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Name: Jip Vader
Student ID: 40405352

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Preliminary Data on the Movement Ecology and Behaviour of Ten Adult Male African Savannah Elephants (*Loxodonta africana*) in Botswana and Zimbabwe

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Supervisor: Professor Rob Briers
External supervisor: Dr Kate Evans

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1 Abstract

The African savannah elephant, a critical keystone species, plays an essential role in biodiversity, impacting habitat creation and nutrient dispersal. This study aimed to examine the movement ecology of 10 adult male African savannah elephants, and their habitat use in both protected and unprotected lands and even traversing international boundaries in Botswana and Zimbabwe, home to the largest remaining elephant population. The analyses focused on their habitat use and environmental and physiological impact on movement. The data was collected using GPS and VHF transmitters on August 22 and 23, 2022 and were analysed through Kernel Density Estimation (KDE) and compositional analysis using R and QGIS, showing the importance of variations in habitat preferences and spatial use. Important observations into daily patterns, hourly variations, monthly trends, temperature influences, individual preferences, feeding and resting patterns, ecological insights and musth's influence on all these factors were obtained. The findings reveal the complexity of elephant behaviour and habitat interaction and use, offering a better understanding of their spatial behaviour, movement patterns and responses to environmental factors. Unexpected preferences and avoidance of particular environments were observed, indicating the need for more research on this important population for a better understanding of how elephants are using this region, in this important area for elephant conservation, to make effective long-term management decisions. The findings of the study provide a foundation for future study and conservation efforts by highlighting the necessity of a thorough understanding of elephant interactions with their surroundings, including complex behaviours like crop raiding and different physiological states such as musth.

Keywords: *adult male African savannah elephant; movement; speed; musth; Kernel Density Estimation; Spatial use/selection, habitat selection*

2 Scientific Background and Rationale

The African savannah elephant (*Loxodonta africana*), one of the two recognised species of African elephants, is a fundamental keystone species that plays a pivotal role in upholding biodiversity (de Knegt et al., 2011). These majestic creatures are the largest terrestrial animals on Earth and are sometimes referred to as "landscape architects" because of their capacity to mould and sustain the ecosystems they inhabit. Elephants have been a subject of extensive scientific interest due to their remarkable size and ecological significance. Over time, a combination of genetic, morphological and behavioural research established that there are in fact two African elephant species—the forest elephant (*Loxodonta cyclotis*) and the savannah (or bush) elephant (*Loxodonta africana*) (Comstock et al., 2002). This finding extends beyond taxonomical significance and also influences further conservation efforts. This has resulted in the development of targeted strategies, preservation of genetic diversity, more efficient allocation of resources and enhanced public engagement, ensuring that both species receive the attention and protection they require. As the largest land mammal, it has significant influence on its habitat, as they play an active role in the functioning of ecosystems through its contributions to habitat creation and maintenance, as well as its role in seed and nutrient dispersal. These activities are crucial for the survival and well-being of various other species within the ecosystems elephants inhibit (Poulsen et al., 2018).

There are significant distinctions in the social structures, behaviour and responses to environmental stressors between male and female African Savannah elephants. Female elephants typically establish matriarchal herds, while males engage in complex social dynamics characterized by fission-fusion relationships—where the composition and size of the group evolve over time and with environmental movement—as well as age-dependent social networks that exhibit hierarchical queuing behaviour in high-stakes situations (O'Connell-Rodwell et al., 2011). The study by Lee et al. (2022) examines the varying impacts of environmental and social difficulties on male and female elephants. While the impact of family disturbance appears to have a greater effect on females, possibly due to their involvement in matriarchal social systems, males are more significantly affected by drought, especially at critical periods of their development. The variations in behaviour and response to external influences highlight the intricate interaction between gender, age, and surroundings within the social ecology of African savannah elephants.

Understanding the behaviour and ecology of male African savannah elephants is crucial for effective conservation and mitigation of human-elephant conflict. Studies have shown that male forest elephants exhibit unique movement ecology and behaviour when selecting habitats, operating at a different spatial scale than females (Beirne et al., 2021; de Knegt et al., 2011). Male African savannah elephants use chemical information to monitor female movements, which may be crucial for mate selection and reproduction (Poole, 1987). Older males also play a leadership role in all-male elephant groups, facilitating cooperation and guiding group movements (Allen et al., 2020). However, male elephants' long-distance movements in search of mates and resources can make them more vulnerable to human-wildlife conflict, particularly in fragmented habitats (Gara et al., 2021). Male elephants have been found to modify their behaviour in response to human threats and can discriminate between different levels of danger (Wittemyer et al., 2008). Additionally, crop-raiding behaviour in male African savannah elephants is influenced by their social networks and life history milestones (Chiyo et al., 2012). Therefore, understanding male elephant movement patterns and behaviour at different spatial scales and in different contexts is essential for effective conservation management and mitigating human-elephant conflict.

Crop raiding by male African elephants is a multifaceted issue with various influences and implications. According to Osborn (2004) findings, there is a seasonal variation in the feeding patterns of elephants that engage in crop-raiding activities in Zimbabwe. This indicates that the timing of these raids has a crucial role in shaping the behaviour of these elephants. Further research expanded upon previous findings by showing a connection between lunar cycles and the likelihood of elephants to engage in risk avoidance behaviour while utilising crops grown by humans (Gunn et al., 2014).

In Botswana the extent to which farmers in the Okavango Delta region embraced deterrent innovations, revealed a notable inclination towards the adoption of novel practises especially the use of chilli pepper (Noga et al., 2015). Another kind of olfactory repellent was introduced in Uganda and Kenya which was very successful and deterred 82% of all the crop raiding attempt during the study (Tiller et al., 2022). More traditional methods approaches were also taken into account, including the implementation of beehive fences in the northern region of Kenya (King et al., 2011). This method was not preferred by farmers in the Okavango Delta region in Botswana as it was perceived as a low deterrent (Noga et al., 2015). Ahlering et al. (2011) found that crop raiding has a significant correlation with heightened stress levels in male elephants, indicating potential physiological consequences. Troup et al. (2020) further found that elephants exhibit complex movement patterns during crop-raiding, with variations in speed possibly reflecting a valuation of risks and rewards. The observed navigation patterns of elephants could potentially be linked to their awareness of human activities, physical barriers, and the spatial arrangement of crops within the area. Collectively, these studies provide a comprehensive perspective on crop raiding, highlighting the significance of individualised techniques.

Alongside crop raiding, the role of protected areas in the conservation and behaviour of African elephants emerges as a key factor. Elephants are moving out of their protected areas in southern Kenya. This could be a sign of natural growth patterns and human-elephant conflicts (Ahlering et al., 2012). A study conducted in the Marsabit protected region reveals the apparent seasonal movement patterns of elephants, which are influenced by several factors such as accessibility to forage and water, as well as human activities, ultimately determining their migratory behaviour (Ngene et al., 2010). Another study demonstrated that protected areas have an important impact on the home and habitat use ranges of elephants, highlighting the role these areas play in providing safety for elephants while also potentially constraining their habitat (Wall et al., 2021). The present distribution of elephants comprises just 17% of their potential habitat, while a significant 57.4% occurs outside of protected regions (Wall et al., 2021). It is further hypothesised that elephants also increase their speed outside of protected areas (Douglas-Hamilton et al., 2005). To secure the future of elephants, one important management strategy is to find areas of high use outside protected areas that could be potentially become future protected areas could serve as a corridor to connect two protected areas.

Corridors are essential for species conservation and protected area planning, particularly for species, to enhance gene flow, population viability, and conservation of critical processes (Jachowski et al., 2013). The present efforts to determine, organise and give importance to corridors for the protection of species concentrate on how individual species move in reaction to habitat preservation and management along these corridors (Sawyer et al., 2011). Recently, African savannah elephants have been observed to be restricted to protected areas due to disturbed or broken wildlife corridors and display streaking behaviour, a behaviour where they rapidly run through an area without stopping or browsing (Douglas-Hamilton et al., 2005). Streaking has further been hypothesised to be the response to environmental factors such as nutrient availability, reproductive tactics (Taylor et al., 2020) and water sources (Yussuf A. Wato et al., 2018). However, Douglas-Hamilton et al. (2005) and Jones et al. (2012) found that human disturbance in corridors caused a decrease in corridor usage and an increase in streaking behaviour. Jachowski et al. (2013) examined the relationship between the physiological state of African savannah elephants and their use of corridors and streaking behaviour and discovered that elephants in poor physiological condition were more likely to use corridors and exhibit streaking behaviour, which highlighted the importance of considering the physiological state of elephants. So even though this behaviour has been studied the ecological significance is not yet fully understood.

Another behaviour that is poorly understood is why predominantly male African savannah elephants are found in the Makgadikgadi Pans National Park, a low nutrient and water area. According to a study by Douglas-Hamilton et al. (2005) the Makgadikgadi Pans in Botswana are an essential ecosystem for African savannah elephants as it provides a critical source of nutrients during the dry season when food is scarce, and elephants rely on this area for survival. Despite this importance, there is a lack of knowledge about how elephants search for nutrients and the factors that influence their movement patterns within this region, which may be due to the vastness of the Makgadikgadi Pans making it difficult to track individual elephants and monitor their movements and habitat use. However, advancements in tracking technology and analysis methods have enabled researchers to study elephant movement patterns in more detail; GPS collars and remote sensing data are now used to track their movements over large areas and analyse the factors that affect their decisions (Owen-Smith et al., 2020).

The broadened understanding of spatial use and habitat selection by elephants extends to other regions, offering critical insights into their complex ecology, behaviour and interactions with human-dominated areas. Habitat selections by elephants is multifaceted, affected by various natural and anthropogenic factors. One study found that a functional response was observed in the selection of habitats in relation to tree cover, both spatially and temporally (Roever et al., 2012). During the rainy season, it was shown that tree cover did not significantly influence habitat selection in the mesic, eastern populations, but there was further increased variability in selection during this period; meanwhile, selection for low slopes, high tree cover and greater distance from anthropogenic factors was consistent across populations, yet the variability in selection coefficients changed as a function of the abundance of a given resource within the home range (Roever et al., 2012). De Boer et al. (2000) discovered similar findings of preference of dense forest patches among males (de Knegt et al., 2011) and have adjusted their habits and diet in response to factors such as water salinity, seasonal changes, poaching, and the vital presence of forest patches. Bastille-Rousseau et al. (2020) found that there were seasonal changes in habitat selection and noted that elephants clustered around permanent water sources and human settlements during the dry season and moved to seasonal waters during the rainy season. Elephants demonstrate the ability to adapt their spatial behaviours in response to human presence and various risk factors, such as poaching (Graham et al., 2009). These adaptations are observed in both dry and rainy seasons, as well as in unfenced ecosystems where human-induced pressures are prevalent. A case study conducted in Gorongosa National Park in Mozambique exemplifies how elephants strategically modify their movements and exhibit a preference for engaging in risky activities during the night while seeking refuge during the day (Gaynor et al., 2018).

The life stage of an animal significantly influences movement patterns; for instance, migratory patterns of adolescent birds can differ markedly from mature individuals (Newton, 2007), and the roaming behaviours of sub-adult lions stand apart from those of territorial adults (Davidson et al., 2013). In male African savannah elephants, musth, a period of heightened sexual activity characterised by physiological and behavioural changes (Poole, 1987), illustrates another influential life stage. During musth, elephants secrete temporin from their temporal glands located behind their eyes, a fluid rich in chemical compounds that convey an elephant's age, health, reproductive status, and dominance, facilitating peer assessments for mating or social decisions (Poole, 1987). As the condition develops, behavioural shifts make elephants more aggressive and unpredictable, pushing them into scent-marking activities like urine dribbling and dung dropping, emblematic of their dominance (Poole, 1987). Musth is thought to be triggered by hormonal changes and is more commonly observed in older males, who may experience longer periods of musth and exhibit more extreme behaviours than younger males (Ganswindt et al., 2003, 2005). This comprehension of male elephants' chemical signals during musth is pivotal for conservation and management, serving as tools to observe elephant populations and guide decisions on their mobility and habitat preference.

In summary, the African savannah elephant is a keystone species that plays an essential role in maintaining biodiversity in the ecosystems they inhabit. Understanding the movement patterns and behaviour, impacted by various environmental stressors, social structures, of male elephants is crucial for effective conservation management and mitigating human-elephant conflict. The complexity of male elephant behaviour extends to unique habitat selection, responses to human threats and musth. Crop raiding is a complex problem that involves variations in feeding patterns. In response to this issue, different deterrents are utilised (King et al., 2011; Noga et al., 2015; Tiller et al., 2022). Additionally, the impact of protected areas, wildlife corridors and the disturbances caused by human activities present new challenges and opportunities for understanding this behaviour. The Makgadikgadi Pans National Park (MPNP) is a unique environment that is critical to the survival of the largest remaining elephant population in the world and is a key component of the Kavango Zambezi Transfrontier Conservation Area, about which little is known about in terms of its importance to elephant movement across this landscape. Finally, musth, with its profound impact on movement patterns and habitat requirements, plays a crucial role in male elephant conservation and management. Understanding how musth affects male elephant spatial needs will ensure key habitats are conserved to ensure future populations. Overall, continued research and conservation efforts are necessary to ensure the survival of this iconic species and the ecosystems they inhabit.

2.1 Aim and Research Objectives

The aim of this study is to analyse the initial movement data of 10 adult male African savannah elephants. These elephants were fitted with satellite radio collars in MPNP in August 2022 by the Botswana-based NGO, Elephants for Africa (EfA). The study seeks to identify potential wildlife corridors. Additionally, it aims to offer a comprehensive preliminary analysis, which can lead to recommendations for subsequent conservation efforts based on the results.

This data was used to investigate the following objectives;

1. To determine home ranges of 10 male African savannah elephants
2. To assess the impact of environmental factors such as water sources and human activity on the movement behaviour of male African savannah elephants.
3. To compare the movement patterns and behaviour of male African savannah elephants during different times of day, month, and temperatures.
4. To identify areas of high conservation value based on the movement patterns of male African savannah elephants and devise recommendations for these areas, future research and monitoring efforts based on the findings of the study.

3 Methods

3.1 Study Site and Study Species

Ten male African savannah elephants were darted and collared in the Makgadikgadi Pans National Park (MPNP), a partially fenced protected area, thus the elephants where not restricted to this location and the study site includes areas of Botswana and Zimbabwe, as dictated by the elephants' movements. The elephants were collared by the NGO, Elephants for Africa (EfA, as part of a larger research project investigating the male elephants of this region and the potential nutritional deficiencies driving range expansion in this region. EfA operates out of a research camp, located in the village of Khumaga on the banks of the Boteti River, bordering MPNP (Figure 1.).

To mitigate the potential risk of drowning after being darted, the 10 adult male African savannah elephants (assessed to be adults from the air by their size, tusk size and other features by two very experienced personnel) were deliberately not collared in close proximity to the Boteti River, to ensure their safety during the darting process. During the study, one of the elephants, identified as IR SAT 6214, entered the state of musth. For data on the elephants refer to Appendix 1.

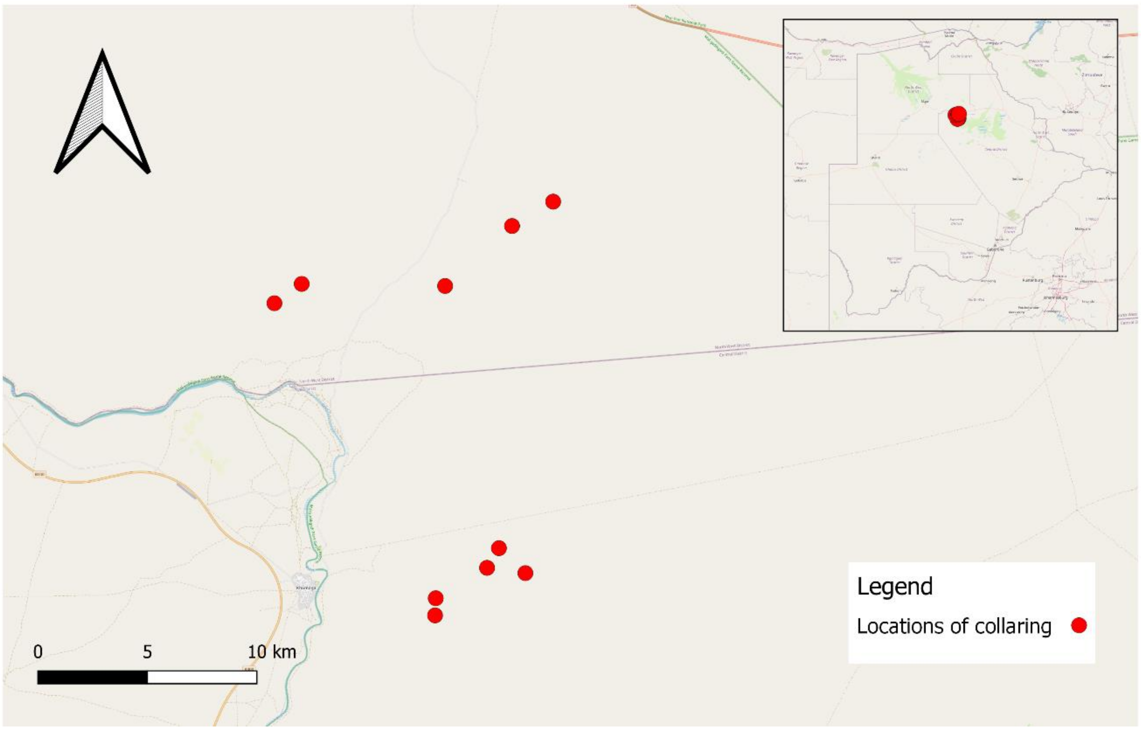

Figure 1. Map of area near the Boteti River in Botswana where 10 adult male African savannah elephants (*Loxodonta africana*) were fitted with Iridium Satellite and UHF collars (AFRICA WILDLIFE TRACKING, n.d.).

3.2 Data collection

The author did not collect the data used in this study. Instead, a collaboration was established between the author and Elephants for Africa, a registered charity in England and Wales and NGO in Botswana dedicated to protecting the endangered African savannah elephant through research and education. Elephants for Africa focuses on understanding the ecological and social needs of male African savannah elephants and aims to mitigate human-wildlife conflicts (Elephants for Africa, 2023). They work collaboratively with researchers to disseminate scientific information to local authorities and raise community awareness. In alignment with the organisation's research objectives, the data collection method employed in this study was adapted from established techniques previously used by Elephants for Africa and resembles the methodology outlined by Evans (2006).

10 adult male elephants were selected randomly in MPNP by flying a small spotter plane to locate the elephants, once spotted a helicopter was radioed in, from which the veterinarian and an experienced elephant biologist assessed the age of the elephant(s), if a suitably aged elephant was present, they were darted by the veterinarian. The elephants were darted with etorphine hydrochloride (M99) by a veterinarian using gun-propelled syringes. Seven elephants were darted on August 22, 2022, while the remaining three were darted on August 23, 2022. Once sedated, the elephants were measured and fitted with GPS (Global Positioning System) collars. The GPS collars are the IR-SAT Tag (Iridium Satellite and UHF Tag) which provide wildlife tracking and telemetry by utilising a low-power UHF Transceiver and an IR-SAT module (AFRICA WILDLIFE TRACKING, n.d.). In three cases, a vehicle crew assisted in the process. The collars were programmed to collect and transmit the date, time, geographical coordinates, and temperature every hour. Additionally, each collar had a VHF (Very High Frequency) transmitter with a unique frequency, enabling tracking from the air and ground.

3.3 Analyses Using R and QGIS for each objective

The analyses of the dataset consisting of the tracking data collected from 10 adult male African savannah elephants was done using RStudio (Version 2023.06.0 Build 421), R version 4.3.0 (2023-04-21 ucrt) (R Core Team, 2023) and QGIS version 3.24.1-Tisler (QGIS.org, 2023).

The dataset spans from August 22nd, 2022, to June 1st, 2023, with GPS points recorded at hourly intervals. First to ensure data quality and reliability the data was cleaned and the timestamps were reformatted. The timestamps were then manipulated. The aim of this manipulation was to isolate the month and time components for analytical purposes (Wickham, 2017).

3.3.1 Objective 1 analyses

For the first objective of this study, raw coordinates were extracted from the dataset in QGIS. The "adehabitat" package (Calenge, 2006) was used to perform kernel density estimation (KDE) find the habitat use (at 95% confidence interval) and the core home ranges (at 50% confidence interval) of each elephant and of all the data together. This study utilised the ad hoc smoothing parameter, 'href,' which dynamically adjusts the bandwidth based on the distribution of the data. This data-driven approach mitigates over-smoothing or under-smoothing issues, leading to more accurate KDE outcomes (Schuler et al., 2014). The KDE polygons were turned into 'sf' (simple features) objects with EPSG:32735 (WGS 84 / UTM zone 35S) coordinate reference systems.

3.3.2 Objective 2 analyses

A multifaceted approach was employed for the second objective of this study. The following data were added onto the map; habitat landuse data set, which is a 10m raster with global landuse but only one section was downloaded that covers the study area (Esri & Microsoft, 2022), waterways for both Zimbabwe and Botswana (OpenStreetMap contributors, 2020; rcmrd., 2015), roads for both countries (AICD., 2017; OpenStreetMap contributors, 2023) and protected areas for both countries (UNEP-WCMC & IUCN, 2023).

The linear features on the layers were buffered to 20m. This buffer allowed elephants to be detected using the road and waterways within these 20m. All the layers were merged and dissolved into a comprehensive land use layer displaying all the available habitat for analyses. The Kernel Density Estimation (KDE) polygons were used to cut areas from the land use layer to determine the habitat selection preferences of each elephant.

3.3.3 Objective 3 analyses

To assess objective 3, the habitat use was calculated using compositional analysis. The protected areas were unionised with the dissolved land-use map. The KDE shapefiles were clipped to the dissolved land-use layer. The areas found within these clipped layers were then saved into two CSV files; one file with the 50% confidence interval called “all50” and another with the 95% confidence interval called “all95”. The landuse layer’s areas were also saved as a CSV file. The available area, and used areas at 95% and 50% confidence intervals, were extracted, and the mean composition within each area were calculated and visually represented through pie charts. Compositional analysis was conducted using the 'compana' function on both 95% and 50% confidence interval data, and the resulting ranking matrices were interpreted further.

3.3.4 Objective 4 analyses

To achieve the fourth objective of this study, analyses were done on how elephant speed varies during different hours, months, temperatures and day and night.

Speed between consecutive points were computed.

Day and night were distinguished in RStudio. Four boxplots were generated to visualise the distribution of elephant speeds at different hours; nighttime and daytime; months and temperature. A Wilcoxon rank sum test showed the significant difference in speed between day and night and a spearman’s rank correlation test was calculated to show the correlation for the rest.

Lastly, the speed within and without protected areas was considered for tagged African savannah elephants. Using QGIS software, GPS coordinates were transformed to delineate locations falling inside and outside designated protected zones. Timestamps across these segmented areas were harmonised and speed calculations were subsequently performed based on the GPS coordinates. A boxplot depicted the results and Wilcoxon rank sum test calculated the significance.

4 Results

4.1 Kernel Density Estimations

In Table 1., Kernel Density Estimation reveals striking variability in the spatial usage patterns among 10 individual adult male African Savannah elephants. KDE was employed with the ad hoc smoothing parameter (href) to analyse the home ranges and spatial use. The analyses are presented at two distinct confidence levels: 50% and 95%, measured in meters^2, presented on Figure 2.. The 50% confidence interval represents the core home range, reflecting the primary area where an individual elephant is most likely to be found. The 95% confidence interval defines the broader habitat use, encompassing the wider areas frequented by the elephant. It was found that the broader habitat use and home-range for IR SAT 6208 (2922587.0m2 and 576297.9m2, respectively) is a lot larger than the other elephants. IR SAT 6209 has the smallest home range (21120.7 m2) and smallest total habitat use (191008.4 m2).

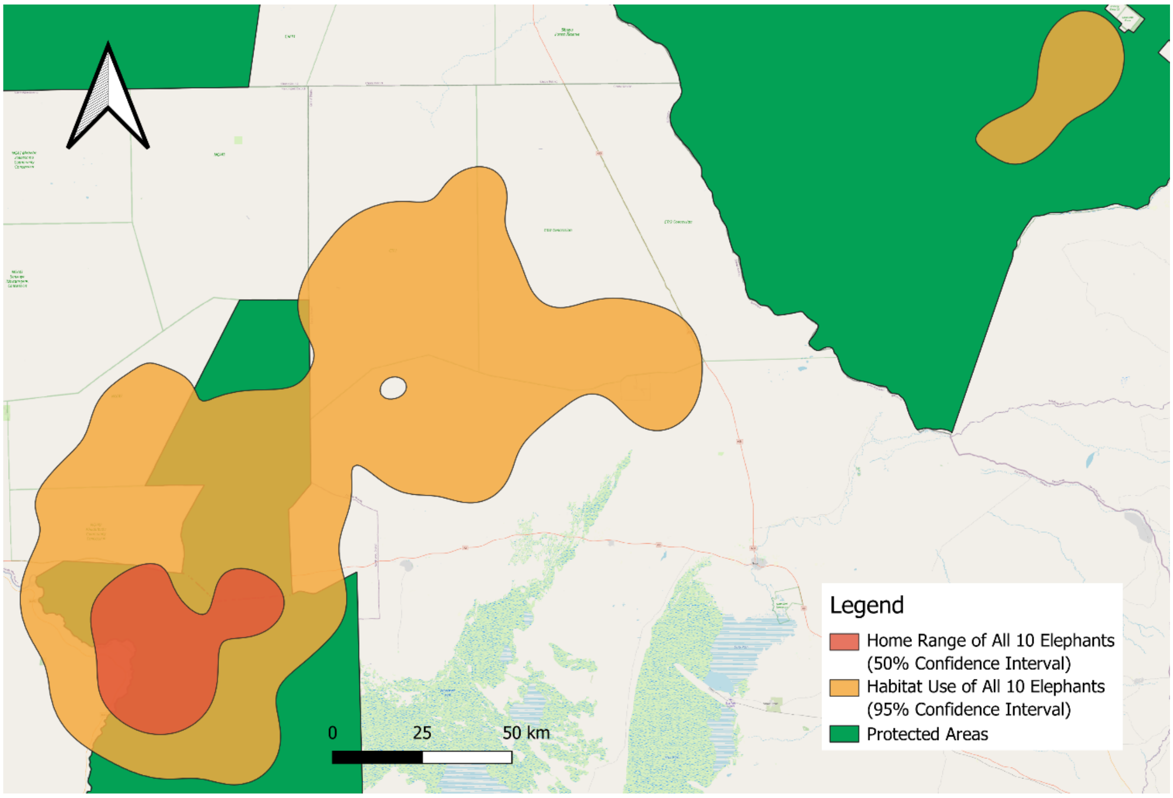

Figure 2. visualisation of the Kernel Density Estimation (KDE) for all 10 adult male African savannah elephants at 50% (red) and 95% (orange) confidence intervals.

Table 1. Kernel density estimation (KDE) of each individual 10 adult male African savannah elephants at 50% and 95% confidence intervals using the ad hoc smoothing parameter (href). The areas are calculated in m^2.

Individual	Kernel Density Estimation at 50% (m^2)	Kernel Density Estimation at 95% (m^2)
IR SAT 6207	67712.0	441867.5
IR SAT 6208	576297.9	2922587.0
IR SAT 6209	21120.7	191008.4
IR SAT 6210	33935.3	238710.9
IR SAT 6211	46826.5	256529.1
IR SAT 6212	123024.2	751151.6
IR SAT 6213	32090.9	402591.8
IR SAT 6214	56780.1	469369.4
IR SAT 6215	61338.5	645400.3
IR SAT 6216	152075.5	923998.1
All Individuals	160890.1	1501758.0

4.2 Habitat Selection and Compositional Analysis

The compositional analysis and habitat selection matrices presented in Table 2. offer key insights into the preferences of African Savannah elephants for different types of land cover. Figure 3. provides a visualisation of habitat utilisation, indicating that the elephants' actual habitat use at both 50% and 95% confidence intervals diverges markedly from the available land composition within the study area. When the available habitat is compared to the habitat the elephants utilised, there is a clear and similar selection of habitat by the elephants at both the 95% and 50% confidence interval for home range (Figure 3.). Table 2. shows avoidance/selection ranking for each of the habitats. The selection was the same for both the 95% and 50% confidence intervals. The three habitats that was most selected for were, Shrub/Scrub in PA, Roads in PA and Roads. The three habitats that were most avoided were Crops in PA, Crops and Bare Ground.

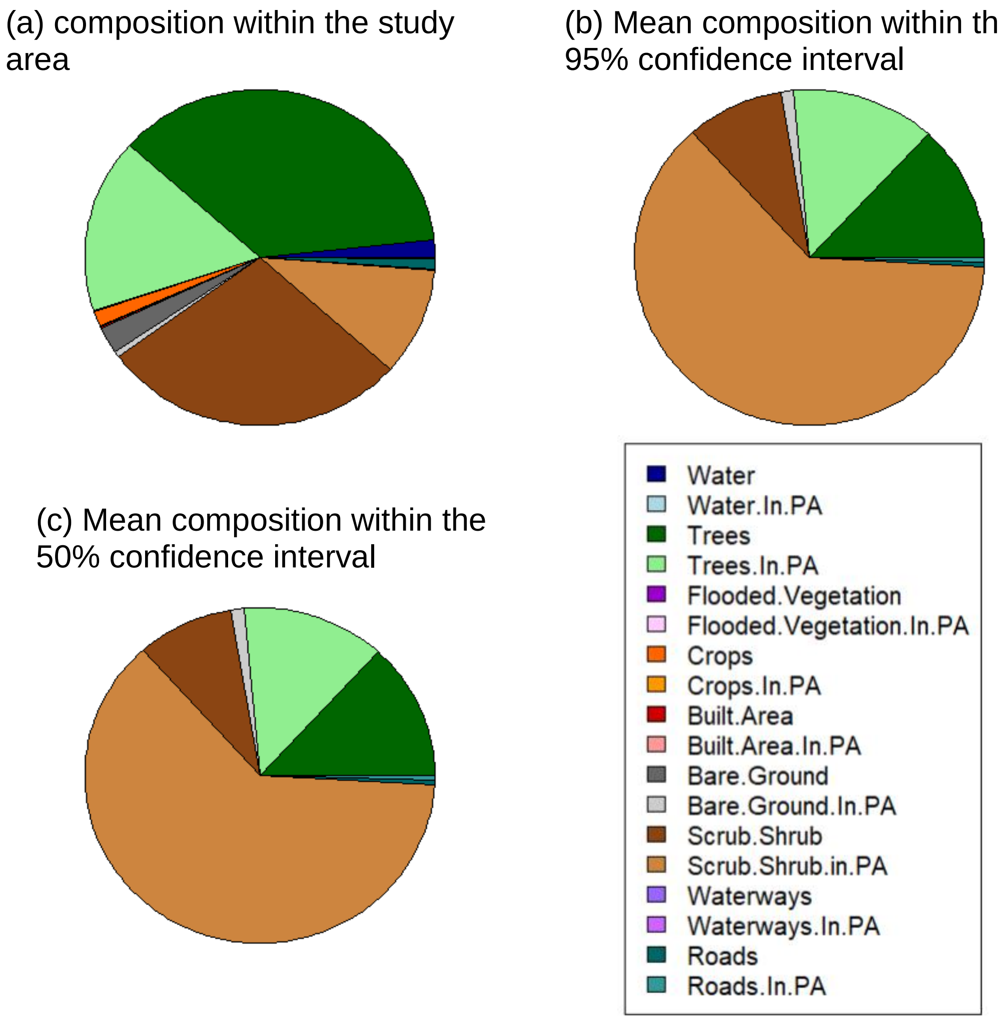

Figure 3 (a-c). a) Pie chart of land composition available within the study area utilised by all 10 collared adult male African savannah elephants, land type is divided into nine habitat types within and without protected areas (PA), **b)** and **c)** pie charts showing actual habitat utilised by the 10 collared adult male African savannah elephants at 50% and 95% confidence intervals

Table 2. habitat selection ranking matrices for two distinct compositional analyses (a and b). The presence of the "+" or "-" symbol indicates whether the row habitat was ranked higher (+) or lower (-) than the column habitat, indicating a greater or lesser degree of habitat selection. The plus or minus sign is tripled (+++) in cases where the pairwise difference was found to be statistically significant ($p < 0.05$). The ranking of row habitats is determined based on the frequency of higher rank places, denoted as either "+" or "++". A rank of 1 indicates the highest level of selection, while a rank of 18 indicates the highest level of avoidance.

Table 2.

Row Habitats	W	WPA	T	TPA	FV	FVPA	C	CPA	BA	BAPA	BG	BGPA	S	SPA	Wa	WaPA	R	RPA	RANK
	Column Habitats																		
(a) Full habitat use (95% confidence interval) within																			
Water (W)	0	–––	–––	–––	–––	+	+++	+++	+	+++	+++	+	–––	–––	–––	–	–––	–––	11
Water in PA (WPA)	+++	0	+	–	+	+++	+++	+++	+++	+++	+++	+++	–	–––	+	+++	–	–––	6
Trees (T)	+++	–	0	–––	+	+++	+++	+++	+++	+++	+++	+++	–––	–––	–	+	–––	–––	8
Trees in PA (TPA)	+++	+	+++	0	+++	+++	+++	+++	+++	+++	+++	+++	+	–––	+	+++	–	–––	5
Flooded Vegetation (FV)	+++	–	–	–––	0	+	+++	+++	+++	+++	+++	+	–––	–––	–––	+	–––	–––	9
Flooded Vegetation in PA (FVPA)	–	–––	–––	–––	–	0	+	+++	+	+++	+++	+	–––	–––	–––	–	–––	–––	12
Crops (C)	–––	–––	–––	–––	–––	–	0	+	–	–	–	–	–––	–––	–––	–––	–––	–––	17
Crops in PA (CPA)	–––	–––	–––	–––	–––	–––	–	0	–––	–––	–	–	–––	–––	–––	–––	–––	–––	18
Built Area (BA)	–	–––	–––	–––	–––	–	+	+++	0	+++	+	+	–––	–––	–––	–––	–––	–––	13
Built Area in PA (BAPA)	–––	–––	–––	–––	–––	–––	+	+++	–––	0	+	–	–––	–––	–––	–––	–––	–––	14
Bare Ground (BG)	–––	–––	–––	–––	–––	–––	+	+	–	–	0	–	–––	–––	–––	–––	–––	–––	16
Bare Ground in PA (BGPA)	–	–––	–––	–––	–	–	+	+	–	+	+	0	–––	–––	–	–	–––	–––	15
Scrub/Shrub (S)	+++	+	+++	–	+++	+++	+++	+++	+++	+++	+++	+++	0	–––	+	+++	–––	–––	5
Scrub/Shrub in PA (SPA)	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	0	+++	+++	+++	+++	1
Waterways (Wa)	+++	–	+	–	+++	+++	+++	+++	+++	+++	+++	+	–	–––	0	+++	–	–––	7
Waterways in PA (WaPA)	+	–––	–	–––	–	+	+++	+++	+++	+++	+++	+	–––	–––	–––	0	–––	–––	10
Roads (R)	+++	+	+++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	–––	+	+++	0	–––	3
Roads in PA (RPA)	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	–––	+++	+++	+++	0	2
(b) Core home -range (50% confidence interval) within																			
Water (W)	0	–––	–––	–––	–––	+	+++	+++	+	+++	+++	+	–––	–––	–––	–	–––	–––	11

Water in PA (WPA)	+++	0	+	−	+	+++	+++	+++	+++	+++	+++	+++	−	−−−	+	+++	−	−−−	6
Trees (T)	+++	−	0	−−−	+	+++	+++	+++	+++	+++	+++	+++	−−−	−−−	−	+++	−−−	−−−	8
Trees in PA (TPA)	+++	+	+++	0	+++	+++	+++	+++	+++	+++	+++	+++	+++	−−−	+	+++	−	−−−	4
Flooded Vegetation (FV)	+++	−−−	−	−−−	0	+	+++	+++	+++	+++	+++	+	−−−	−−−	−−−	+	−−−	−−−	9
Flooded Vegetation in PA (FVPA)	−	−−−	−−−	−−−	−	0	+	+++	+	+++	+++	+	−−−	−−−	−−−	−	−−−	−−−	12
Crops (C)	−−−	−−−	−−−	−−−	−−−	−	0	+	−−−	−	−	−	−−−	−−−	−−−	−−−	−−−	−−−	17
Crops in PA (CPA)	−−−	−−−	−−−	−−−	−−−	−−−	−	0	−−−	−−−	−	−	−−−	−−−	−−−	−−−	−−−	−−−	18
Built Area (BA)	−	−−−	−−−	−−−	−−−	−	+++	+++	0	+++	+	+	−−−	−−−	−−−	−−−	−−−	−−−	13
Built Area in PA (BAPA)	−−−	−−−	−−−	−−−	−−−	−−−	+	+++	−−−	0	+	−	−−−	−−−	−−−	−−−	−−−	−−−	14
Bare Ground (BG)	−−−	−−−	−−−	−−−	−−−	−−−	+	+	−	−	0	−	−−−	−−−	−−−	−−−	−−−	−−−	16
Bare Ground in PA (BGPA)	−	−−−	−−−	−−−	−	−	+	+	−	+	+	0	−−−	−−−	−−−	−	−−−	−−−	15
Scrub/Shrub (S)	+++	+	+++	−−−	+++	+++	+++	+++	+++	+++	+++	+++	0	−−−	+	+++	−−−	−−−	5
Scrub/Shrub in PA (SPA)	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	0	+++	+++	+++	+++	1
Waterways (Wa)	+++	−	+	−	+++	+++	+++	+++	+++	+++	+++	+++	−	−−−	0	+++	−	−−−	7
Waterways in PA (WaPA)	+	−−−	−−−	−−−	−	+	+++	+++	+++	+++	+++	+	−−−	−−−	−−−	0	−−−	−−−	10
Roads (R)	+++	+	+++	+	+++	+++	+++	+++	+++	+++	+++	+++	+++	−−−	+	+++	0	−−−	3
Roads in PA (RPA)	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	−−−	+++	+++	+++	0	2

4.3 *Speed of Movement Within and Without Protected Areas*

A slight difference in the median speeds exhibited by the 10 adult male African savannah elephants in both protected and unprotected areas is visualised (Figure 4). This observation implies that there are modest behavioural adjustments made by the elephants in response to varying degrees of human activity and environmental security.

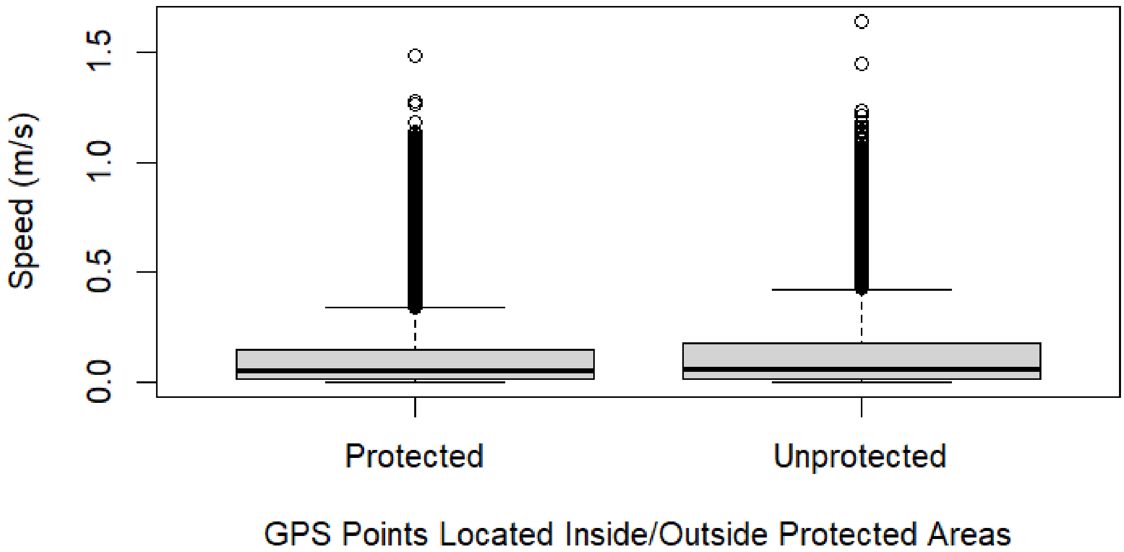

Figure 4. Comparative analysis of speed (m/s) of 10 adult male African savannah elephants inside and outside of protected areas.

The median speeds in Figure 4 were found to be 0.056 m/s and 0.057 m/s for protected and unprotected areas, respectively, indicating a slight increase in speed in unprotected areas. The interquartile range also exhibited a difference between protected (0.13) and unprotected (0.16) areas. The Wilcoxon rank sum test with continuity correction revealed a statistically significant difference in speed between the protected and unprotected areas ($W = 412263539$, p-value < 0), supporting the alternative hypothesis that the true location shift is not equal to 0.

4.4 *Speed During Day and Night*

There were distinct fluctuations in the speed of the elephants throughout the day (figure 6), with subtle but statistically meaningful differences between daytime and nighttime activities.

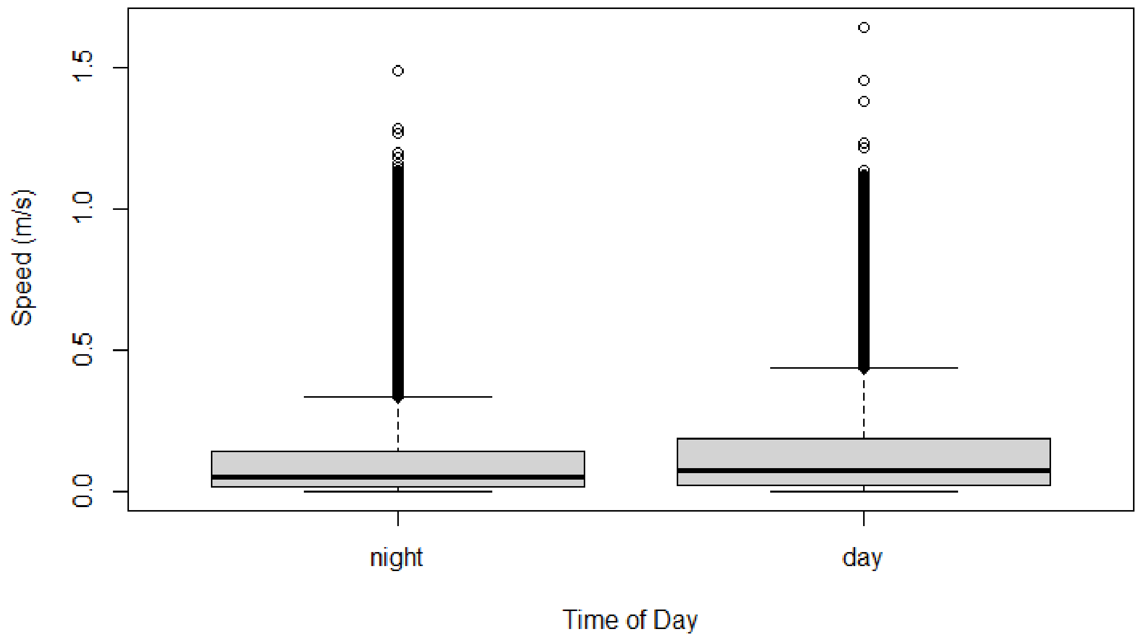

Figure 5. Comparison of combined speed (m/s) of 10 adult male African savannah elephants during day (between 6am and 6pm) and night (between 6pm and 6am) periods.

Figure 5 illustrates the distribution of combined speed measurements across day and night periods of 10 adult African savannah elephants. The mean for the day was 0.14m/s and the mean for the night was 0.12m/s. However, the median speeds of day and night were 0.07m/s and 0.05m/s, respectively. The interquartile range was 0.13 for the night and 0.17 for the day. The Wilcoxon rank sum test reported a statistically significant difference in speed between day and night ($W = 459{,}526{,}416$, p-value > 0)

4.5 Speed During Different Hours of Day

Figure 6 highlights distinct fluctuations in speed throughout the day, possibly reflecting the elephants' adaptive behavioural rhythms in response to environmental conditions and activity levels.

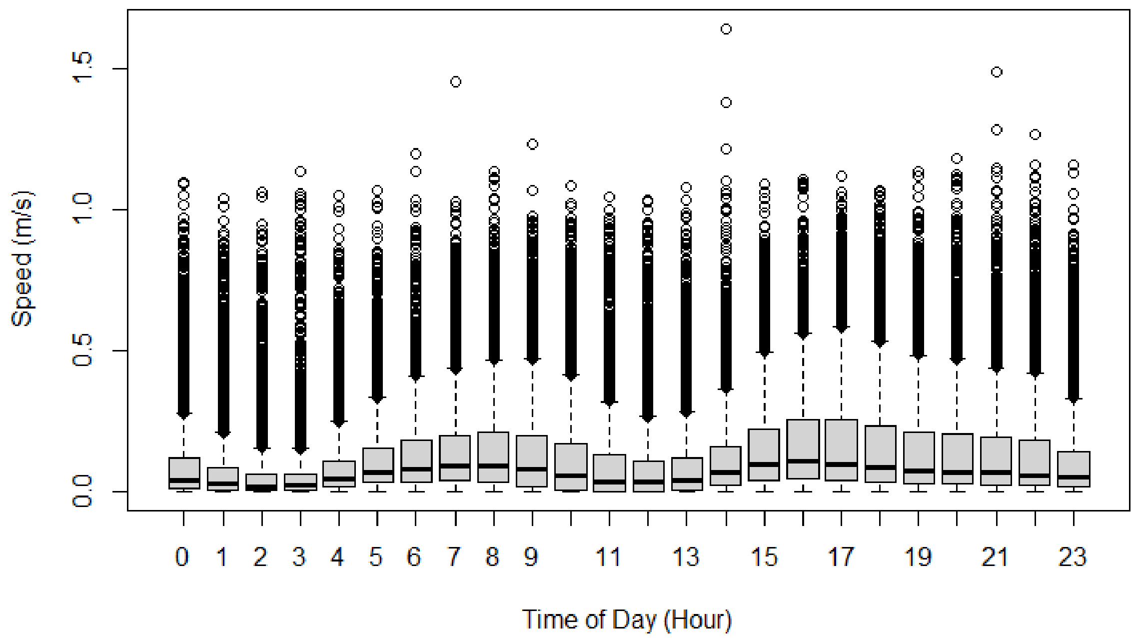

Figure 6. Variation in combined speed (m/s) of 10 adult male African savannah elephants across different hours of the day.

The boxplot Figure 6 shows a clear pattern of fluctuation in combined speed of the 10 elephants in relation to the time of day. The median speeds exhibit a noticeable increase starting from the early morning at 0.04m/s at hour 4, then reaching a peak at 0.09m/s at hour 8, then a slight dip at hour 12tot 0.03m/s, another peak is reached at 0.11m/s at hour 16, after that the speed is gradually decreasing towards the night (hour 23 at 0.05m/s). The interquartile ranges, representing the spread of the data, follow a similar trend with the highest values observed during the late afternoon hours 16 to 18 with ranges at 0.21, 0.22 and 0.20, respectively. The shortest IQR found was at hour 3 with a range of 0.06. The Spearman's rank correlation test showed a statistically significant, but weak, positive correlation between speed and hour (rho = 0.144 and a p-value < 0).

4.6 Speed During Different Months

The following results investigate the speed variations among 10 adult male African savannah elephants over different months.

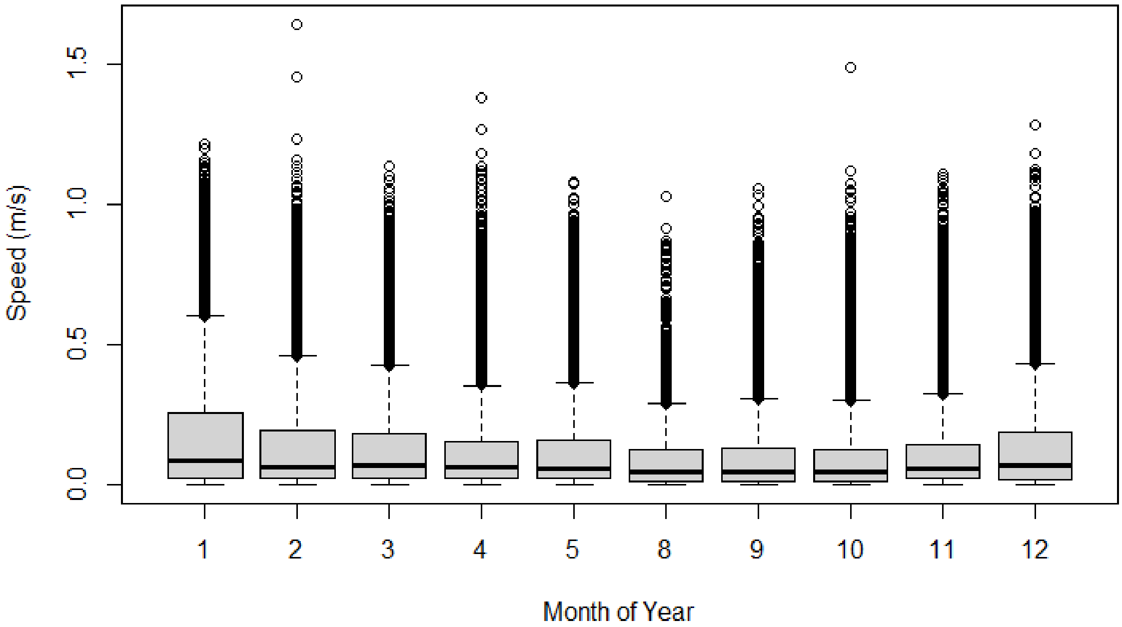

Figure 7. Combined speed (m/s) of 10 adult male African savannah elephants compared to different months of the year.

The boxplot in Figure 7 visualises the distribution of combined speed (m/s) of 10 adult African savannah elephants over 10 months (August 2022 to May 2023), June was removed as there was only one day of data. The median values show that the speed is higher during the beginning of the year, specifically in January, month 1 (0.09 m/s), and shows a decreasing trend towards the middle of the year, reaching its lowest point in August, month 8 (0.05 m/s). Additionally, the interquartile range (IQR) reveals the spread of the data around the median, with the highest IQR observed in January (0.23) and the lowest in August (0.11). The results of the Spearman's rank correlation test indicate a statistically significant negative correlation between speed and month (rho = -0.07045441, p-value < 0). This suggests that there is an inverse relationship between the two variables, though this relationship is weak.

4.7 Speed During Different Temperatures

The following section investigates how varying temperature conditions (ranging from 14°C to 49°C) influence the speed of 10 adult male African savannah elephants, highlighting both median speeds and variations within interquartile ranges.

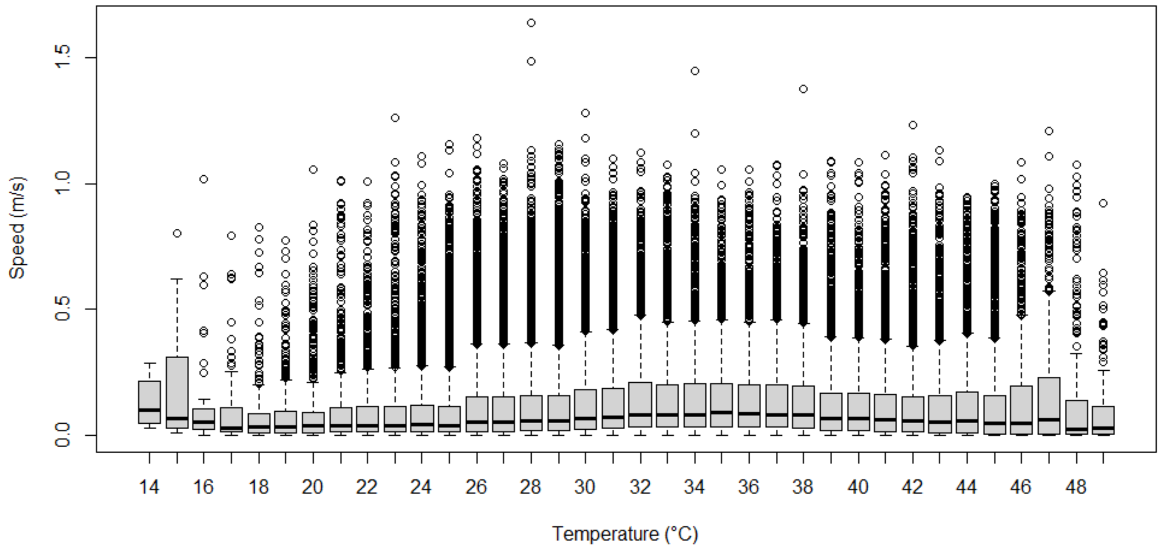

Figure 8. Variation in combined speed (m/s) of 10 adult male African savannah elephants across different temperature ranges (14°C to 49°C).

The median speed shows a complex pattern across the studied temperature range (14°C to 54°C) in Figure 8. The median speed declines from 14°C to 17°C with speeds form 0.10m/s at 14°C down to 0.03m/s at 17°C, the speed then stabilises and gradually increases until 35°C with 0.09m/s, this is followed by a decrease until 46°C with 0.05m/s, the speed then spikes at 47°C (0.06m/s) and decreases dramatically at 48°C and 49°C (0.03m/s for both temperatures). The interquartile range generally exhibited fluctuations within a relatively confined range from 0.08 to 0.23 across the majority of temperatures. Notable exceptions include a considerable increase in range at 14°C and 15°C with ranges of 0.12 and 0.25, respectively and then another increase between 46°C and 47°C with a range of 0.19 and 0.23, respectively, and followed by a sudden decrease at 48°C to 49°C (0.14 and 0.11, respectively). The Spearman's rank correlation test indicated a statistically significant, but weak, positive correlation between speed and temperature (rho = 0.0439, p-value < 0).

5 Discussion

This study provides insights into the intricate relationship among spatial use, habitat selection and movement dynamics in adult male African Savannah elephants. The analysis of KDE demonstrates a significant variation in the size of core home ranges and broader habitat utilisation across individual elephants. This highlights the necessity for adaptable conservation strategies that take into account the unique characteristics of each elephant's mobility patterns. The difference seen between the composition of available land and the actual use of habitats, underscores the discerning behaviour of elephants with regards to their selection of habitat types. This choice is consistent with specific habitat types, particularly Shrub/Scrub in Protected Areas and Roads, while avoiding others such as Crops and Bare Ground. As a result, this has significant implications for land management and the reduction of human-elephant conflict. Moreover, our research outcomes validate slight yet statistically noteworthy differences in the speeds of elephants both within and outside designated prtotected areas. These distinctions perhaps indicate adaptive behavioural changes in reaction to human presence and the level of environmental protection. Diurnal and seasonal variations in movement speed are also evident, indicating that elephants are not solely responding to human-altered environments, but are also adjusting their behaviours in a multifaceted manner in response to natural environmental factors, such as temperature and diurnal cycles. Therefore, the findings support the need for a comprehensive understanding of elephant ecology, which is crucial for the development of more efficient conservation approaches.

The spatial use and home ranges of African savannah elephants have long been subjects of interest, especially with the increased application of KDE to wildlife studies. KDE provides a nuanced lens through which animal movement and habitat utilisation can be assessed, particularly in relation to available resources. The use of KDE in this study demonstrates the considerable variation in spatial use patterns among 10 individual adult male African Savannah elephants (refer to Appendix 2. for the individual visualisations). The huge home range of IR SAT 6208, especially when contrasted against the comparatively small range of IR SAT 6209, may suggest changes in resource distribution, according to our analysis of these KDE values. Disparities in spatial utilisation can be attributed to changes in water availability, specifically during the dry season as opposed to the rainy season (Bastille-Rousseau et al., 2020). The observed patterns of movement are consistent with the existing knowledge that animals, including elephants, tend to travel greater distances to locate water sources during seasons of low rainfall (Bastille-Rousseau et al., 2020). Furthermore, it is evident that elephants' actual habitat use at both confidence intervals differs significantly from the available land composition within the study area, highlighting the selective nature of their spatial behaviour. The divergence seen could potentially be attributed to the regional and temporal variability of resources, as well (Ngene et al., 2010). For example, it was observed that shrub/scrub habitats within protected areas (PA) and roads within PAs were the most favoured environments. Conversely, crops within PAs, crops, and bare ground were found to be mostly unpreferred by the subject of study. These decisions could be influenced by factors such as the availability of food, the presence of potential threats and ease of movement (Ngene et al., 2010). However, as the data was collected during the same time this difference of some individuals greater range could also be explained by the fact the individuals with the smaller ranges were mostly in protected areas thus limited by the constraint of the protected area (De Boer et al., 2000). The KDE analysis showed significant differences in the spatial behaviour of individual male elephants. For instance, IR SAT 6208 exhibited a notably larger home range compared to others. This extensive range may imply that IR SAT 6208 travelled great distances, possibly in search of another protected area, eventually reaching Hwange National Park in Zimbabwe. Additionally, the elephant's larger and more diverse habitat use could make it more likely to engage in crop-raiding activities.

The relationship between crop-raiding by elephants and the role of protected areas in elephant conservation presents a complex relation influenced by various human and environmental factors. The movement patterns of adult male African savannah elephants further reveal intriguing insights into their adaptive behaviours in response to human activities and environmental conditions (Graham et al., 2009). For instance, in this study there is a significant difference in the elephants' speed of movement within and outside of protected areas, suggesting that elephants adjust their behaviour depending on the level of human activity and environmental security they encounter. The individual calculations (appendix 5) show that certain individuals have a more significant difference, this may be due to these individuals spending a greater amount of time in unprotected areas. The significance of protected areas in the conservation of elephants should not be ignored. Elephants find a degree of security in these regions, while a significant portion of their habitat is situated beyond the boundaries of these protected areas (Wall et al., 2021). These results support past studies that show male elephants can recognise different levels of threat and adjust their behaviour in accordance with those perceptions (Wittemyer et al., 2008). The understanding of this concept holds significant importance in the development of effective conservation strategies and the reduction of human-elephant conflict. Such conflicts frequently arise when male elephants wander beyond designated protected zones in pursuit of mates and resources (Gara et al., 2021). The issue of crop-raiding by elephants is a significant source of conflict between human populations and wildlife. In response, a range of efforts have been implemented to deter this behaviour. A few examples of deterrents are chilli pepper as an olfactory deterrent (Noga et al., 2015) and beehive fences, which have demonstrated diverse levels of effectiveness (King et al., 2011; Noga et al., 2015). Further research has indicated that the occurrence of crop raiding by male elephants is impacted by their social networks and life history milestones (Chiyo et al., 2012).

One possible hypothesis that has been proposed how elephants are mitigating the effects of habitat fragmentation is to utilise human-constructed roads as a means of facilitating more efficient migration between fragmented areas. The theory is supported by the compositional analysis. It appears that their preference lies towards Shrub/Scrub vegetation in protected areas (PAs), as well as roads within PAs and roads in general (as seen in Table 2). This observation is consistent with recent academic findings indicating that elephants, particularly those inhabiting densely forested areas, have a preference for utilising man-made and unpaved roads for movement, predominantly during nighttime hours (Scalbert et al., 2023). One plausible rationale for this choice may be attributed to the fact that roads provide easier and more energy-efficient travel pathways, particularly when moving large distances within their vast home ranges. Contrarily to what was expected, the elephants did not prefer tree habitat, although trees are the most abundant habitats available. Nevertheless, the lack of a preference for trees could suggest an alternative adaptive approach adopted by elephants in this area, potentially to the comparatively low poaching rates and therefore lower necessity to seek canopy shelter (Graham et al., 2009). Although the overall patterns provide a comprehensive understanding of habitat selection and spatial utilisation, it is imperative to acknowledge the presence of individual variations among the elephants (see Appendix 3 and 4). As an example, it is observed that elephant 6216 exhibits a pronounced inclination towards tree environments, which deviates from the prevailing pattern in this study. However, when looking at the individual habitat use most elephants do have a preference to trees habitats outside of protected areas, which may suggest that the elephants do use trees as cover in areas which they may feel threatened (see Appendix 3). The observed variance in habitat and road usage choices may potentially be attributed to factors such as age, social standing or past experiences.

The African savannah elephant is one of many animals whose conservation efforts are greatly aided by the existence of corridors. According to Jachowski et al. (2013), the presence of these narrow strips of land have an important function in allowing the movement of animals between habitats that are fragmented. As there is a distinct selection of habitats, it is implied that not all available areas are suitable for elephants, highlighting the need for carefully built corridors that connect these favoured habitats. The behaviour of elephants is significantly influenced by human activities and the consequent disturbances in corridors. The findings of Douglas-Hamilton et al. (2005) and Jones et al. (2012) indicate that these disruptions have resulted in a reduction in the utilisation of corridors and an increase in the occurrence of "streaking" behaviour. The term "streaking" describes an elephant's inclination to pass through an area quickly and unabated, possibly as an adaptive reaction to increased human activity or unfavourable environmental conditions. It is interesting to note that an elephant's tendency to use corridors or engage in streaking behaviour is correlated with its physiological state (Jachowski et al., 2013). The necessity of corridors is further supported by the elephants' speed of movement, which is dependent upon the conservation condition of the region and many environmental elements. For example, the observed differences in speed between regions with protective measures in place and those without, as well as fluctuations during different time periods, suggest that elephants exhibit adaptive behaviour in response to human presence and environmental factors. The presence of these subtle behaviours suggests that the design of corridors should include not only the spatial aspects, but also the time patterns of elephant movement.

This paper's findings illustrate subtle fluctuations in the speeds of adult male African savannah elephants, particularly within the context of the rainy and dry seasons. The data suggests that there is a tendency for speeds to be higher in the month of January, which could be linked to an increased level of activity to move (see for individual differences refer to Appendix 5,6 and 8). The variations in speed may be associated with the availability of resources such as temporary waterholes and fresh vegetation, which are more abundant during periods of rainfall, therefore increasing movement (Ngene et al., 2010). During periods of low precipitation, elephants have been observed to decrease their range and stay closer to permanent water sources (Ngene et al., 2010). This discovery provides additional support for the statement made by Douglas-Hamilton et al. (2005) on the significance of Makgadikgadi Pans in Botswana as a crucial ecosystem for these elephants, specifically in terms of nutrient accessibility during the dry season. In Individuals where this trend was not observed, could have been observed to expand their range and travel at higher velocities in order to locate essential resources, during the dry season (Osborn, 2004); or stayed within a smaller area during the rainy season due to the availability of and abundance of resources. Individuals with a larger range could be evidence to suggest that some elephants may be more vulnerable to climatic fluctuations due to their more extensive and varied areas of movement (see Appendix 2). Elephants also exhibit strong and consistent preferences for certain land cover types, avoiding areas like "Crops" and "Bare Ground," which might particularly have occurred during resource-scarce dry periods.

The influence of temperature on the movement speed of adult male African savannah elephants was examined, revealing a nuanced pattern of speed variations across a temperature range of 14°C to 49°C (Appendix 9.). It is important to acknowledge that the reported association between speed and temperature may be influenced by other underlying causes. Elephants may exhibit decreased speed at high temperatures because of energy conservation or to minimise the potential risks of overheating. This observation is supported by the data presented Appendix 7, where a decrease in elephant movement during the peak noon hours, when temperatures reach their highest, is seen. Likewise, the observed decrease in speed at lower temperatures may suggest sleep during lower temperatures, specifically around the second hour (Figure 6, Appendix 7). Therefore, the complex pattern implies that despite a slight correlation, temperature is one of many variables exerting influence on the speed of these elephants. These results correlate with prior studies that have demonstrated the multifaceted nature of elephant movement, which is influenced by a combination of environmental and anthropogenic influences (Owen-Smith et al., 2020; Roever et al., 2012; Bastille-Rousseau et al., 2020).

Musth in male African savannah elephants, which is defined by heightened sexual activity and increased aggression, was observed Elephant 6214. The elephant was captured on a camp trap deployed by Elephants for Africa, with obvious signs of musth (wet back legs and heavy discharge from his temporal glands). Using the satellite data, it be could seen that he then left the MPNP and ended up north of his location. The collar data showed a clear increase in speed (see Appendix 8), together with a noticeable change in patterns of range and spatial use changes in locomotion and speed, and thus it can be concluded that Elephant 6214 was in musth from the beginning of January 2023 until approximately mid-March 2023. His homerange at the 95% confidence interval illustrated two distinct and large areas, indicating that the elephant exhibited more movement while in musth (see Appendix 2). The behaviour of "streaking" observed during musth likely represents a search for mates, a theory that is further supported by the elephant's travel towards the north. This direction is less frequently chosen by other males in the study, who predominantly moved towards the east, northeast, or slightly northwest.

The distinctive directional preference seen in Elephant 6214 suggests that it was actively seeking female, as there are few females in the MPNP (Evans, 2019). Furthermore, this particular individual had much greater speeds in areas without protection (see Appendix 5) and maintained an average speed that was noticeably higher compared to the other collared elephants (see Appendices 6-9).

While the study offers comprehensive insights into the spatial use, movement dynamics, and habitat selection of adult male African Savannah elephants, several limitations should be acknowledged in the discussion. Firstly, the study relies heavily on KDE for analysis, which, although nuanced, may not fully capture all factors influencing elephant movement. Another limitation within the KDE analysis may be the ad hoc smoothing parameter, href. The smoothing value for href is determined based on the distribution of points. However, it has been shown that this parameter may over smooth multimodal distributions that arise from clustered sites, leading to an overestimation of home range sizes (Gimenez et al., 2005). The study's sample size is also quite small so the findings must be interpreted with care as this may not be a good representative for the entire population within the MPNP. Additionally, individual variations among elephants, such as Elephant 6214 showing unique behaviours during musth, suggest that the results may not be universally applicable across all individuals. The study took into account seasonal factors like as rainfall and temperature, but other environmental variables may also impact elephant movement. The collected temperatures revealed anomalies, reaching a maximum value of 54°C, (Appendix 9). It was evident after speaking with the manufacturer that these may be caused by either equipment failure or the elephant itself becoming very hot. Furthermore, temperatures within MPNP rarely exceed 45°C. The study suggests that adaptive behavioural changes are influenced by the presence of humans and protected areas. However, it is important to acknowledge that there may be more elements that have not been thoroughly investigated, which could also play a role in determining these behaviours.

6 Conclusion

In conclusion, this study provides significant observations on the intricate relationship of spatial use, habitat preference, and movement behaviours in adult male African Savannah elephants. The use of Kernel Density Estimation (KDE) revealed significant differences in the core home ranges, usage of habitats, and speed of elephants. These findings indicate that the movement patterns of individual elephants are distinct and impacted by a multitude of biological, environmental, and anthropogenic factors. The elephants exhibited selective behaviour when choosing their habitats. These findings hold significant implications for the development of conservation strategies and land management practises aimed at mitigating human-elephant conflict.

The investigation also exposed subtle adaptive behaviours in elephants, as indicated by the small but statistically significant variations in their movement speeds both inside and outside designated protected areas, as well as in response to natural environmental conditions. These findings hold significant value in the development of more efficient and sophisticated conservation methods, particularly in relation to the establishment of wildlife corridors and the mitigation of human-elephant conflict.

Additionally, the study highlighted the significance of individual variability observed among elephants, emphasising the necessity for adaptable and localised conservation strategies. As an example, the behaviour exhibited by Elephant 6214 during its musth period exhibited higher speeds and larger territories, potentially driven by the pursuit of potential mates. This illustrates the intricate influence of behavioural states such as musth on spatial dynamics.

In conclusion, this study enhances our comprehension of elephant ecology and shows the importance of adaptable conservation policies grounded in evidence. These strategies should consider the intricate relationships between spatial utilisation, habitat preference, and migratory patterns exhibited by these magnificent creatures. It further stresses the need for a comprehensive and flexible strategy towards elephant conservation, which acknowledges the delicate relationship between elephants and their surrounding ecosystems, the need for wildlife to have access to unprotected lands and thus the continued need for viable human-elephant mitigation strategies to enable human-elephant coexistence.

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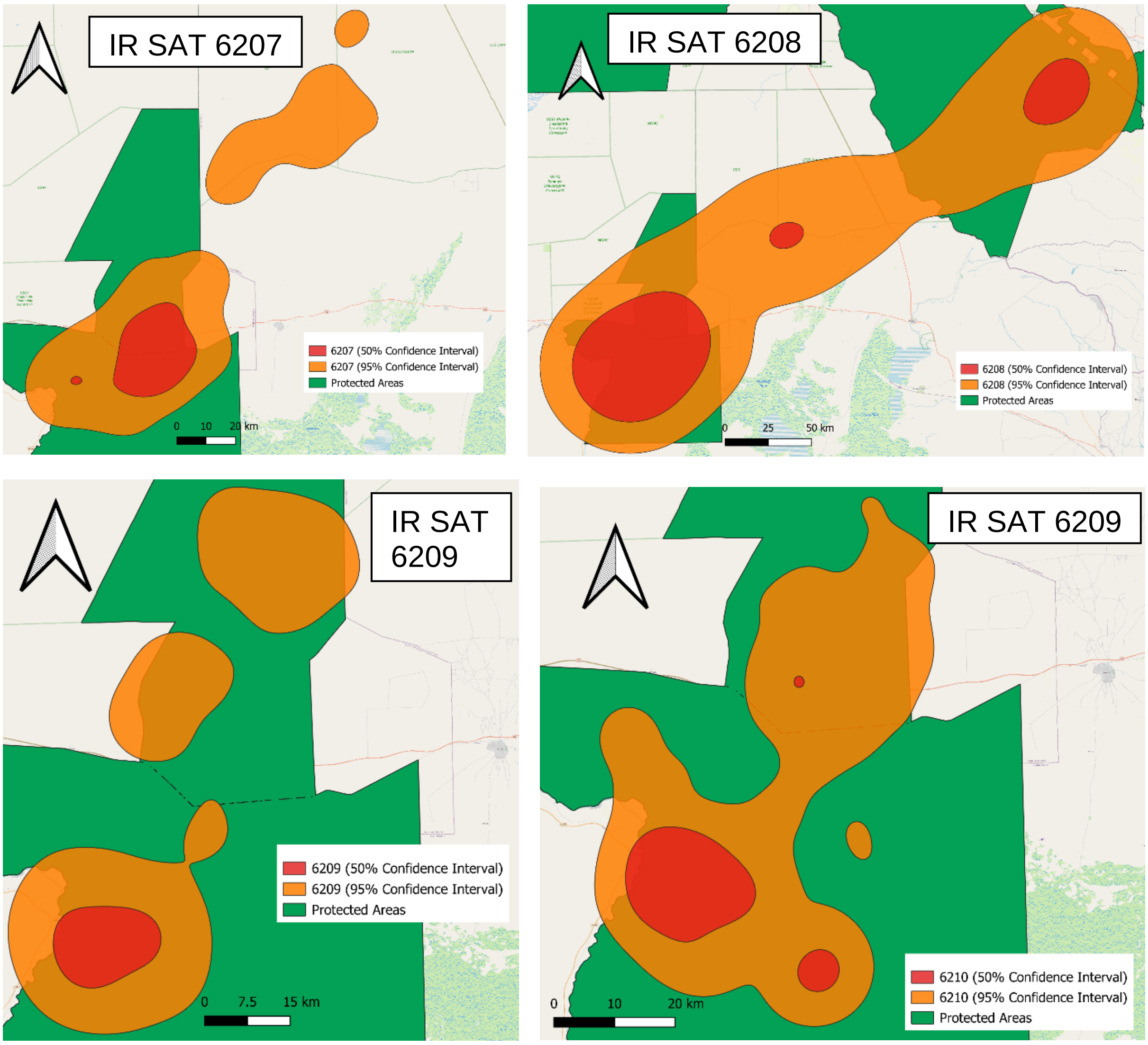
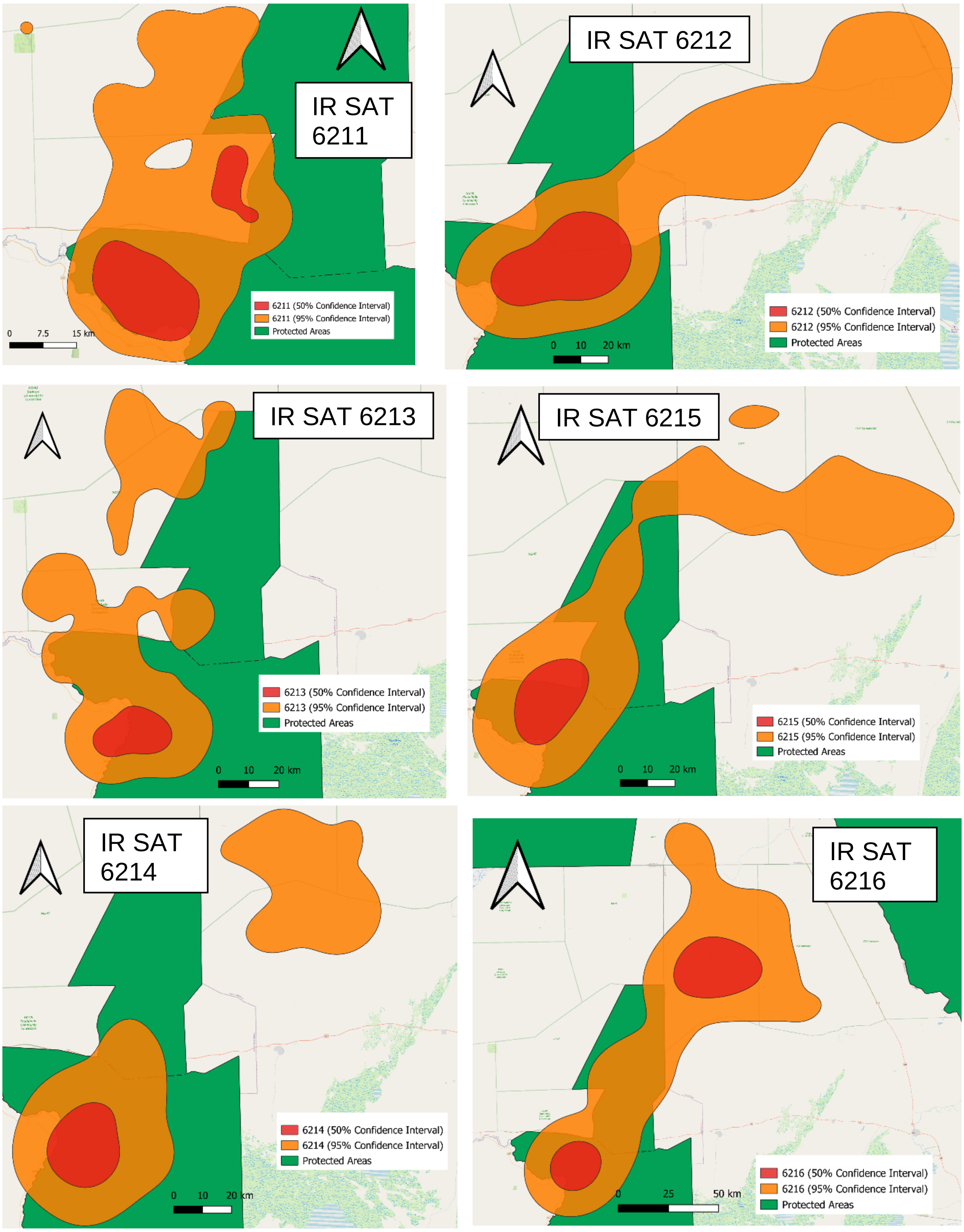
9 Appendices

Appendix 1. Collaring data of all 10 adult male African savannah elephants (*Loxodonta africana*). Elephants for Africa unpublished data.

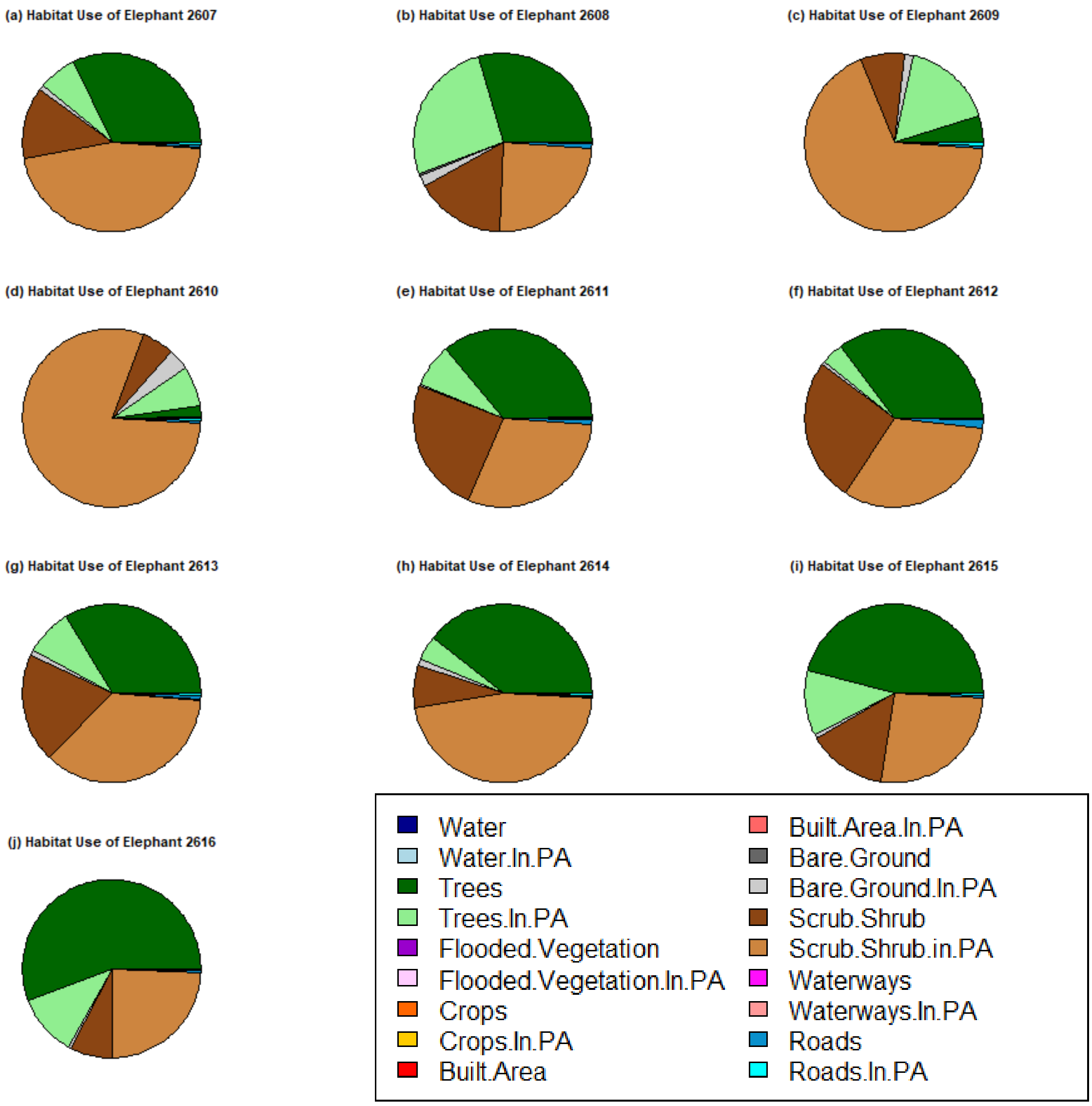
	1	2	3	4	5	6	7	8	9	10
Date of collaring	22/08/22	22/08/22	22/08/22	22/08/22	22/08/22	22/08/22	22/08/22	23/08/22	23/08/22	23/08/22
Time darted	09:16:00	10:03:00	11:49:00	12:44:00	13:34:00	15:06:00	15:43:00	08:54:00	09:55:00	10:55:00
Collar number	IR SAT 6210	IR SAT 6209	IR SAT 6214	IR SAT 6208	IR SAT 6213	IR SAT 6215	IR SAT 6211	IR SAT 6216	IR SAT 6212	IR SAT 6207
GPS S	-20.45458	-20.46482	-20.46266	-20.47514	-20.48219	-20.346	-20.35393	-20.34684	-20.32219	-20.31218
GPS E	24.59488	24.60646	24.58967	24.567203	24.5669	24.50847	24.49653	24.5713	24.60062	24.61863
Estmated age	36yr+	36yr+	36yr+	36+yr	36+yr	36+yr	36yr+	26-35yr	36yr+	26-35yr
Sex	M	M	M	M	M	M	M	M	M	M

Appendix 2. visualisation of the KDE for each of the 10 individual adult male African savannah elephants at 50% and 95% confidence intervals.

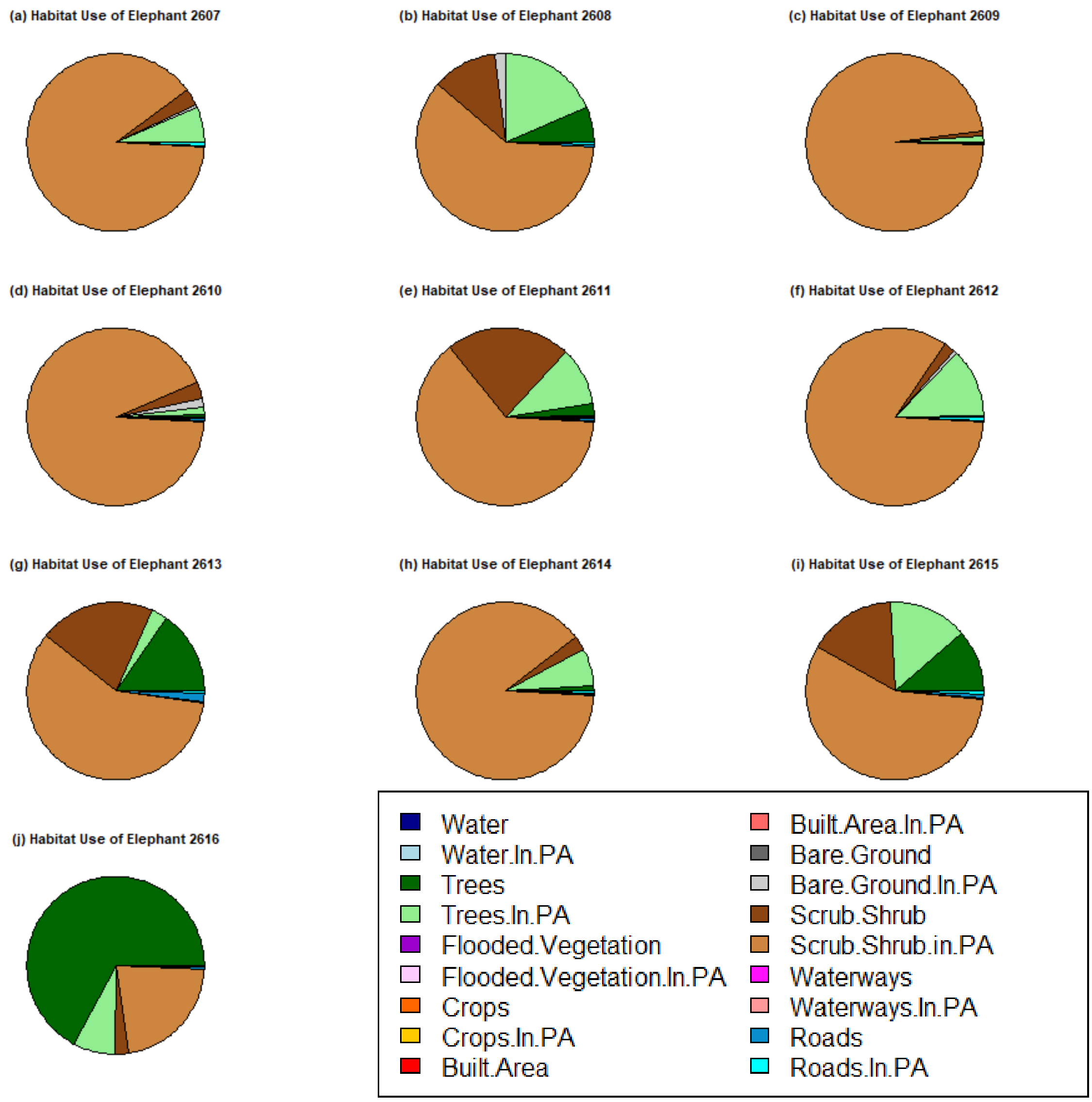



IR SAT 6211
6211 (50% Confidence Interval)
6211 (95% Confidence Interval)
Protected Areas
0 7.5 15 km
IR SAT 6212
6212 (50% Confidence Interval)
6212 (95% Confidence Interval)
Protected Areas
0 10 20 km
IR SAT 6213
6213 (50% Confidence Interval)
6213 (95% Confidence Interval)
Protected Areas
0 10 20 km
IR SAT 6215
6215 (50% Confidence Interval)
6215 (95% Confidence Interval)
Protected Areas
0 10 20 km
IR SAT 6214
6214 (50% Confidence Interval)
6214 (95% Confidence Interval)
Protected Areas
0 10 20 km
IR SAT 6216
6216 (50% Confidence Interval)
6216 (95% Confidence Interval)
Protected Areas
0 25 50 km

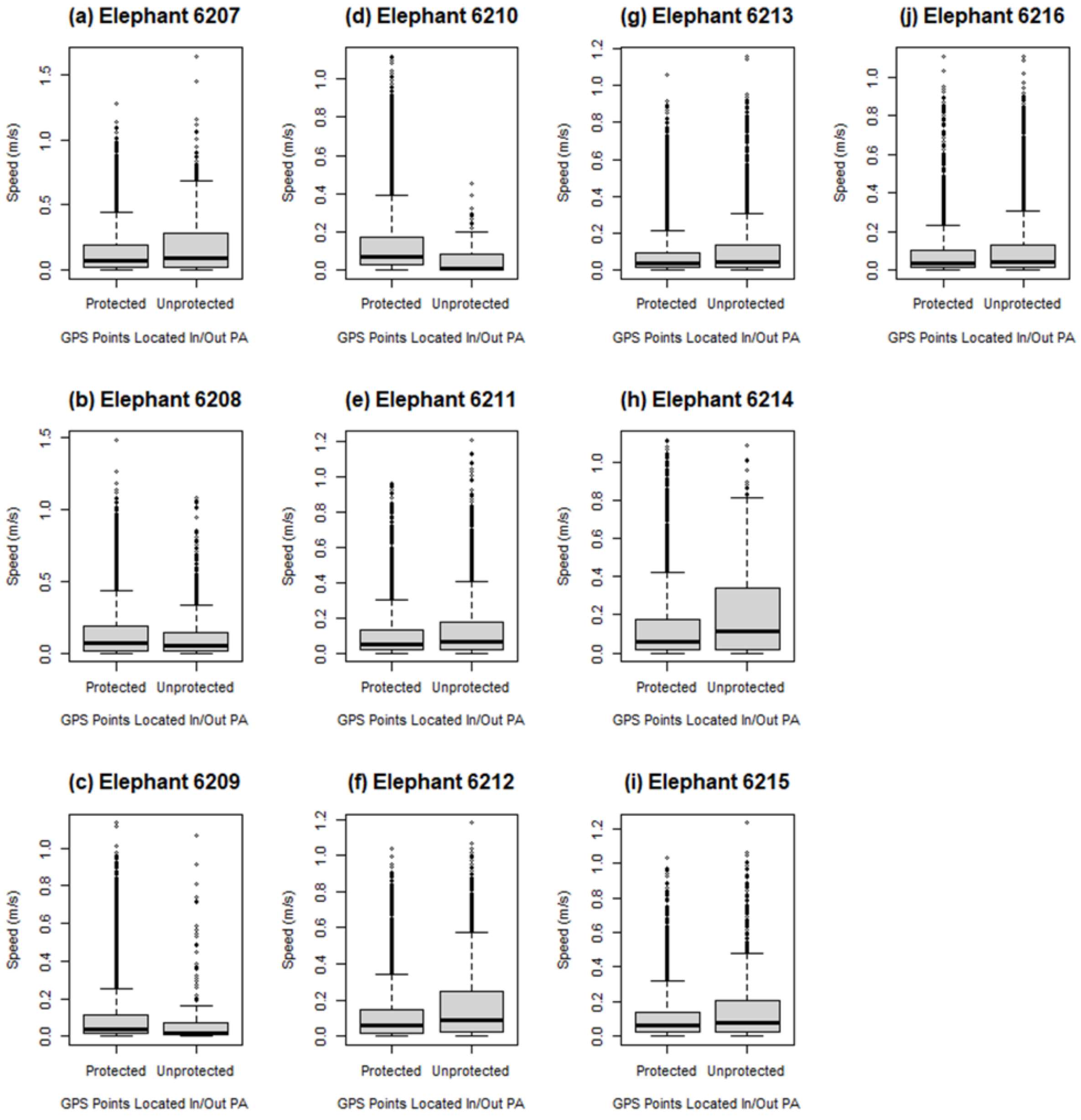
Appendix 3 (a-j). Pie charts showing actual habitat utilised by each individual collared adult male African savannah elephant within the study at 50% confidence interval, land type is divided into nine habitat types within and without protected areas (PA)



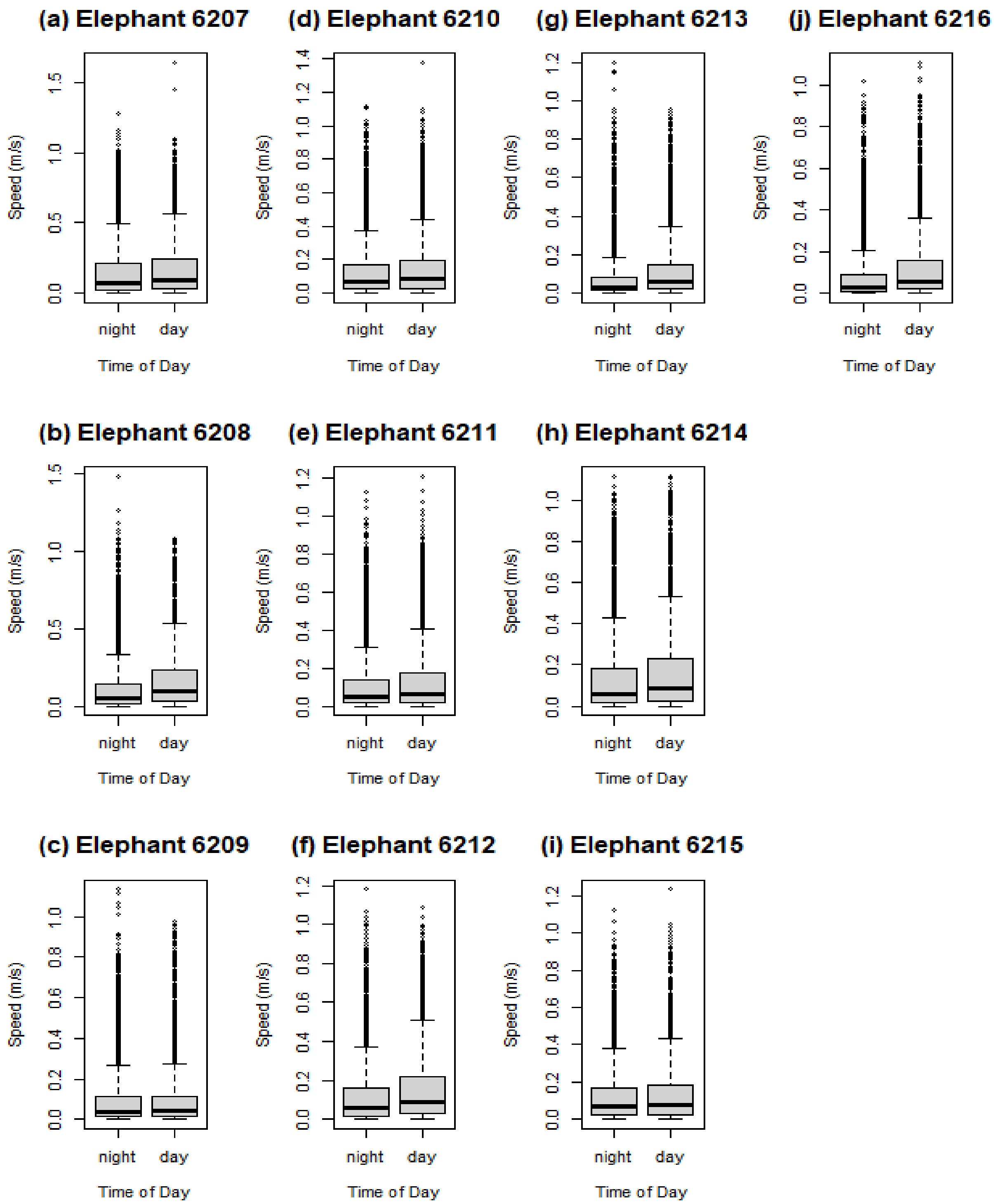
Appendix 4 (a-j). Pie charts showing actual habitat utilised by each individual collared adult male African savannah elephant within the study at 95% confidence interval, land type is divided into nine habitat types within and without protected areas (PA)



Appendix 5 (a-j). Movement speeds (m/s) in protected areas (PA) and unprotected areas for 10 different adult individual African savannah elephants (6207 to 6216). Elephants 6208, 6209 and 6210 exhibited higher median speeds in protected areas, while all others moved significantly faster in unprotected areas. The interquartile ranges also showed variations, such as the largest value of 0.32 in unprotected areas for Elephant 6214 and the smallest value of 0.07 in unprotected areas for Elephant 6209.

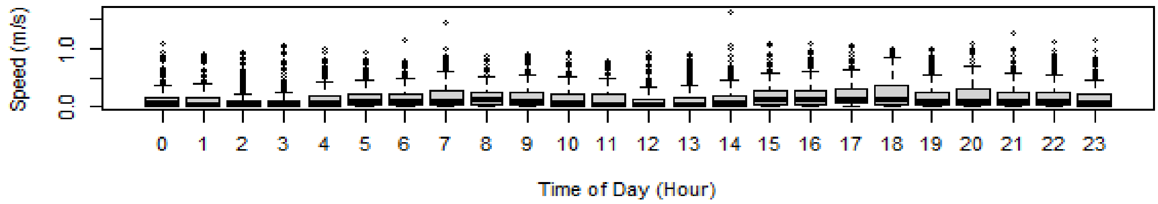


Appendix 6 (a-j). Speed (m/s) in 10 different adult individual African savannah elephants (6207-6212) compared to day and night periods. The median speeds consistently showed higher values during the day for the majority of the elephants, except for Elephant 6209 where the difference was minimal. Interquartile range (IQR), representing the dispersion of speed, also varied among the elephants, often showing a broader spread during the day

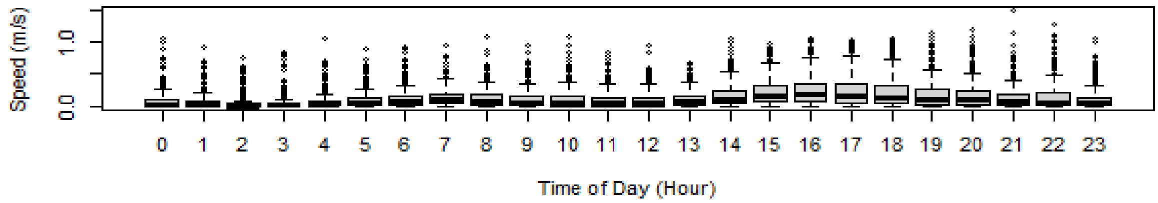


Appendix 7 (a-j). Analysis of speed (m/s) in 10 different adult individual African savannah elephants (6207-6212). The median speeds are typically lowest during the early hours of the night and increased in speed during early morning and late afternoon.

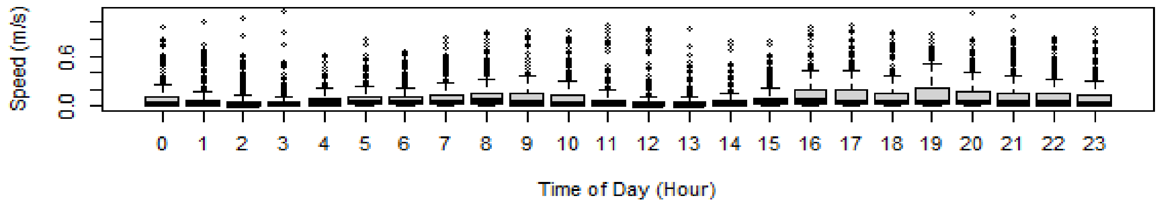
(a) Elephant 6207



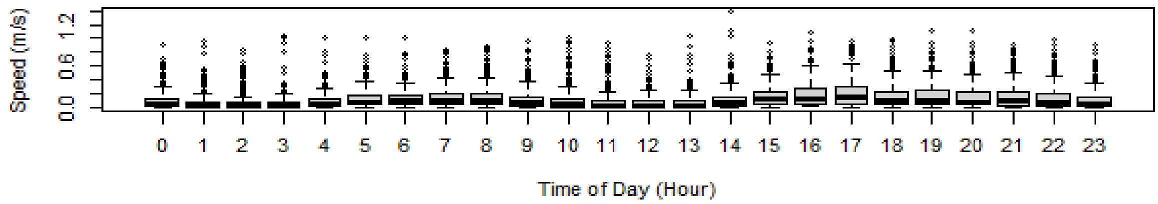
(b) Elephant 6208



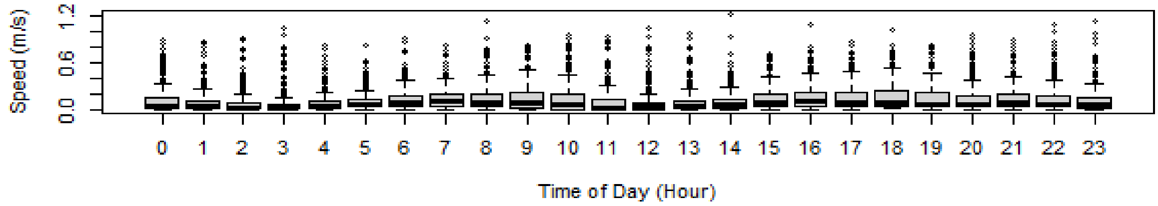
(c) Elephant 6209

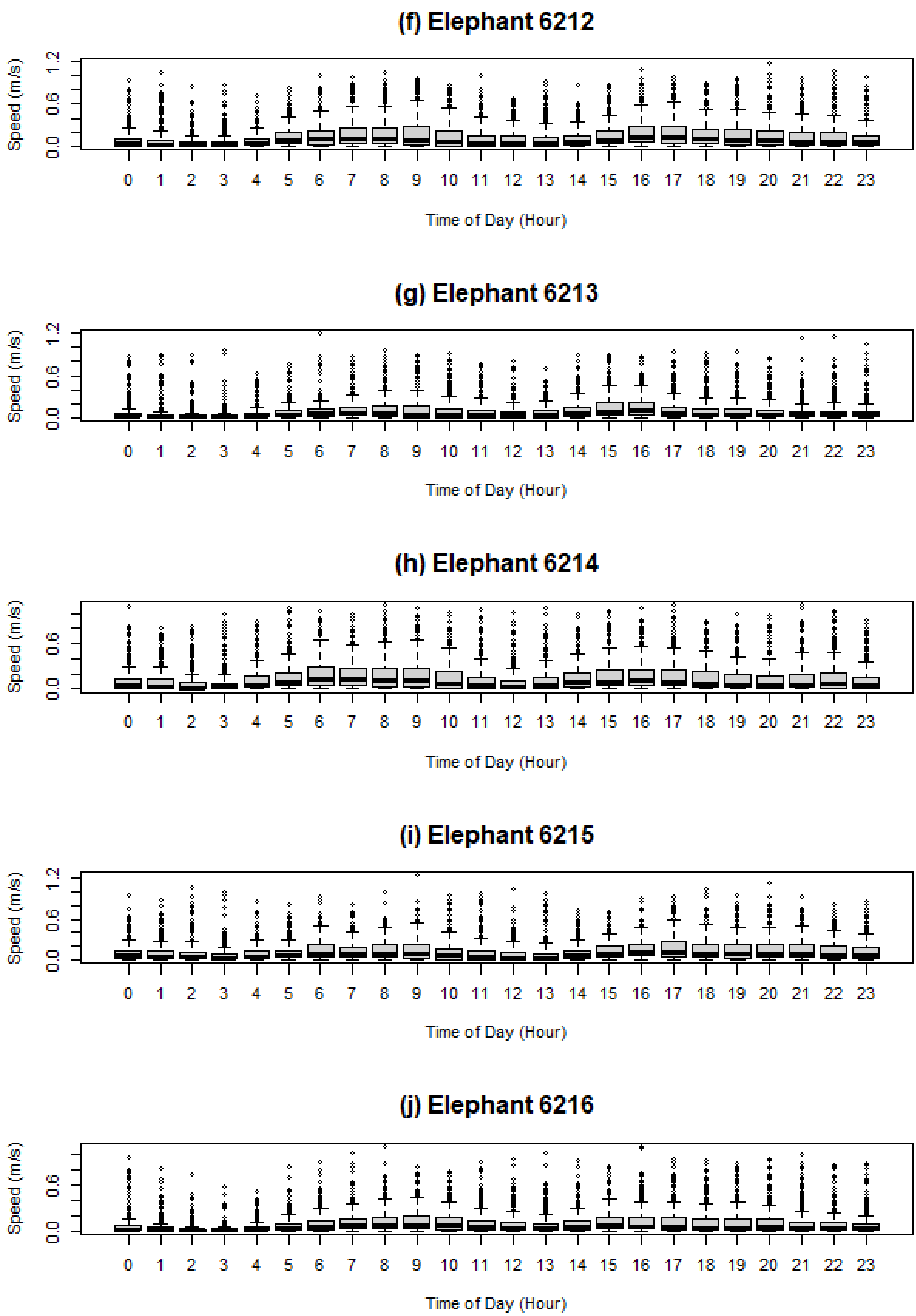


(d) Elephant 6210

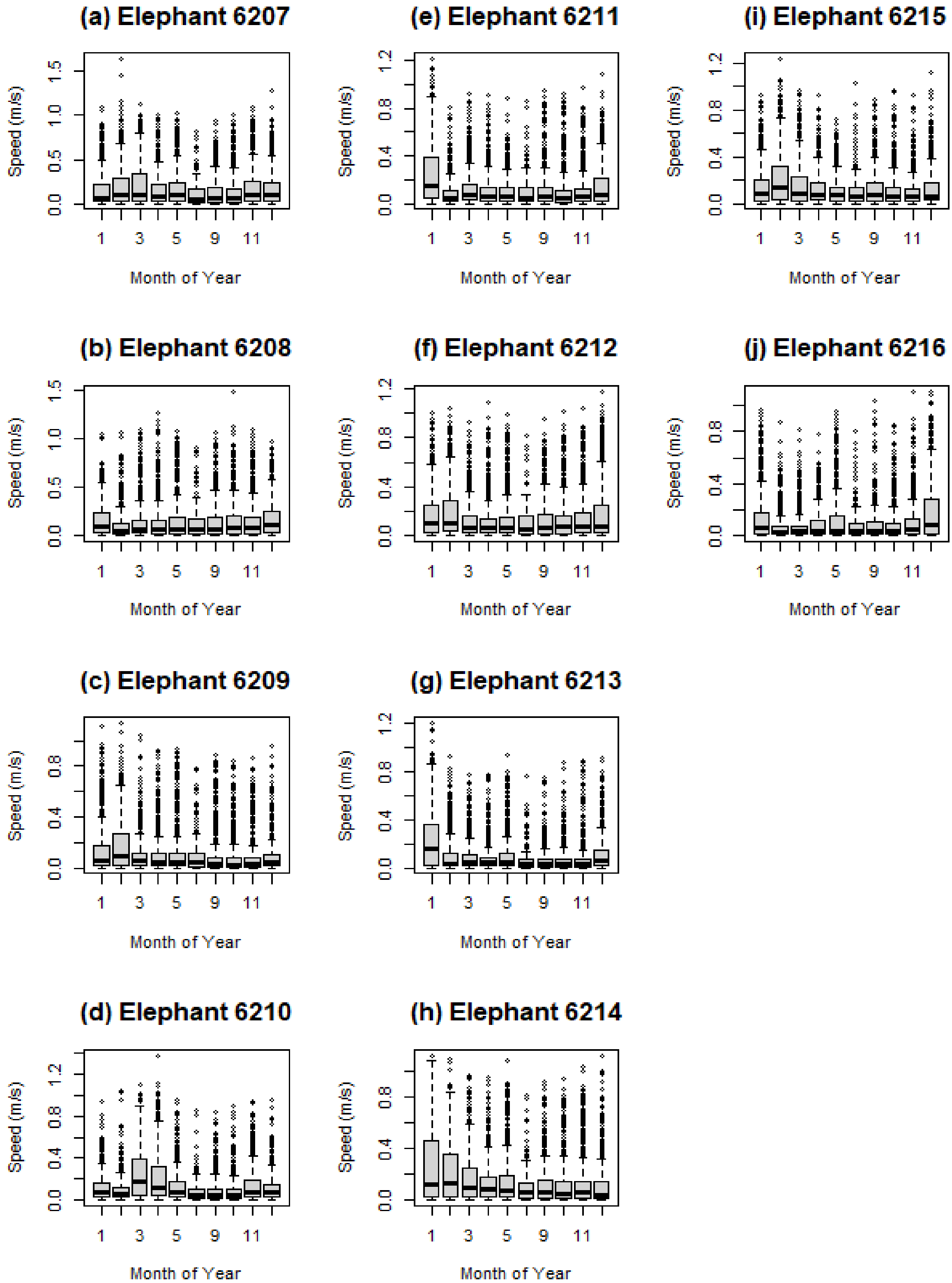


(e) Elephant 6211



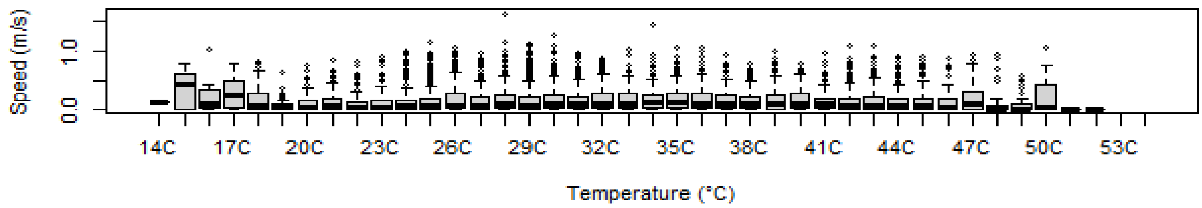


Appendix 8 (a-j). Speed (m/s) in 10 different adult individual African savannah elephants (6207-6212) compared to different months. The median speeds showed values ranging from 0.02 m/s to 0.17 m/s, with variations between the individuals. The interquartile range, displayed a wide difference across datasets.

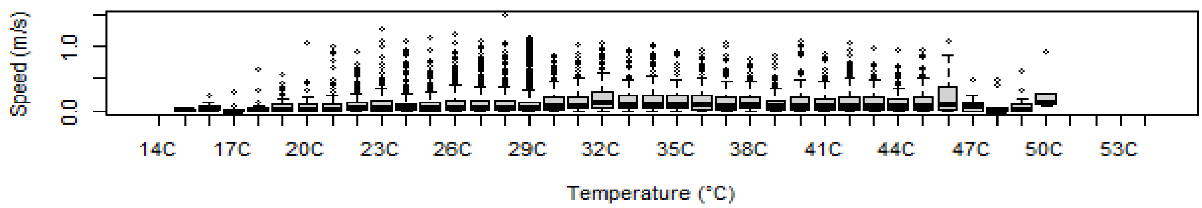


Appendix 9 (a-j). Temperature-dependent analysis of speed (m/s) variations in 10 different adult individual African savannah elephants (6207 to 6216). A complex relationship between temperature and speed is demonstrated among all 10 individuals. There are individualised and intricate patterns of variations across temperatures, fluctuations and unique trends in median speeds across temperatures, with inconsistencies and missing data points at certain temperatures.

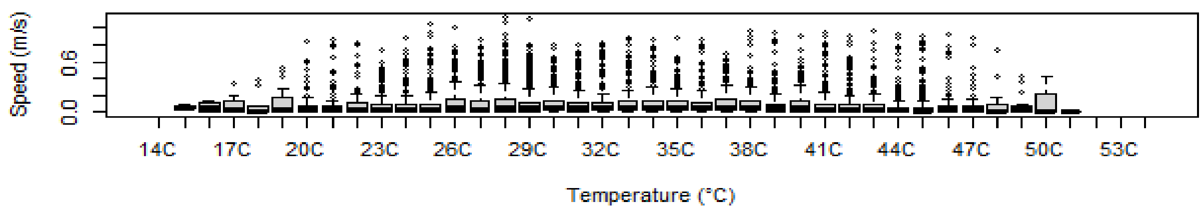
(a) Elephant 6207



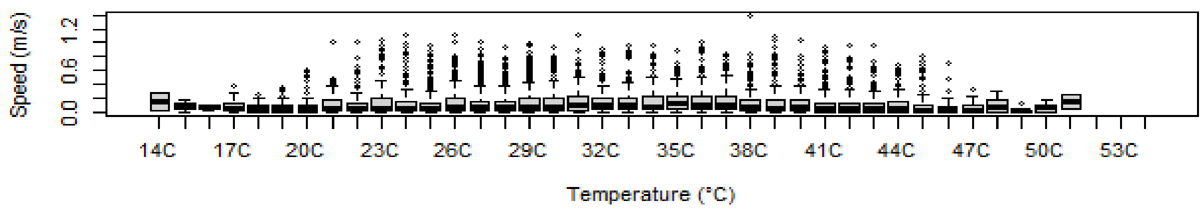
(b) Elephant 6208



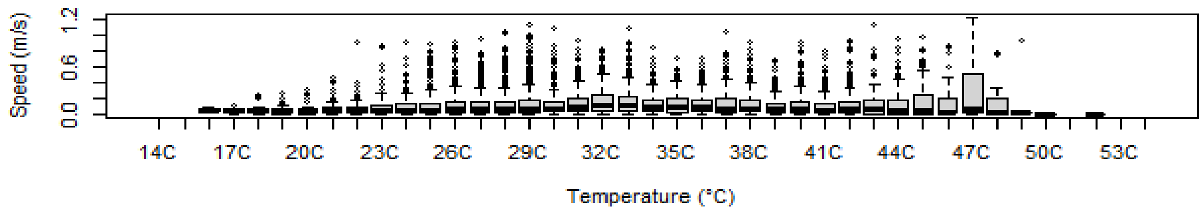
(c) Elephant 6209

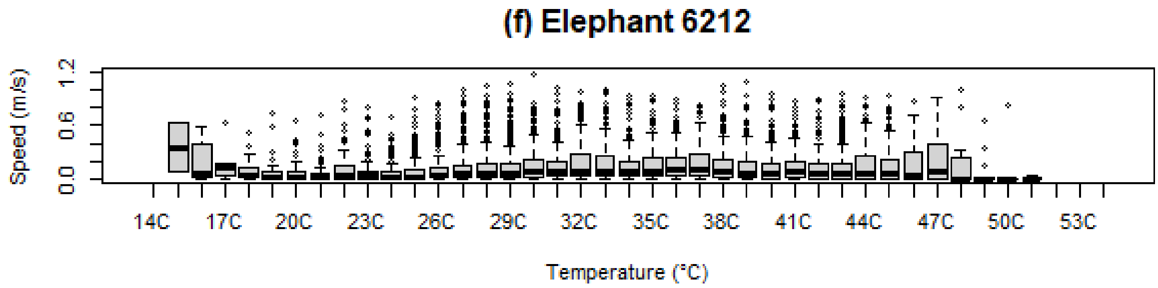


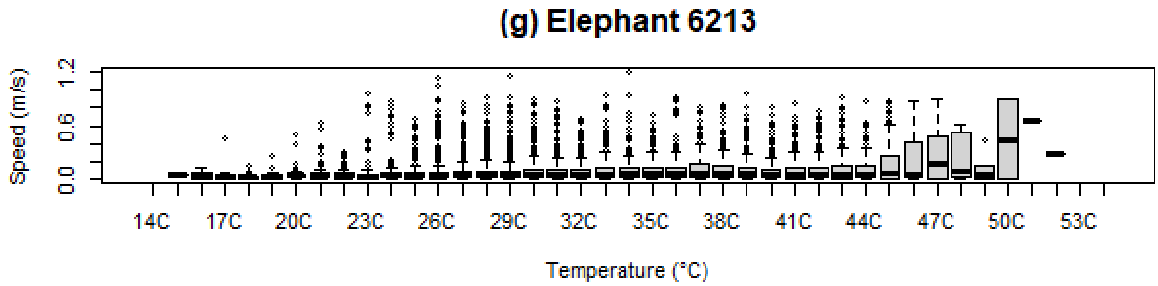
(d) Elephant 6210

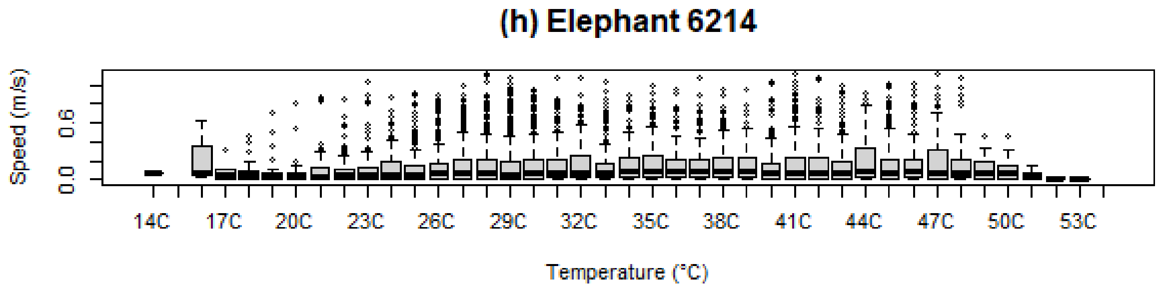


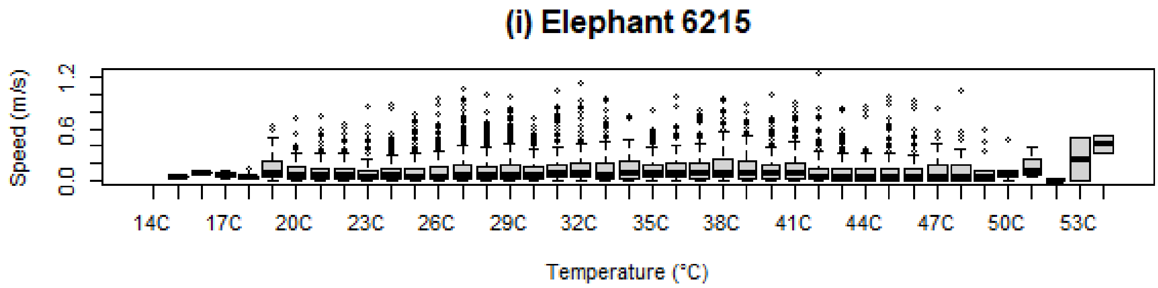
(e) Elephant 6211

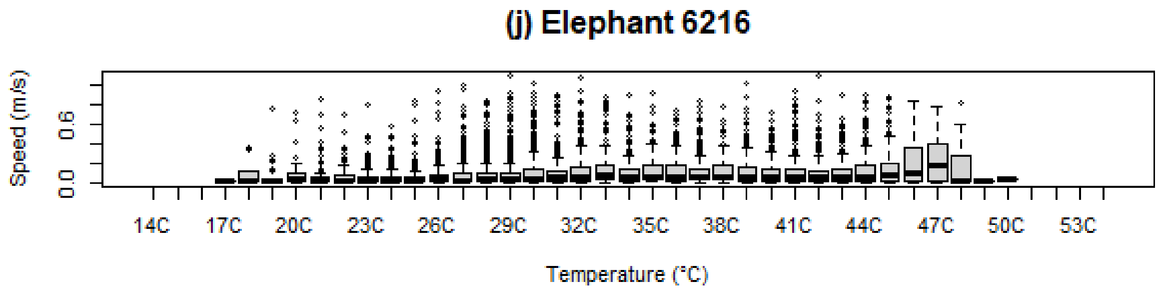



(f) Elephant 6212
Speed (m/s)
0.0 0.6 1.2
14C 17C 20C 23C 26C 29C 32C 35C 38C 41C 44C 47C 50C 53C
Temperature (°C)


(g) Elephant 6213
Speed (m/s)
0.0 0.6 1.2
14C 17C 20C 23C 26C 29C 32C 35C 38C 41C 44C 47C 50C 53C
Temperature (°C)


(h) Elephant 6214
Speed (m/s)
0.0 0.6
14C 17C 20C 23C 26C 29C 32C 35C 38C 41C 44C 47C 50C 53C
Temperature (°C)


(i) Elephant 6215
Speed (m/s)
0.0 0.6 1.2
14C 17C 20C 23C 26C 29C 32C 35C 38C 41C 44C 47C 50C 53C
Temperature (°C)


(j) Elephant 6216
Speed (m/s)
0.0 0.6
14C 17C 20C 23C 26C 29C 32C 35C 38C 41C 44C 47C 50C 53C
Temperature (°C)