EFFECTIVENESS OF PROTECTED AREAS IN PRESERVING BIODIVERSITY IN THE CONGO BASIN

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CONTENT

ABSTRACT

The Congo Basin's tropical rainforests are globally important ecosystems, crucial for climate regulation, carbon sequestration, and biodiversity conservation. Despite covering less than 5% of the global land area, these forests store approximately 25% of terrestrial carbon and contribute to 33% of the world's net primary production. Protected areas (PAs) are established to safeguard these ecosystems, but their effectiveness in preserving biodiversity and genetic diversity remains underexplored. This thesis investigates the role of PAs in the Congo Basin in conserving ecological and genetic diversity. A review of existing literature was conducted to evaluate species richness, genetic diversity, and the impact of conservation strategies. Historical climatic fluctuations and geographic barriers, such as the Congo River, have shaped the region's biodiversity, resulting in significant spatial variations in species richness and genetic diversity. Using the Grauer's gorilla (*Gorilla beringei graueri*) as a case study, the thesis explores the conservation status of this keystone species within PAs, highlighting the complex interplay between habitat protection, human activities, and species survival. Studies found that the most important areas for mammal movement are currently unprotected. Findings also indicate that some conservation efforts, like FSC-certified forest management, benefit large mammal populations. However, current strategies often overlook the importance of connectivity between PAs. Enhancing connectivity through habitat corridors is critical for facilitating species movement and gene flow, essential for maintaining ecosystem resilience. Despite the clear need for connected and genetically diverse populations, there is a notable gap in research and practical efforts targeting these aspects. In conclusion, the thesis underscores the urgent need for comprehensive conservation strategies that prioritize connectivity and genetic diversity within the PAs of the Congo Basin. Addressing these gaps is vital for improving the effectiveness of PAs in preserving the region's biodiversity, ensuring the long-term survival of its unique flora and fauna, and maintaining the ecological integrity of this globally important rainforest ecosystem.

INTRODUCTION

Tropical rainforests are crucially important ecosystems. They play a pivotal role in global climate regulation, carbon sequestration, and biodiversity conservation (Marquant, 2015). These forests, which span the equatorial regions of the world, are home to an extraordinary diversity of flora and fauna. They provide essential ecosystem services such as stabilizing the climate, maintaining water cycles, and supporting the livelihoods of millions of people (Goodman & Herold, 2014). Their ecological significance extends beyond regional borders, playing a critical role in global carbon storage. Although tropical forests cover less than 5% of the global land area, they store about 25% of terrestrial carbon and contribute to about 33% of the world's net primary production (Díaz et al., 2005; Doug Boucher, 2011). Alarmingly, tropical deforestation was responsible for the release of 10.3 billion tons of CO_2 in 2013, roughly double the greenhouse gas emissions of the United States (IPCC, 2013). Other threats that rainforests face are hunting, the presence of human settlements, mining, agricultural practices and armed conflicts (Tranquilli et al., 2014).

To protect rainforest ecosystems, protected areas (PAs) are being designated. According to the International Union for Conservation of Nature (IUCN), a PA is "a clearly defined geographical space, recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008). The primary goals of PAs are to preserve species and genetic diversity, maintain ecosystem services, and protect landscapes of cultural and aesthetic value. In tropical rainforests, PAs are particularly important because they help mitigate threats such as deforestation, habitat fragmentation, and poaching. By restricting human activities and promoting sustainable management practices, PAs contribute to the long-term survival of species and the resilience of ecosystems.

A great example of a tropical rainforest that facilitates many PAs is the Congo Basin. It is the world's second-largest tropical rainforest, located in the heart of Central Africa. This region boasts a rich tapestry of biomes, including flooded savannas, mangroves, mountain meadows, tropical and subtropical savannas, and dense humid forests (Proces et al., 2020). The climatic gradient, with mean annual rainfall ranging from 250 mm to 10,000 mm, underpins the diversity of these ecosystems (Doumenge et al., 2015). The Congo Basin is a biodiversity hotspot, harboring approximately 10,000 plant species, 1,000 bird species, 700 fish species, and 400 mammal species, including iconic species such as forest elephants, lowland gorillas, and chimpanzees (Mason et al., 2020).

For preserving and managing biodiversity, it is crucial to have accurate measures of species richness at a regional scale, connectivity between PAs, and genetic diversity within and among PAs. However, in most reports assessing the quality of national parks, the focus is primarily on the prevention of anthropogenic activity, such as poaching and deforestation (Eba'a Atyi et al., 2022). This narrow focus often overlooks the broader ecosystem dynamics, including regional species richness, ecological connectivity, and genetic diversity. Moreover, assessments tend to concentrate on how PAs address immediate threats rather than evaluating the overall ecological health and connectivity of the landscape. Studies that address these broader aspects are necessary to assess the overall impact of PAs on biodiversity conservation in the Congo Basin. Understanding these elements is essential for improving conservation strategies and ensuring the long-term preservation of biodiversity.

In this thesis, the effectiveness of PAs in the Congo Basin rainforest in preserving biological and genetic diversity will be assessed. The focus will be on understanding how PAs contribute to the conservation of biodiversity, the factors influencing their success, and how they could be improved. Key questions addressed include: How effective are Central Africa's tropical protected areas in preserving ecological and genetic diversity? What factors influence the success of protected areas in conserving biodiversity? I hypothesize that PAs are generally successful in preserving biodiversity within individual national parks but that the predominant focus on individual parks risks overlooking significant threats to ecological connectivity and regional genetic diversity. This may result in fragmented conservation efforts that fail to maintain the broader ecosystem dynamics essential for long-term biodiversity conservation.
Existing literature will be reviewed to evaluate the success of PAs in the Congo Basin. This thesis will cover various aspects of biodiversity conservation, including species richness, genetic diversity, and the effectiveness of different conservation strategies. Through this analysis, the aim is to provide insights into improving conservation practices and enhancing the overall effectiveness of PAs in the region.

LITERATURE REVIEW

Overview of protected areas in Central Africa

Historical overview

The concept of protected areas (PAs) in Central Africa has deep historical roots. The first generation of PAs were created during the colonial period in the 1930s, driven by European powers' desire to conserve wildlife for hunting and scientific research. This era saw the establishment of large reserves that often disregarded the land rights and livelihoods of local communities (Herzog, 2021). The creation of these parks was part of broader colonial strategies that sought to control great tracts of land and resources under the guise of nature conservation (Vandergeest & Peluso, 1995). This trend grew after WWII, when colonial nations selected conservation territories (Protected Areas, 2015). Another boost of PA creation and expansion was brought by the decolonization period in the 1960s and the 1970s, as the newly independent states sought to establish their sovereignty and economic stability. During this time, PAs were celebrated and seen as vital for national identity and tourism development. However, many of these expansions continued the colonial legacy of excluding local communities from their decision-making and land use (Brockington & Igoe, 2006). In the 1990s, international conservation organizations played a significant role in further expanding PAs, aligning with global biodiversity goals set by conventions like the Convention on Biological Diversity (CBD). From this period, a few large national parks and reserves in Central Africa were established. These were often created with significant international funding and influence, which was a new development (Proces et al., 2020). However, it wasn't until the 2000s and 2010s that the region saw a substantial increase in the creation of new protected areas. Since the year 2000, there has been remarkable growth in regional cooperation and coordination efforts among Central African countries, supported by organizations such as the Congo Basin Forest Partnership (PFBC) and the Economic Community of Central African States (CEEAC) (OFAC, 2015).

Geographical overview

Due to these historical events, Central Africa is now home to 257 PAs, covering a total area of 680.496 km^2, which is 20% of the total land area (see appendix). This report will refer to central Africa as consisting of the following six countries: Cameroon, Central African Republic, Equatorial Guinea, Gabon, Congo, and the Democratic Republic of Congo (see Figure 1).

The network of tropical rainforests in Central Africa, also known as the Congo Basin, is one of the three largest remaining blocks of such forests in the world together with the Amazon Basin and Indonesia (Brandon, 2014). These forests are not only vast but also critically important for biodiversity conservation. Within the Congo Basin, many national parks are well monitored and assessed on their prevention of

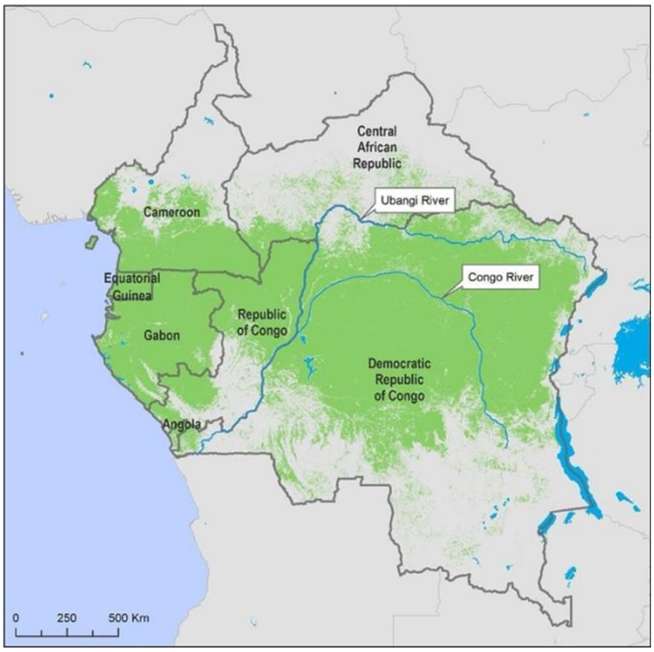

Figure 1. The range of the Congo Basin. Green shows the primary tropical forest (Shapiro, 2021).

anthropogenic activity, providing extensive data for analysis. However, existing research and monitoring efforts have predominantly focused on preventing poaching and logging, often overlooking the crucial aspects of species richness and genetic diversity. This review aims to address this gap by evaluating the effectiveness of protected areas in preserving both species richness and genetic diversity in Central Africa's tropical rainforests.

Biodiversity of the Congo Basin

Introduction to biodiversity indices

Understanding biodiversity is fundamental to ecology and conservation. Biodiversity can be quantified and interpreted through various measures, primarily classified into alpha, beta, and gamma diversity. These concepts provide a framework for analyzing diversity at different scales, which can then be quantified using specific indices.

Alpha diversity refers to the diversity within a particular area or ecosystem, typically measured by counting the number of species (species richness) and considering the relative abundance of each species (species evenness). Beta diversity measures the variation in species composition between different ecosystems or along environmental gradients, highlighting the differences in species assemblages across habitats. Gamma diversity is the total diversity observed across multiple ecosystems within a larger region (Fath, 2019).

To quantify alpha diversity, several indices are commonly used, correlating species richness with the relative abundance or dominance of each species. These indices are critical for avoiding uniform values across structurally different assemblages. In this section, we discuss three widely used indices—Shannon-Wiener, Pielou's Evenness, Fisher Alpha and Simpson — that are commonly employed in ecological studies.

The Shannon-Wiener index is a well-known and widely used index in ecology and ecological monitoring (Fath, 2019). This index quantifies species diversity in a community by considering both species richness (the number of different species) and species evenness (how evenly the individuals are distributed among those species). It has been derived from the Shannon function *H* and is expressed as follows:

$$H = -\sum_{i=1}^{n} \rho_i \ \ln \rho_i$$

where *H* is the index of species diversity, n is the total amount of species in the community and ρ_i is the relative abundance of ith species.

The Shannon-Wiener index is based on the concept of evenness. The concept of evenness or equitability refers to the extent to which each species is represented in the sample. To measure the evenness in a population we will use the Pielou evenness index. This index ranges from close to zero, where one species is dominant and the rest is present in low numbers, to 1 where all species are being represented in equal numbers. Pielou’s evenness index based on the Shannon index (E_H) can be calculated as:

$$E_H = \frac{H}{\ln S}$$

where *H* is the Shannon index of species diversity and *S* is species richness.

Another index of alpha diversity is the Fisher Alpha Index, which assumes that the abundance of species follows a log series distribution. The index is calculated as:

$$S = \alpha \ln\left(1 + \frac{N}{\alpha}\right)$$

with α being the index, *S* being the total number of species in the sample, and *N* being the total number of individuals. This index provides a measure of diversity that is less sensitive to sample size and is particularly useful for comparing different communities.

The last index that will be discussed is the Simpson Index. This index quantifies the probability that two randomly selected individuals in a sample belong to the same species. It is expressed as follows:

$$\lambda = \sum_{i=1}^{S} \frac{n_i(n_{i-1})}{n(n-1)}$$

Where *S* is the total number of species, n_i is the number of individuals of the individuals of the *i*-th species, and n is the total number of individuals.

Species richness and abundance

Studies on species richness and abundance within PAs in the Congo Basin emphasize the influence of environmental and spatial factors on geological time scales on current biodiversity patterns. Historical climatic fluctuations, such as those during the Pleistocene, have shaped the region's biodiversity by affecting forest cover and species distributions over time. These climatic oscillations have led to variations in vertebrate species richness across different ecoregions (Matvijev et al., 2022). For instance, the central ecoregions of the Congo Basin exhibit notably lower vertebrate species richness compared to northern ecoregions due to these historical climatic constraints (Van de Perre, 2019). The Congo River has acted as a significant biogeographic barrier, promoting allopatric speciation and resulting in distinct community structures and species richness levels between northern and central ecoregions (Van de Perre et al., 2020).

Studies on species diversity are mostly done on specific areas within the Congo Basin, and then these sites are compared with each other. For instance, research focused on tree diversity and structure in the Ipendja evergreen lowland moist forest of northern Republic of Congo (Ekoungoulou et al., 2017). This study employed the Shannon-Wiener Index and Pielou's Evenness Index to analyze tree diversity patterns across two plots that are 25 km apart. The findings revealed that the Shannon-Wiener Index for species diversity was 4.29 bits in Mokelimwaekili and 4.22 bits in Sombo, indicating slightly higher diversity in the former site. Additionally, Pielou's evenness index ranged between 0.88 and 0.90 for Mokelimwaekili and Sombo sites, showing a relatively even distribution of species in both locations. These findings are shown in Figure 2.

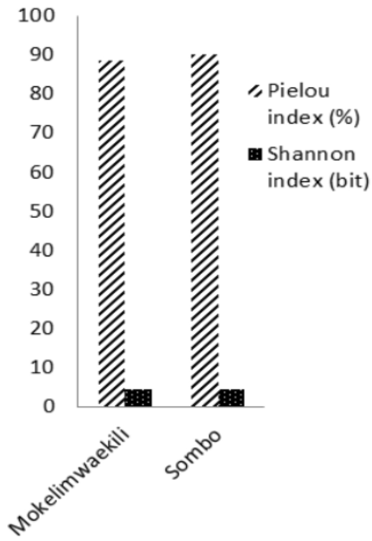

Figure 2. Values of Shannon Wiener index of species diversity and Pielou evenness index of Mokelimwaekili and Sombo (Ekoungoulou et al., 2017).

Another study on vegetation diversity within the Congo Basin had similar results. This study revealed significant spatial variations in species diversity and composition. In a study conducted in northeastern forest sites, such as Ituri and Rubi-Tele, lower species diversity was observed compared to areas around Kisangani, such as Yoko and Uma. This spatial variation suggests that different factors may influence species richness in distinct forest blocks. The study utilized the Fisher alpha-diversity index. Detailed findings are presented in Table 2 in the Appendix (Lisingo et al., 2015).
Lastly, research in the Eloumden mountain in Cameroon highlights the region's unique ecological dynamics and high bird diversity. The mix of Equatorial forest and montane vegetation in this area supports a diverse avifauna (Nguembockv et al., 2019). To perform the bird survey, they used the mist-netting method during six months. They captured 158 individuals belonging to 20 bird families. With a Simpson diversity index value of 0.96, the results confirm high diversity within the Eloumden avifauna.

Presence and conservation status of a keystone species

The Grauer's gorilla (*Gorilla beringei graueri*), the world's largest primate, is only found in the east of the Democratic Republic of Congo. They are a great example of a keystone species, meaning that they have a disproportionately large impact on its environment relative to their abundance. As prey, predators, and mutualists, these gorillas significantly influence ecosystem structure and function. Their evolution and feeding ecology are closely linked to the diversification of angiosperms, making them important pollinators and seed dispersers (Sussman et al., 2012). These frugivorous primates disperse seeds over long distances, enhancing forest regeneration. These changes severely impact forest dynamics and the sustainability of many tree species. Therefore, conserving primates is essential for maintaining biodiversity and ensuring the health and resilience of tropical forest ecosystems (Estrada et al., 2017).
The overall population of Grauer's gorillas faces severe threats. New roads, agricultural expansion, refugee camps, human settlements, illegal logging, and mining have fragmented their habitat. Poaching, bushmeat trafficking, and disease epidemics, including Ebola, further threaten their existence, contributing to over 90% of gorilla deaths in some areas. Grauer's gorillas are particularly sensitive to hunting pressure due to their extremely low reproductive

rate, with females giving birth for the first time at around 10 years old and having an interbirth interval of over four years (Consolee et al., 2024).
Therefore, the conservation status of the Grauer's gorilla has deteriorated significantly over the years. Prior to the civil war, the population was estimated at 16,900 individuals. However, the conflict beginning in 1996 caused severe declines due to increased hunting and resource extraction as armed groups settled in the park. In Kahuzi-Biega National Park (KBNP), which once protected about 86% of the global population, gorilla numbers have plummeted (Spira et al., 2016). Surveys have shown an 87% decline in the park's gorilla population, with encounter rate data at 10 sites across their range indicating declines of 82–100% at six of these sites. By 2016, it was estimated that only 3,800 Grauer's gorillas remained in the wild—a 77% decline in one generation—justifying their elevation to Critically Endangered status on the IUCN Red List of Threatened Species (Plumptre et al., 2016).
Despite these severe declines, there have been some positive trends due to conservation efforts. Regular censuses by the Wildlife Conservation Society (WCS) and the Institut Congolais pour la Conservation de la Nature (ICCN) in the high-altitude sector of KBNP have shown a promising increase in gorilla numbers. The most recent survey in 2015 estimated a minimum of 213 individuals in this sector — a 64% increase since the post-war decline. However, estimates vary, with some surveys suggesting up to 325 individuals in this sector (Spira et al., 2016).

Genetic diversity of the Congo Basin

Historical fragmentation

Research on the genetic diversity of species within the Congo Basin reveals intricate patterns shaped by historical fragmentation and limited dispersal mechanisms. For instance, a study on *Scorodophloeus zenkeri*, a shade-tolerant tree with limited seed dispersal, highlights significant genetic discontinuities across the region. This species exhibits higher genetic diversity in Lower Guinea compared to the Congo Basin, reflecting the impact of historical forest fragmentation on genetic structures (Vanden Abeele et al., 2021). These genetic discontinuities are indicative of persistent barriers to gene flow, resulting from past climatic events that fragmented forest habitats.
Further, a spatially explicit phylogeographical reconstruction has shed light on the historical forest cover dynamics in the Congo Basin. This study demonstrated distinct differences in genetic diversity between Lower Guinea and Congolia. Lower Guinea, identified as a Pleistocene refugium, shows higher plastid lineage and nucleotide diversity, suggesting long-term stability and preservation of genetic diversity in this area. Conversely, Congolia's lower genetic diversity, characterized by fewer extant lineages and recurring haplotypes, indicates more recent range expansions and limited historical refugia (Matvijev, 2022).

The findings from these studies align with several genetic theories. Gene Flow and Genetic Drift are central to understanding these patterns. In species like *S. zenkeri*, limited seed dispersal reduces gene flow between populations, allowing genetic drift to cause significant allele frequency changes in isolated populations. Over time, this leads to distinct genetic differentiation, especially in regions that experienced historical fragmentation (Kardos, 2021). The Founder Effect also plays a crucial role. This theory explains how new populations established from a small number of individuals can have reduced genetic variation compared to the original population. In the Congo Basin, the lower genetic diversity observed in areas like Congolia may result from populations being re-established by a few individuals after significant climatic events or habitat disturbances. These founder populations often carry only a subset of the genetic variation present in the original population, leading to reduced genetic diversity and distinct genetic signatures (Depecker, 2023).

The role of PAs in reducing fragmentation and promoting connectivity.

Biodiversity often transcends political borders. A significant portion of terrestrial species occupy ranges that extend across multiple countries. For instance, over half of all terrestrial species, including mammals, amphibians, and birds, have ranges that cross international boundaries. This phenomenon is even more pronounced among threatened species, with a notable percentage of them inhabiting transboundary regions. These statistics highlight the critical need for collaborative, cross-border conservation strategies to effectively protect biodiversity (Mason et al., 2020). Recent studies on the functional connectivity of the world's PAs emphasize the need for enhanced connectivity to support conservation. One study generated a global resistance-to-movement surface from empirical estimates of animal movement (624 individuals of 48 mammalian species) in response to the human footprint index (HFI), which describes the combined effects of infrastructure, land use and human access across the planet. They revealed that reducing the human footprint within PAs could improve connectivity more effectively than establishing new PAs alone. However, the combination of reducing human impact and creating new PAs yields the greatest benefits for animal movement (Brennan et al., 2022). Additionally, the study found that the most important areas for mammal movement are currently unprotected. About 71% of these critical areas overlap with global biodiversity priority regions. Additionally, 6% of these essential movement areas are located on lands with moderate to high human modification. This underscores the urgent need for targeted conservation and restoration efforts to ensure PA connectivity and support broader conservation goals (Brennan et al., 2022).

In the Congo Basin, these principles are particularly crucial due to the region's complex landscape and numerous threats to biodiversity. Ensuring the connectivity of PAs in this region helps protect individual species and maintains the ecological processes essential for the ecosystem's health. Strategic planning that incorporates both structural and functional aspects of connectivity, as well as efforts to reduce human impact within and around PAs, is necessary for effective biodiversity conservation in the Congo Basin. By maintaining large, contiguous areas of habitat and creating corridors that link these areas, PAs can facilitate gene flow and species movement, which are essential for maintaining genetic diversity and ecosystem resilience.

Despite the clear importance of connectivity for conservation, there is a notable gap in research and efforts aimed at improving connectivity between PAs in the Congo Basin. Current conservation strategies often focus on preventing poaching and logging, with insufficient emphasis on connectivity and gene flow. This oversight represents a significant challenge to the long-term effectiveness of PAs in preserving biodiversity and genetic diversity in the region.

Conservation strategies and their effectiveness

Management outcomes

PAs in the Congo Basin are crucial for conserving the region's rich biodiversity, but they face numerous challenges. Illegal activities such as poaching, mining, and deforestation severely impact these areas. Poaching targets key species like elephants and gorillas, while mining and deforestation degrade habitats and disrupt ecological balance. Effective governance is essential to combat these issues, yet weak governance and corruption often undermine conservation efforts, allowing illegal activities to persist.

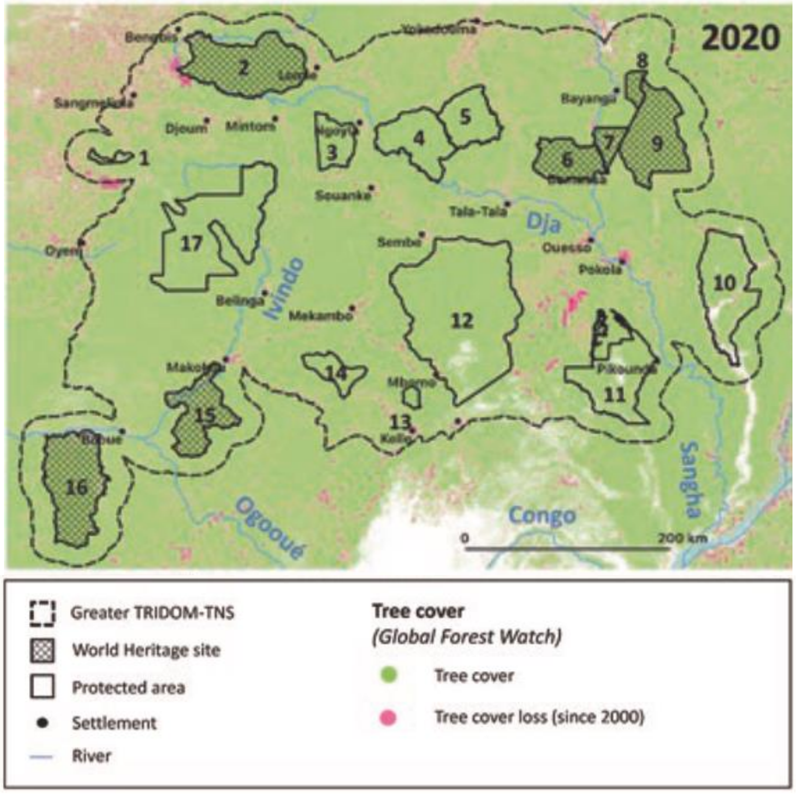

Figure 3 Tree cover changes in the Greater TRIDOM-TNS landscape since 2000 (Resende & Meikengang, 2023).

Currently, about 20% of the total forest area of the Congo Basin has protected area status. The management of these protected areas is now based on a new paradigm: the landscape conservation approach (Resende & Meikengang, 2023). This approach integrates larger landscapes beyond political boundaries and encompasses entire ecosystems, considering the interests of stakeholders such as local communities and the private sector. It helps ensure the integrity and connectivity of protected areas and their peripheral zones, maintaining genetic flows and biological processes to prevent habitat fragmentation. Twelve landscapes have been identified as priorities in the Congo Basin due to their taxonomic importance, overall integrity, and resilience of ecological processes. Among these, the TRIDOM (Trinational Dja-Odzala-Minkébé) and TNS (Trinational Sangha) landscapes stand out, hosting the majority of the last remaining forest elephants, lowland gorillas, and chimpanzees in Central Africa. These landscapes are also home to four of the eight natural World Heritage sites in the Congo Basin, highlighting their exceptional importance. However, as you can see in Figure 3, the forest between the protected areas is not safe from logging practices.

Other conservation efforts

In addition to protected area management, sustainable practices in logging concessions and tools for assessing forest degradation are being used for conservation efforts.

The Forest Stewardship Council (FSC) aims to reduce direct environmental impacts by maintaining high conservation value forests and applying reduced impact logging practices. A major concern for biodiversity is that timber extraction, through the creation of roads, opens previously remote forests, enabling illegal and unsustainable hunting. This indirect effect of logging mainly influences medium- to large-sized forest mammals, which are particularly vulnerable to human pressure. FSC certification may alleviate these pressures by reducing accessibility to concessions by closing off old logging roads, prohibiting wild meat transport and hunting materials, providing access to alternative meat sources for workers and their families, and conducting surveillance by rangers. A study using 1.3 million camera-trap photos across 14 logging concessions in western equatorial Africa found higher mammal encounter rates in FSC-certified areas compared to non-FSC concessions, particularly for high conservation priority species like the critically endangered forest elephant and western lowland gorilla. FSC certification helps mitigate logging's negative impacts, maintaining higher biodiversity and reducing the prevalence of small species like rodents (Zwerts et al., 2024).

The Forest Condition (FC) metric developed by Shapiro et al. (2021) offers a valuable tool for assessing forest degradation. Based on changes in above-ground biomass and forest fragmentation, it estimates that less than 70% of Congo Basin forests remain fully intact, down from 78% in 2000. Integrating forest condition assessments into conservation planning is crucial, as about half of all Congo Basin ecosystem types are threatened, with four ecosystems critically endangered. These insights are essential for effective forest monitoring, planning, and management to sustain the region's biodiversity. To improve the effectiveness of PAs, constructing habitat corridors has been proposed. These corridors link isolated habitat patches, facilitating species movement and genetic exchange. Their success depends on factors like width, length, habitat composition, and the surrounding habitat matrix, tailored to specific species' needs (Holyoak et al., 2019). This is a promising insight, although its implementation in planning PAs seems to be underexplored in the Congo Basin.

Addressing these challenges and harnessing innovative conservation approaches are critical for preserving the vital ecosystem of the Congo Basin for future generations. The integrated landscape conservation approach, coupled with sustainable practices like those promoted by the FSC and advancements in forest condition assessment, offers a promising framework. However, the adoption of strategies such as habitat corridors remains underexplored in the region's PA planning. Continued research, adaptive management, and strengthened governance are essential to effectively meet conservation goals amidst evolving environmental and socio-economic dynamics.

DISCUSSION

The literature review provides an overview of PAs in Central Africa, tracing their historical development, geographical distribution, and crucial role in biodiversity conservation. Initially established during the colonial era for wildlife preservation, PAs expanded during decolonization and international conservation efforts. Today, they encompass 20% of Central Africa's land area, spanning 257 PAs across Cameroon, Central African Republic, Equatorial Guinea, Gabon, Congo, and the Democratic Republic of Congo.
Central Africa's tropical rainforests, part of the Congo Basin, are globally significant for biodiversity. Historical climatic fluctuations and biogeographic barriers like the Congo River have shaped distinct ecoregions, influencing species richness and composition across forest blocks. Conservation efforts face significant challenges, exemplified by the plight of keystone species like the Grauer's gorilla, threatened by habitat fragmentation, poaching, and disease. Genetic studies highlight complex patterns influenced by historical fragmentation and limited dispersal mechanisms. Species like *Scorodophloeus zenkeri* exhibit significant genetic discontinuities across the region, underscoring the importance of connectivity between PAs to preserve genetic diversity and ecosystem resilience. A combination of reducing human impact and creating new PAs yields the greatest benefits for animal movement. The most important areas for mammal movement are currently unprotected, underscoring the urgent need for more targeted conservation and restoration efforts.
Effective PA management in the Congo Basin is hindered by illegal activities, weak governance, and habitat degradation. Adoption of landscape conservation approaches and sustainable practices, such as those advocated by the Forest Stewardship Council (FSC), shows promise. However, innovative strategies like habitat corridors remain underdeveloped in PA planning. This necessitates continued research, adaptive management, and strengthened governance frameworks.

Since we have used some biodiversity indices, it is crucial to acknowledge their limitations. While alpha diversity indices like the Shannon-Wiener Index, Pielou Evenness Index, and Fisher Alpha Index offer valuable insights into species richness and evenness, they are not without their downsides. The Shannon-Wiener Index, for instance, can be disproportionately influenced by rare species, skewing the perceived diversity. Pielou's Evenness Index, although useful for understanding species distribution uniformity, becomes less informative when species richness is low. The Fisher Alpha Index, while robust to sample size variations, assumes a log series distribution of species abundance that may not accurately reflect real-world communities.

The emergence of a transboundary network of protected areas and new World Heritage sites in the Greater TRIDOM-TNS can be used as a lever to strengthen forest governance in the landscape. Despite these significant advances, forest governance in the Congo Basin countries is still weak (Resende, 2023). Coordination between institutions on land and forest governance issues is insufficient and there is a crucial need to harmonize sectoral policies at the national level to strengthen transboundary cooperation. Thus, the consolidation of partnerships with the private sector, the certification process in favor of sustainable forest management (FSC), and the promotion of integrated and sustainable planning tools remain encouraging vectors for good forest management at the national level.

In biodiversity research, particularly focusing on genetic diversity, the existing literature reveals significant gaps and limitations. Few studies delve into genetic diversity compared to other facets of biodiversity, such as species diversity. Moreover, the available literature predominantly focuses on historical perspectives, particularly in relation to fragmentation events of the past. There is a noticeable scarcity of studies that investigate current genetic diversity dynamics across various ecosystems and species. One notable reason for this scarcity is the substantial resources and funding required for such research (Pérez-Espona, 2017). Studies involving genetic diversity necessitate extensive sampling efforts, molecular analyses, and often long-term monitoring to effectively capture the complex dynamics of genetic variation within populations. Additionally, innovative strategies like habitat corridors remain underexplored, as the available literature on their implementation and effectiveness is limited. This gap underscores the need for more contemporary studies on genetic diversity and corridor efficacy to inform current conservation strategies effectively.
It was also notable that many studies conducted in Central Africa were only available in French. For greater accessibility, it would be beneficial to have these studies available in multiple languages, including English.

Exploring the effectiveness of PAs in Central Africa necessitates considering the critical role of funding. The allocation and utilization of financial resources significantly influence the capacity to protect designated areas. Understanding these funding dynamics is crucial for assessing their impact on conservation outcomes. Moreover, different management strategies implemented in PAs can variably affect their success, highlighting the need for further research to grasp their implications (Baghai et al., 2018).
To provide a better overview of the status of the Congo Basin, it is essential to delve deeper into the diverse threats facing its biodiversity and explore effective mitigation strategies. This includes addressing issues such as habitat fragmentation, illegal wildlife trade, and the impacts of climate change.
Furthermore, comparing the Congo Basin with other tropical regions like the Amazon Basin and Indonesia can offer valuable insights into biodiversity, genetic diversity, and conservation efforts. Such comparative studies could facilitate knowledge exchange on effective management practices, research methodologies, funding mechanisms, and regional cooperation strategies. This comparative approach holds promise for enhancing conservation strategies across tropical ecosystems worldwide.

CONCLUSION

The biodiversity of Central Africa, particularly within the Congo Basin, is intricately shaped by historical climatic fluctuations and biogeographic barriers such as the Congo River. Studies on species diversity and genetic structures underscore significant spatial variations influenced by these historical legacies. For instance, research on vertebrate species richness highlights distinct patterns between northern and central ecoregions, reflecting past climatic impacts and biogeographic constraints.

Genetic diversity studies, exemplified by *Scorodophloeus zenkeri,* further illuminate the impact of historical fragmentation on genetic discontinuities across the Congo Basin. These findings underscore the role of past climatic events in shaping genetic diversity and emphasize the need for targeted conservation strategies that consider genetic connectivity and population viability. A combination of reducing human impact and creating new PAs yields the greatest benefits for animal movement. Additionally, conservation can be targeted more accurately, as the most important areas for mammal movement are currently unprotected.

In evaluating PA effectiveness, our review highlights the critical factors influencing their success, including regional cooperation, FSC-certification, and the FC-metric. Despite significant achievements in establishing transboundary PA networks, challenges persist, necessitating enhanced institutional coordination, policy harmonization, and sustainable funding mechanisms. Addressing these challenges is essential for ensuring the long-term viability of biodiversity conservation efforts in the Congo Basin.

In conclusion, while progress has been made in biodiversity conservation in Central Africa, ongoing efforts must focus on addressing research gaps and implementing adaptive strategies to safeguard biodiversity and ecosystem services. By embracing innovation, strengthening governance frameworks and fostering international cooperation, we can pave the way for sustainable conservation practices that benefit both current and future generations.

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APPENDIX

Country	Nr. of PAs	Area of PAs (km^2)	Total land area (km^2)	% land area covered
Cameroon	54	51.538	469.428	10,98
Central African republic	38	112.827	624.568	18,06
Equatorial Guinea	16	5.228	27.136	19,27
Gabon	62	59.708	266.045	22,44
Congo	34	126.427	343.737	36,79
Democratic Republic of Congo	53	324.768	2.344.275	13,85
Total	**257**	**680.496**	**4.075.189**	**20,23166667**

Table 1. The number of PAs, the total area covered by PAs and the coverage of the total land in percentage by the PAs in central Africa. For total of the coverage the average is used. Information is retrieved from Protected Planet.

	Ituri	Uma	Rubi-Tele	Yoko	p-value
Fisher	13,66 ± 7,8	24,81 ± 9,6	10,67 ± 5,5	30,1 ± 9,14	0,000

Table 2. the Fisher alpha diversity index within N plots of 0.25 ha. P-value: Kruskal-Wallis test for difference between sites (Lisingo et al., 2015).