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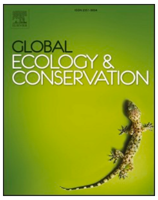

Original research article

Patterns of spatial dynamics and distribution of african elephants (*Loxodonta africana*) in the Central Kalahari Game Reserve, Botswana

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ABSTRACT

The African elephant (*Loxodonta africana*), once thought to be absent from the Kalahari Desert in Southern Africa, has recently reestablished or expanded its range into the Central Kalahari Game Reserve (CKGR), Botswana, with documented occurrences over the past decade. This study explores the temporal and spatial dynamics of elephants in and around the CKGR, focusing on their largely understudied movement patterns. Movement and home range data was obtained from two adult female and eight adult male elephants using GPS/UHF collars. The analysis revealed distinct seasonal ranging behaviours. Collared females migrated between CKGR and the Okavango Delta periphery, while collared male showed both migratory and sedentary patterns around artificial water points and Gope mine in CKGR. Some collared male elephants migrated to the Kavango Zambezi Transfrontier Conservation Area (KAZA) during the wet season, returning to the CKGR in the dry season. This pattern confirms established migration routes and the emergence of pseudo-resident male elephants within CKGR. These findings highlight the importance of management strategies that integrate water distribution, elephant movement, and human-elephant conflicts. Ensuring ecological connectivity beyond the KAZA region is vital for the long-term survival of elephants and other key species.

1. Introduction

The movement patterns of large herbivores between discrete seasonal habitats is a global phenomenon (Berger, 2004; Harris et al.,

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2009). Literature suggest that these movements involve seasonal migrations (Leggett, 2006; Lindeque and Lindeque, 1991; Thouless, 1995; Viljoen, 1988) or localized sedentary behaviours (De Villiers and Kok, 1997; Douglas-Hamilton, 1971). Research to date suggests that the movement patterns of large herbivores are driven by surface water and forage quality and quantity (Boone et al., 2006; Fryxell and Sinclair, 1988; McNaughton, 1985; Murray, 1995; Williamson et al., 1988) and human activities (Adams et al., 2022; Boettiger et al., 2011; Gaynor et al., 2018). The African elephant (*Loxodonta africana Blumenbach*) follows a mixed-feeding strategy, incorporating both browse and grass into its diet. In African ecosystems, elephants act as ecosystem engineers, playing a crucial role in shaping and maintaining ecological processes. (Kerley et al., 2008; Laws, 1970; Lewis, 1986; Loarie et al., 2009), and their impacts are noticeable when in higher densities (Laws, 1970; Lewis, 1986; Loarie et al., 2009; Shannon et al., 2008). This has been noted particularly around wetlands and artificial waterpoints (AWPs) (Leggett, 2006; Sianga et al., 2017a).

Northern Botswana's permanent wetlands, including the Okavango Delta, Kwando, and Chobe Rivers, provide crucial foraging resources for the region's large elephant population (Chase, 2017; Chase et al., 2018; Spinage, 1990). High-quality resources and permanent water sources attract a high density of elephants during the dry season, while in the wet season, elephants prefer woodlands located farther from permanent water (Stokke and Du Toit, 2002). The timing of seasonal shifts between these ranges over time has been linked to rainfall and forage availability (Babaasa, 2000; Thouless, 1995; Western and Lindsay, 1984; White, 1994). However, the establishment of artificial water points in woodlands distant from wetlands has altered the seasonal migration patterns of elephants between habitats (Ofithile, 2012). These AWPs exert a significant influence on the seasonal movement behaviours of elephants, ultimately impacting the surrounding woody vegetation and ecosystem (Teren, 2016).

In the Central Kalahari Game Reserve (CKGR), there are currently sixteen Artificial Water Points (AWPs). Nine of these (Matswere, Sunday Pan, Passarge, Motopi, Letiahau, Piper Pan, Quee Pan, Xaka, and Moriso) were established between 1986 and 1990 (Bonifica, 1992), while the remaining AWPs (*i.e.,* Xade, Tsau, Tsetseng, and Sex) were established after 2000. This was a strategy to mitigate high mortalities of wildlife particularly during drought periods, as evidenced through the massive die offs of blue wildebeest *Connochaetes taurinus* and red hartebeest *Alcelaphus buselaphus* populations between 1982 – 1986 (Williamson and Mbano, 1988; Williamson and Williamson, 1984). AWPs were established to serve as drinking points for a diversity of wildlife populations during the dry seasons when surface water in the ephemeral pans gets depleted. However, with water being available annually in CKGR, a new phenomenon unfolded, where the first signs of elephant were seen in 2009, and with the first elephant sighted in 2010 (Personal Comm, DWNP). Aerial survey conducted in 2015 estimated about 786 elephants in the Ghanzi Region. There have been frequent sightings of elephants, often in higher densities around AWPs in CKGR (Chase, 2011). This has resulted in the need to investigate and understand their movement patterns for management and policy formulation purposes.

In this study, we investigated the movement patterns and spatial distribution of elephants in CKGR using GPS telemetry data from collared individuals. The objectives for this study were to, (i) investigate the movement patterns of African elephants within the CKGR

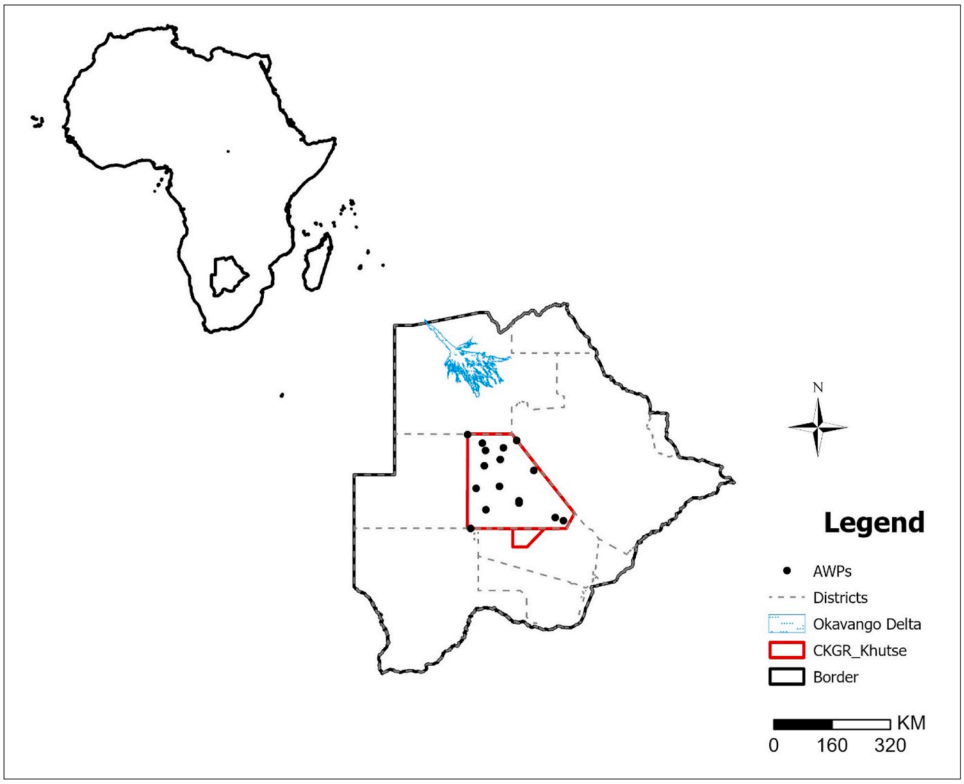

Fig. 1. : Map showing the study area, Central Kalahari Game Reserve, Botswana.

through the analysis of GPS telemetry data, and (ii) establish the spatial distribution and home range of GPS-collared male and female elephants in the CKGR and surrounding areas.

2. Materials and methods

2.1. Study area

The CKGR, located between latitude 21° and 24°south and between longitude 22° and 26° east and covers an area of 52,000 km^2 in the Kalahari Desert covers about 40 % of the Ghanzi District, Botswana (Fig. 1). Climate is semi-arid, with mean annual rainfall ranging between 350 and 400 mm, in the north and western sides of the reserve, respectively, most of which occurs between December and March (Bhatora, 1985; Botswana Meteorological Services, 2023). Annual temperatures ranges between −1–37 °C, with lowest and maximum records in June and October, respectively (Botswana Meteorological Services, 2023).

Soils in the CKGR are dominated by calcrete and clays around the pans, whereas outside the pans, the deep Kalahari sandy soils dominate (Departmentof Surveys and Mapping, 2022). Vegetation in the CKGR can be categorized into; (i) fossil river valley and pan habitats – dominated by grasslands interspersed by trees, (ii) dune habitats, (iii) interdunal habitats and (iv) plain habitat – characterised by mixed shrub and grasslands. The dune and dunal habitats are characterized by a mosaic of woodlands, shrub, and grassland. Woody species such as *Philenoptera nelsii*, *Vachellia/Senegalensis spp* and *Terminalia sericea* dominate, while edges of pans are associated with pockets of *Rhigozium brevispinosum* and *Catophractes alexandrii*. Herbaceous layer is dominated by *Stipagrostis spp*., *Aristida spp*., *Eragrostis* and *Schmidtia spp*. (DHV, 1980; Makhabu et al., 2002).

2.2. Elephant collaring

The study primarily targeted female elephants for collaring because they typically maintain stronger social bonds within family units, and their movements are often constrained closer to these units. In contrast, adult males tend to exhibit looser social bonds, frequently moving independently and often traveling farther from family groups (Duffy et al., 2011). Mature bulls are generally associated with female herds primarily during musth periods (Poole, 1987). However, initial surveillance of elephant herds in the Central Kalahari Game Reserve (CKGR) conducted a week prior to and during the collaring operation revealed a higher proportion of male herds than female dominated herds. From May 16–19, 2023, we immobilized and fitted GPS-enabled collars (Africa Wildlife Tracking, Pretoria, South Africa) on ten individuals for this year-long study. The group included two females and eight males, with five adult males and three sub-adult males from various herds (Table 1). The elephants were immobilised using 13 mg of M99 (Etorphine hydrochloride) and 20 mg of Azaperone, and the sedation was reversed with 130 mg of Naltrexone following collar installation. Observations continued until the elephants stabilized and rejoined their herds. The GPS collars were programmed to record four location fixes per day at six-hour intervals, enabling consistent data collection. Although the study period spanned 365 days, the exact number of days varied slightly among individual elephants, depending on their collar deployment dates (Table 1). Notably, no collar malfunctions occurred throughout the study period, ensuring uninterrupted data collection.

This study, conducted in collaboration with the Department of Wildlife and National Parks (DWNP) of Botswana, adhered to strict ethical standards and guidelines on handling wildlife species during research. All procedures were carried out by a government-registered wildlife veterinarian and authorized under research permit ENT 8/36/4 LV (23) and supplementary permit ENT 8/36/4 LV (55) from the Ministry of Environment, and Tourism of Botswana. Darting was performed from vehicles or helicopters, following best practices to minimize animal distress. During these operations, efforts to mitigate heat stress included actively cooling the elephants by pouring water over them. We consistently monitored the vital signs of the elephant, including its breathing and heart rate, during sedation to maintain stable health conditions. Top of Form Post-collaring, continuous monitoring was conducted to assess any adverse effects of the collars on the health and well-being of the elephants. The collars, equipped to record GPS data for a full year, were planned for removal after two years.

Table 1
Summary of collared African elephant, sex, group size and place of collaring in CKGR, Botswana.

Collar ID	Sex	Group Size	Collaring Place	Collaring date	No. of data points
7104	Male	7	Gope	5/18/2023	1359
7105	Female	8	Tsao Hill 2	5/19/2023	1349
7106	Male	12	Xaka Waterhole	5/17/2023	1360
7107	Male	8	Tsao2	5/19/2023	1352
7108	Male	7	Qwee Pan	5/17/2023	1361
7109	Male	11	Xade Waterhole	5/17/2023	1363
7110	Male	10	Gope	5/18/2023	1361
7111	Male	14	Xade Waterhole	5/16/2023	1721
7112	Female	15	Tsao Hill 1	5/19/2023	1356
7113	Male	8	Tsao	5/19/2023	1420

2.3. Data analysis

2.3.1. Movement patterns and home ranges estimation

We analysed all fixes or locations (n = 13,101) from collared elephants over a period of 12 months to delineate their movement pathways using ArcGIS Pro 3.0 (ESRI, 2022). To facilitate for accurate displacement distance and home range area calculations, we cleaned the data and further transformed the latitude and longitude coordinates into a planar coordinate system (e.g., UTM) using the sp package (Bivand et al., 2013) in R version 4.4.0 (R Core, 2023). The diel displacement between consecutive GPS fixes was calculated using the 'distVincentySphere' function from the 'geosphere' package (Hijmans, 2010). This function computes the shortest distance between two points on the Earth's surface, assuming an ellipsoidal Earth model. The displacement between consecutive GPS points

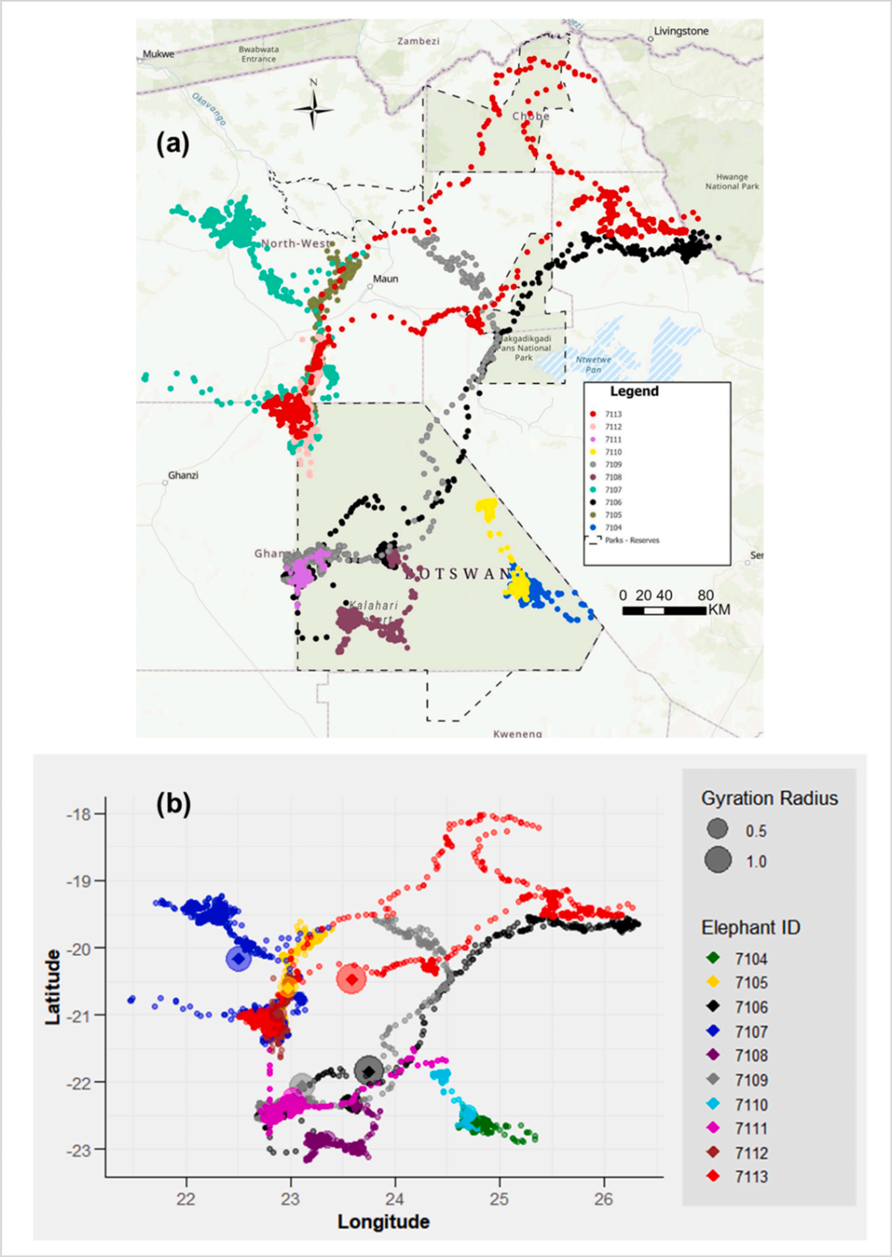

Fig. 2. Movement patterns and spatial extent of African elephants in Central Kalahari Game Reserve, Botswana. *Notes: (a) Movement paths of individual elephants (IDs 7104–7113) overlaid on a map of Botswana including protected areas and surrounding landscapes. (b) Spatial extent and movement trajectory of elephants (IDs 7104–7113) based on gyration radii (0.5 and 1.0). The size of the circles represents the gyration radius, with larger circles indicating a greater spatial extent of movement. Colour coding corresponds to individual elephant IDs as shown in the legend.*

was calculated using the methods outlined by Yang et al., (2019). In this study, we defined dial displacement as the movement or distance traveled by elephants within a 24-hour cycle (Spooner, 2013). We further explored seasonal diel displacement to understand how the daily movement patterns of elephants would vary across different seasons.

To establish movement patterns and clustering, spatial extent and gyration radii for each elephant were analysed using the 'sp' and 'sf' packages (Pebesma, 2018). The fixes were used to calculate the home range area of the 95 % kernel density estimate (KDE) using the 'adeHabitatHR' package, with the reference bandwidth used as a smoothing parameter to estimate the UDs (Calenge, 2007). We used this method because it is robust and effectively accounts for the spatial distribution of data points and provides a smooth estimate of the utilization distribution, which is critical for identifying core areas within the seasonal home ranges. Segmentation of data on displacement and home range sizes was based on three seasons (cool dry, hot dry, hot wet) based on the date and GPS coordinates. In this study, we defined the seasons as follows: (i) hot wet season (December, January, February, March and April) (ii) cool dry season (May, June and July); and (iii) hot dry season (August, September and October, and November) based personal observations and previous studies (Sianga et al., 2024).

2.4. Statistical analyses

Descriptive statistics, including mean, median, standard deviation, skewness, and kurtosis, were calculated for both displacement rates and home range sizes to characterize the central tendency and distribution profile of the data. We assessed for normality and homogeneity of variances using the Shapiro-Wilk test, Levene's test respectively. The Shapiro-Wilk test indicated a non-normal distribution of daily displacement data across sex and season groups ($p < 0.05$). Levene's test also revealed unequal variances between these groups ($p < 0.045$). Given the non-normal distribution and heterogeneous variances, the Mann-Whitney U test was used for pairwise comparisons of between sexes.

Displacement distances (km) for each individual elephant were computed for three distinct seasons and stratified by sex (females and males) for comparative analysis. A Kruskal-Wallis test was used to assess statistically significant differences in median displacement across seasons, with effect sizes calculated using epsilon-squared (ϵ^2) to quantify the variance in displacement due to seasonal differences. Significant results were followed by Dunn's post-hoc tests with Holm-Bonferroni correction for pairwise comparisons. The analysis and visualization were conducted in R using the 'ggstatsplot' package (Patil, 2021), with violin plots generated to display the distribution of displacement distances, highlighting medians and annotating significant pairwise comparisons between sexes with adjusted p-values.

3. Results

3.1. Movement patterns, spatial extent and displacement rates

The collared elephants moved within the CKGR, as well as the Okavango Delta (OD), Chobe region, and Hwange National Park (HNP) in Zimbabwe. Movement patterns varied, with females 7105 and 7112 primarily ranging between the Tsau DWNP gate in CKGR and the southern OD near Khoemacau Mine, while bull 7107 stayed near the Tsau DWNP gate and the western OD (Fig. 2a). In contrast, males 7104, 7108, 7110, 7111, and 7112 remained within the CKGR year-round. Three male elephants exhibited extensive migratory behaviour: 7109 migrated seasonally between Old Xade (CKGR) and the eastern OD, 7113 moved between the Tsau entrance (CKGR), OD, Chobe, and HNP, and 7106 travelled from Old Xade (CKGR) to HNP via Makgadikgadi National Park (MNP), returning along the same route during the dry season (Fig. 2a).

The spatial extent of elephant trajectories across study areas, segmented by individual elephant IDs and their respective gyration radii. Elephants exhibited diverse movement patterns with notable spatial differentiation and distinct movement clusters. Each elephant showed unique trajectories, with some elephants, such as IDs 7106 (black) and 7113 (red), demonstrating extensive movement across the landscape, while others, like ID 7104 (green), exhibited more localized movement (Fig. 2b). The gyration radii, represented by the circle sizes, indicate variations in the spatial extent of movement among the elephants. Larger circles denote a

Table 2
Diel displacement rates of African elephants in the study area across three seasons. *Notes: values displayed show the median and inter quartile range (km).*

Elephant ID	Sex	Season		
		Cool Dry	Hot Dry	Hot Wet
		Median (IQR)	Median (IQR)	Median (IQR)
7104	Male	6.69 (4.68)	8.79 (4.84)	8.70 (5.23)
7105	Female	7.98 (6.80)	10.02 (8.27)	7.82 (5.33)
7106	Male	5.21 (4.21)	8.62 (6.86)	13.69 (11.08)
7107	Male	12.20 (6.13)	10.92 (7.49)	11.89 (7.94)
7108	Male	8.94 (4.08)	9.33 (4.90)	8.00 (5.72)
7109	Male	11.45 (6.54)	9.65 (7.05)	11.16 (12.63)
7110	Male	6.06 (4.21)	7.28 (4.78)	8.60 (5.38)
7111	Male	9.27 (5.64)	9.92 (7.86)	13.30 (8.58)
7112	Female	8.34 (6.37)	9.88 (5.99)	8.75 (6.26)
7113	Male	8.09 (4.34)	8.71 (5.73)	11.48 (11.49)

broader range of movement, suggesting elephants with extensive roaming areas (*e.g.,* Elephant IDs 7106, 7107, 7109, and 7113). Conversely, smaller radii (*e.g.,* Elephant ID 7104) suggest more sedentary movement patterns. Noticeable spatial clustering and overlap in the movement paths of different elephants suggest common areas of activity or habitats used by multiple individuals (Fig. 2b).

The median diel displacement and their respective interquartile ranges (IQRs) for each elephant across the three seasons are shown in Table 2. Variability, based on IQR values, was notably higher in the hot wet season, suggesting greater dispersion and pronounced seasonal effects on movement patterns. Overall, Mann-Whitney U test showed a statistically significant difference in displacement rates between female and male elephants (U = 873,343, p = 0.026).

Both male and female elephants displayed distinct seasonal variability in diel displacement (Fig. 3). Movements were highest during the hot wet season (December–April), with females regularly covering over 30 km/day and occasionally reaching 50 km/day. In contrast, during the cool dry season (May–July), female movements were lower, typically below 15 km/day, with a similar reduction observed during the hot dry season (August–November), though occasional spikes exceeded 20 km/day. Male elephants also showed increased displacement during the hot wet season, reaching up to 35 km/day, with rare outliers exceeding 100 km/day. During the cool dry and hot dry seasons, male movements were more moderate, generally staying below 15 km/day, and were more consistent than those of females, with fewer extreme spikes.

The Kruskal-Wallis test showed a significant difference in diel displacement across seasons among females ($\chi^2 = 22.06$, p = 1.62e-05). Dunn's post-hoc test revealed significant pairwise differences between the cool dry and hot dry season (p = 1.07e-04), as well as between the cool dry and hot wet season (p = 2.32e-04). Median diel displacement values were highest in the hot dry season (9.91 km), followed by the Hot Wet (8.48 km) and cool dry (8.08 km) seasons (Fig. 4). Similarly, there was a significant difference in diel displacement ($\chi^2 = 98.50$, p = 4.08e-22) for males across seasons. Dunn's post-hoc test confirmed significant pairwise differences between all season pairs; cool dry and hot dry (p = 1.98e-03), cool dry and hot wet (p = 4.48e-12), and hot dry and hot wet (p = 7.70e-20). The median diel displacement values were highest in the hot wet season (10.54 km), followed by the hot dry (9.02 km) and cool

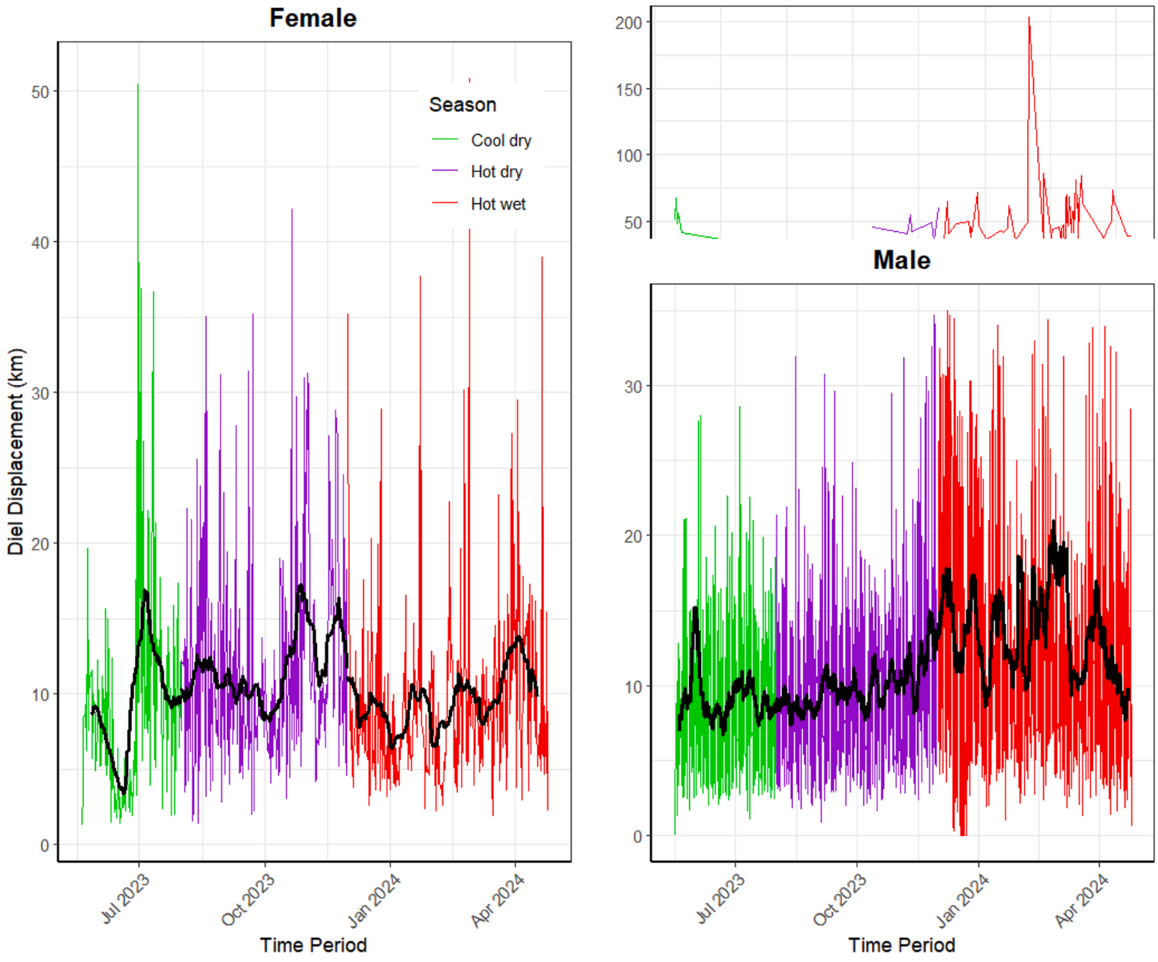

Fig. 3. Seasonal variation in African elephant diel displacement by sex with a 30-day rolling average. Notes: Black line represents the 30-day rolling average for diel displacement. The plot for males employs a broken y-axis, with the lower section showing displacements ≤ 35 km and the upper section showing displacements > 35 km.

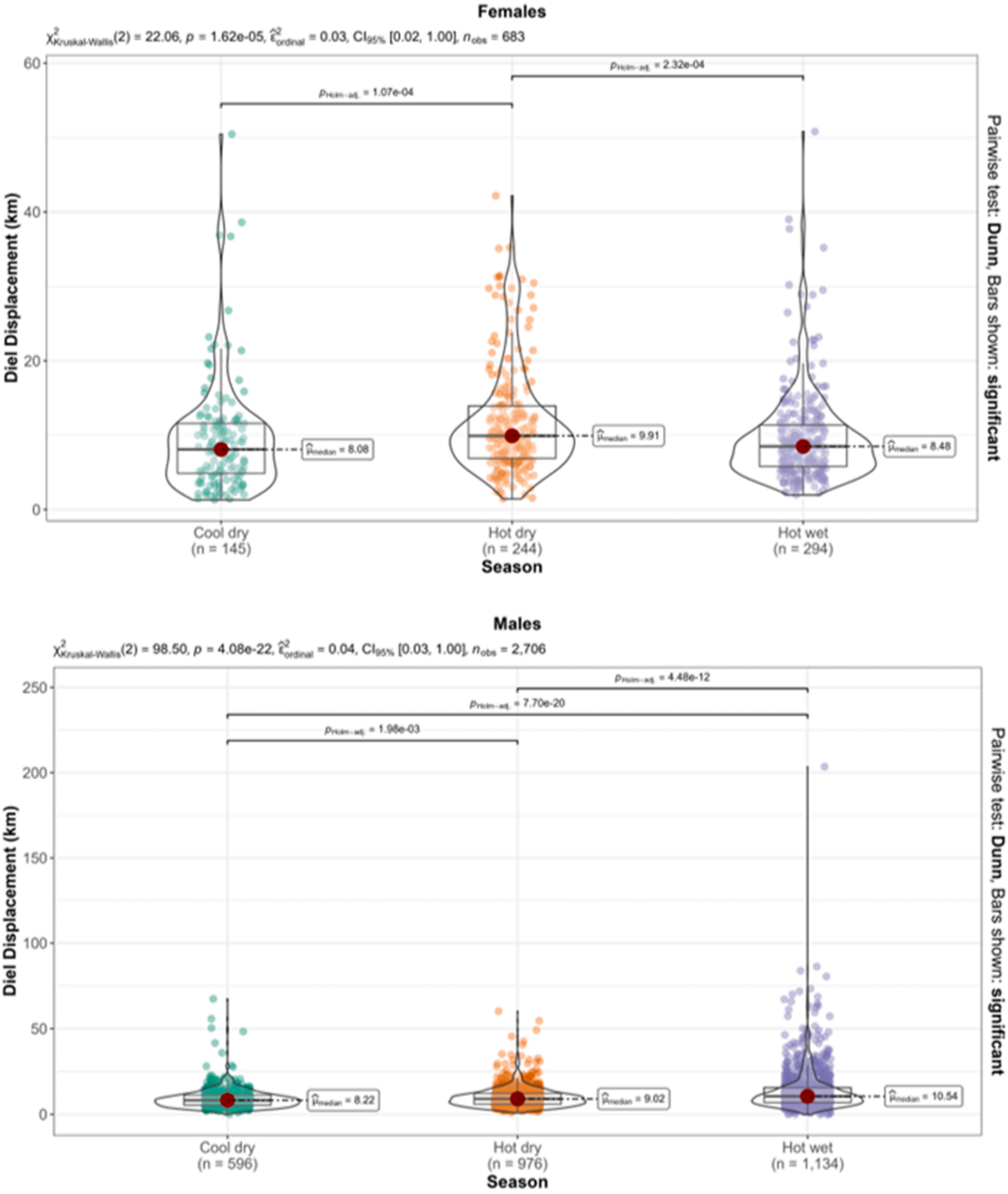

Fig. 4. Seasonal differences in diel displacement of female and male African elephants for the study period.

dry (8.22 km) season (Fig. 4).

3.2. Seasonal and annual home ranges

The Kernel Density Estimation (KDE) results revealed significant variation in elephant home range sizes, influenced by both sex and season (Table 3 and Fig. 5). Males generally had larger home ranges than females, with individuals like Elephant IDs 7106 and 7113

Table 3
Seasonal and annual home range areas (km^2) estimated using kernel density estimation (KDE) for African elephants in the Central Kalahari Game Reserve.

Elephant ID	Sex	Season			Annual
		Cool Dry	Hot Dry	Hot Wet	
		KDE (km^2)	KDE (km^2)	KDE (km^2)	KDE (km^2)
7104	Male	21.29	16.90	209.91	1890.10
7105	Female	436.65	276.64	184.39	4224.65
7106	Male	53.56	140.45	7422.32	38367.94
7107	Male	544.37	1820.99	1867.70	14639.83
7108	Male	56.27	5.78	359.70	3468.04
7109	Male	20.92	45.15	3248.51	33882.97
7110	Male	8.24	5.14	198.74	1432.54
7111	Male	40.08	18.70	2201.31	23733.00
7112	Female	49.49	10.80	244.39	1824.13
7113	Male	46.30	18.96	6850.29	58931.75

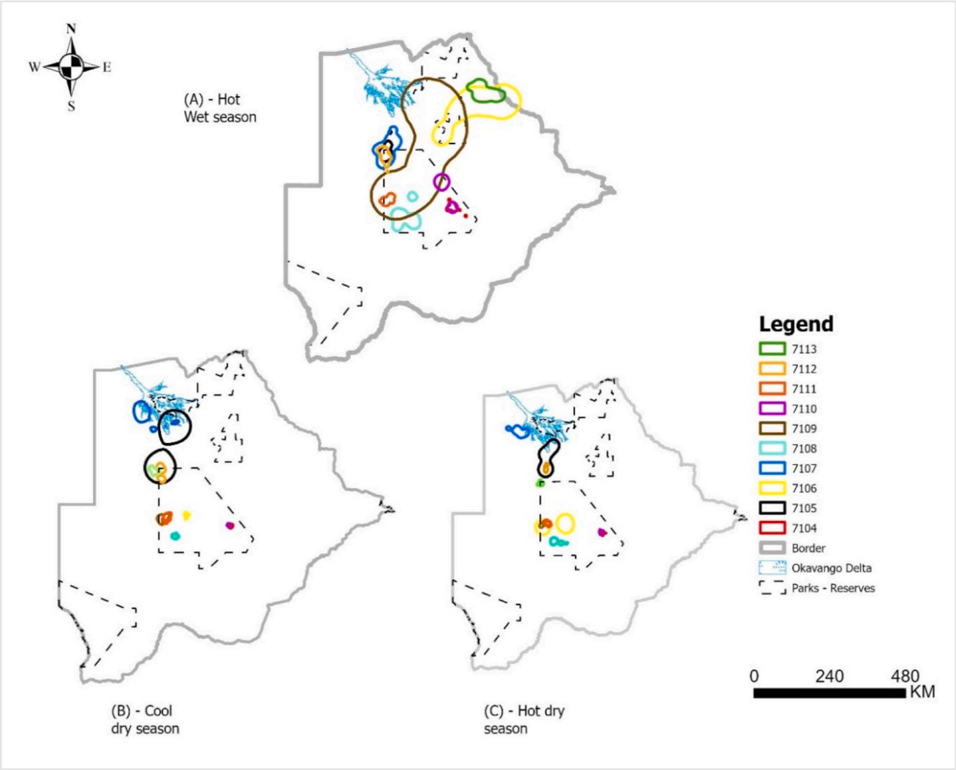

Fig. 5. **:** Seasonal home ranges of GPS-collared African elephants in the Central Kalahari Game Reserve and surrounding areas, Botswana. *Notes: (A) Hot wet season, (B) – Cool dry season and (C) Hot dry season.*

showing particularly extensive ranges during the hot wet season. Females, on the other hand, exhibited smaller and more stable ranges, except for Elephant ID 7105, which displayed an unusually large annual range. Seasonal effects were evident, with home ranges expanding significantly during the hot wet season compared to the cooler dry seasons. This suggests that seasonal shifts in environmental conditions, such as resource availability, strongly influence elephant movement patterns within the Central Kalahari Game Reserve.

4. Discussion

This study marks a significant advancement in understanding the seasonal movement patterns of elephants across the CKGR, OD, Chobe, and HNP regions within the KAZA landscape. GPS-collar data offered the first quantitative insights into how these large herbivores utilise the landscape in response to seasonal fluctuations in water availability, forage, and environmental conditions. These movement patterns highlight the critical importance of maintaining ecological connectivity between the KAZA and the Central Kalahari Game Reserve. This connectivity is essential for the effective management and conservation of large herbivores across these interconnected landscapes, with significant implications for biodiversity and ecosystem resilience (Dures et al., 2020, 2021; McCarthy and Ellery, 1998).

The study showed significant differences in movement patterns between male and female elephants, with males exhibiting wider ranges and more pronounced movement behaviour. The introduction of artificial water points has likely increased male elephants' residency within the CKGR; previously, they migrated north during the wet season in search of natural water sources. (Spinage, 1990). The strategic placement of AWPs at locations such as Tsau Gate, Xaka, and Matswere has provided consistent water availability, enabling male elephants to occupy areas that were historically part of their migratory routes year-round (Naha et al., 2019; Perkins, 2020). This shift aligns with similar observations in other semi-arid ecosystems, where artificial water sources alter traditional migration and ranging patterns (Chamaillé-Jammes et al., 2007; De Beer et al., 2006; Evans and Harris, 2008; Illius, 2006; Wato et al., 2018). This shift in behaviour suggests that while AWPs provide essential resources, they may also alter traditional migratory patterns, potentially leading to increased human-wildlife conflict (Buchholtz et al., 2023, 2021; Graham et al., 2009; Kikoti et al., 2010) and localized habitat changes (Dzinotizei et al., 2019; Hilbers et al., 2015; Shannon et al., 2009).

The male elephants in the CKGR maintain a regular presence near artificial water points and moved north to Okavango Delta (OD), Chobe, and Hwange National Park (HNP) during the wet season, returning in the dry season. In contrast, female elephants primarily migrate between northern CKGR and southern OD. Historically, large herds in the OD and Chobe regions migrate to dryland woodlands during the wet season, influenced by water availability in ephemeral pans (Spinage, 1990; Stokke and Du Toit, 2002). The establishment of artificial water points (AWPs) at Tsao Gate, Xaka, Matswere, Motopi, Sunday Pan, Piper Pan, Qwee, and Old Xade likely contributed to the permanent residency of male elephants during the dry season by improving water access. Similarly, areas near artificial water sources at the Gope and Ghagho mines have become important habitats for elephants in the CKGR. This pattern is consistent with research in semi-arid ecosystems, where water availability and forage are key drivers of elephant distribution (Bucciarelli et al., 2024; Dzinotizei et al., 2019; Perkins, 2020; Shannon et al., 2009). Reports from the Department of Wildlife and National Parks (DWNP) indicate that elephants were first observed in the CKGR in 2010 near the Tsau AWP, with subsequent data showing a steady rise in elephant density around AWPs in both wet and dry seasons.

The results showed ecologically significant seasonal movement patterns around artificial water points (AWPs) during both wet and dry periods. Female elephants with calves strategically position themselves near the Okavango Delta (OD), particularly between Tsau Gate and OD, highlighting their dependence on OD's permanent water sources. This behaviour likely reduces the risks posed by water scarcity at Tsau AWP, where solar pump failures have caused prolonged shortages, threatening juvenile survival. These findings align with broader research indicating that water shortages significantly increase dehydration risks for vulnerable young elephants (Foley et al., 2008; Leggett, 2006; Loveridge et al., 2006; Young and Van Aarde, 2011).

The displacement rates observed in this study generally show consistent movement patterns across seasons, with some variability among collared elephants. Arguably, the observed differences in displacement rates between females and males can be attributed to their distinct social structures (Archie et al., 2011; Moss et al., 2011), and divergent foraging strategies (Lee et al., 2011). Males, with their broader foraging ranges, often explore unfamiliar habitats in search of forage and mates, venturing further from water sources to access high-quality habitats, especially during dry seasons. (Lee et al., 2011; Skarpe et al., 2014). In contrast, female herds are constrained by the mobility of calves at varying developmental stages, limiting the distance they can travel from water sources (Ngene et al., 2010). The movement patterns observed in this study show key regions with high overlap and frequent elephant activity, suggesting areas where intensified conservation efforts could be most effective (Beger et al., 2022; Huang et al., 2022).

By analysing spatial trajectories and gyration radii, this study highlights the complexity and variability in elephant movement, emphasising the necessity for conservation strategies that are both site-specific and adaptable to individual and collective behaviours (Cushman et al., 2005; Polansky et al., 2015). Insights from elephant movement trajectories and spatial extent are crucial for developing effective management plans to protect critical habitats patches and movement corridors (Adams et al., 2022; Douglas-Hamilton et al., 2005), mitigate human-elephant conflicts (Gerhardt et al., 2014; Jiren et al., 2021; König et al., 2021; Ostermann-Miyashita et al., 2021), and ensure the long-term sustainability of elephant populations in the region.

Research on elephant home ranges across Africa consistently shows that annual home ranges are significantly larger than seasonal or monthly estimates. Studies in northern Botswana (Chase, 2007; Ofithile, 2012) and South Africa (Loarie et al., 2009c) report similar patterns. In this study, annual home ranges for the collared male elephants exceeded the combined seasonal ranges, with notable differences between sexes and seasons. This aligns with findings from other studies on African elephants (Bastille-Rousseau et al., 2020; Wittemyer et al., 2007), where seasonal movements, driven by the need to access scarce resources during dry periods, result in overlapping space use and range expansion (Mlambo et al., 2021).

We argue that the expansive home ranges of male elephants in this study some exceeding 30,000 km^2, result from extensive movements in search of mates and widely dispersed resources, particularly in resource-scarce regions like the Kalahari. These ranges are comparable only to those recorded in Gourma, Mali, where collared female elephants exhibited a home range of 32,062 km^2, and males had ranges of up to 24,196 km^2 (Wall et al., 2013). Some males exhibited exceptionally large ranges, consistent with exploratory or migratory behaviors observed in other studies (Bohrer et al., 2014; Ofithile, 2012; Wato et al., 2018). Males typically travel farther than females, venturing beyond core areas to maximize mating opportunities and access seasonal resources (Stokke and Du Toit, 2002). Environmental factors, such as seasonal water availability and social behaviors like musth, further contribute to this increased mobility by male African elephants (De Beer and Van Aarde, 2008; Loarie et al., 2009). In contrast, females maintained smaller, more stable ranges, especially when accompanied by calves, staying closer to reliable water sources (Bastille-Rousseau et al., 2020; Benitez et al., 2022; Cushman et al., 2005; Polansky et al., 2013). These patterns highlight elephants' adaptive strategies to fluctuating resources and emphasize the critical need to conserve connected habitats across the Central Kalahari ecosystem and surrounding areas to sustain their wide-ranging movements.

During the wet season, core home ranges for three male elephants extended into woodlands between the CKGR, OD, MNP, and HNP, with these individuals venturing beyond their dry season ranges in CKGR. This behaviour mirrors patterns observed in Namibia's Hoanib River, where male elephants travel vast distances to access wet season habitats (Leggett, 2006; Viljoen, 1988). Such extensive movements are typical of large herbivores, driven by the need to exploit diverse resources across wet and dry periods (Gordon et al., 2004). In CKGR, elephant ranging patterns seem influenced by the spatial distribution of water, indicating an ecological awareness of artificial water points (Wato et al., 2018), similar to behaviours observed in Tsavo National Park, Kenya (Polansky et al., 2015). The wet season dispersal into woodlands across CKGR, OD, MNP, and HNP reflects the seasonal abundance of resources, consistent with patterns documented among large herbivores in northern Botswana (Bennitt et al., 2014; Naidoo et al., 2014, 2016; Sianga, 2014; Sianga et al., 2017b).

5. Implications for conservation and management

This study provides insights into the complex spatial dynamics of elephants within the CKGR and highlights its critical connectivity with the KAZA, one of the world's largest and most significant transboundary conservation landscapes (Kaszta et al., 2021; Osipova et al., 2018; Purdon et al., 2018; Zacarias and Loyola, 2018). The establishment of artificial water points within the CKGR has significantly altered traditional elephant movement patterns, prompting a shift toward more sedentary behaviour among male elephants in areas that were historically occupied only seasonally. While these water provisioning is important in the arid CKGR environment, there are concerns about habitat degradation, increased competition with other herbivores, disrupted ecosystem dynamics, and the potential for escalating human-elephant conflicts (Buchholtz et al., 2023, 2021; Gerhardt et al., 2014; Graham et al., 2009; Kaszta et al., 2021; Naha et al., 2019; Pozo et al., 2018). The findings highlight the critical need to maintain ecological connectivity between protected areas beyond the KAZA region to secure the long-term viability of elephant populations and other key species (Chibeya et al., 2021; Gara et al., 2021; Giliba et al., 2023; Keeley et al., 2017; Zacarias and Loyola, 2018).

Given the increasing threat of climate change exacerbating water scarcity and altering resource distribution, it is imperative to adopt holistic, ecosystem-based adaptive management strategies that prioritize ecological integrity (Birgé et al., 2016; Nasr and Orwin, 2024), while balancing social and economic needs (van de Water et al., 2022). These approaches are particularly crucial in regions where human activities, such as mining and agriculture, intersect with essential wildlife habitats and potential dispersal routes or corridors (Schüßler et al., 2018). Further research is needed to monitor these shifting dynamics, particularly the long-term effects of artificial water points and environmental change on elephant movement, population health, human-elephant coexistence, and ecosystem resilience. This research will be essential for informing conservation policies and management practices that enhance the resilience of wildlife and human communities amid environmental change.

Ethics Statement

A research permit was applied and availed before the study was conducted.

Author contributions

Keoikantse Sianga, Shimane Makhabu, Victor Muposhi: Conceptualization; **Keoikantse Sianga, Shimane Makhabu, Victor Muposhi**: Methodology; **Keoikantse Sianga, Shimane Makhabu, Victor Muposhi, Tebogo Selebatso, Mpho Setlalekgomo, Albertinah Matsika, Boipuso Legwatagwata, Amo Barungwi, Kelebogile Selala, Maitumelo Losologolo, Emang Molojwane, Comfort Nkgowe, Oreemetse Dingake**: Data curation; **Keoikantse Sianga, Victor Muposhi**: Formal analysis; **Keoikantse Sianga**: Writing- Original draft preparation; **Keoikantse Sianga, Victor Muposhi, Shimane Makhabu, Tebogo Selebatso, Amo Barungwi, Albertinah Matsika**: Writing - review and editing; **Shimane Makhabu, Keoikantse Sianga, Victor Muposhi**: Funding acquisition; **Keoikantse Sianga, Victor Muposhi**: Software; **Keoikantse Sianga, Victor Muposhi**: Visualization; **Keoikantse Sianga, Shimane Makhabu, Victor Muposhi**: Resources; **Keoikantse Sianga, Victor Muposhi, Shimane Makhabu**: Validation; **Victor Muposhi**: Supervision; **Shimane Makhabu, Keoikantse Sianga**: Project administration.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Keoikantse Sianga reports financial support was provided by Conservation Trust Fund. None reports a relationship with None that includes: non-financial support. None has patent None pending to None. None If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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