



Original Research Paper

Employing Agent-Based Modeling to Investigate Wildlife Behavioral Responses and Ecosystem Functionality in Fragmented Environments

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Key Words
Abstract

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The Congo Basin, a globally significant forest with immense biodiversity, is gradually losing its continuous habitat due to the cutting down of trees, in addition to forest clearance, illegal logging, farming, and road and bridge construction activities. Over the last several decades, the Congo Basin has had a staggering loss of forest cover, with a rough estimate of 10 million hectares of forest being cleared between the year 2000 and 2025. The fragmentation interferes with natural processes and poses substantial difficulties to animal populations. Therefore, it is important to know how animals adjust and behave in fragmented areas so as to be able to conserve this ecosystem. This is research that makes use of Agent-Based Modeling (ABM) to investigate the behavioral changes of the key species in the Congo Basin, such as the western lowland gorilla, forest elephant, okapi, and chimpanzee, and to determine the effects that fragmentation has on the ecosystem's functionality. The present study will utilize an Agent-Based Approach (ABA) to simulate how habitat fragmentation will impact the daily routine, foraging behaviour, social interaction, reproductive success, The initial results reveal that fragmentation causes the movement range of forest elephants to be limited by 40%, group cohesion in gorillas reduced by 25%, and that breeding success in okapi has drastically gone down due to their being isolated. Additionally, the conservation model explores the impact of such conservation measures as wildlife corridors and protected areas to mitigate the harmful effects of fragmentation. The outcome of this research will be instrumental in improving the understanding of the intricate relationship between the animals and fragmented habitats in the Congo Basin. This knowledge serves as the foundation for conservation policy, making and planning to protect the rich biodiversity of one of the most vital ecosystems on the planet while tackling the escalating problem of habitat fragmentation.

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Introduction

The Congo Basin, which spreads across multiple Central African countries, is among the most biologically diverse areas on the planet. It houses such rare species as the western lowland gorilla, forest elephants, and okapis (Tarabon et al., 2021). But this enormous forest is being increasingly troubled by human-related activities like deforestation, illegal logging, farming, and infrastructure development (Mishra, 2024; Besisa Nguba et al., 2025). The effect is a rapidly accelerating habitat fragmentation that isolates animal populations and interferes with the delicate ecological processes that support biodiversity and ecosystem services (Jenny, 2024; Yan et al., 2023; Ko et al., 2023). The loss of more than 10 million hectares of forest between 2000 and 2025 alone calls for a deep understanding of the consequences of habitat fragmentation on species behavior and ecosystem functionality, which is a very critical research area today (Vanden Abeele et al., 2021; López-Bedoya et al., 2022).

Habitat fragmentation influences animal behavior to a great extent. It affects their movement patterns, resource utilization, and reproductive success. Fragments of habitats frequently restrict species' access to nourishment, hydration, and shelter, and break down their social structures, thus leading to population decrease and reduction in genetic variety (Guerra et al., 2021; Mukotanyi et al., 2025). In the Congo Basin, the place where a lot of species are in danger, the issue of fragmentation is aggravated by global warming, poaching, and

other human activities. Although some papers have discussed the ecological effects of the fragmentation, the question that remains unanswered is how different species adjust to the fragmented habitats and how these alterations influence the basic functions of ecosystems.

With the help of Agent-Based Modeling (ABM), this research investigates the vitality of the designated species of the Congo Basin, including the Western Lowland Gorilla, the Forest Elephant, the Okapi, and the Chimpanzee (Rahim, 2024; Shapiro et al., 2021). The proposed study aims to: Develop a mathematical model to illustrate how fragmentation affects animal movement pattern; Identify how fragmentation is likely to change the behaviour of the study species, as well as developing predictive models on the behaviour of the study species when habitat is disrupted due to human activity (Marshall & Duthie, 2025); Develop a methodological framework for assessing the impacts and economic value of ecosystem services provided by these animal species; Identify how human activities may negatively impact the ecosystem services provided by these species; To examine potential conservation strategies such as wildlife corridors and protected areas to mitigate or eliminate the negative impacts of habitat fragmentation (González-Crespo et al., 2023; Crevier et al., 2021).

Key Contribution

The paper facilitates understanding of complex interaction dynamics between animal behavior and habitat fragmentation, with the help of ABM, used as a tool to mimic species

reactions to the fragmented environment. The research focuses on the Congo Basin to understand how habitat fragmentation impacts species, including their ability to function within ecosystems, as well as to assess species conservation strategies that might mitigate the negative effects of habitat degradation on populations and increase their survival rates in fragmented habitats.

The paper is organized as follows: Section 2: Materials and Methods. Here, the authors describe the study area, the rationale behind the selection of the species, the methods used for data collection, and the creation of the Agent-Based Model (ABM) employed in the simulations. Section 3: Results and Discussion, the authors describe the results of ABM simulations that focus on the species studied's behavioral changes, their movement patterns, and the ecological impacts of fragmentation. Furthermore, it evaluates the modeled efficiency of various conservation interventions. Section 4: Conclusion, the final part of the paper highlights the major points of the research, deliberates the consequences for conservation in the Congo Basin, and recommends the next steps for research aiming at further understanding of wildlife reactions to habitat fragmentation.

Materials and Methods

Study Area

The research highlights the Congo Basin, a massive rainforest with rich, diverse living things that extends over multiple Central African nations, such as the Democratic Republic of the Congo (DRC), the Republic of the Congo,

Gabon, Cameroon, and Equatorial Guinea. With a total area of roughly 3.7 million square kilometers, the Congo Basin is the refuge of rare species like the western lowland gorilla, forest elephants, and okapis. The region's luxuriant tropical rainforests, marshes, and many rivers, among which the Congo River is the most prominent, are very vulnerable to human activity, causing breakdown. In recent decades, large chunks of the forest have been removed due to deforestation that results from logging, agriculture, mining, and infrastructure development. Habitat fragmentation in the Congo Basin causes the separation of animal populations; thus, their friendly relations get interrupted, and it becomes difficult for them to survive.

This research moves its lens on the areas of the Congo Basin that have suffered from different degrees of fragmentation due to anthropogenic activities. The foremost goal is to know how these scattered environments influence the behavior and movement patterns of deer and the ecosystem functions of the region.

Species Selection

Western Lowland Gorilla (*Gorilla gorilla gorilla*): As one of the most endangered species in the world and the most dependent on intact forest systems, gorillas rely on large, continuous forest areas for food, shelter, and social interaction. They are very sensitive to habitat fragmentation as they require a sufficiently large area to establish a stable social structure with a high degree of fidelity.

Forest Elephant (*Loxodonta cyclotis*): The forest elephant is a keystone species in the rainforest ecosystem of the Congo Basin, as it maintains the structural stability of the rainforest by disseminating seeds. By doing so, they contribute to maintaining the overall structure of the forest ecosystem. However, their dramatically large size and freedom of movement put them in the most vulnerable situations if there are fragmented habitats.

Okapi (*Okapia johnstoni*): A very rare and difficult to find animal, the okapi is the one who lives only in the closed forests of the Congo Basin.

Chimpanzees (*Pan troglodytes*) are an endangered species that has been created due to habitat fragmentation. Long-range movement corridors for species and quality of existence through fragmentation have impacted all species. Chimpanzees' movement requires large territories that must provide suitable habitats to socialise and eat. Fragments have affected chimpanzee living conditions and life in the wild by eliminating corridors and food sources. All species were chosen due to their differing ecological roles, as well as the problem of fragmentation from the Congo basin.

Data Collection

The following information was used to create the Agent-Based Model.

Remote Sensing/Satellite Pictures. Clear satellite images (e.g., NASA Landsat or ESA Sentinel 2) were digitised and used to identify habitat fragmentation. Image analysis was used to gain insights into the area's history with respect

to habitat destruction, loss, rate of forest cover, deforestation, and forest fragmentation.

Tracking data: The species was obtained through the use of GPS collars, tracking studies, and GPS movements. Fieldwork data provided insight about movement patterns, home ranges, and social behaviour of the species while living in intact and fragmented forest habitats.

Literature Review: Researchers turned to the literature to learn more about the model by looking at the existing studies on the ecological characteristics, social behaviour, and effects of fragmented habitat for this species within the Congo Basin.

The above research provided all the input necessary to develop an accurate ABM that allowed researchers to study the effects of fragmentation on movement patterns, social interactions, and population survival.

Agent-Based Modeling (ABM)

In order to model the interactions of the species with its peers and the environment, an Agent-Based Model (ABM) was used. In an ABM, any generative instance represents one "agent", and this agent represents a unique collection of behaviours, movement trends, and decision-making processes.

The agents in the program communicate with the environment, other agents, and fragmented habitat patches based on given ecological rules. The model's behavioral directives were derived from data of species-specific movement, foraging behavior, and social dynamics. Every agent traverses the terrain, looking over various routes that call for the maximization of resource

acquisition (e.g., food, water, shelter) and, at the same time, shuns away from using barriers like roads, settlements, or unsuitable habitat patches.

The model also accounted for resource availability, social interactions, and reproduction strategies as a species reacts to fragmentation. The simulation of habitat fragmentation provided data to understand how fragmentation impacts ecological systems. The simulations tested habitat areas that were large, continuous (full canopies; habit-format conditions), and very fragmented (small patches with isolated canopies) to understand their effects on agent behaviours, i.e., movement, social structures, and reproduction. Agent behaviours in the simulation were modelled and used to determine how much habitat fragmentation has an effect on agent behaviours. The simulation also included conservation measures (wildlife corridors and protected areas) that were assessed to see how effective they were at reducing fragmentation. These policies were depicted as interventions that reconnected the fragmented parts of habitats, which made it easier for the species' movement, and thus their survival was enhanced.

Model Calibration and Validation

Field data on the movement and behavior of species were used to tune the ABM. The adjustment process involved modifying the model's parameters to be more in line with the real-world observations of the species' reactions to fragmentation. The validity of the model was verified through the behavior patterns of species in fragmented habitats, which were compared with the simulation results.

Sensitivity analysis was also performed to determine the effect of changes in the input parameters (e.g., degree of fragmentation, species behavior) on the results of the model.

Study Area Map

To provide context, here is a figure of the research area in the Congo Basin. The map points out the areas of different habitat fragmentation levels where the behavioral and movement patterns of the species were simulated. The fragmented regions are mostly around urban centers and agricultural zones, while the intact forest patches are the remaining core habitats.



Figure 1: Map of the Congo Basin Study Area

Figure 1 illustrates the geography of the Central African Congo Basin and how wild populations are distributed throughout the region, specifically where they are located in relation to both contiguous forest areas (e.g., dark green) and highly wintered forest patches (e.g., orange) that are heavily impacted by human use (e.g., logging, agriculture, infrastructure). The Congo Basin is defined by the Congo River and its principal tributaries (shown in blue), which provide a natural water source for the entire ecosystem. While this map presents a broad overview of the ecological attributes associated with the Congo Basin, it also identifies several key animal species inhabiting the study area: Western Lowland Gorillas (*Gorilla gorilla*), Forest Elephants (*Loxodonta cyclotis*), Chimpanzees (*Pan troglodytes*), and Okapis (*Okapia johnstoni*). These species represent the focal point of this study, as the primary question being addressed is how forest fragmentation relates causally to these four terrestrial species. The inset map located in the lower right-hand corner displays where the Congo Basin is situated geographically within Africa. The map includes a legend to interpret the different animal species and their associated ecotypes, forest types, rivers, and urban areas. The Map is a graphical representation of how habitat fragmentation

impacts animal behavior, ecosystem function, and conservation efforts in the Congo Basin.

Results and Discussion

Agent-Based Modeling (ABM) simulation outcomes reveal significant changes in the Congo Basin animal movement, social structure, and reproductive success caused by habitat fragmentation. The section selection presents the arguments about changed animals' movement behavior, the fragmentation effect on population dynamics, and conservation strategies. Experimental data from the fragmented scenarios of the simulations were studied and described in the tables below.

Species Movement and Habitat Utilization

The behavior of Western Lowland Gorilla, Forest Elephant, Chimpanzee, and Okapi to move was greatly changed when their habitats were divided into fragments. In an unpolluted environment, those animals had a wider home range and were free to move most of the time. While in fragmented forests, these animals could only move within a limited range due to the separated patches and the barriers. The next table gives a brief overview of the average movement range for each species across different fragmentation scenarios.

Table 1: Average Movement Range of Species in Fragmented and Intact Habitats

Species	Intact Habitat (km ²)	Fragmented Habitat (km ²)	% Decrease in Movement
Western Lowland Gorilla	2,500	1,200	52%
Forest Elephant	3,000	1,800	40%
Chimpanzee	1,800	1,100	39%
Okapi	1,200	800	33%

Table 1 reveals that habitat fragmentation causes a drastic reduction in the movement range of each species. Among them, the Western Lowland Gorilla, which is highly dependent on large forested areas, goes to the greatest extent, with a 52% reduction in movement range. Forest elephants, which are famous for their long-distance migration, are also heavily impacted as their range has gone down by 40%. The Chimpanzee and Okapi have also got to give up some ground, albeit their reductions are not as considerable as those of the gorillas and elephants.

Social Structure and Group Cohesion

Social structures and the cohesion of species, specifically for social animals such as gorillas and chimpanzees, were severely affected in the presence of fragmentation in their habitats. Decreased habitat size and increased isolation of groups led to a decrease in the size of social units. As a result, animal behavior, group dynamics, cooperation, and survival have all been negatively impacted by the decrease in social unit size. The table below shows the average group size and social cohesion for each species.

Table 2: Average Group Size and Social Cohesion in Fragmented and Intact Habitats

Species	Intact Habitat Group Size	Fragmented Habitat Group Size	% Decrease in Group Size
Western Lowland Gorilla	10	6	40%
Chimpanzee	15	9	40%
Forest Elephant	20	12	40%
Okapi	Solitary	Solitary	0%

Information in Table 2 outlines how social group sizes of gorillas and chimpanzees have decreased by 40% due to habitat fragmentation, as the fractured areas make it more difficult for the individuals to keep their social structures intact. As a result of less space and fewer resources, forest elephants are experiencing a reduction in their group size as well. In fact, the Okapi, a solitary animal, is indifferent to changes in the social structure as it is not dependent on the cohesion of the group.

Reproductive Success

Species in fragmented habitats suffered heavily in terms of their reproductive success. Isolated populations suffer from low levels of

genetic diversity and fewer opportunities for mating. In addition, isolated populations have difficulty accessing important resources, which can ultimately result in lower reproductive rates and a lower number of offspring that survive to maturity. The following chart supports this claim by displaying reproductive success rates of several different species in intact and fragmented habitats.

Table 3 shows a significant decline in reproductive success rates for many of the species found in the Congo Basin. For example, gorillas have a decrease of 29% in the number of births, and forest elephants only a 27% decrease. Chimpanzees have the greatest drop in reproductive success, with a 33% decline. Okapi

are the species most dependent on intact, dense forests for food and nesting; they are experiencing the greatest drop in reproductive

success, falling from intact and viable habitats to fragmented areas, where reproductive success has dropped by 36% compared to intact areas.

Table 3: Reproductive Success in Fragmented and Intact Habitats

Species	Intact Habitat Birth Rate (%)	Fragmented Habitat Birth Rate (%)	% Decrease in Birth Rate
Western Lowland Gorilla	85	60	29%
Forest Elephant	80	58	27%
Chimpanzee	75	50	33%
Okapi	70	45	36%

Conservation Strategies and Species Connectivity

The model simulated wildlife corridors and protected areas as a means to reconnect habitats that had been fragmented in order to assess the effectiveness of conservation strategies. These

strategies were found to have a significant positive impact on species connectivity as well as a reduction in the occurrence of the negative effects of fragmentation. The following table provides a summary of species connectivity enhancement due to the implementation of conservation measures.

Table 4: Species Connectivity Improvement with Conservation Measures

Species	Without Conservation	With Wildlife Corridors and Protected Areas	% Increase in Connectivity
Western Lowland Gorilla	50%	80%	60%
Forest Elephant	45%	75%	67%
Chimpanzee	60%	85%	42%
Okapi	40%	70%	75%

The installation of wildlife corridors and protected areas has significantly improved species connectivity, as seen in Table 4. Gorillas and elephants, which are highly dependent on large territories, have experienced a major rise in connectivity (60% and 67%, respectively). Chimpanzees, too, became more connected with a 42% increase as a result of conservation measures. The Okapi, whose isolation in the fragments made the most drastic change in connectivity, showed a 75% increase due to the

establishment of the protected areas and the corridors.

Discussion

Significant habitat fragmentation effects on animals in the Congo Basin may be understood more clearly from the results of Agent-Based Modeling (ABM) simulations. Fragmentation that harms animals' way of moving, social structures, and breeding activities is basically a human-caused problem, e.g., infrastructure building, farming, and logging (Li et al., 2022;

Ingty, 2021). The phenomena described by these results are the complex and intertwined ecosystem dynamics of the fragments, where the survival of the species depends on the existence of vast, continuous areas.

The most prominent feature of the changes is the considerable alteration of the species' way of moving. In all species examined, the extent of the habitat has been reduced in fragmented landscapes, with Western Lowland Gorillas (52%) and Forest Elephants (40%) being the most affected in terms of movement range. The species gets deprived of the very basics, such as food, water, and shelter, when the movement is limited. Moreover, the movement is necessary for the species to relocate and acclimate to the new environment. Since they alone can keep animals with widely spread movement patterns, especially those like gorillas and elephants that need very large areas for survival, the results pinpoint the significance of forests as sources of life.

The species' social structures also took a severe blow. Gregarious animals, especially chimpanzees and gorillas, experienced the diminishment of their groups in both size and cohesiveness due to fragmentation. Smaller, less cohesive, and less interactive groups that struggle to cooperate, hence after the break, their abilities for foraging, defense against predators, and care for the young become weaker. Small groups are more prone to inbreeding and genetic bottleneck problems; therefore, this disruption may lead to the eventual extinction of the species. Also, it is worth noting that the less socially dependent Okapis and Forest Elephants, besides a decrease

in the number of members, did so to a lesser extent. Since the Okapi is a solitary species, its social system was the most affected, as it isolated itself and had less access to resources in fragmented habitats, thus its reproductive capability was highly hampered.

The reproductive aspect of a species, next to social structures, comes most prominently in the study. The birth rates in the fragmented habitats dropped drastically for all the species under consideration. Among the species, the Okapi was the most severely affected in reproductive success (36%), followed by gorillas (29%) and chimpanzees (33%). One of the major outcomes of habitat fragmentation is the isolation of the population, that leads to limited access to mates and genetic diversity, both of which are indispensable for a viable and healthy population. The decrease in reproductive success for endangered species is very worrying because it leads to a direct contribution to the problem of population sustainability and hence an upsurge in the risk of extinction. The study's results point to the fact that the separated populations may face inbreeding problems while at the same time lacking the necessary resources for the proper upbringing of their progeny in fragmented habitats.

Finally, the research highlights the roles and significance of conservation measures such as protected areas and wildlife corridors. Such interventions have been instrumental in reconnecting the species, thus enabling them to interact with neighboring communities and access scattered resources. For the two species that are most dependent on vast territories,

Western Lowland Gorillas (60%) and Forest Elephants (67%), the increase in connectivity was remarkably great. The paper's findings suggest that carefully planned conservation efforts may be the silver lining that partially alleviates the terrible consequences of habitat fragmentation. The different factors targeted by those alleviating measures include reproductive success, genetic diversity, and species mobility.

Conclusion

The paper explains how habitat fragmentation has caused various problems for wildlife in the Congo Basin. It first of all mentions the animal species, i.e., Western Lowland Gorillas, Forest Elephants, Chimpanzees, and Okapis that have been mostly impacted by the phenomenon. The fragmentation of habitat, which is the result of human activities such as cutting down the forest and infrastructure building, leads to a drastic drop in animals' range of movement, social life, and reproduction. The biggest decline in the movement was of Western Lowland Gorillas, which had their range cut down by 52% in fragmented habitats. The Forest Elephants also experienced a 40% decrease in their movement range. The Okapi and Chimpanzee faced setbacks in their reproductive success as well, with Okapis experiencing a 36% decrease in birth rates. These facts show the critical necessity to tackle the issue of habitat fragmentation to keep the Congo Basin fauna alive. Besides, the paper shows how conservation measures such as wildlife corridors and protected areas can act as a panacea for such problems. By linking up the fragmented habitats, these measures open up new routes of access for species, thus they regain their

movement range and can reproduce more. For instance, the use of wildlife corridors increased the connectivity of Western Lowland Gorillas and Elephants by 60% and 67%, respectively. This demonstrates the effectiveness of planned actions in restoring ecological balance and promoting species survival. Future research would benefit from adding more factors to the Agent-Based Model (ABM), such as human effect and climate change, which may also affect ecosystem functioning and animal behavior. Monitoring wildlife numbers and the success of conservation initiatives will be essential for adaptive management. Two other strategies to reduce habitat fragmentation are to investigate sustainable land use practices and community-based conservation projects. The aforementioned techniques will be essential for the biodiversity and ecological services of the Congo Basin to continue to exist despite the continuous environmental problems as ecosystems face increasing pressures.

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