of LULC changes on VNP's biodiversity via habitat fragmentation, connectivity, and species diversity. Employing remote sensing, spatial modelling, and field data, we reveal profound transformations within the park's periphery. Forests and woodlots have significantly declined, replaced by agriculture, grasslands, and built-up areas, particularly in the 5.1–10 km belt (92.29% forest loss). While reforestation efforts exist, they are outpaced by deforestation, creating a stark deforestation-to-reforestation ratio of 12:1 in the 5.1 10 km belt and 6:1 in the 0–5 km belt. This alarming trend threatens VNP's biodiversity as resource dependent communities continue to extract firewood, construction materials, and beanpoles from the park. To mitigate these impacts, we propose integrated strategies encompassing strengthened law enforcement, sustainable land management practices, community-based conservation initiatives, and alternative livelihood development.

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Biodiversity conservation; deforestation; habitat fragmentation; remote sensing and spatial modelling; resource dependence

Introduction

Around the globe, human activities are rapidly reshaping landscapes, with land-use change emerging as a potent driver of both biodiversity loss and food insecurity. The primary culprit is the conversion of natural ecosystems to agriculture, fuelled by a burgeoning global population projected to reach 9.7 billion by 2050 (Brondizio et al. 2019; United Nations 2023). This relentless expansion fragments and destroys crucial habitats, triggering cascading extinctions across diverse taxa (Oliver et al. 2015; Guerra et al. 2020; Díaz et al. 2019). Beyond the immediate loss of species, this ecological disruption undermines the very ecosystem services essential for sustainable food production, such as pollination, nutrient cycling, and soil fertility (Brondizio et al. 2019). The consequences are already manifesting as food insecurity tightens its grip on vulnerable communities worldwide. Intensification of agricultural practices exacerbates this challenge through soil degradation, freshwater depletion, and disruption of ecological networks that underpin pest control and crop yields (Paudel et al. 2016; Rockström et al. 2009). Furthermore, climate change, inextricably linked to land-use change through deforestation and greenhouse gas emissions, acts as a potent threat multiplier, exacerbating both biodiversity loss and food insecurity with unpredictable weather patterns and extreme events (Pörtner et al. 2022; Parmesan, Morecroft, and Trisurat 2022).

However, the story is not monolithic. While agricultural expansion is the leading culprit, a nefarious entourage of unsustainable practices follows close behind. Unsustainable logging depletes vital carbon sinks and disrupts forest ecosystems (Gakaev 2023; Guégan et al. 2023). Hunting and overfishing, often fuelled by illegal trade and unsustainable resource management, push countless species towards extinction, further disrupting the delicate ecological balance (Ripple et al. 2017). These cumulative impacts, intertwined with the ever-present threat of climate change, paint a complex picture for the future of biodiversity and the delicate balance of our planet's ecosystems.

Intensive food production systems, characterized by heavy reliance on chemical fertilizers, pesticides, and monoculture cropping, exemplify the tightrope we tread. While prioritizing yield maximization, these

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practices disrupt ecosystem equilibrium, triggering a cascade of negative consequences that ultimately undermine the very food systems they aim to support (Godfray et al. 2010). Soil degradation, pesticide-induced pollinator decline, and water pollution from agricultural runoff are just a few examples of the ecological footprint of these systems (Rockström et al. 2009; Carpenter et al. 1998; Bechmann and Stålnacke 2019; Potts et al. 2016).

Ultimately, this cocktail of environmental ills threatens not only biodiversity and ecosystem services, but also the long-term viability of intensive systems themselves, leaving us precariously balanced on the precipice of further food insecurity (Brondizio et al. 2019). Amidst this challenge, however, hope emerges from an unexpected source: small-scale landholdings. Often relegated to the margins of agricultural discourse, these diminutive holdings (typically less than 2 ha) contribute significantly to global food production, accounting for an estimated 30% of crop output and caloric intake while utilizing only a quarter of agricultural land (Brondizio et al. 2019). This impressive feat stems from a unique blend of factors.

Driven by subsistence needs and deep knowledge of their local ecosystems, small-scale farmers often employ diverse and adaptive agricultural practices that mimic natural ecosystems and foster biodiversity. These practices, characterized by polycultures, crop rotation, and integrated pest management, enhance agricultural productivity and resilience while minimizing reliance on external inputs and environmental impact (Deguine et al. 2023; Nicolétis et al. 2019). Moreover, small-scale farmers frequently act as stewards of traditional agricultural knowledge and biodiversity, preserving valuable genetic diversity within crops and fostering the survival of locally adapted breeds and varieties (Mestmacher and Braun 2021; Ewert, Baatz, and Finger 2023; Niggli, Sonnevelt, and Kummer 2023; Šeremešić 2020). This wealth of biodiversity not only contributes to food security through increased resilience and adaptability to changing environmental conditions, but also safeguards future food options in the face of climate change and emerging threats.

Understanding the effects of agricultural development on biodiversity is critical to ensure that long-term food production is supported by the natural resource base. However, the current approaches neglect some necessary elements that also affect conservation of biodiversity and food security such as resources use rights (Conway and Schipper 2011) and lack of equity and social justice in sharing benefits from biodiversity conservation (Uhrqvist and Lövbrand 2014; Lambin et al. 2001). Integrating food security and biodiversity conservation requires a more integrated approach for socio-ecological systems due to the complexity of agricultural landscapes and management of national parks that are in most cases government-owned (Mandima et al. 2011).

Between 1990 and 2002, Rwanda experienced a dramatic shift in land use, characterized by a substantial expansion of cultivated land at the expense of natural ecosystems (Kathiresan 2012; Mpyisi et al. 2003; Nambajimana et al. 2019; REMA 2009). This trend, driven by a growing population and declining landholdings, resulted in a 16% increase in cultivated area, primarily encroaching upon forests and grasslands (REMA 2009). This rapid transition not only fragmented and degraded valuable habitat, but also compromised crucial ecosystem services like soil fertility and pollination, potentially jeopardizing long-term agricultural productivity and environmental sustainability (Brondizio et al. 2019).

The rapid conversion of natural ecosystems, particularly forests and grasslands, contributed to habitat fragmentation and degradation, jeopardizing biodiversity and crucial ecosystem services (Brondizio et al. 2019). The loss of forests, which are vital carbon sinks, further exacerbated climate change concerns. Additionally, the intensified cultivation without fallow periods led to soil erosion, nutrient depletion, and reduced soil fertility (REMA 2009). These unsustainable land-use practices not only compromised long-term agricultural productivity but also threatened the very foundation of food security in a resource-limited nation.

Further, the pressure to expand subsistence agriculture into national parks to satisfy immediate food needs of local people can be reduced by increasing farm yields and local labour productivity through land use planning that is led by communities and supported by adequate strategy, policy, market, and management interventions. There is also a need to ascertain that local people derive benefits from national parks, receive incentives, get involved in park management, have rights to land tenure (Fischer et al. 2017; Speelman et al. 2014), and receive compensation for damages caused by wildlife (Mandima et al. 2011). Guinness (2014) recommended revising national policies to resolve the persisting conflicts between subsistence of local communities and the management of national parks.

According to Kathiresan (2012), Rwanda underwent significant changes in land use patterns between 1990 and 2002. The area of cultivated land increased from 64% to 74%, the area covered by forests decreased from 11% to 7%, and pastureland and land under fallow decreased from 22% to 14%. Such land scarcity and the fact that subsistence agriculture employs more than 90% of the population (Musahara et al. 2014; Rurangwa 2013) justify the persistent food insecurity and human pressure on national parks in Rwanda. Almost 78% of the country is used for crops, livestock farming and exotic tree plantations. Around 21% is under natural cover, mainly wetlands, lakes and open water, and natural forest. Urban areas account for about 1% of Rwanda's area (Mendelson et al. 2016) which is 26,338 km^2.

Over the past 40 years, Rwanda national parks lost more than 60% of their land area, mainly due to agriculture development (Republic of Rwanda, 2013b). Nyungwe, Gishwati, Akagera, and Volcanoes National Parks (VNP) are all experiencing significant reductions in size. The Nyungwe natural forest decreased in size from 114,125 ha to 97,138 ha between 1958 and 1978 due to forest clearing for agriculture development. This huge forest was already being destroyed by commercial timber production and poaching of mammals including elephants, buffaloes, duikers, etc. Currently, the Nyungwe natural forest comprises about 90,000 ha, and it became a national park in 2005.

The Gishwati natural forest was gazetted as a forest reserve in the 1930s, and at that time its size was 21,000 ha. In 1981, 5000 ha of this area was converted into grazing land by a World Bank-financed project (Republic of Rwanda 2014). After the genocide against the Tutsi, between 1994 and 2005, 95% of Gishwati forest has been redistributed to some of the former 1959 refugees who returned to the country. Today, the remaining forested area includes only 600 ha of secondary forest and 900 ha under restoration that was reclaimed in 2010 from local people (Mendelson et al. 2016).

The government of Rwanda created the Akagera National Park in 1956, with an area of 331,000 ha. This size decreased to 255,000 ha in 1992 and to 90,000 ha in 1997 as the government gave the remaining area to refugees returning from exile in 1997 for resettlement pursuant to the Arusha Peace Accords. The Akagera region experiences prolonged droughts that have negative effects on mammals in the park and on the cattle around the park. For instance, 22 hippopotamus died in 2000 due to a lack of water, and about 30,000 cows died in 1997 due to lack of fodder and water (Republic of Rwanda 2014).

The VNP's forest area was 35,000 ha in 1958, but it lost 49% of its surface area in 1973 due to land settlements and the introduction of pyrethrum in the region. Currently, this forest has an area of 15,000 ha (Republic of Rwanda 2014). The VNP region is the most populated in rural Rwanda (outside the City of Kigali) with an average population density of 703 inhabitants per km^2 (Republic of Rwanda 2012b).

In VNP's vicinity, subsistence agriculture dominates livelihoods, supplemented by limited zero-grazing livestock. However, population growth fragments land through inheritance, hindering food production. Scarce arable land necessitates minimal fallow, leading to soil infertility and seasonal food shortages (October–November and April–May). Consequently, residents rely heavily on VNP resources for sustenance. Insufficient food production manifests as food insecurity, malnutrition, poverty, and low household income (< \$540/year). Market linkages and alternative incomes are limited, while crop losses due to wild animals exacerbate food insecurity and drive VNP resource exploitation. Land consolidation efforts near VNP vary, while vast areas face constraints from an agro-industry cash crop scheme demanding 40% of land for pyrethrum cultivation.

Despite widespread national efforts to increase forest cover, recent mapping data (Republic of Rwanda 2019) paints a concerning picture vis-à-vis the Volcanoes National Park. While the surrounding districts boast a commendable average afforestation rate of 31.1%, this rate plummets to a meager 8.3% within the sectors directly bordering the park. This stark discrepancy exposes a critical gap in conservation efforts at the VNP periphery, highlighting the need for targeted interventions to enhance afforestation in these ecologically sensitive buffer zones.

While the importance of VNP for Rwandan biodiversity and tourism is recognized, the spatiotemporal dynamics of land use and land cover (LULC) changes surrounding the park and their implications for biodiversity conservation remain incompletely understood. Existing research has primarily focused on individual aspects such as deforestation rates or gorilla habitat fragmentation, but a holistic, spatiotemporal analysis is lacking. Additionally, the interplay between these changes and broader socio-economic drivers in the region requires further investigation.

In this article, we aim to comprehensively analyse the spatiotemporal dynamics of LULC changes surrounding VNP and their multifaceted implications for biodiversity conservation in Rwanda. By combining remote sensing analysis with other methods, the research will provide a deeper understanding of the drivers, patterns, and consequences of LULC changes for protected area management and biodiversity conservation strategies. More specifically, this study aims (1) to map and measure the extent, rate, and type of LULC changes around VNP and within the park boundaries, and (2) investigate the impact of LULC changes on the area's biodiversity, focusing on the interrelated effects of habitat fragmentation, connectivity loss, and species diversity, within and around the VNP.

Materials and methods

Location and extent of the study area

The study area is Volcanoes National Park (VNP) in Rwanda. Located in northwest Rwanda (1°21′–1°35′S, 29°22′–29°44′E), VNP forms part of the Virunga massif alongside Mgahinga National Park and Virunga National Park in Uganda and the Democratic Republic of Congo, respectively. The VNP is a natural mountain forest established in 1925 to conserve mountain gorillas. The study area has two landscape types: the mountain range, with altitude ranging from 1900 m to 2000 m; and the volcanic plains, at an average altitude of 1860 m.

Around 70% of the soils in the study area are volcanic. Others are clay, sandy, and lateritic, especially in Shingiro and Gataraga sectors where crop production is low compared to the areas with volcanic soils. Geologically, the volcanic region is covered by lava sediments from multiple volcanic eruptions many years ago (Uwiduhaye, Mizunaga, and Saibi 2018). Inside VNP the vegetation is natural, while on agricultural land the dominant tree species is eucalyptus followed by agro-forestry species such as grevilleas and alinus. The majority of agricultural land surface in the study area is covered by crops (Republic of Rwanda 2012a).

The hydraulic network in the study area comprises permanent water bodies and temporary torrents caused by water running downhill from the volcanoes. During strong storms, these water overflows create heavy sedimentation, floods and erosion, and destroy crops. Permanent water bodies around the VNP include rivers, springs, and lakes of Burera, Ruhondo, Mukamira and Nyirakigugu, all in the Nile basin. Their water flows into Mukungwa River, which discharges into the Nyabarongo River, which in turn flows into the Akagera River, which ends in Lake Victoria (Republic of Rwanda 2012a).

For better localization of the study area, it is important to mention that Rwanda is located in East Africa. It borders Uganda to the north, Tanzania to the east, Burundi to the south, and the Democratic Republic of Congo to the west. The area of the study was demarcated using ArcGIS and shapefiles of the boundaries for the VNP and Rwanda administrative units were used to define its spatial extent. The study area comprises two belts, of 0–5 km and 5.1–10 km from the park edge outward, to enable the comparison of findings in the vicinity of the park and places far away. The 0–5 km belt is labelled zone 1 while the 5.1–10 km belt is labelled zone 2, as per Figure 1.

The main economic activity around VNP is subsistence agriculture, in addition to a limited number of livestock under zero-grazing conditions. However, food production is constrained by parcelling out land via inheritance from fathers to sons, due the rapid growing population. Fallow land is rare due to the scarcity of arable lands, resulting in soil infertility and the ensuing insufficiency of food produced. Periods of significant food shortages are October to November and April to May of each year (Weber 1987). As a consequence, local residents depend greatly on VNP resources for subsistence needs. Besides the VNP, the environment in the study area is highly anthropogenic due to permanent human occupation for several decades.

Illegal activities within VNP include poaching, bamboo cutting, firewood collection, water collection, and beanpole harvesting. These activities pose significant threats to the park's biodiversity and conservation efforts (Republic of Rwanda 2015). Hickey et al. (2018) recommend enforcing protective measures and addressing emerging threats to ensure longer term increase of the mountain gorilla population in the Virunga massif. These authors warn that the increasing proximity between humans and gorillas causes a high threat of disease outbreaks that soon may rapidly reverse the gains made during the last three decades. They recommend to effectively enforce and implement all International Union for Conservation of Nature (IUCN) best practices and guidelines for great ape conservation throughout the mountain gorilla habitat, as the survival of this species will continue to depend on conservation for the foreseeable future.

Data collection procedures

The cornerstone of our data collection effort was ranger-based monitoring data meticulously gathered over a 20-year period (2000–2019). Trained park rangers diligently recorded observations of LULC changes inside the VNP as well as within a 10 km buffer zone surrounding the park (Munanura et al. 2020). This comprehensive dataset included spatiotemporal information on agriculture and grassland, bare land, built-up area, forest and woodlots, and water bodies. Following Turner, Lambin, and Verburg (2021) we employed a fine-grained spatial resolution, which enabled us to analyse the dynamics of land-use change and its potential impact on biodiversity over two decades.

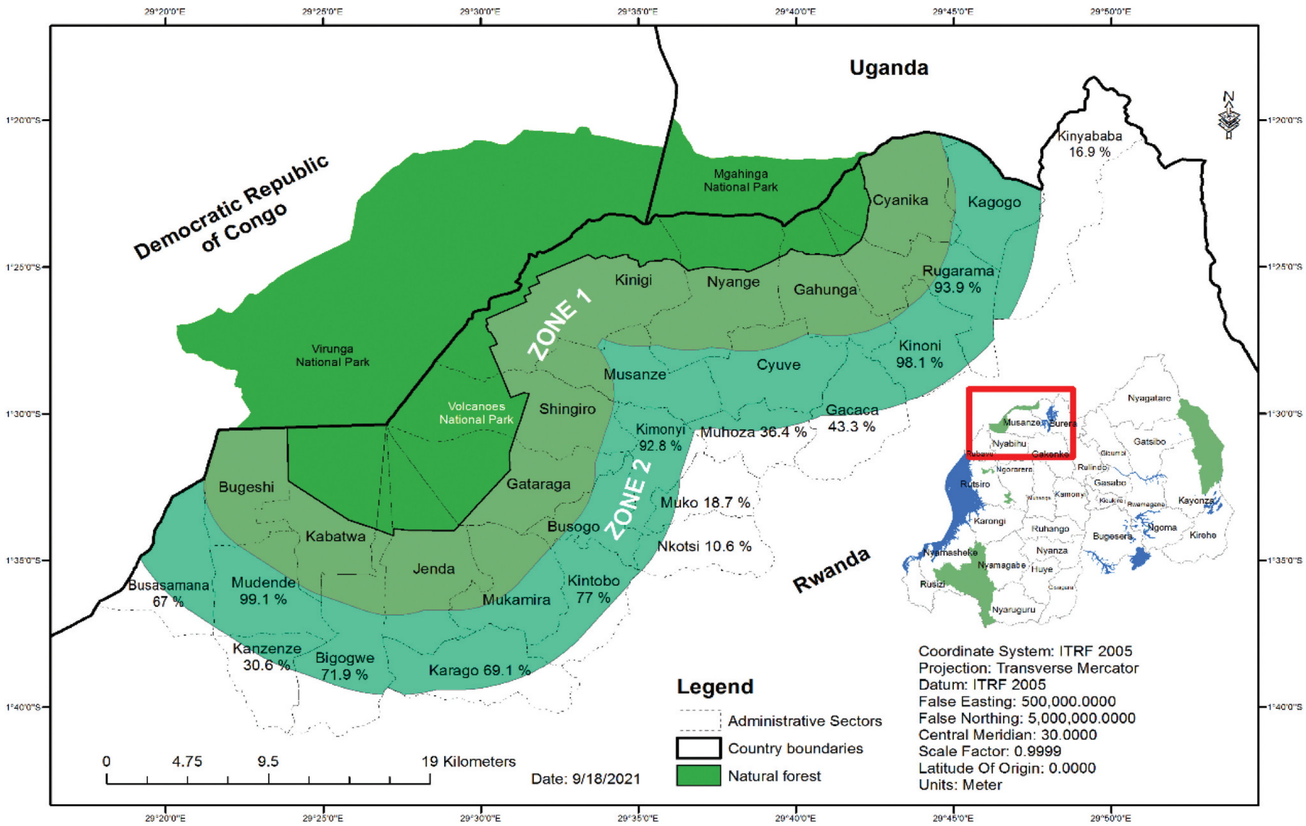


Figure 1. Location of the study area. Source: GIS data (2017); Republic of Rwanda (2012b).

To delve deeper into the social and cultural dimensions of land use changes around VNP, we conducted focus group discussions (FGDs) with local communities residing in the buffer zone (within the 0–5 km belt around the park). These semi-structured discussions, involving diverse groups of participants, provided valuable insights into local perceptions, attitudes, and knowledge regarding land-use practices and their potential implications for park resources, including rich qualitative data on lived experiences and perspectives regarding land use changes. We also conducted key informant interviews with park officials, conservation experts, and local leaders, which yielded in-depth knowledge on specific aspects like policy interventions, conservation initiatives, and community-based resource management practices (Miles and Huberman 1994). By triangulating this qualitative data with the quantitative ranger-based observations, we aimed to achieve a more holistic understanding of the drivers and consequences of land-use change in the vicinity of VNP (Bryman 2016) as well as a more nuanced understanding of the complex socio-ecological dynamics influencing VNP and its biodiversity conservation (Flick 2022).

Data analysis procedure

Exelis ENVI software was used to examine the satellite images of the LULC by employing a combination of feature extraction and image classification tools. This study used Landsat images to examine change trends in LULC. Images from four time series covering the study area and VNP were analysed from 2000 to 2019 (2000, 2010, 2015 and 2019). No map was produced for 2005 because the landscape was covered by clouds, rendering it unsuitable for presentation and visual analysis. Unfortunately, budgetary constraints prevented the development of maps for adjacent years, particularly the critical year immediately before or after 2005.

In addition, ESRI ArcMap was used to digitalize built-up areas and agriculture and grassland polygons. Remote sensing tools for assessing LULC changes were adopted (see Nkundabose 2021). Outputs included four detailed land use maps and additional continuous maps indicating variability in vegetation cover in the study area from 2000 to 2019. Drawing upon a comparative framework spanning 2000 and 2019, the study quantifies LULC changes as gains, losses, or no change (Tables 3 and 4). This differentiation is achieved through a subtractive approach, calculating the difference between LULC states in the designated start and end years.

Concerning the classification accuracy of the study area maps, the producer's accuracy and user's accuracy were computed. The classification accuracy is the degree to which a classified map accurately represents the actual land cover or land use on the ground (Foody 2002). In this case, producer's accuracy is the proportion of reference pixels of a given class that are correctly classified on the map (Olofsson et al. 2014). The producer's accuracy is computed as per Equation (1).

$$PA = \left[\frac{TP}{(TP + FN)}\right] * 100 \qquad (1)$$

In Equation (1), PA means producer's accuracy; TP means true positives, which are the pixels that are correctly classified as belonging to a specific class (e.g. forest pixels classified as forest in the map); FN stands for false negatives, which are the pixels that belong to a specific class but are incorrectly classified as another class (e.g. forest pixels classified as water in the map). Essentially, the producer's accuracy shows what percentage of pixels from the true reference data for a specific class were correctly classified in the map.

As for the user's accuracy, it is defined as the proportion of pixels classified as a certain class on the map that are actually that class on the ground (Olofsson et al. 2014). It reflects the probability that a user can trust the class label assigned to a pixel on the map. User's accuracy is computed as per Equation (2).

$$UA = \left[\frac{TP}{(TP + TN)}\right] * 100 \qquad (2)$$

In Equation (2), TP stands for true positives and has the same meaning as in Equation (1), while TN stands for true negatives. In the context of pixel classification, TN refers to pixels that correctly do not belong to a specific class and are accurately identified as such.

It is important to mention that Equations (1) and (2) were used to estimate the accuracy of data produced by Exelis ENVI software. Accordingly, our assessment for the area of this study (the 10 km belt around VNP) reveals that in 2000 the overall accuracy and kappa were 88.67% and 86.8%, respectively. In 2010, the overall accuracy was 87.42% and kappa was 85.17%, while in 2015 the overall accuracy was 88.33% and kappa was 86.28%. In 2019, the overall accuracy was 87.00% while kappa was 65.48%. Although the results of this assessment show a slight variation of kappa and accuracy from 2000 to 2019, these two metrics are statistically significant: above 85% which is the minimum required for accuracy (Anderson et al. 1976), or above 80% (Carletta 1996).

For the map of the area inside VNP, the results show that in 2000, overall accuracy was 85.21% and kappa was 83.12%. For 2019, the overall accuracy was 86.35% and kappa was 84.82%. Table 1 presents a comprehensive analysis of producer's and user's accuracy for multiple land cover classifications within the study area. Producer's accuracy quantifies the proportion of reference pixels correctly classified within each map class, while user's accuracy reflects the probability that a pixel classified as a certain class corresponds to its true land cover.

The land cover categories presented in Table 1, including the additional category of bare land, are applicable to the VNP's environs. Similarly, within the park itself, two primary land cover classes exist: forest and bare land. While forested areas harbour vegetation, specific forest patterns manifest in response to altitudinal variations (Cinnirella 2009; Hörsch 2003; Lu 2001; Willig and Presley 2016). At lower elevations, an 'open forest' dominates, characterized by a dispersed tree canopy permitting substantial sunlight penetration to the ground (Cinnirella 2009; Hitimana, Kiyiapi, and Njunge 2004). This canopy cover fosters a more open and park-like ambiance compared to denser forest ecosystems (Lupp et al. 2022). As elevation increases and environmental conditions become harsher, a transitional 'sub-alpine zone' emerges between the open forest and the alpine zone. This zone exhibits a gradual decline in tree cover (Lütz 2011; Nitzu et al. 2014), often featuring stunted trees known as 'krummholz', adapted to the harsher conditions at higher elevations compared to their lower-altitude counterparts. At the highest elevations, the VNP transitions to an 'alpine zone' where vegetation is typically low-growing and adapted to harsh conditions, frequently dominated by grasses, sedges, mosses, and lichens (Ebrahimnezhad 2014). Finally, at the mountain peaks, vegetation is entirely absent, forming the 'bare land' category.

Table 1. Classification accuracy of the maps of the study area.

	2000 (%)		2010 (%)		2015 (%)		2019 (%)	
Land use/land cover category	PA	UA	PA	UA	PA	UA	PA	UA
Water body	81.25	92.86	55.56	83.33	64.29	90	81.25	86.67
Planted forest and woodlots	96.4	89.17	73.68	80	91.3	91.3	95.31	87.14
Agriculture and grassland	76.92	76.92	91.25	82.02	96.05	87.95	71.43	83.33
Built-up area	30	100	55.56	83.33	42.86	75	50	100

Source: Field survey (December 2018).

Finally, even though they were not used extensively, additional data collected through key informant interviews and FGDs were analysed using descriptive statistics. Overall, data analysis involved descriptive statistics and thematic analysis for quantitative and qualitative data, respectively. Ranger-based monitoring data (2000–2019) served as the foundation for understanding land-use change trends and illegal resource use within VNP. Subsequently, FGD insights were layered upon this foundation to enrich the interpretation of these trends within the 0–5 km belt. Similarly, key informant interview data complemented the ranger-based data on illegal resource use by providing deeper context and understanding of the drivers and complexities behind these activities. This multi-pronged approach utilizing FGDs and key informant interviews enabled a comprehensive examination of the intricate relationship between land-use changes and VNP's biodiversity, ultimately strengthening the research findings and policy recommendations.

Results

LULC dynamics inside the VNP

To better understand the relationship between the LULC dynamics around VNP and the park resources' status, the changes in land cover inside the park were also analysed. The findings show that there was no change in the size of the park; only changes in the vegetation cover took place between 2000 and 2019. Between 1990 and 2000, the VNP underwent a high rate of deforestation primarily caused by the war and genocide against the Tutsi that the region went through. For this, several areas of the park were encroached upon for farming and cattle rearing, while others became settlements for refugees and rebel groups. In 1999, some conservation non-governmental organizations (NGOs) and the government resumed conservation and tourism activities in the park that were implemented together with park restoration.

With conservation and restoration efforts, the size of the open forest increased from 78.14% in 2000 to 88.33% in 2019. This does not mean local people did not illegally use the park resources during this period. The fact is, rather, that the magnitude of illegal use of the park was smaller than massive park invasion that took place between 1990 and 2000.

Table 2 serves as a concise yet encompassing snapshot of LULC composition within the designated park boundaries over a two-decade timeframe (2000–2019). It meticulously dissects the LULC landscape by presenting the total area and relative proportion (percentage) occupied by each category in both 2000 and 2019. This comparative tabulation allows for a clear-cut and readily digestible understanding of the spatial patterns and potential transformations within the park's interior over the two decades, offering valuable insights into the dynamics and potential drivers of LULC change inside the park.

While Table 2 provides valuable statistics on land cover changes within the VNP between 2000 and 2019, it lacks the spatial detail to fully understand the ecological shifts at play. To bridge this gap, Figure 2 comes into play. This visually compelling map transcends the limitations of tabular data, offering a geographically explicit representation of the transformations that have occurred within the park's boundaries.

Illegal utilization of VNP resources

With the information contained in Table 2 and that provided in Figure 2, it was difficult to link the detected forest cover changes with the findings on LULC dynamics in the study area outside VNP. Therefore, the information from ranger-based monitoring data collected by rangers inside the park from 2000 to 2019 on the illegal uses of the VNP resources enabled us to examine the implications of LULC changes in the park vicinity for the land cover changes inside the park. The findings show that local people still illegally enter the park in search of water, wild meat, bamboo, timber, and honey, as shown in Figure 3.

Despite ranger-based monitoring data indicating consistent levels of poaching and bamboo harvesting, significant land-use changes around VNP suggest

Table 2. Land cover changes inside Volcanoes National Park between 2000 and 2019.

	2000		2019	
Land use/land cover category	Area (ha)	Area (%)	Area (ha)	Area (%)
Open forest	12,503	78.14	14,133	88.33
Alpine	2355	14.72	1751	10.94
Sub-alpine	1137	7.11	116	0.73
Bare land	5	0.03	0.741	0.00
Total	**16,000**	**100**	**16,000**	**100**

Source: Field survey (February 2019).

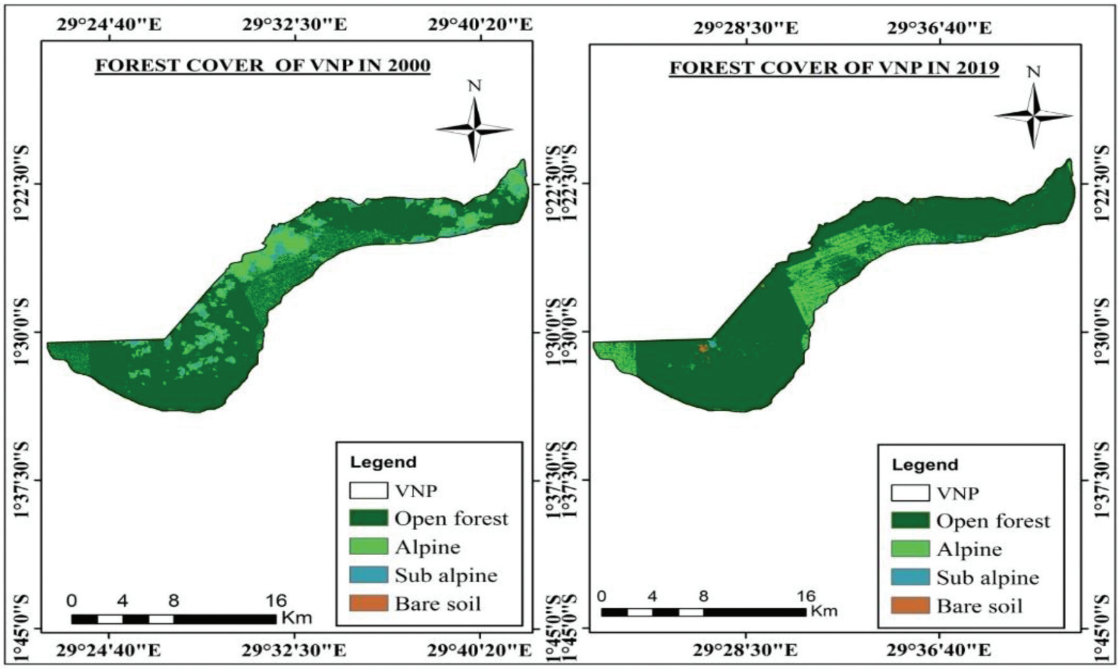


Figure 2. Land cover changes inside Volcanoes National Park (VNP) between 2000 and 2019. Source: GIS data (2019).

complex factors underpinning illegal activities. Both the 0–5 km and 5.1–10 km buffer zones experienced alarming deforestation exceeding 92%, primarily driven by agricultural expansion. Ranger monitoring data corroborates this, highlighting firewood collection and timber harvesting within VNP as persistent issues. Further concerns involve illegal night bamboo cutting and crop raiding by wild animals, exacerbated by insufficient mitigation efforts. Notably, the land cover analysis reveals a stark 11:1 and 6:1 deforestation:afforestation ratio in the 0–5 km and 5.1–10 km belts, respectively, underscoring the need for intensified reforestation initiatives.

Results also reveal that the absence of permanent water sources in the 0–5 km belt contributes significantly to illegal water fetching from VNP, as ranger data confirms. This aligns with the land-use analysis and revenue-sharing data, revealing minimal investment in water supply and rainwater harvesting infrastructure (2.85%). Addressing water scarcity through increased community water provision is crucial. Encroaching on agricultural and forest land, the rapid

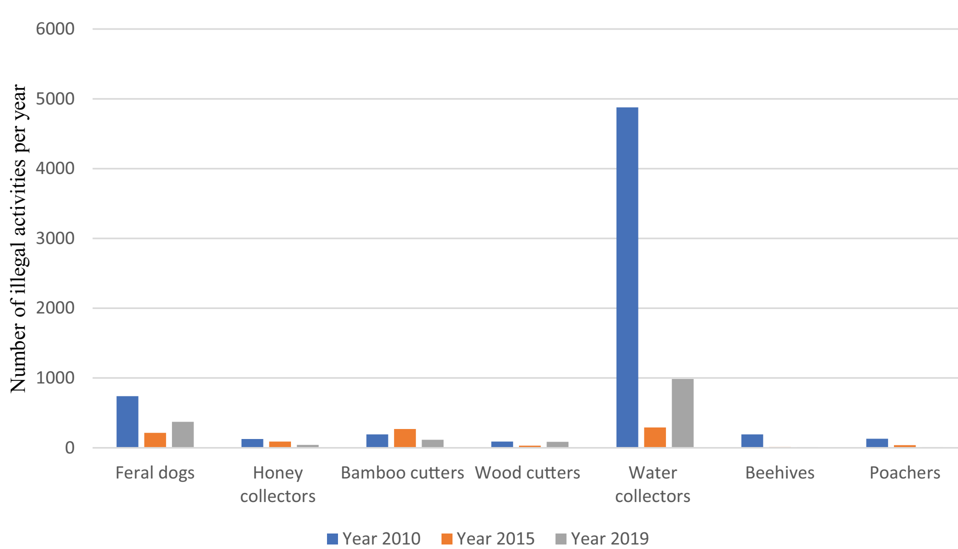


Figure 3. Illegal uses of Volcanoes National Park (VNP) resources between 2010 and 2019. Source: Field survey (March 2019).

expansion of built-up areas in both belts is linked to poaching concerns. With an average household landholding of 0.3 ha and 98% reliance on subsistence agriculture, infrastructure development threatens food security and incentivizes land sales to investors, further reducing arable land and fuelling poaching. Revenue-sharing data highlighting limited investment in enterprise development (0.92%) reinforces the need for alternative livelihood opportunities, particularly for the landless, to reduce pressure on VNP resources.

It is also important to mention that the ranger data showing peak illegal activity in May and September coincides with food scarcity periods for local communities, suggesting a strong link between food insecurity and resource exploitation. This aligns with the finding that 71% of households in the area are food insecure. Strengthening law enforcement and awareness campaigns must be coupled with interventions addressing food insecurity, deforestation, and landlessness. For instance, promoting alternative energy sources for cooking alongside off-farm job creation could free up land for reforestation and reduce reliance on VNP resources.

Long-term conservation of this park depends on improving the food security of the people living around it. They will not stop entering the park illegally if their food security situation does not change. Strengthening law enforcement and awareness raising should be supported by appropriate measures to improve local food security. For instance, 80% of interviewed key informants indicated that due to the small amount of land owned by households (0.3 ha in average), farmers even uproot tree seedlings provided or planted by the government and NGOs around VNP to reduce local pressure on the park. This may be the reason for the wide deforestation:afforestation ratio in the area. This means that the VNP management and stakeholders should have a clear long-term plan for improving food security in VNP. For instance, in the case that local people continue to rely on subsistence agriculture on the small-owned plots, there will be no space for trees that should be the source of firewood and construction material. An alternative source of cooking energy should be provided to these people. Alternatively, if more off-farm jobs are created, more land will be available for tree planting. Addressing the complex interplay between land-use changes, vulnerable livelihoods, and resource competition requires multifaceted interventions. Prioritizing food security through sustainable agricultural practices, alternative energy provision, and off-farm job creation are critical steps towards mitigating pressure on VNP and ensuring its biodiversity persists. By adopting a holistic approach that recognizes the interconnectedness of conservation and human well-being, we can chart a path for the harmonious coexistence of VNP and its neighbouring communities.

Notably, water collection within the park exhibits a concerning anomaly in 2010, with reported instances of illegal activity exceeding those observed in other years within the study period. This necessitates further investigation to elucidate the underlying factors driving this surge in illicit water extraction. A deeper analysis, incorporating additional data sources and potentially employing qualitative methods, would be instrumental in unravelling the complexities associated with this phenomenon and informing targeted interventions for curbing such behaviour.

LULC transitions around VNP

Four classes were identified during image classification, where a clear blue colour represents the area occupied by agriculture and grasses, dark green forests, and woodlots; dark red indicates the built-up locations distributed in the study area; dark blue represents the area covered by water; and grey represents bare land area.

The LULC map from 2000 shows that the 0–5 km belt around VNP was dominated by agriculture and grassland (86%), followed by built-up area (9.25%), then planted forest and woodlots (4.63%) followed by bare lands (0.11%) and lastly water bodies (0.01%). Agriculture and grassland area increased from 80.13% to 95.55% between 2000 and 2010 but declined over time since then to 93.89% in 2015 and to 86% in 2019. The planted forest and woodlots decreased considerably, from 19.25% in 2000 to 3.83% in 2010, and slightly increased since then to 4.4% in 2015 to 4.63% in 2019. The built-up area did not change between 2000 and 2010 (0.58%). It increased to 1.7% in 2015 and to 9.25 in 2019 (an increase by more than 5 times in only 4 years). Also, the bare land area remained unchanged between 2000 and 2010 (0.04%), decreased to 0.01% in 2015 and increased to 0.11% in 2019. There were no water bodies in this belt between 2000 and 2015. In 2019, water bodies covered 0.01% of the area. Ground truth data have shown that there are no water bodies in the 0–5 km belt, only a few small water sources in Kinigi area. Most of the 2.97 ha shown on the map was covered by temporary water that was running from VNP to Mukungwa River after rain when the satellite image was taken. Table 3 presents a spatiotemporal analysis of land cover changes in the environs of VNP, documenting the transformations that occurred between 2000 and 2019.

The information in Table 3 reveals the trends in land cover changes in the vicinity of VNP between

Table 3. Land cover changes in the 0–5 km and 5.1–10 km belts around the park between 2000 and 2019.

	2000		2010		2015		2019	
Land use/land cover category	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Land cover changes in the 0–5 km belt around the park								
Built up	197.1	0.58	197.01	0.58	575.46	1.7	3,120.21	9.25
Agriculture and grass	27,032.40	80.13	32,236.56	95.55	31,670.50	93.89	29,015.10	86
Planted forest and woodlots	6494.49	19.25	1290.78	3.83	1485.95	4.4	1562.49	4.63
Water bodies	0.27	0	0.18	0	0.45	0	2.97	0.01
Bare land	12.51	0.04	12.24	0.04	4.41	0.01	36	0.11
Total	**33,736.77**	**100**	**33,736.77**	**100**	**33,736.77**	**100**	**33,736.77**	**100**
Land cover changes in the 5.1–10 km belt around the park								
Built up	584.91	1.6	771.75	2.11	1673.10	4.58	3,395.07	9.28
Agriculture and grass	19,924.20	54.47	27,689.64	75.7	28,248.47	77.22	28,405.89	77.66
Planted forest and woodlots	12,915.36	35.31	4928.16	13.47	3503.17	9.58	2017.62	5.52
Water bodies	3084.30	8.43	3119.67	8.53	3091.50	8.45	2740.23	7.49
Bare land	70.02	0.19	69.57	0.19	62.55	0.17	19.98	0.05
Total	**36,578.79**	**100**	**36,578.79**	**100**	**36,578.79**	**100**	**36,578.79**	**100**

Source: Field survey (February 2019).

2000 and 2019. However, it cannot indicate to what extent things have changed. On this subject, Figure 4 highlights the LULC changes in both the 0–5 km and 5.1–10 km belts (zones) during 2000 and 2019, showing mainly the side of the park which is mostly affected.

This study delves into the complexities of LULC changes within a 10 km buffer zone surrounding VNP between 2000 and 2019. Focusing on the critical 0–5 km belt directly influencing park conservation, the analysis reveals significant transformations within this crucial zone. The 0–5 km belt witnessed a complex interplay between various land-use categories. While agriculture and grassland remained dominant throughout the study period, deforestation and built-up area expansion emerged as key drivers of change. Notably, forest and woodlots suffered a drastic decline, shrinking by over 90%, primarily due to conversion to agriculture and grassland. This alarming trend poses a major threat to VNP's ecological integrity and its ability to provide resources for local communities. Conversely, built-up area exhibited remarkable growth, fuelled by population influx, booming gorilla tourism, and increased NGO presence. Interestingly, both gains and losses of built-up area occurred, suggesting a dynamic interplay between different land uses within this zone.

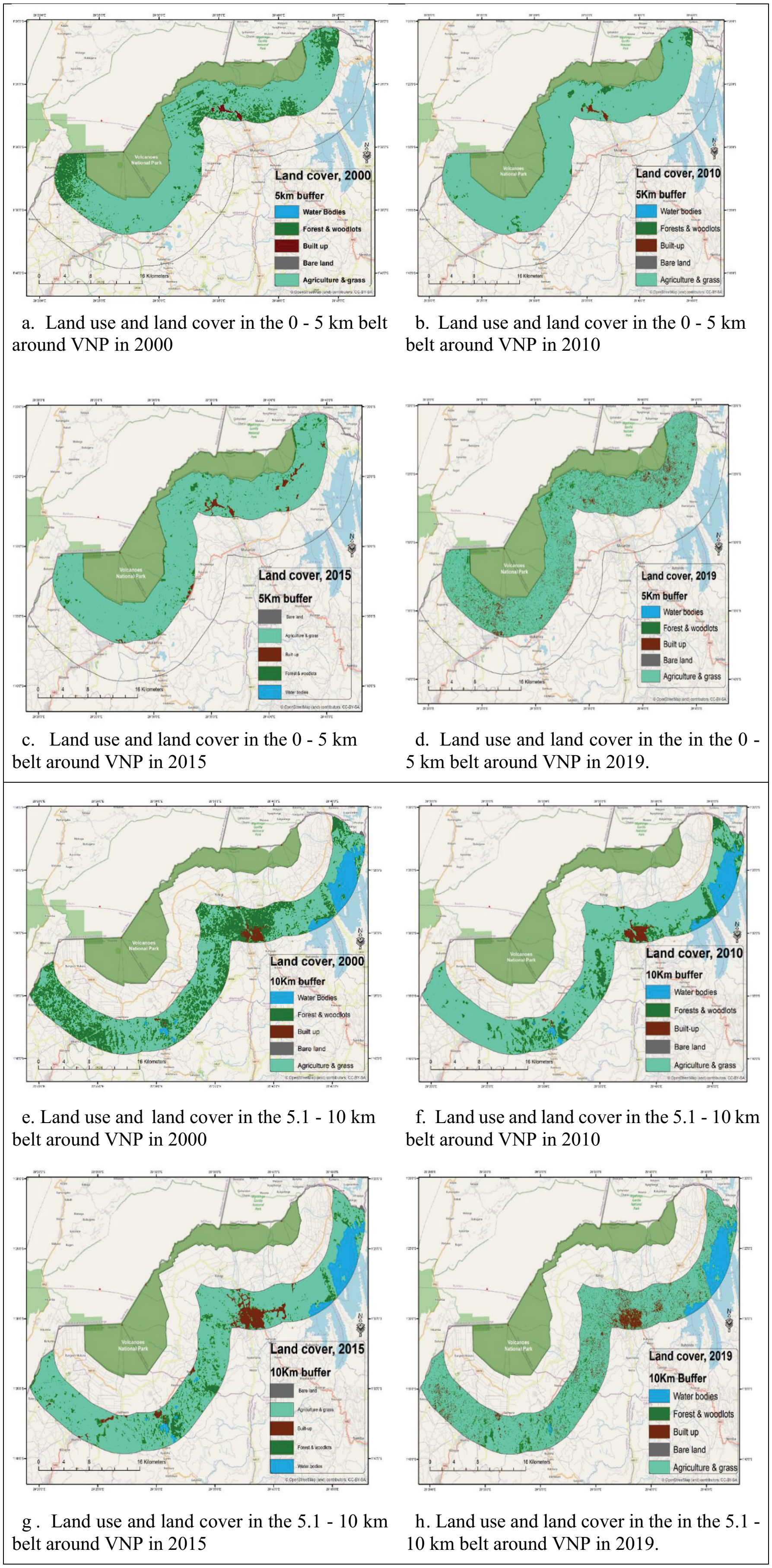
Moving outward to the 5.1–10 km belt, similar patterns emerged, but with some key differences. Agriculture and grassland again dominated, but deforestation also played a significant role in driving land-use change. Forest and woodlots experienced a similarly drastic decline, exceeding 90% loss primarily due to conversion to agriculture and grassland. Water bodies, however, showed more complex dynamics in this zone, with fluctuations driven by agricultural encroachment, sedimentation, and conversion from other land uses. Built-up area expansion mirrored trends observed in the 0–5 km belt, highlighting the influence of similar driving forces across the buffer zone.

Consequently, the analysis paints a nuanced picture of LULC dynamics around VNP, revealing both continuities and variations across the two buffer zones. While agriculture and grassland remain the dominant land uses, deforestation and expansion of built-up area pose significant challenges for park conservation. Understanding these complex dynamics is crucial for informing effective conservation strategies that address the ecological, social, and economic considerations surrounding VNP.

Supplementing the information provided in Figure 2, Table 4 presents a comprehensive analysis of LULC dynamics in the environs of VNP over two decades (2000–2019). It meticulously details the total area occupied by each LULC category in 2000 and 2019, along with quantifying the absolute changes (gains or losses) in area for each category. These changes are expressed as both absolute values (hectares) and relative values (percentages) to provide a nuanced understanding of the LULC transformations within the designated buffer zone. This table serves as a valuable resource for comprehending the spatiotemporal trends and drivers of LULC change in this specific region.

A comparative analysis of the implications of LULC dynamics in the environs of VNP between 2000 and 2019

Compared to the 0–5 km belt, the 5.1–10 km belt exhibited a lower percentage of agriculture and grassland in 2000 (54.47% vs. 80.13%). This can be attributed to the partial inclusion of Musanze city within the latter zone. However, the two belts displayed similar percentages of unchanged agriculture and grassland between 2000 and 2019 (86.30% and 86.15%, respectively). The



a. Land use and land cover in the 0 - 5 km belt around VNP in 2000

b. Land use and land cover in the 0 - 5 km belt around VNP in 2010

c. Land use and land cover in the 0 - 5 km belt around VNP in 2015

d. Land use and land cover in the in the 0 - 5 km belt around VNP in 2019.

e. Land use and land cover in the 5.1 - 10 km belt around VNP in 2000

f. Land use and land cover in the 5.1 - 10 km belt around VNP in 2010

g. Land use and land cover in the 5.1 - 10 km belt around VNP in 2015

h. Land use and land cover in the in the 5.1 - 10 km belt around VNP in 2019.

Figure 4. Land use and cover around Volcanoes National Park (VNP) between 2000 and 2019. Source: GIS (2019).

Table 4. Gain, loss, and no change in the 0–5 km and 5.1–10 km belts between 2000 and 2019.

Land use/land cover category	2000 to 2019											
	Gain (ha)	Gain (%)	Loss (ha)	Loss (%)	Unchanged (ha)	Unchanged (%)	Total 2000 (ha)	Total 2000 (%)	Total 2019 (ha)	Total 2019 (%)	Overall gain/loss in 2019	Overall gains/loss in 2019 (%)
Gain, loss, and no change in the 0–5 km belt												
Agriculture and grass	5725.98	21.18	3743.28	13.85	23,289.12	86.15	27,032.40	80.13	29,015.10	86	1982.70	7.33
Bare land	36	287.77	12.51	100	–	–	12.51	0.04	36	0.11	23.49	187.77
Built up	3049.11	1,546.99	126	63.93	71.1	36.07	197.1	0.58	3120.21	9.25	2923.11	1483.06
Planted forest and woodlots	1076.85	16.58	6008.85	92.52	485.64	7.48	6494.49	19.25	1562.49	4.63	−4932.00	−75.94
Water bodies	2.97	1,100.00	0.27	100	–	–	0.27	0	2.97	0.01	2.7	1000
Total							**33,736.77**		**33,736.77**			
Gain, loss, and no change in the 5.1–10 km belt												
Agriculture and grass	11,211.66	56.27	2729.97	13.7	17,194.23	86.3	19,924.20	54.47	28,405.89	77.66	8481.69	42.57
Bare land	19.98	28.53	70.02	100	–	–	70.02	0.19	19.98	0.05	−50.04	−71.47
Built up	2936.52	502.05	126.36	21.6	458.55	78.4	584.91	1.6	3395.07	9.28	2810.16	480.44
Planted forest and woodlots	1022.13	7.91	11,919.87	92.29	995.49	7.71	12,915.36	35.31	2017.62	5.52	−10,897.74	−84.38
Water bodies	25.38	0.82	369.45	11.98	2714.85	88.02	3084.30	8.43	2740.23	7.49	−344.07	−11.16
Total							**36,578.79**		**36,57,879**			

Source: Field survey (February 2019).

overall gain in this land cover type was significantly higher in the 5.1–10 km belt (42.57% vs. 7.33%), primarily driven by deforestation (10,747.71 ha vs. 5589.18 ha), conversion of bare land (61.2 ha vs. 11.79 ha), and shrinkage of water bodies (278.55 ha vs. 0.27 ha). The 5.1–10 km belt encompasses several lakes, which experienced significant encroachment for agriculture, grazing, and sedimentation between 2000 and 2005 before stricter environmental regulations took effect.

As in the 0–5 km belt, the built-up area in the 5.1–10 km belt showed substantial growth (480.44%) between 2000 and 2019. While the initial built-up area was higher due to the presence of Musanze city, the 0–5 km belt witnessed a three-fold increase compared to the 5.1–10 km belt. Expansion primarily originated from encroaching agriculture and grassland (2638.71 ha) and forest and woodlots (409.95 ha) in the 0–5 km belt, highlighting concerns about land security for local communities dependent on agriculture and woodlots.

Initially, the 5.1–10 km belt boasted nearly double the forest and woodlot cover compared to the 0–5 km belt (35.31% vs. 19.25%). However, both belts experienced alarming deforestation rates exceeding 92%, with forest conversion primarily driven by agricultural expansion (90.16% and 92.52%, respectively). While afforestation efforts were observed in both belts, the 0–5 km belt received double the investment (16.58% vs. 7.91%). This aligns with conservation efforts prioritizing the buffer zone closest to the park. Notably, the deforestation:afforestation ratio remained concerning in both belts (12:1 and 6:1, respectively), emphasizing the need for increased reforestation initiatives to reduce pressure on VNP resources.

Water bodies comprised a significant portion of the 5.1–10 km belt (8.43% in 2000) due to the presence of several lakes and the Mukungwa river. In contrast, the 0–5 km belt lacked permanent water sources, leading to water scarcity challenges for local communities. While both belts experienced minor gains in water area, primarily from reclaimed land, the gains in the 0–5 km belt primarily reflected temporary seasonal watercourses. This disparity underscores the need for improved water management infrastructure in the 0–5 km belt to mitigate water scarcity issues.

Both belts exhibited negligible amounts of bare land throughout the study period. The observed fluctuations stemmed from temporary cultivation and woodlot harvesting rather than long-term land degradation. Figure 5 shows the overall LULC dynamics in the study area between 2000 and 2019 around the VNP.

Discussion

The analysis of LULC changes within the boundaries of VNP reveals a fascinating and complex narrative. While the designated park boundaries remained stable throughout the study period (2000–2019), the vegetation cover within the park underwent significant transformations. Notably, the

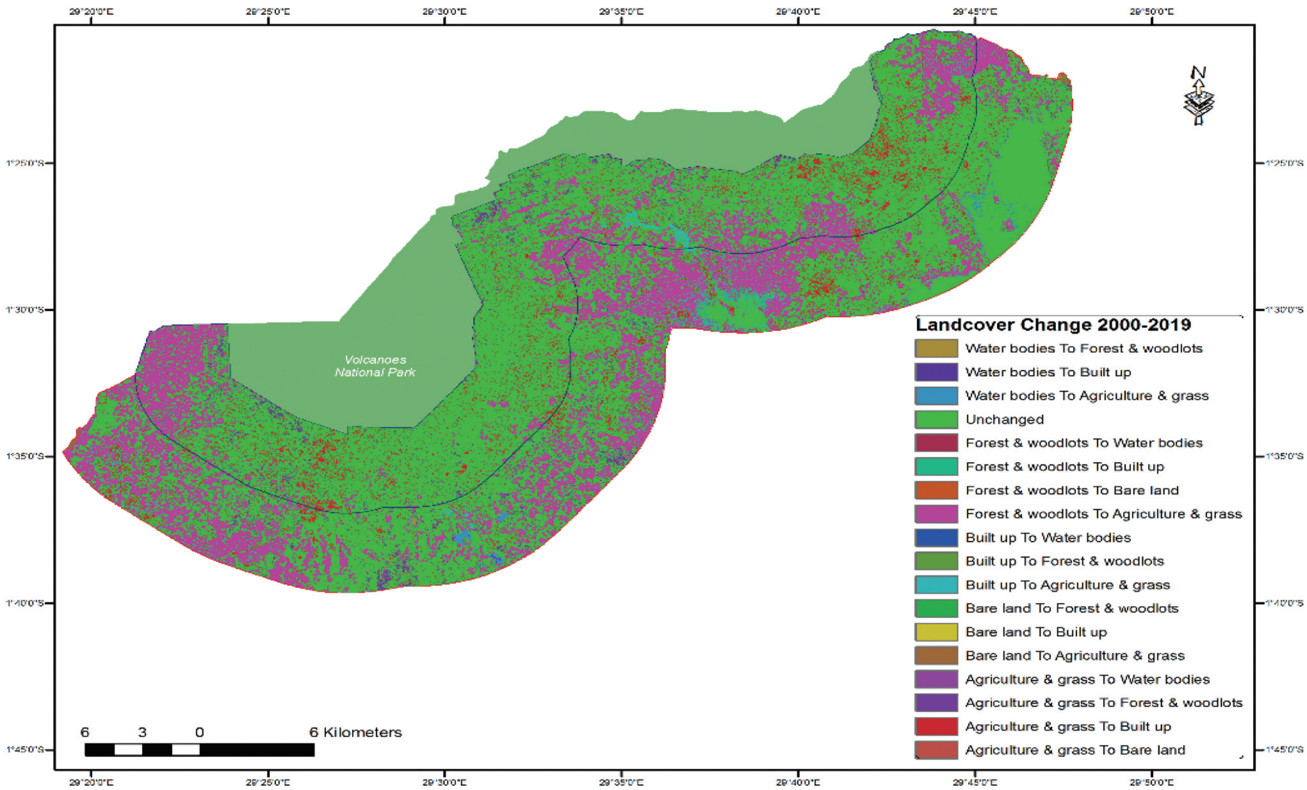


Figure 5. Overall land use and land cover dynamics in the environs of Volcanoes National Park (VNP) between 2000 and 2019. Source: GIS data (2019).

period between 1990 and 2000 witnessed extensive deforestation driven by the war and conflict in Rwanda, with land converted for agriculture, cattle rearing, and even settlements (Kayiranga et al. 2018). This aligns with broader observations highlighting the detrimental impacts of armed conflict on protected areas, often leading to increased resource extraction and habitat degradation.

Fortunately, the post-conflict era ushered in a wave of successful conservation and restoration efforts, significantly increasing open forest cover within VNP. From 78.14% in 2000, the open forest cover expanded to 88.33% by 2019. This remarkable recovery exemplifies the potential of well-coordinated conservation initiatives, echoing similar successes documented in post-conflict restoration projects elsewhere (Vanegas-Cubillos et al. 2022). However, the research also acknowledges the persistence of illegal resource use within the park, albeit at a substantially reduced scale compared to the pre-2000 period. This finding underscores the ongoing need for effective anti-poaching measures and community engagement strategies to ensure the long-term sustainability of VNP's resources (Bello, Lovelock, and Carr 2017).

One of the most alarming findings is the rampant deforestation within the 5 km and 10 km belts surrounding VNP. Driven by agricultural expansion and pasture development (Akinyemi 2017; Kayiranga et al. 2018), this trend mirrors a broader pattern in Rwanda, where forest cover has shrunk significantly due to population pressure and land scarcity (Akimenyi 2017; Arakwiye, Rogan, and Eastman 2021). Such deforestation has dire consequences for the park's biodiversity, fragmenting habitats, disrupting essential ecological corridors, and jeopardizing the mountain gorillas' food sources (Tuyisingize et al. 2023). As Lyster (2017) and Thomaz et al. (2020) warn, deforestation within protected areas like VNP can trigger 'cascading ecological impacts' that undermine conservation goals.

The study also reveals a rapid expansion of built-up areas around the park, fuelled by tourism development and population growth (Akinyemi 2017; Kayiranga et al. 2018). While tourism can inject valuable income into local communities, unchecked urban sprawl poses a significant threat. Encroaching on park boundaries, fragmenting ecosystems, and introducing pollution, it can create a significant challenge for conservation efforts (Leung et al. 2018; Sarmiento-Mateos et al. 2019). This necessitates a delicate balancing act: how can we harness the economic benefits of tourism while safeguarding the park's ecological integrity? Solutions may lie in promoting sustainable tourism practices, implementing stringent buffer zone regulations, and investing in green infrastructure within urban areas.

The study further highlights the plight of water bodies within the study area. Though small in size, these vital resources face increasing pressure from encroachment and sedimentation due to deforestation (Akinyemi 2017; Kayiranga et al. 2018). This is particularly concerning given the crucial role water plays in maintaining the park's hydrological balance and supporting its diverse ecosystems. As Bayramoglu, Chakir, and Lungarska (2020), Larned et al. (2020), and Lin et al. (2021) emphasize, unsustainable land use practices can exacerbate water scarcity and threaten the health of freshwater ecosystems. Therefore, integrated water resource management strategies that balance conservation needs with community water requirements become crucial for ensuring the long-term sustainability of the park's water resources.

The intricate tapestry of LULC changes woven around VNP necessitates a nuanced and multifaceted approach to its conservation. While mitigating deforestation, urban sprawl, and ensuring sustainable water management are undeniably crucial (Bayramoglu, Chakir, and Lungarska 2020), a deeper understanding of the underlying socio-economic drivers of these transformations is equally critical (Gurney et al. 2015; Brechin, Murray, and Mogelgaard 2010).

Addressing rampant deforestation within VNP's buffer zones, fuelled by agricultural expansion and pasture development (Akinyemi 2017; Kayiranga et al. 2018), requires more than just stringent regulations. As Lyster (2017) and Thomaz et al. (2020) warn, deforestation within protected areas can trigger cascading ecological impacts, jeopardizing biodiversity and ecosystem services. Sustainable land management practices that address the root causes of deforestation, such as poverty and land scarcity (Akinyemi 2017; Arakwiye, Rogan, and Eastman 2021), hold promise for long-term conservation success. Similarly, tackling urban sprawl requires balancing the economic benefits of tourism with the ecological integrity of VNP (Sarmiento-Mateos et al. 2019). Investing in green infrastructure within urban areas and promoting sustainable tourism practices can offer potential solutions (Leung et al. 2018).

However, a truly sustainable approach to VNP's conservation cannot ignore the socio-economic realities of surrounding communities. As Akinyemi et al. (2017) and Kayiranga et al. (2018) highlight, landlessness and poverty often compel local communities to rely on park resources for their livelihoods, creating conflict between conservation goals and community needs. Moving beyond traditional, top-down protected-area management strategies, collaborative approaches that address poverty, promote alternative income sources, and foster community participation in conservation efforts are crucial for achieving long-term success (De Koning et al. 2017). By acknowledging the complex interplay of ecological and socio-economic factors shaping VNP's landscape, we can pave the way for a future where conservation and community development thrive in harmony.

The study underscores the importance of not neglecting the socio-economic factors driving resource use around VNP. Landlessness and poverty compel many local communities to rely on park resources like firewood and timber, creating a conflict between conservation goals and livelihood needs (Akinyemi et al. 2017; Kayiranga et al. 2018). This highlights the need to move beyond traditional protected area management approaches and embrace a holistic perspective. As Brechin, Murray, and Mogelgaard (2010), Gurney et al. (2015), and De Koning et al. (2017) advocate, addressing poverty, promoting alternative income sources, and fostering community participation in conservation efforts are crucial for achieving long-term success in protected area management.

Conclusion and recommendations

This study employed satellite imagery and geospatial techniques to examine spatiotemporal land use and land cover (LULC) changes within a 10 km buffer zone surrounding Volcanoes National Park (VNP) in Rwanda. The study revealed concerning trends, particularly within the innermost 0–5 km belt, where rapid deforestation outpaces reforestation efforts and agricultural expansion fragments critical habitats. While tourism contributes to local economies, its unbridled development in the 0–5 km belt poses potential threats through habitat fragmentation, increased human–wildlife interactions, and noise pollution.

Results reveal that VNP's periphery bears the brunt of deforestation. The 0-5 km buffer zone experienced a considerably higher deforestation rate compared to the 5.1-10 km zone. Afforestation efforts within the inner buffer were significantly outpaced by forest clearing, with a deforestation-to-afforestation ratio of 6:1, while the outer buffer still exhibits a substantial deforestation rate (12:1). Nevertheless, the sheer extent of lost forest cover across both zones paints a worrisome picture for the park's ecological integrity.

As forests recede, agricultural lands and grasslands march forward, claiming ever-increasing swathes, particularly within the 5.1–10 km belt. This inexorable expansion, fuelled by a potent cocktail of population growth and dependence on natural resources, underscores the intricate link between human livelihoods and the park's ecosystem. While agriculture sustains local communities, its encroachment fragments habitats and disrupts vital ecological processes, posing a significant threat to biodiversity.

Tourism's double-edged nature necessitates a shift towards ecotourism principles. Educating visitors on responsible behaviour and ensuring equitable revenue sharing with local communities can transform tourism into a tool for conservation and a source of sustainable income. By fostering a symbiotic relationship between the park and its human neighbours, we can create a future where both communities thrive.

Effectively mitigating LULC impacts around VNP demands a multifaceted approach that tackles the environmental, social, and economic dimensions of the issue. Based on the above research findings, we recommend strengthening park management, promoting sustainable land use practices, providing alternative income sources for surrounding communities, and developing integrated water resource management plans. By adopting this comprehensive approach, Rwanda can ensure the continued protection of VNP's unique biodiversity and secure a sustainable future for both the park and its surrounding.

Despite revealing troubling land-use trends around Volcanoes National Park, the study itself points to gaps demanding further research. Satellite limitations and missing socio-economic data hinder a complete picture. Specifically for the study's temporal scope, while a map for the target year 2005 was generated, significant cloud cover renders its interpretability limited. However, budgetary constraints prevented the development of maps for adjacent years, particularly the critical year immediately before or after 2005. This lack of temporal context hinders our ability to definitively assess potential trends and nuances within the analysed timeframe. While maps were produced and interpreted for four other periods, the absence of data for an adjacent year introduces uncertainty in establishing the identified patterns' temporal stability and generalizability. Future research with expanded temporal coverage is crucial to strengthen the study's conclusions. Additionally, the focus solely on land-use changes overlooks crucial ecological factors like wildlife, climate, and invasive species. To address these shortcomings, future research should use high-resolution imagery and ground data for accuracy, include socio-economic factors to understand drivers of change, broaden the scope to consider ecological factors and conservation effectiveness, and study local communities' perspectives for participatory conservation.

By addressing these limitations and pursuing the proposed research avenues, we can gain a deeper understanding of the complex interplay between human activities and ecological resilience around VNP. This knowledge will be instrumental in designing and implementing effective conservation strategies that safeguard the park's biodiversity and promote sustainable development for generations to come.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Madeleine Nyiratuza is a seasoned environmental leader with over 15 years of experience in conservation and sustainable development. Her career spans roles with renowned organizations like the Wildlife Conservation Society (WCS) and the United Nations Development Programme (UNDP) in Rwanda. Currently, she works with the UN in Addis Ababa, Ethiopia, leveraging her expertise at a regional level. She holds a PhD from Kenyatta University, demonstrating her commitment to academic excellence and evidence-based solutions. Her dedication to environmental protection and community empowerment makes her a valuable asset in addressing Africa's complex challenges.

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Caleb Mireri, a Kenyan associate professor of environmental planning and management working with Kenyatta University, tackles East Africa's environmental challenges through a multifaceted lens. His D.Phil. in geography, economics and sociology (University of Duesseldorf) informs his research on climate change adaptation, natural resource conservation, and environmental planning, while his extensive experience across public, private, and non-profit sectors, including the World Bank, equips him with practical insights. He actively publishes, collaborates, and mentors, shaping sustainable solutions for food security, land degradation, and water scarcity.

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Availability of data and materials

The data used during this study can be shared by the corresponding author on request.

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