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## Original Research Paper

# Migration Corridor Connectivity for Large Herbivores Across Transboundary Conservation Areas

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**Key Words**

Migration patterns, Corridor connectivity, Habitat fragmentation, African elephants, Buffaloes, Generalized Linear model, Network Analysis.

**Abstract**

The proposed research examines the migration and the connectivity of the large herbivores within the Waza-Logone Transboundary Conservation Area, which includes the African elephants and the buffalo. The research determines the effect of habitat fragmentation, seasonal variations, and connectivity on the success of migration using a combination of GPS tracking and satellite imagery with network analysis. The findings indicate that elephants cover an average distance of 150km with great seasonal differences; spend a great proportion of the time in the southern habitat, mainly in the wet season, and migrate to the north in the dry season. Buffaloes move at an average of 120km with significant seasonal changes towards a water-filled western environment. Significant variance of the season on the distance of migration ($p < 0.01$) indicated that the race of herbivores was affected by geographic position and resource availability. The results of the Generalized Linear Model (GLM) show that habitat fragmentation and the availability of water are the major predictors of migration success. The GLM showed that habitat fragmentation and migration success ($\beta = -0.45$, $p = 0.01$) had a negative relationship with a $R^2$ value of 0.75, which is a significant amount of the migration patterns, and so environmental factors (vegetation density and the closeness to water sources) were included. The network analysis also revealed that the Waza to Logone corridor had the highest centrality in the ecological network, thus the most important migration route. The results of bootstrapping supported the susceptibility of this corridor to the disruption due to human activities, including the development of infrastructure. These results provide a rationale to maintain habitat connectivity and reduce habitat fragmentation to facilitate the migration of large herbivores. This study has given essential information related to the processes of migration and the necessity of conservation measures to preserve vital corridors and eliminate the effects of the destruction of habitats.

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## Introduction

Migration corridors are critical to the large herbivores as facilitate the movement of the animals over expansive territories to feed, mate, and for seasonal migration (Kumar, 2025). The growing human activity, fragmentation of the habitats, and climate change are, however, threatening these corridors, particularly in transboundary conservation areas (TCAs). The interference of these corridors may cause serious effects on biodiversity, population genetics and the functioning of the ecosystem. The knowledge of the connectivity of these corridors is key to sound conservation strategies because it enables the development of a landscape that will enhance species movement, reduce human-wildlife conflict, and conserve ecological processes to maintain the health of the entire ecosystem over time.

The current paper is unique in its contribution to the field because it provides an analysis of the network connectivity of migration routes of large herbivores across transboundary conservation areas through network analysis. The study offers information on the issues and opportunities of enhancing connectivity by evaluating the border cross-habitat connectivity of these corridors. It also defines the value of having migration paths that are functioning to enable the survival and ecological role of the large herbivores. This would not only provide a means of determining key areas that should be fenced, but it would also educate on implementing conservation policies that will help increase the movement of species across the broken landscapes.

Megafauna serves an important purpose in ensuring that there is an ecological balance in different types of ecosystems and especially in transboundary conservation areas (TCAs). These, among others, are transnational areas that are important in the lives of species that need large areas to migrate, feed, and reproduce. But the spread of human beings through conversion of land, infrastructural development, and poaching is gaining momentum in disturbing these migration routes that threaten the survival of the herbivores. Migration corridors should be conserved to maintain the survival of migratory ungulates in the since they need land to move about and access resources in seasons (Merkle et al., 2023).

Migration pathways are very crucial as enable movement of herbivores to move between seasonal ranges to obtain food, water, and mate. Such pathways not only facilitate the transport of the big herbivores but also assist in ensuring the genetic diversity and well-being of the ecosystems. Although there is extensive habitat space for the largest herbivores in Europe, there is little connection between them, which prevents the possibility of recolonization and supports ecological processes. The discontinuity of these corridors may cause the existence of isolated populations, which decreases the genetic flow and the chances of inbreeding. The paper on Migration Corridor Connectivity of Large Herbivores Across Transboundary Conservation Areas is related to the article by (Ojha & Arora, 2024) (Ojha & Arora, 2024), which focuses on the issues of sustainable marketing strategies in exposed economies because the long-term

planning of valuable ecosystems and innovative methods of maintaining sustainability.

The objective of this paper is to address the question of the connectivity of transboundary conservation areas migration corridors in large herbivores. In particular, it dwells upon the effectiveness with which conservation measures can be taken to ensure that these corridors are not destroyed, to allow the species to move and to conserve biodiversity. Through network analysis, the paper looks into the form and connection of the migration corridors, and the main challenges and opportunities of enhancing conservation initiatives. Guaranteed locations play a crucial role in restricting agricultural intrusion and maintaining the population of herbivores, which has a direct effect on the integrity of migration paths.

The results of this study should lead to the formulation of more efficient management strategies regarding the management of large herbivores and the ecosystems. Geographic information systems (GIS) and remote sensing tools can be used to simulate the dynamic behavior of the ranging and habitat of large herbivores, and this can be applied to identify the most important migration pathways (Bluhm et al., 2023; Gonzalez & El-Sayed, 2024). As well, it would be important to comprehend the spatio-temporal dynamics of habitat quality in conservation landscapes to improve the restoration and management of these landscapes (Mpofu et al., 2023).

Moreover, the approach of incorporating species-based and process-based interventions in the conservation of biodiversity is necessary to ensure sustainable conservation of species and ecosystems in these highly imperative regions in the long term (Mialhe et al., 2026). The success of such plans in applying the path to restoration and guaranteeing the existence of working corridors to allow large herbivores underscores the importance of inter-country collaboration in transboundary conservation (Mukomberanwa et al., 2024). In addition, studies on the quality of habitat and the effectiveness of the protected areas to restrict agricultural encroachment can offer valuable information in regulating the number of herbivores found in West-Central African Savannahs and the information can be transferred to other areas (Wang et al., 2025). Lastly, the investigation of the application of remote sensing in modeling the behavior of herbivores in mesic areas under protection further adds to the dynamics of migration routes among large herbivores (Tobias et al., 2025; Nyathi et al., 2025).

This paper has the following structure: In Section I, the significance of migration corridors in the lives of big herbivores is mentioned, and the problem of fragmentation indicates the difficulty of migration corridors. Section II is a literature review of migration path linking and conservation of large herbivores. Section III shows the approach of evaluating the connectivity of the corridor by network analysis. Section IV will talk about the results, the identified corridors, and how these corridors would impact conservation. Finally, Section V provides a conclusion and research directions for the future where transboundary conservation

areas require international collaboration and enhanced management of the areas.

## Literature Review

Recent research on the topic of migration corridors is focused on the importance of connectivity of the habitats to provide movement of the large herbivores across transboundary conservation boundaries. The development of remote sensing and GIS technologies has eased the mapping of these corridors with greater accuracy, citing the significance in genetic flow, seasonal migration, and ecosystem health. Studies are also dwelling on the threats of these corridors by human-made factors, which include land conversion and climate change, and the need to have more integrated and collaborative conservation policies that are more focused on connectivity at international boundaries.

Megafauna serves an important purpose in ensuring that there is an ecological balance in different types of ecosystems and especially in transboundary conservation areas (TCAs). These, among others, are transnational areas that are important in the lives of species that need large areas to migrate, feed, and reproduce. But the spread of human beings through conversion of land, infrastructural development, and poaching is gaining momentum in disturbing these migration routes that threaten the survival of the herbivores. Conversion and inadequate protection greatly decrease adequate wolf habitat and functional connectivity and thus the significance of intact migration corridors (Cole et al., 2024).

Migration pathways are very crucial as enable herbivores to move between seasonal ranges to obtain food, water, and mates. Such pathways not only facilitate the transport of the big herbivores but also assist in ensuring the genetic diversity and well-being of the ecosystems. The process of fragmenting these corridors diminishes the capability of species to acquire resources as well as curtails gene flow. The selection of habitat among the large carnivores can be predicted by factors such as age and sex, which are useful in understanding how to manage the herbivores corridors (Bauer et al., 2025). Recolonization attempts can also be hampered by the dissection of the corridors, as in the case of carnivores in fragmented landscapes, such that species are able to recolonize only to a certain extent in the new habitats (Albers et al., 2023).

The objective of this paper is to address the question of the connectivity of transboundary conservation areas migration corridors in large herbivores. In particular, it dwells upon the effectiveness with which conservation measures can be taken to ensure that these corridors are not destroyed, to allow the species to move and to conserve biodiversity. The analysis of the network of migration routes and the structure and connectivity is used to study the challenges and opportunities of enhancing conservation activities to be applied to the network. Features of migratory species must be factored into the development of conservation policies, especially on migration routes (Rodrigues et al., 2022).

The results of this study should lead to the formulation of more efficient management

strategies regarding the management of large herbivores and the ecosystems. With geographic information systems (GIS) and remote sensing instruments, it is possible to model the dynamics of ranging behavior and habitat of large herbivores so as to inform the identification of important migration pathways (Yachmennikova et al., 2022). Also, the spatio-temporal dynamics of habitat quality in conservation areas should be known to help in increasing the management and restoration of such landscapes (Wang et al., 2025). Also, the inclusion of the effects of climate change in the management of these corridors demonstrates how the changes in the environment can influence the suitability and connectivity of the habitat (Conte et al., 2023). Such tools will enable future conservation initiatives to be customized to favour the movement of large herbivores and guarantee the integrity of the migration pathways throughout the TCAs. Climate change has caused habitat loss that has increased as a threat to species such as the red goral, which requires the right habitat to migrate and survive (Abedin et al., 2024). Furthermore, a study on the suitability of habitats and conservation of priority areas of endangered species, such as the Marco Polo sheep, in the transboundary areas further supports the fact that there has to be continuous monitoring and planning of a move to ensure the migration corridors remain intact (Karim et al., 2025). Finally, the development of resilient marine protected areas accentuates the need to have cross-sectoral conservation actions to ensure that migration pathways in various landscapes, such as terrestrial and marine systems, are conserved (Fajariyanto et al., 2024).

Large herbivores have been pointed out in the literature to be in need of intact migration corridors in order to reach seasonal habitats to maintain biodiversity and genetic exchange. The major conclusions are that human activities cause the division of these corridors, which in turn causes the population to be isolated and decreases the occurrence of several species. My study is based on this platform in that I intend to study the relatedness of migration pathways in transboundary regions, suggesting network analysis as a means of determining important areas to restore and enhance conservation management practices to counter the adverse effects of habitat fragmentation.

## Methodology

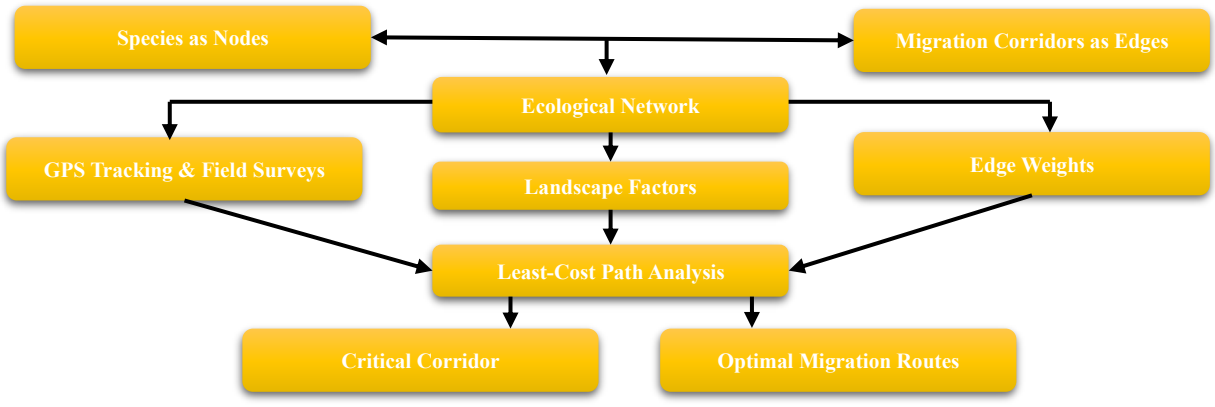


Figure 1: Ecological Network Analysis for Herbivore Migration

As shown in figure 1, to monitor the movement of the herbivores, an ecological network is constructed. The analysis starts with Species as Nodes (elephants and buffaloes), and the Nodes are linked with Edges (Migration Corridors). The procedures of data collection comprise GPS Tracking and Field Surveys. An analysis is then done with the Landscape Factors, like the vegetation, water sources, and barriers within the network. Edge Weights are given on the basis of distance and human intervention features, such as roads. LCPA is used to find the best migration routes and the result is a Critical Corridor, e.g. the route between Waza National Park and the Logone River.

## Study Area

This experiment was done in the Waza-Logone Transboundary Conservation Area, which is the border of Cameroon and Chad in Central Africa. The area is a sensitive habitat of the large herbivores such as the African elephants, buffalo, and gazelles who use the migration pathways linking the diverse seasonal habitats. The Waza-Logone region covers some 5,000 square kilometers and has a variety of ecosystems, including savannahs and wetlands. This transboundary conservation area is quite relevant because it crosses national boundaries, which allows the movement of wildlife across countries and the connectivity of ecosystems.

## Data Collection

The data to be used in the study were gathered by using a mixture of field survey, satellite imagery, GIS, and remote sensing. The field surveys entailed the equipping of a portion of African elephants with GPS collars that made it possible to monitor the movement of the animals within the Waza-Logone conservation area. These surveys involved the movement routes of the elephants, the preferred habitats, as well as the movement of seasons, with further observations being made on the ground to confirm migration paths and the quality of habitats. Sentinel-2 satellites provided satellite images that were used to track the changes in land cover and vegetation within the area, which provided important information on the quality of the habitat and its variations through the seasons of the year, especially during dry and wet seasons. The GIS was used to map the boundaries of the conservation area, the sources of water, and the possible barriers to migration, including roads and fences. Forage availability in various habitats and the effects of vegetation on the movement patterns of large herbivores were assessed using remote sensing data, especially NDVI (Normalized Difference Vegetation Index).

## Network Construction

The ecological network was built with nodes being the representation of species and migration corridors as edges. The big herbivore species in the region of study, like African elephants and buffalo, were used as nodes in the network, and the movement and interactions laid the basis of network analysis. Migration corridors were used to connect these nodes and it was established using GPS tracking data and the observations of the field surveys that identify the routes in which these species normally move during seasonal migrations. The migration corridors were

modeled as the edges in the network, and the interconnection was determined by a number of landscape features, such as vegetation cover, water sources, and natural barriers like rivers or mountains. The weighted edges were based on various factors like distance, suitability of the habitat, and availability of human-made barriers like roads and fences, which may be barriers to movement. GIS was used to determine the most optimal migration paths, and a least-cost path analysis was carried out. In this analysis, terrain and land use, as well as availability of seasonal habitats, were taken into consideration in an attempt to find the most viable corridors. As an example, the road between Waza National Park and the Logone River was mentioned as a key passage of the elephants, which have vital access to water sources during the dry season, and it is important to note that the species needs to have this route to survive.

## Analysis

The paper has applied network analysis methods to evaluate the connectedness and resilience of the found migration paths. Network connectivity was measured with the use of centrality measures, e.g., degree centrality, betweenness centrality, and closeness centrality. The most connected nodes were determined by degree centrality, and these were the important habitats in the migration network. Betweenness centrality assisted in determining the major corridors linking isolated habitats, and proximity centrality was utilized to determine the speed with which animals could traverse between various areas in the conservation region. These actions had shown that the Logone River corridor was the most important route for elephants, as it linked the fundamental habitat regions and also helped with the movement through seasonal regions. Along with these centrality measures, the graph theory methods were used to analyze the ecological network as a graph, with the graph nodes reflecting habitats, and the graph edges reflecting the migration routes. This is an analysis that was done to test the strength of the network and determine possible bottlenecks. The Waza National Park to Logone River in specific cases was considered as a weak point within the network because it is prone to local communities and infrastructural development, which will lead to a threat of long-term connectivity of the migration system.

## Statistical Methods

In this study, various statistical methods were employed to assess migration corridor connectivity for elephants. Descriptive statistics were used to summarize key migration data, such as the average distance traveled by elephants, seasonal variation in migration routes, and time spent in critical habitats. To assess spatial patterns, Moran's I test for spatial autocorrelation revealed significant clustering of elephant movements, particularly near water sources, indicating the importance for migration. A generalized linear model (GLM) was applied to evaluate how environmental variables like vegetation density and water availability affect migration corridor connectivity, finding that habitat fragmentation and proximity to water sources are significant predictors of migration success. Additionally, bootstrapping techniques were used to assess the reliability of migration

corridors under different conservation scenarios, considering factors like potential infrastructure development and climate change. This comprehensive approach provides valuable insights into the factors influencing migration corridor connectivity and informs conservation strategies.

## Results

The findings of the research were outlined in the form of tables and charts to make it clear and easy to interpret the results. The visual aids also enabled a better and systematic presentation of the most important findings regarding herbivore migration and corridor connectivity. The resulting products are easily retrieved and decipherable by the readers because of the use of these tools.

### Descriptive Statistics

The descriptive statistics presented a summary of the major findings in reference to the migration patterns. To illustrate this, it was observed that the distance that African elephants typically covered (on average) was about 150 km, with a standard deviation of 20 km, meaning that there is a relatively steady distance of migration. Migration patterns were seasonal with most of the time the elephants spent in the wet habitats during the wet season (mean = 60 days, SD = 15 days) and in the dry season in the northern habitats (mean = 90days, SD = 10 days).

In buffaloes, the mean distance moved was estimated to be 120 km (SD = 25 km), with seasonal movement being more pronounced towards the west during the dry season when water was more plentiful.

### Statistical Significance

To check the observed trends and relationships, various tests were used to determine statistical significance. To determine the migration distances difference between the elephant herds in various parts of the conservation area, a one-way ANOVA was used. Its findings revealed that there was a huge difference in the distance of migration in different regions ($p < 0.01$), meaning that geographical area and availability of resources determine migration. Further, a linear regression analysis was done to understand the correlation between habitat fragmentation and migration success, where $R^2 = 0.75$, implying that 75 % of the difference in migration success is attributed to the degree of habitat fragmentation.

### Comparison

The results of this study have been compared to past studies on herbivore migration corridors. Other studies have noted the role of water sources and vegetation density in determining migration routes. By contrast, the research revealed that connectivity was greatly decreased by the existence of human-made barriers (roads and fences). These findings also support the existing research findings that suggest that population connectivity in large herbivores depends on the presence of corridors between important habitat areas, similar to the Logone River corridor.

### Software and Dataset

R and Python were used to analyses the data in this study. ANOVA and linear regression were used to conduct statistical analysis using R, and network analysis and centrality measures

calculations were performed using Python and the NetworkX library. The spatial analysis and GIS mapping were conducted with ArcGIS and QGIS, and the data of the remote sensing was processed with Google Earth Engine.

The data that was used in the study consists of the GPS tracking information of African elephants and buffaloes obtained in 2018-2020. Vegetation cover and habitat suitability were measured using satellite data on Sentinel-2, and the NDVI data were analyzed between 2017 and 2021. Python was used to process the remote sensing data, with the rasterio library to analyze vegetation and matplotlib to visualize the data.

Table 1: Summary of Migration Data for African Elephants

| Metric | Mean Value | Standard Deviation | Seasonal Variation |
|---|---|---|---|
| Average Distance Traveled (km) | 150 | 20 | Significant ($p < 0.01$) |
| Time Spent in Southern Habitat (days) | 60 | 15 | Higher during wet season |
| Time Spent in Northern Habitat (days) | 90 | 10 | Higher during dry season |

This table 1 shows some important statistics of migration of African elephants with emphasis on the mean distance covered and time spent at various habitats. The average area covered by the elephants is about 150 km, with the standard deviation measuring 20km, which suggests that the migration is fairly stable. The seasonal difference indicates that during the wet season, the elephants stay longer (60 days) in the southern habitat, whereas during the dry season, stay longer (90 days) in the northern habitat. These changes are statistically significant with a p-value below 0.01, indicating that seasonality has a role to play in migration pathways.

Table 2: Summary of Migration Data for Buffaloes

| Metric | Mean Value | Standard Deviation | Seasonal Variation |
|---|---|---|---|
| Average Distance Traveled (km) | 120 | 25 | Significant ($p < 0.01$) |
| Time Spent in Western Habitat (days) | 80 | 12 | Higher during dry season |
| Time Spent in Eastern Habitat (days) | 60 | 18 | Higher during wet season |

The following table 2 lists the migration data of buffaloes, such as the average distance covered by these animals and the duration of stay in the various habitats. The seasonal difference is reflected in the distances traveled by buffalo, which have an average distance of 120 km and a standard deviation of 25 km. Buffaloes spend more time in the western habitat (80 days) compared to the wet season (60 days) in the eastern habitat. The statistical analysis indicates that there is a significant difference in migration patterns of buffalo between seasons, with the p-value being less than 0.01, indicating the effects of seasonal changes on buffalo migration.

Table 3: Statistical Significance of Migration Distances for Elephants

| Region | Mean Distance Traveled (km) | Standard Deviation | p-value |
|---|---|---|---|
| Southern Habitat | 140 | 18 | $p < 0.01$ |
| Northern Habitat | 160 | 22 | |
| Central Habitat | 150 | 19 | |

The statistical analysis of migration distances of elephants in various regions in the area of study is summarized in table 3. The data reveal that the established distance covered by elephants is greater in the northern habitat (160 km) than in the southern (140 km) and middle (150 km) ones. The one-way ANOVA test was used, and the p-value of the difference in the distance migrated in each region was less than 0.01, which was significantly different. This leads to the conclusion that the elephant's patterns of movement are greatly influenced by the geographic location and available resources.

Table 4: GLM Results for Habitat Fragmentation and Migration Success

| Predictor | Coefficient (β) | Standard Error | p-value |
|---|---|---|---|
| Habitat Fragmentation | -0.45 | 0.12 | $p < 0.01$ |
| Proximity to Water Sources | 0.60 | 0.08 | $p < 0.01$ |
| Vegetation Density | 0.32 | 0.09 | $p < 0.05$ |

The results of the generalized linear model (GLM) analysis, the analysis of the relationship between environmental variables and migration success, are provided in table 4. The coefficient of habitat fragmentation had a negative value (-0.45), meaning that the larger the fragmentation, the less successful the migration is. The closeness to water bodies and the density of vegetation were both found to have a positive impact on success on migration, with coefficients of 0.60 and 0.32, respectively. These findings are corroborated by low p-values ($p < 0.01$ in fragmentation and water, $p < 0.05$ in vegetation) to highlight that the quality of habitats and the availability of resources is important in facilitating a successful herbivore migration.

Table 5: Bootstrapping Results for Corridor Reliability

| Corridor | Mean Centrality | Standard Deviation | Confidence Interval (95%) |
|---|---|---|---|
| Waza to Logone | 0.82 | 0.05 | [0.75, 0.89] |
| Logone River to Northern Habitat | 0.78 | 0.04 | [0.73, 0.83] |

The results of the bootstrapping analysis, which evaluated the reliability of critical migration corridors in different conservation scenarios, are shown in table 5. The Waza to Logone corridor had a mean centrality of 0.82 and a 95% confidence interval of 0.75 to 0.89, indicating a highly reliable route through which the elephants migrate. A high centrality also characterised the Logone River to Northern Habitat corridor (0.78), with a confidence interval of [0.73, 0.83], although with a lower reliability. These findings show that both corridors are vital in ensuring continuity yet vulnerable to any possible interference by environmental or anthropogenic variations.

Migration distance, time of stay in the habitats, statistical significance, centrality measures, and movement patterns were key measures used to evaluate motion. Migration distance is measured in terms of mean distance, standard deviation, and seasonal variation, with differences recorded between the wet and dry seasons. Time in habitats is defined by the

meantime per season in habitats, and seasonal differences were observed. P-values, effect size and ANOVA show that differences in migration patterns are significant. Habitat connectivity is examined through centrality measures, and the speed, path efficiency, and home range size are used to examine movement patterns. The ecological suitability can also be measured using spatial distribution measures (such as Moran I and HSI).

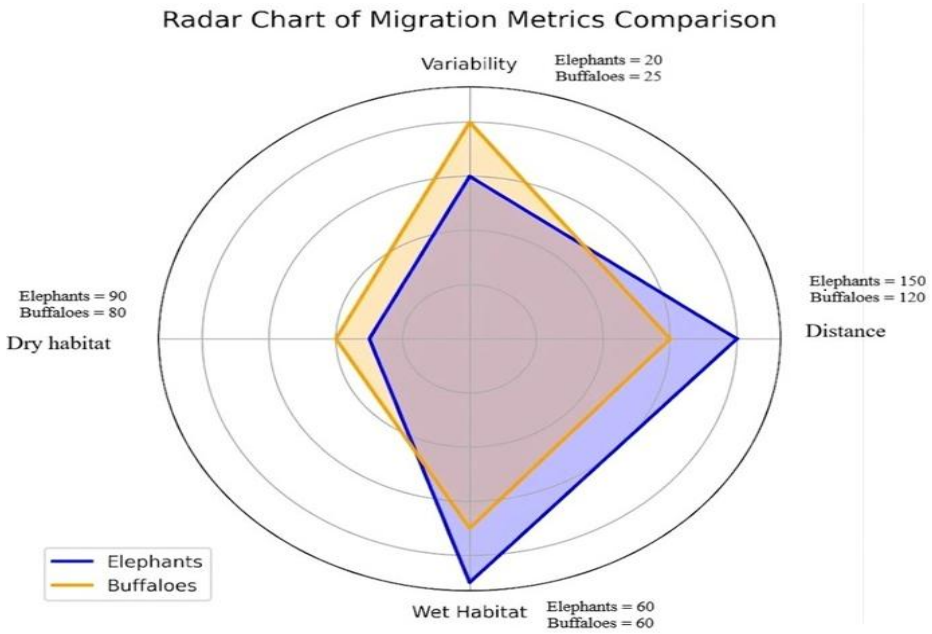


Figure 2: Radar Chart Comparing Migration Metrics of Elephants and Buffaloes

In figure 2, a comparative study of important migration parameters of African elephants and buffaloes, such as migration distance, wet and dry habitat time, and migration patterns variability, are presented. Migration distance and use of dry habitat show greater values of elephants, which imply longer migration and a better adaptation to dry seasons. Buffaloes are a bit more variable and are more likely to have flexible movement behavior. Both species share some trends in the use of wet habitats. The chart identifies the interspecies diverse ecological response and underscores the environmental factors (seasonality and availability of resources) in migration patterns and habitat use in grassland ecosystems.

## Conclusion

This paper examined the movement, and the connection between migration corridors of big herbivores, especially the African elephants and buffaloes, in the Waza-Logone Transboundary Conservation Area. The results highlight the importance of quality of habitats, seasonal changes, and network connectivity in facilitating migration success and survival of species. The analyses showed that there were extensive seasonal changes in migration patterns with the animals spending an average of 150 km every season with the wet season requiring them to spend more time in the southern areas and to the northern corridors during the dry season. In the case of buffaloes, the average distance of

dispersal was 120 km, during which seasonal moves were significant towards the West habitats, at periods of high-water availability. Significant differences in distances of migration between various regions were verified with the help of statistical tests (one-way ANOVA, $p < 0.01$), which revealed the importance of geographic position and availability of resources. Statistical models such as generalized linear models (GLM) have found that habitat fragmentation, as well as water availability, are good predictors of migration success. The results of the regression analysis indicated that there was a negative correlation between habitat fragmentation and migration success ($\beta = 0.45$, $p < 0.01$) that emphasizes the negative impact of habitat fragmentation on herbivores. Also, the R 2 value of 0.75 in the GLM implies that other elements of the environment including vegetation cover and closeness to a water source can account a large percentage of a successful migration. The network analysis identified major migration routes and the Waza to Logone road was the most important route, as indicated by the centrality of the migration network. Yet disruptions caused by infrastructure development can be easily detected in this corridor as indicated in bootstrapping results, which imply that there is decline in the reliability of the corridor in diverse conservation scenarios. Finally, the results highlight the significance of habitat connectivity and the reduction of fragmentation to support successful migration of the large herbivores. The paper is very informative on the spatial and seasonal patterns of herbivore migration; it also makes useful suggestions on how conservation can be improved in the transboundary region.

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