How well do buffer circles capture the ranging behaviours of territorial raptors?

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Abstract

As the world's human population increases, so does the competition for natural resources between humans and wildlife. This competition may be intense for apex predators, such as raptors, which generally require large natural areas in order to maintain their populations. Anthropogenic development within territories can cause individuals to either abandon these sites, reduce their breeding productivity, or cause direct mortality to the territory holding birds. To mitigate such impacts, one method, employed as part of Environmental Impact Assessments (EIA), is the use buffer circles centred on nest sites. Within these buffers the most damaging forms of development are prohibited. This approach assumes that raptors use the space around their nest in a uniform way, but this assumption may not always be correct and few have evaluated the effectiveness of buffer circles at protecting a species' home range.

This study uses tracking data to evaluate the effectiveness of buffer circles to cover the ranging movements of six southern African raptor species, throughout the year, as well as during their breeding and non-breeding season. My study revealed that buffer circles whose dimensions were based on the species' 95% Kernel Density Estimate (KDE) did relatively well at capturing the proportion of individual GPS fixes, but did less well at capturing the KDE area from tracked birds. For buffer circles to capture 95% of the home range polygons (95% KDE) they would generally need to be at least twice as large as those that were derived from the 95% KDE home range area, and for some species with very large home ranges (e.g. Lappet-faced Vultures) even buffer circles that were 3 times the size failed to cover 95% of the KDE polygons.

Keywords: raptors; buffer circles; KDE; African Crowned Eagle; Bearded Vulture; Black Sparrowhawk; Lappet-faced Vulture; Martial Eagle; Verreaux's Eagle; conservation

Introduction

The current world population stands at over 7.7 billion (World Population Review 2019) and continues to increase. Such large numbers of people require more resources to support and sustain them – which includes transforming large tracts of natural land into settlements, agriculture, resource harvesting, or for energy development. Unfortunately, such land use changes can result in degradation and disruption of the natural ecosystems on which many species depend on. While some species have the potential to adapt to degraded habitats, and may even thrive in an urbanised or agricultural landscape (Malan & Robinson 1999; Suri et al. 2017; Kettel et al. 2018), others are unable to adapt as well and can abandon their territories (Blair 1996; McKinney 2002; Fischer et al. 2015; Krüger et al. 2015). Some developments, such as energy infrastructure may be so damaging that they can lead to direct mortality and decline of local populations (Carrete et al. 2009; Dahl et al. 2013).

Infrastructure and raptors

Energy infrastructure can have a negative effect on many avian species at risk. Raptors are affected both directly (increased risk of mortality due to collisions or electrocution) and indirectly (increased avoidance behaviour, habitat loss, habitat fragmentation, and species displacement) (Dwyer et al. 2018). In most cases, raptor populations are more greatly affected by collision mortalities than passerine populations due to their longevity and lower reproductive rate (Kuvlesky, Jr. et al. 2007). These K-selected traits make these species more susceptible to population decline due to the low numbers of offspring produced and/or the number of years that it takes for the individual to reach sexual maturity. Larger raptors take multiple years to reach sexual maturity, with juveniles dispersing far from their natal site – which may also place them at risk of encountering energy infrastructure (Krüger et al. 2014).

Power Lines

Electrocutions and collisions with power lines are a prominent threat to many large raptor species across the world and African continent (Jenkins et al. 2010; Slater et al. In Press.), with 64 species that are known to have been electrocuted globally (Hunting 2002). Characteristics of the habitat can also influence the risk of collision risk – such as the distance from an active nest site or a possible food source (Harness et al. 2003). In a study that analysed 1428 records of raptor mortalities that were confirmed to be caused by electrocution, it was found that 96% of the recorded electrocutions consisted of eagles (748), hawks (278) and owls (344) (Harness & Wilson 2001). These results indicate that such groups are at a considerable risk of electrocutions. In each group, one species made up a significant proportion of the confirmed electrocutions; with the bias being strongly towards recently fledged and dispersing juveniles (Harness & Wilson 2001).

Wind Farms

Wind farms have been found to impact raptors both directly through collisions with the rotating blades and indirectly through loss of suitable habitat, avoidance of altered landscape, and complete displacement from the landscape (Dwyer et al. 2018). Despite this, avoidance behaviour is possible and some raptor species can detect and change their flight patterns to avoid the turbines (de Lucas et al. 2004). Habitat features that affect the value of a territory to raptors can also influence the collision risk; such as nesting and perching sites, food resources and availability, and the presence of updrafts (Hunt & Watson 2016). These features, especially that of prey abundance and the placement of nest sites, should be taken into account when analysing the placement of wind farms in order to prevent raptor mortalities (Hunt & Watson 2016). For example, a study on a breeding population of White-tailed eagles *Haliaeetus albicilla* at the Smøla wind-power plant revealed that breeding success in territories within the wind farm decreased after construction due to both displacement and collision-related mortalities (Dahl et al. 2012). Sub-adult White-tailed eagles were also found in greater abundances than adults within the wind farm area, indicating that the farm area is seen as a potential habitat for dispersing individuals (Dahl et al. 2012, 2013).

In most cases, species-specific traits determine which species are more likely to collide with wind turbines. These traits can include the area that dispersing sub-adults use, or more commonly the altitude that individuals most commonly use. A study on the spatial analysis of the movements of Bearded Vultures *Gypaetus barbatus* in southern Africa found that adult and non-adult (fledgling, juvenile, immature and sub-adult) Bearded Vultures spent 55% and 66% of their time at altitudes that put them at great risk of colliding with wind turbines respectively (Reid et al. 2015). Similarly, adult Verreaux's Eagles *Aquila verreauxii* spend on average 68% of their flight time at a collision risk altitude (Murgatroyd et al. In Prep).

Exclusion and Mitigation

Raptors typically require areas with enough resources to support a breeding pair and their offspring of the year. Resident raptor species maintain an occupied home range all year round, regardless of the season or their breeding status (Naveen 2011). Other species, and in particular annual or partial migrant raptors only maintain a home range during the breeding season and migrate to warmer foraging areas during the winter (Terrill & Able 1988; Naveen 2011). In both cases, these home ranges can vary in size across both species and individuals, and are usually tied to a nest site. When plans for land development are made, buffer zones, within which development should not occur are often recommended to protect species that are sensitive to habitat change or disturbances. These buffer zones, or circles, are created by studying the spatial movements of a tagged individual, with greater attention being given during the breeding season (Knight & Skagen 1988; Camp et al. 1997). The buffer zone is meant to prevent human disturbance that may cause the adult birds to either abandon their nest and chick (Postovit & Postovit 1987; Speiser 1992), disrupt regular feeding of their offspring (Delaney et al. 1999; Morrison et al. 2011), disrupt prey availability or distribution (Lõhmus 2005), or invoke a flight reaction from nesting raptors during the breeding season (González et al. 2006). In the worst cases of development, they aim to reduce the likelihood of direct mortality caused by the development (e.g. wind turbines).

To mitigate the negative impacts that human development may have on sensitive species such as raptors, Environmental Impact Assessments (EIAs) are usually required (Chiebáo 2018). EIAs often recommend buffer circles be set up around the nest sites of sensitive raptor species inside which development should be avoided (Chiebáo 2018). Recommendations are often based on restricting developments in the territory or core home range. However, the exact size or shape of these areas for individual development is usually unknown and without individual tracking data from the pair or pairs concerned must be approximated. This is usually done through a placing a buffer circle around the nest with the total area of the buffer based on home range estimates for the species of concern (Watson et al. 2014; Sumasgutner et al. 2016). This method assumes that habitat use is uniform around a nest site. However, how this differs from reality has rarely been explored (Watson et al. 2014).

Watson et al. (2014) is the only study , as far as I know, to explore this issue in any detail. Watson et al.'s study (2014) estimated the home range area and resource selection of 17 tagged adult Golden Eagles (*Aquila chrysaetos*). They then constructed buffer circles of various radii and tested them on each KDE polygon in order to test at what size the buffer circle would capture 50%, 95% and 99% of the home range (Watson et al. 2014). With the 95% KDE polygon, it was determined that the annual home range area for the Golden Eagle was 82.3 km^2, and a buffer circle with a radius of at least 12.8 km would capture 95% of the home range area (Watson et al. 2014).

There are multiple methods used to calculate the home ranges for animal species, but the method which is most commonly used currently is the 95% Kernel Distribution Estimations (KDE) (Worton 1989). The 95% KDE polygon examines the maximum home range area while excluding the extreme 5% of GPS fixes (Fieberg 2007). Prior studies have revealed that home ranges tend to have an irregular shape instead of being circular and that home range size can vary across species, individuals, and habitat types. Individual variation within a species can sometimes be considerable. For example Sumasgutner et al. (2016) found that the 95% KDE home ranges varied nearly 10 fold from 3.81 km2 to 36.47 km2 for individual Black Sparrowhawks (*Accipiter melanoleucus*) on the Cape Peninsula, South Africa.

Similarly, Murgatroyd et al. (2016b) found 2 to 3 fold differences in the home ranges of Verreaux's Eagles tracked during their pre-breeding period in different habitats. Thus, there may be considerable variation and a single species-specific buffer circle whilst appropriate for capturing the ranging behaviours of some pairs, may not be adequate for others.

Project Aims

The use of buffer circles based on the species-specific home range areas may offer a useful means of estimating areas within which land development that may be damaging to raptors are excluded. Initially, the collection of the positions of tracked animals and subsequent creation of buffer circles was done through the use of VHF-radiotracking (Very High Frequency) (Recio et al. 2011). Currently, the use of GPS trackers on raptors has greatly increased and thus accurate home range estimates are more frequently being derived for threatened raptors (Watson et al. 2014; Meyburg 2015; Garcia-Heras et al. 2019). However, the lack of prior studies evaluating the effectiveness of this approach means that it is difficult to know how reliable this approach is. However, even a cursory visual inspection of the many published studies, shows that the KDE polygons are rarely completely uniform around a nest site.

In this current study, I aim to quantify how well the use of buffer circles perform in protecting the home range of multiple individuals from six African raptor species for which I had tracking data. I first use these tracking data to determine the annual home range for the species, and thus derive a species-specific buffer circle size. I then explore how well these buffer circles protect the different individuals. I explore this question based on their tracking data over the entire year (annual) and also during the breeding and non-breeding season. Finally, I investigate two measures of protection – firstly, what proportion of fixes are captured by the buffer circles in these different times, and secondly, what proportion of the 95% KDE is captured by the buffer circle for each species (Watson et al. 2014).

Methods

Data collection

I explored literature to identify tracking data for the various raptor species collected from various studies associated with the Percy FitzPatrick Institute of African Ornithology that were conducted throughout southern Africa. Each species had GPS trackers which transmit GPS coordinates at set time intervals – from as often as every few seconds to every second hour (Krüger et al. 2014; Murgatroyd et al. 2016b; Sumasgutner et al. 2016; Van Eeden et al. 2017; McPherson et al. 2019). For this study, the data were already in existence, and were provided by the lead researcher who was in charge of the respective study. The tracking data was sorted into hourly intervals to reduce excessive clustering of the GPS fixes, except for two species (Lappet-faced Vulture *Torgos tracheliotos* and African Crowned Eagle *Stephanoaetus coronatus*), where two-hour intervals were used instead due to the nature of the data (McPherson et al. 2019; Garbett et al. 2019 Unpublished data). The data for each tagged individual was divided into both yearly and seasonal (breeding and non-breeding) time periods, with incomplete years or seasons only being used where at least half the length of the season or year was present. This was to ensure that a suitable amount of the season or year was present to provide a reliable sample of the individual's movements during the year or season.

Study Species

African Crowned Eagle (*Stephanoaetus coronatus*)

The African Crowned Eagle (hereafter Crowned Eagle) is a large eagle species resident to sub-Saharan Africa (BirdLife International 2018a), most commonly found in forested habitats where it is a tree-nesting species (Ferguson-Lees & Christie 2001). Its southern African distribution is principally along the southern and eastern coast of South Africa; Zimbabwe and Mozambique (Ferguson-Lees & Christie 2001; BirdLife International 2018a). It primarily feeds on medium to large mammal (Brown 1971; Swatridge et al. 2014). Classified as 'Near-Threatened' by the International Union for Conservation of Nature (IUCN) Red List (BirdLife International 2018a), the species is declining and is threatened by human activities such as habitat loss through deforestation, prey competition with humans, destruction of nest sites, trapping and shooting (Ferguson-Lees & Christie 2001; BirdLife International 2018a). The individuals used for this study came from a population breeding in the urban greenspaces of the eThekwini municipality in KwaZulu-Natal, South Africa, where their home range was found to be 6.3 km^2 (McPherson et al. 2019). For this species, 90 days was used as half the length of both the breeding and non-breeding season.

Bearded Vulture (*Gypaetus barbatus*)

The Bearded Vulture has a fragmented extant distribution across Africa, the Middle East, Europe and Asia (BirdLife International 2017a). It is classified by the IUCN as 'Near-Threatened' due to its fairly rapid decline over the past three generations (BirdLife International 2017a). Threats to this species include collisions with powerlines, habitat degradation, breeding site disturbances, and accidental and targeted poisoning (Ferguson-Lees & Christie 2001; BirdLife International 2017a). The species prefers high mountain cliffs and uses the surrounding mountain for foraging and nesting (Hiraldo et al. 1979; Brown 1997; BirdLife International 2017a). It feeds exclusively on carrion, with a significant proportion of its diet consisting of bones which are shattered by dropping onto a rock to reach the marrow inside (BirdLife International 2017a). Individuals used for this study come from the southern African population, which is located in the Maloti-Drakensberg Mountains in Lesotho and South Africa, and are regionally classified as being 'Critically Endangered' (Krüger 2014; Krüger et al. 2014). A study on this population revealed that on average, around 54% ± 74% (175 – 91%) of the breeding pairs bred every second year; although annual attempts did occur (Krüger & Amar 2017). The average home range for territorial adults for the region was calculated to be 286 km^2 (Krüger et al. 2014), and was seen to vary between the breeding (148 ± 108km^2) non-breeding season (105 ± 62km^2) when they were in a breeding year (Krüger et al. 2014). Half of the breeding season was 120 days, while half of the non-breeding season was 60 days.

Black Sparrowhawk (*Accipiter melanoleucus*)

The Black Sparrowhawk is a locally common African species with a wide distribution and is classified as 'Least Concern' (BirdLife International 2016a). It experienced an expansion of its range into the Western Cape in the 1980s (Martin et al. 2014) and like elsewhere in its range, it uses not only tall-tree woodlands and forests, but it has also adapted to nesting in exotic tree plantations (Malan & Robinson 1999, 2001; BirdLife International 2016a). This species primarily feeds on birds, with the South African population showing a preference for three species of dove (*Streptopelia semitorquata*, *Columba livia*, *Columba guinea*) (Tate et al. 2016; Suri et al. 2017). The individuals used in this study came from a population on the Cape Peninsula in the Western Cape of South Africa (Sumasgutner et al. 2016). Their average annual home range was found to be 18.24 km^2, varying from 16.15 km^2 to 18.56 km^2 in the breeding and non-breeding season respectively, but with considerable intraspecific variability (Sumasgutner et al. 2016). Half of the breeding season was 42 days, while only a third of the non-breeding season (90 days) was used.

Lappet-faced Vulture (*Torgos tracheliotos*)

The Lappet-faced Vulture has a widespread, but fragmented distribution, with the bulk of the population being in Africa (BirdLife International 2017b). The species is classified as 'Endangered' by the IUCN with the fast population decline due to changes to their ecosystem, persecution, and poisoning (Ogada et al. 2016; BirdLife International 2017b). This species is a scavenger and feeds on carrion (Mundy 1982; Mundy et al. 1992). It also nests in trees, with nesting activities seen in *Maerua crassifolia* and *Acacia tortilis* trees in a protected area in Saudi Arabia (Shobrak 2011). The individuals in this study were captured and were breeding in Botswana, and their average home range for territorial adults was calculated to be 16,968 km^2 in the breeding season and 70,207 km^2 in the post- or non-breeding season (Garbett et al. Unpublished). In the analysis to calculate the average home range area, half of the breeding season was 120 days, while half of the non-breeding season was 60 days.

Martial Eagle (*Polemaetus bellicosus*)

The Martial Eagle is a large eagle species that is classified as 'Vulnerable' by the IUCN due to the suspected fast decline of the species over the past three generations caused by various human-induced threats (BirdLife International 2018b). These threats include collisions with power lines, loss of available prey and habitat, targeted and accidental poisoning, and pollution (BirdLife International 2018b). This tree-nesting species (Van Eeden et al. 2017) is seen as a generalist as feeds on large reptiles, mammals and birds (Ferguson-Lees & Christie 2001; BirdLife International 2018b; Naude et al. 2019). The individuals in this study were captured and tracked in the Kruger National Park, South Africa (Van Eeden et al. 2017). Data from the original study on these individuals revealed that the average home range for territorial adults was 108 km^2 (Van Eeden et al. 2017). To calculate the average home range area, half of the breeding season was 120 days, while half of the non-breeding season was at least 60 days – due to Martial Eagles breeding every second year.

Verreaux's Eagle (*Aquila verreauxii*)

The Verreaux's Eagle is a large eagle species with a very wide African distribution and is classified as 'Least Concern' by the IUCN (BirdLife International 2016b). The species is viewed as a specialist predator whose primary prey type are hyraxes – primarily *Procavia capensis* and to a much lesser extent *Heterohyrax brucei* (Gargett 1977, 1990). However, more recent research has suggested that its diet is more adaptable the first thought (Murgatroyd et al. 2016a). This species is also a cliff-nesting species (Brown 1971; BirdLife International 2016b). Five of the individuals sampled in this study came from a population in the Karoo (Ann, Cas, Mag, Sto and Tre); while two were from the Sandveld (Ber and Kat) and one individual was sampled from the Cederberg region (Uil) of South Africa (Table 1 and Appendix Table 1) (Murgatroyd et al. 2016c, 2016a). A study on the pre-breeding movements of territorial adults from the Sandveld and Cederberg found their average home range size to be 27.7 km^2 (Murgatroyd et al. 2016b). For this species, half of the breeding season was 120 days, while half of the non-breeding season was 60 days.

Data Structure and Processing

Individuals selected for this study occupied a defined home range and had bred or fledged offspring successfully at least once. If the chosen individuals experienced a failed breeding year, data for that year was excluded from the data analysis. This was done due to a lack of knowledge in some species where it was not known as to when in the breeding season the failure occurred. This exclusion was applied to all of the sampled species in order to standardise the exclusion of certain data. The data used consisted of the identification of the tagged individual (ID name or number), the GPS fixes (latitude and longitude coordinates), and the breeding status of the species; which consisted primarily of either a breeding season (which included the pre-laying, incubation and nestling period) and the non-breeding season (which also included the post-fledging period).

The data for each individual was selected according to the number of days per season captured in each year of tracking. Full years that included both the breeding and non-breeding season of the tagged individual's species were automatically included as viable data. The non-breeding years of species that are biennial breeders (Martial Eagles and Bearded Vultures) were also included as they would still represent the individual's movements during both the non-breeding seasons and a complete year. For those individuals who had incomplete or partial years, at least half (or 50%) of both the breeding and non-breeding season (see species descriptions above) had to be present in that year to be included when calculating the average annual home range sizes and respective buffer circles (see later). However, where individuals had sufficient data covering a breeding or a non-breeding season, these data were still used when examining the efficacy of buffer circles at capturing those respective periods. With the study species, the same 50% limit for both seasons were used to get a good representation of the individual's movements during the season.

The selection of data within certain time frames was done for various reasons. Having at least half of the breeding and non-breeding season included in a partial year was done as a way to sample an appropriate representation of the tagged individual's movements, and obtain a suitable home range size within each season and year. The use of half of the length of both seasons as the minimum requirement to include partial years was also chosen as a way to standardise treatment of the data across the species. Observations of the breeding season data showed that by the time that half of the season had passed, the tagged parent would be caring for a nestling; while after half of the non-breeding had passed, the individual would be in either the post-fledging stage or their fledgling of the year was fully independent. Separating the year into the two seasons was done to observe whether there was a change in the size of the home range area, while also testing the efficacity of the buffer circle, across the seasons. This 50% limit has resulted in some individuals, years and seasons being excluded from the analyses due to them either not having enough days to use for a season, or their home range area for certain years were unusually large and caused misrepresentation of the data due to only a few odd years for a few individuals.

Analyses of home range sizes

Kernel Density Estimation (KDE) is the most commonly used method to estimate a species home range (Seaman et al. 1999). This method aims to investigate the Utilisation Distribution (UD) of an animal, which is the "distribution of an animal's position in the plane" (Worton 1989); or how an animal uses the space in which it has claimed as a home range. Some form of GPS tracking is used to track an animal's movements across its habitat, and then further analyses can be done to determine various aspects about the territory. This approach is an alternative to using every GPS point to create a territory (Minimum Convex Polygon – MCP). The kernels are favoured over the MCP due to the latter using the most out-lying GPS fixes that a tagged individual has made – resulting in a home range which is much larger than that actually being used (Gregory 2017). Kernel Density Estimates make use of contour lines, or isopleths, that have been fitted over the UD of the animal according to the volume and clustering of the GPS fixes under them (Sumasgutner et al. 2016). The majority of KDE studies use the 95% and 50% kernel density contours to cover the majority of the home range and the core area of intensive use respectively (Fieberg 2007; Sumasgutner et al. 2016). I used the 95% KDE in this study to estimate an individual's home range – which I will refer to hereafter as their 'home range'.

To calculate the annual home range for each of the tagged individuals, I used multiple spatial analyses packages in R, with the most important being "adehabitatHR" (Calenge 2006). I used the getverticeshr() function to produce my home range estimates. When transforming and projecting the GPS fixes into spatial points, the World Geodetic System 1984, or WGS84, was used; along with the Universal Transverse Mercators (UTM) UTM 34S, UTM 35S and 36S. Those UTMs were chosen due to the relevant countries that were present between 18°E - 24°E, 24°E - 30°E, and 30°E - 36°E respectively; and were in the southern hemisphere between the equator and 80°S (Geomatic Solutions 2019a, 2019b, 2019c).

When analysing the home ranges and creating maps for images, the following packages were used: "raster" (Hijmans 2017), "MASS" (Venables & Ripley 2002), "rgdal" (Bivand et al. 2019), "maptools" (Bivand & Lewin-Koh 2019), "rgeos" (Bivand & Rundel 2019), "devtools" (Wickham et al. 2019), "adehabitatMA" (Calenge 2006), "sp" (Pebesma & Bivand 2005; Bivand et al. 2013) and "trip" (MD et al. 2009; MD 2011). These packages were used to clean the data up, create the images of the home ranges and respective kernels, and scale the projections to that of the map location that they represented.

Home Range and Buffer Circle construction

For each bird, with sufficient data, I estimated their annual home range for each year they each bird was tracked. Annual home ranges were estimated for all years where at least 50% of the breeding and non-breeding seasons were represented in the tracking data. If not, then I did not produce an annual home range estimate for that year and thus data for that individual in that year was excluded in the calculation of their overall annual home range size, and thus also eventually excluded from the species-specific annual home range estimates. For the large species, a minimum number of 60 days was needed during the breeding season, and 120 days was needed for the non-breeding season; while for the Black Sparrowhawk, which has a shorter breeding period, the minimum required data was a minimum number of 42 days for the breeding season and 3 months/90 days for the non-breeding season. Observations of the data showed that the clustering of GPS fixes and home range area changed between the seasons, so the separation of the seasons aimed to test the efficacity of the buffer circle in these different seasons.

I also excluded any individuals which displayed an exceptionally large home range in any year in order to not unfairly skew the data in either direction. This was seen primarily in the larger species in the study, especially in the Bearded and Lappet-faced Vultures. In most years, home ranges are fairly stable; but occasionally, these would increase significantly and be many times larger than the rest of the years. Such years were unusual in the fact that they occurred only during a minority of the individual's tagged years and were not normal for the individual. For example, one of the Bearded Vultures that was tracked for eight years (2011 – 2018) had an annual home range that ranged from 104.75 km^2 – 294.57 km^2. However, two of those tracking years (2014 and 2016) were excluded from the individual's data due to the home range increasing to over 7,600 km^2 (i.e. 25X the usual size). When initially analysing the data, including those years produced a significantly larger average home range area and buffer circle. The resultant buffer circle was unnecessarily large and would not have been feasible when determining the average size of a buffer circle to be applied to the species.

For each individual, which had sufficient data to estimate a KDE in multiple years I averaged their measures across these multiple years to get an average annual home range for that individuals, and then averaged these among all the different individuals to obtain a species-specific home range estimate. I then used this average species home range area (A) to construct the radius (r) of the average buffer circle to be used for each individual of the species, using the formula $r = \sqrt{A/_{\pi}}$ to determine the radius (r) of each species-specific buffer circle.

- For an infographic on the construction of the home range and buffer circles, see Appendix Figure 1.

Evaluating the efficacy of buffer circles I - % of GPS fixes captured

For each individual of each species, I calculated the percentage of their GPS fixes that were captured inside the species-specific buffer circle. This was used as an indicator of the effectiveness of the buffer circle. Where data existed, for each year and each individual, I estimated the percentage of fixes captured in one of the three relevant time periods. These were over an annual period, and during the breeding and non-breeding season. These averages for each individual were then used to calculate the average percentage of fixes within the buffer circle for each time period for the species. Measurements were taken as percentages with their respective 95% confidence intervals (CI) and will be presented as percentage captured (lower CI – upper CI).

Evaluating the efficacy of buffer circles II - % of KDE area captured

I also undertook an area-based assessment to quantify the extent to which the buffer circles captured the home range polygon of each bird. This was again done for one of three periods mentioned above (i.e. annual, breeding and non-breeding seasons). For this assessment, in each year, the species-specific buffer circle was overlaid onto the polygon of the home range for each of the three times periods. Thus, I was able to examine what percentage of this polygon was captured by the buffer circle. In another analysis, I also varied the size of the species-specific buffer circle making it either larger (up to 3X the size) or smaller down to only 10% of its size, and again examined the percentage of the home range polygon that was captured by buffer circles of different sizes. This approach is similar to that of Watson et al. (2014).

Results

Data Collection and Study Species

I used data from multiple individuals from each of the six species examined, ranging from a minimum of four individuals (Crowned Eagles) up to eight individuals (Bearded Vultures and Verreaux's Eagles) (Table 1). On average each individual provided data to estimate their home range from 1.82 or 2 years (Appendix Table 1).

Home Range and Buffer Circle construction

The average home range size varied greatly across the species (Table 2). The average annual 95% home range size varied from just over 8 km^2 (for Crowned Eagles) to nearly 40,000 km^2 (for Lappet-faced Vultures) (Figure 1 and 2). This produced buffer circles with radii ranging from 1.62 km to 110.98 km (Figure 1 and 2).

Table 1: The tagged individuals used for each species; with the number of GPS fixes, tagging start and end date, the number of days that each individual was tracked while they were tagged, and the number of years from each individual used to calculate the average annual species-specific home range size.

Species	Individual	GPS fixes	Start date	End date	Days tracked	No. of Years used
African crowned eagle	COTSWOLD	3072	2013/12/07 4:00	2014/12/27 18:00	386	1
African crowned eagle	MT MORELAND	2903	2013/01/01 4:00	2013/12/31 18:00	365	1
African crowned eagle	SPRINGSIDE	2731	2013/11/27 4:00	2014/11/04 18:00	343	1
African crowned eagle	TANGLEWOOD	3331	2013/12/19 4:00	2015/02/12 18:00	421	1
Black Sparrowhawk	IMH	1764	2013/08/19 18:10	2014/02/13 10:21	178	0
Black Sparrowhawk	SC	3154	2013/09/09 15:07	2014/11/26 15:32	443	1
Black Sparrowhawk	SP	5716	2014/10/24 11:45	2015/10/09 17:25	350	1
Black Sparrowhawk	TA	3375	2013/04/23 8:18	2014/10/20 15:37	545	1
Black Sparrowhawk	TP	1799	2014/09/25 4:05	2015/03/04 12:15	160	0
Black Sparrowhawk	ZS	7993	2012/09/04 16:28	2015/04/12 12:56	950	3
Bearded Vulture	Carmella	1007	2010/07/21 10:00	2010/12/31 13:00	163	0
Bearded Vulture	Inkosi	9227	2015/05/01 3:00	2017/12/31 17:00	976	2
Bearded Vulture	Jeremia	18051	2011/09/11 8:00	2018/09/30 17:00	2576	5
Bearded Vulture	Lefuma	1401	2012/08/26 12:00	2012/12/31 18:00	127	0
Bearded Vulture	Lehlwa	13370	2015/05/01 6:00	2018/09/30 18:00	1248	1
Bearded Vulture	Pharoah	21114	2012/08/16 9:00	2018/09/30 18:00	2236	7
Bearded Vulture	Sphinx	3498	2010/08/10 7:00	2011/12/31 16:00	508	1

Bearded Vulture	Springbok	16457	2011/01/01 3:00	2016/09/19 14:00	2088	5
Lappet-faced Vulture	BK1LF	2179	2013/04/01 2:00	2013/11/30 19:00	244	1
Lappet-faced Vulture	BK2LF	2207	2013/04/01 2:00	2013/12/01 18:00	245	1
Lappet-faced Vulture	BK3LF	2214	2013/04/01 2:00	2013/11/30 18:00	244	1
Lappet-faced Vulture	GR1LF	4193	2013/04/01 3:00	2014/11/30 19:00	609	2
Lappet-faced Vulture	LE1LF	3890	2015/04/01 4:00	2016/11/30 23:00	610	2
Lappet-faced Vulture	SA1LF	9618	2015/04/01 0:00	2016/09/25 18:00	544	2
Martial Eagle	G32519	18792	2016/03/22 0:00	2019/11/08 6:00	1326	4
Martial Eagle	G32554	11475	2015/01/01 0:00	2019/11/05 5:00	1769	5
Martial Eagle	G32555	2416	2013/09/13 1:00	2014/02/18 4:00	158	0
Martial Eagle	G34491	12275	2017/06/09 14:00	2019/11/08 3:00	881	3
Martial Eagle	G34492	6782	2018/07/20 1:00	2019/11/08 5:00	476	2
Martial Eagle	G34495	398	2019/10/12 1:00	2019/11/09 6:00	28	0
Verreaux's eagle	ann	8577	2017/01/01 0:30	2018/05/02 12:58	486	2
Verreaux's eagle	ber	3264	2017/10/18 13:01	2018/03/13 18:51	146	0
Verreaux's eagle	cas	1579	2016/06/28 11:38	2016/09/27 1:07	91	0
Verreaux's eagle	kat	3232	2017/10/18 14:00	2018/03/13 18:54	146	0
Verreaux's eagle	mag	5394	2016/07/07 11:00	2017/09/08 13:00	428	2
Verreaux's eagle	sto	5248	2016/06/29 13:50	2017/12/22 16:34	541	2
Verreaux's eagle	tre	8240	2016/04/07 11:00	2018/04/10 7:15	733	2
Verreaux's eagle	uil	1620	2013/01/01 0:21	2013/05/11 8:01	130	1

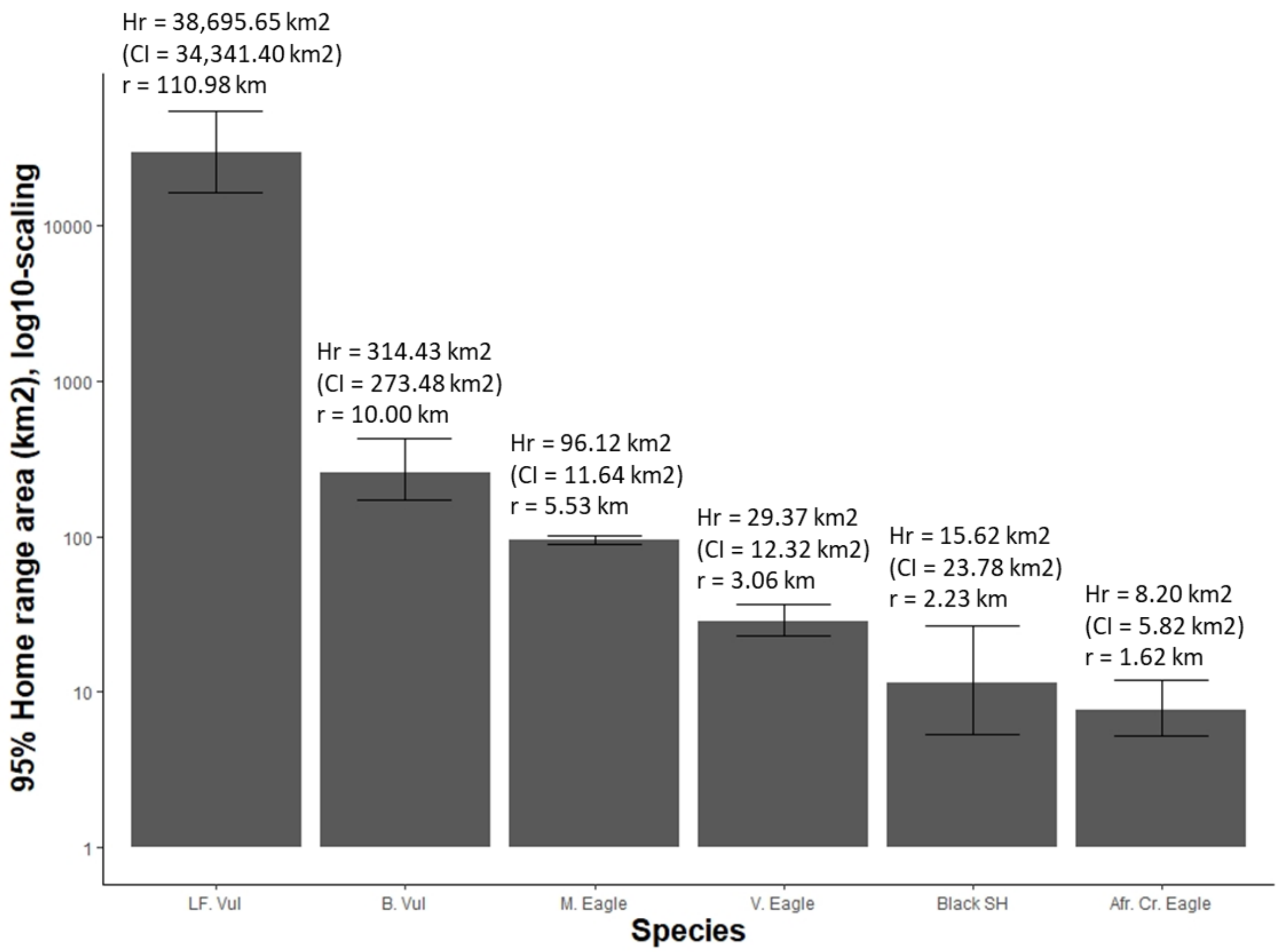


Figure 1: The average species-specific 95% home range area and respective buffer circle for each raptor species. The error bar represents the 95% confidence interval. Note that the y-axis is on a log-scale.

Evaluating the efficacy of buffer circles I - % of GPS fixes captured

The annual GPS fixes captured by the 95% buffer circle generally quite high; for all species it was between 85% and 95%, with the exception of Crowned Eagles, for which only 73% (95%, CI: 50% - 96%) of fixes where captured by the buffer circle. For all species, except the Bearded Vulture, there was a small reduction in the percentage of fixes captured during the non-breeding season compared to the breeding season. However, for the Crowned Eagle considerably more fixes were captured during the breeding season than during the non-breeding season (100% Vs 57%). The confidence intervals for the 95% buffer circle were mostly small in size with very little variation across the time periods – with the exception of the Lappet-faced Vulture, Martial Eagle and Crowned Eagle. Overall, the breeding season was the best captured time period by the 95% buffer across the species, while the non-breeding season had the lowest capture values (Table 2, Figure 1a and Appendix figure 2).

Table 2: The species and seasons sampled, with the average home range area, buffer radius, percentage of GPS fixes and proportion of KDE area captured with the 95% buffer circle.

Species	Measurements captured	Time period	95% Kernel	95% CI
African Crowned Eagle	Average home range area (km^2)		8.20	5.82
	Buffer radius (km)		1.62	-
	GPS fixes (%)	Annual	73	23
		Breeding	100	1
		Non-breeding	64	35
	KDE area (%)	Annual	59	36
		Breeding	100	0
		Non-breeding	57	38
Black Sparrowhawk	Average home range area (km^2)		15.62	23.78
	Buffer radius (km)		2.23	-
	GPS fixes (%)	Annual	88	17
		Breeding	95	6
		Non-breeding	84	11
	KDE area (%)	Annual	67	35
		Breeding	85	16
		Non-breeding	53	21
Bearded Vulture	Average home range area (km^2)		314.43	273.48
	Buffer radius (km)		10.00	-
	GPS fixes (%)	Annual	92	4
		Breeding	90	5
		Non-breeding	90	7
	KDE area (%)	Annual	73	22
		Breeding	71	17
		Non-breeding	71	29
Lappet-faced Vulture	Average home range area (km^2)		38,695.65	34,341.41
	Buffer radius (km)		110.98	-
	GPS fixes (%)	Annual	91	7
		Breeding	97	3
		Non-breeding	78	24
	KDE area (%)	Annual	68	21
		Breeding	89	11
		Non-breeding	57	40
Martial Eagle	Average home range area (km^2)		96.12	11.64
	Buffer radius Buffer radius (km)		5.39	-
	GPS fixes (%)	Annual	86	10
		Breeding	90	21
		Non-breeding	86	8

	KDE area (%)	Annual	75	7
		Breeding	82	18
		Non-breeding	76	7
Verreaux's Eagle	Average home range area (km^2)		43.67	12.32
	Buffer radius (km)		3.73	-
	GPS fixes (%)	Annual	91	4
		Breeding	92	5
		Non-breeding	86	4
	KDE area (%)	Annual	68	8
		Breeding	68	21
		Non-breeding	82	17

Evaluating the efficacy of buffer circles II - % of KDE area captured

For all species and three periods, the proportion of the home range polygon captured by the 95% buffer were generally much less than the proportion of fixes captured (Figure 2). Across the time periods, the captured proportions of KDE areas were very similar to each other within each species (Appendix figure 3), with the exception of the Crowned Eagle and Black Sparrowhawk. The annual and breeding season had the best area of captured polygon, with the non-breeding season generally having less of its area being captured by the buffer (Appendix figure 3).

The Crowned Eagle however had the greatest difference in the proportion of area captured with its entire breeding season being captured (100%); while its annual period and non-breeding season were 59% (23% - 95%) and 57% (19% - 95%) respectively (Table 2). The 95% confidence intervals were generally largest during the non-breeding season; with the only exceptions being the Black Sparrowhawk and Verreaux's Eagle, whose CI was highest during the annual period and breeding season respectively. Overall, the Martial eagle, Verreaux's Eagle and Bearded Vulture had the best captured areas across the time periods.

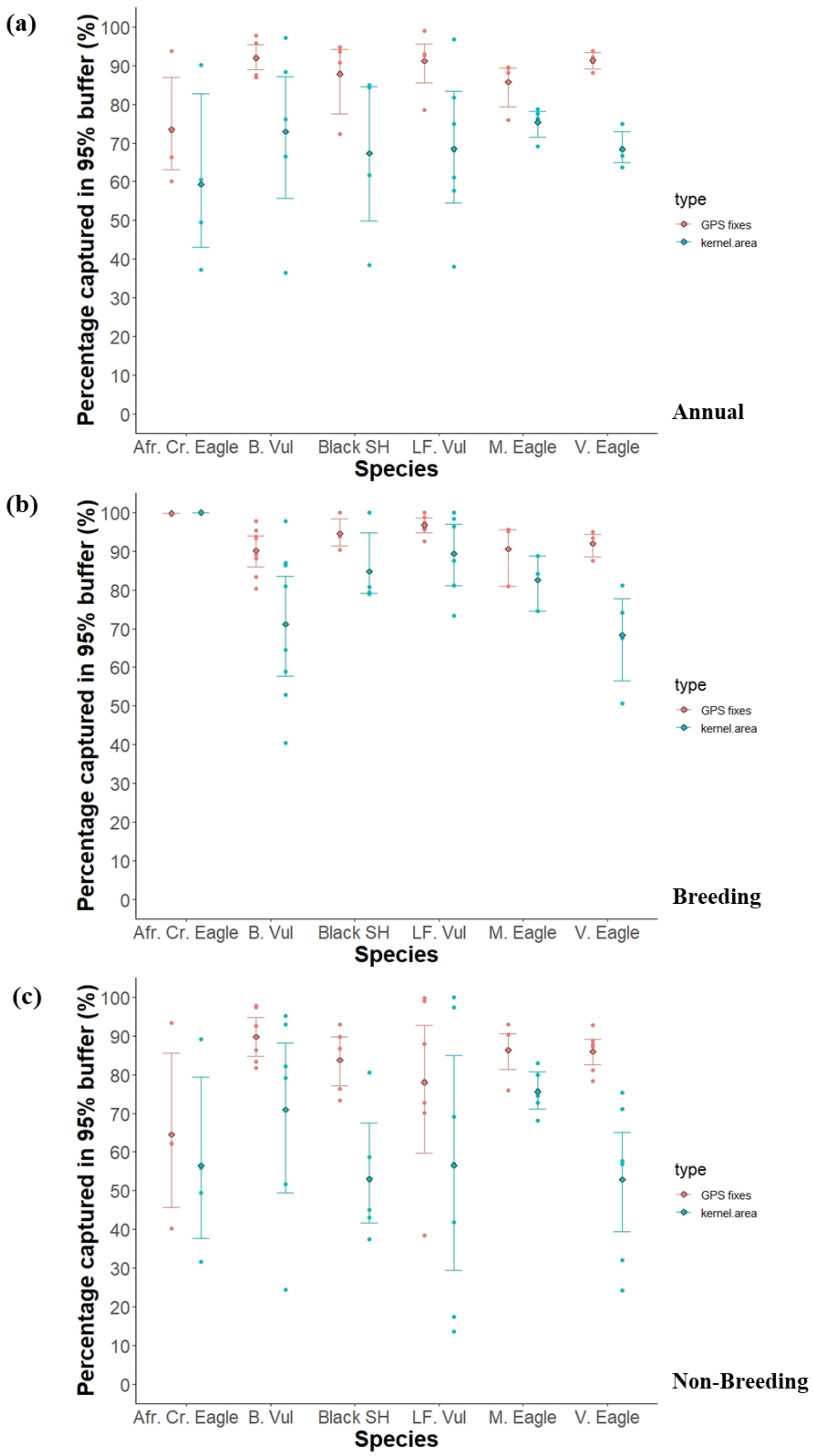


Figure 2: The proportion of the home range GPS fixes and 95% kernel area captured by the buffer circle for six species of raptors during their Annual (a), Breeding (b), and Non-breeding (c) seasons. The mean of captured units is shown by the black outlined diamond, with the 95% confidence interval on either side.

I then explored the proportion of the home range polygon that were captured with increasing or decreasing buffer circle size. For none of the species did the species-specific buffer circle capture 95% of the home range polygon (Figure 3). The buffer circles captured only between 59% (Crowned Eagle) and 75% (Martial Eagle) of the home range polygon. As the size of the buffer circle increased, a greater percentage of the home range polygon was captured (Figure 3). In order to capture around 95% of the home range polygon, the buffer circles needed to be around 1.5 times twice their original size for Martial Eagle and the Verreaux's Eagles (Figure 3b), around 2 times the size for the Crowned Eagle, Black Sparrowhawk and the Bearded Vulture (Figure 3a), and for the Lappet-faced Vultures even increasing the buffer circle to 3 times their original size did not capture 95% of their home range polygon.

Circular buffer recommendations based on the area of the home range did not capture the full movements of any species. However, for the eagles, increasing the buffer recommendation by 50% (i.e. to the 1.5 relative buffer radius) captured nearly all of the home range area (> 95 % Figure 3b), and doubling it captured 100 % of the home range. This was not achieved at the same proportional buffer size increase for any of the other species. Lappet-faced Vultures performed the worse; with even a buffer three times the recommendation only capturing 85% of the home range area (Figure 3c).

These results were seen only with the vultures, which could be due to the Lappet-faced Vulture being more like a partial migrant rather than a resident like the Bearded Vulture. However, this calls for a very large buffer circle that is at least three times the size of the calculated buffers to capture 95% of both species home range areas. In an exploratory data analyses that included years during which a tagged vulture had a significantly large home range area to test the viability of the data, it was found that the resulting average home range area for the species increased substantially due to those few years. This subsequently resulted in a buffer circle radius whose size would be impractical for conservation purposes. Overall, buffer circles whose size are at least twice that of the calculated 95% buffer circle would be needed to capture 95% of the home range area of all the species in this study.

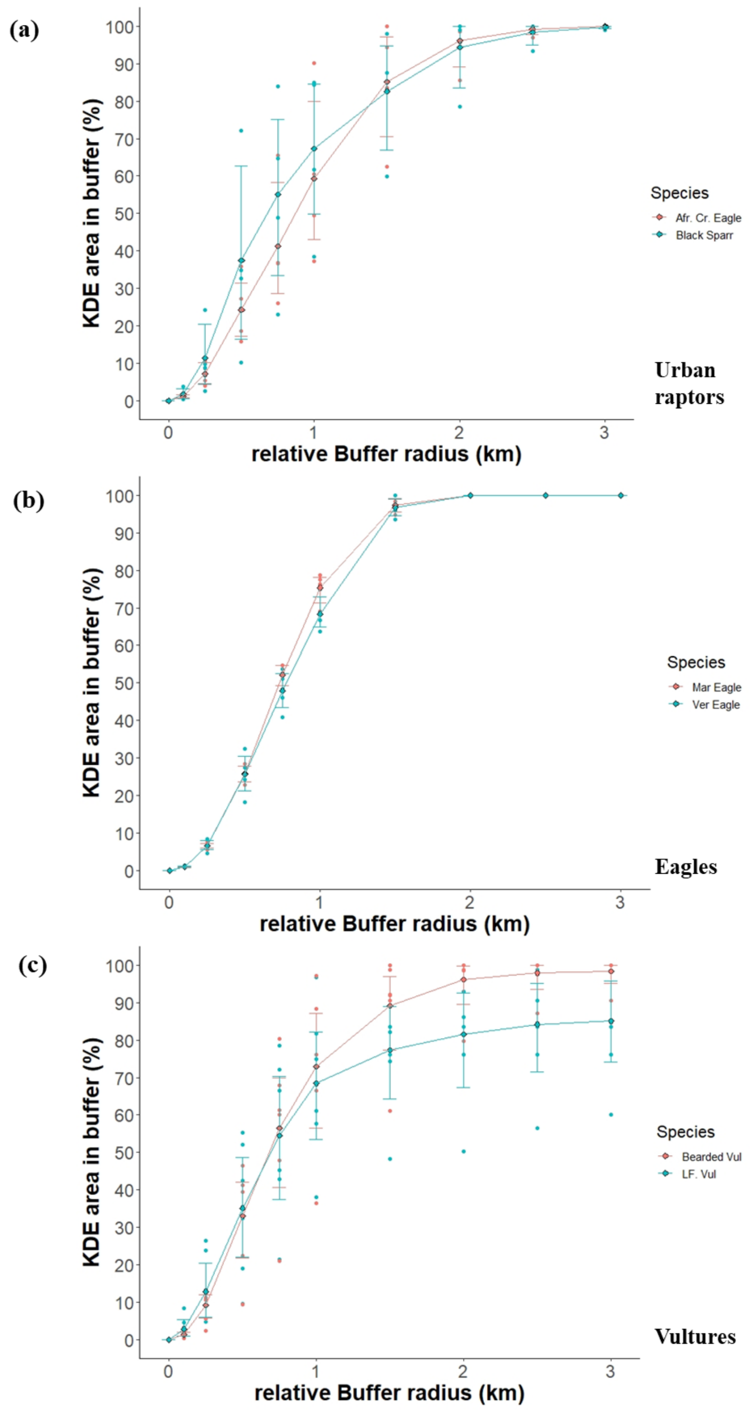


Figure 3: Relationship between changing buffer circle size and the percentage of the annual home range polygon captured. The original species-specific buffer circles, derived from the area of the 95% KDE is set at 1, and the other values on the x-axis are proportional to this value. Similar species/habitats are grouped in panel for clarity, these were (a) Urban raptors (Black Sparrowhawks and Crowned Eagles), (b) Large Eagles of open habitat (Martial Eagles and Verreaux's Eagle) and (c) Vultures (Bearded Vulture and Lappet-faced Vulture). The 95% Confidence interval error bar is on either side of the species mean (diamond outlined in black), and dots show the values for each individual.

Discussion

This study showed that home ranges and their respective buffer circles for individual species vary dramatically in size. From 1.62 km radius for the species with the smallest home range (African Crowned Eagle) up to 110.98 km radius for the species with the largest home range (Lappet-faced Vultures). For some of these species, excluding the most dangerous developments from these areas might be a practical approach; however, for the more wide-ranging species (both vulture species) excluding development within area of this size is unlikely to be acceptable to society, since it will mean excluding huge areas from development and would thus be incompatible with economic development, and the development of renewable energy. When the efficacy of the buffer circles was examined, the outcome and conclusion depended on the approach taken. For all species, and in all three of the different periods examined, buffer circles captured a far higher percentage of the GPS fixes when compared with the percentage of the home range area captured (i.e. the 95% KDE polygon). In the only other study, to have explored a similar question to this study, Watson et al. (2014) used the area approach rather than the percentage of fixes.

These differences between a percentage of fixes and the percentage of home range areas captured suggests that the approach taken when assessing the effectiveness of buffer circles will have a big impact on any subsequent conclusions. At an individual site level, when there is concern that the development might impact a species present, individual tracking studies are often carried out or recommended via EIAs in order to establish the key areas individuals use (Martínez et al. 2007; López-López et al. 2016; Platteeuw et al. 2017). In such cases, the home range (i.e. KDE) would likely be used to demark the areas for developmental exclusion. When comparing how well a buffer circle performs in demarking important areas for a species, it could thus be argued that a similar approach should apply. Therefore, using the percentage of the home range area captured would appear to be the more suitable comparison. In my further analysis, I therefore only explored the percentage of the home range captured by different sized buffer circles, which was the same approach adopted by Watson et al. (2014).

By varying the size of the buffer circle, I found that in order to capture 95% of the home range area, the buffer circle applied would need to be increased from 1.5 (for the three eagle species and Black Sparrowhawk) to over 3 time the original size (for the Bearded Vulture and Lappet-faced Vultures). Thus, it would appear that established the buffer circle based on the 95% KDE home range size is generally not sufficient to adequately protect most species. This is an important finding from this study, and one that has considerably implication for the use of buffer circles to mitigate against impacts from developments.

Despite their widespread usage, buffer zones have not been very well evaluated on whether they do cover the ranging movements of certain species of raptors during their breeding and non-breeding seasons. In my study, for all species, except Verreaux's Eagles, there did appear to be some differences in the ability of buffer circles to protect between the seasons, with a greater percentage of the home range area protected during breeding season than during the non-breeding season. This is perhaps not surprising, given that I know for at least some species that ranging behaviour is more constrained to the area closest to the nest during the breeding season due to the need for the parents to visit nests regularly (López-López et al. 2016; Van Eeden et al. 2017).

Vultures worldwide, especially the Old-World Vultures (Africa and Eurasia), are greatly at risk of extinction; with many species showing declines in their population (McClure et al. 2018). African vultures have undergone rapid reductions in their populations in West and East Africa – to the point where they are only present in large numbers within protected areas (Thiollay 2006, 2007; Ogada et al. 2016). However, their usefulness for vultures will depend to a degree on whether the species is a solitary nester or a colonial nester and also on their ranging behaviour. For colonial nesters it might be possible to exclude development from large areas around colonies as suggested by Venter et al. (2019) for Cape Vultures (*Gyps coprotheres*) because this single buffer circle could protect many individuals. However, for solitary nester such as Lappet-faced Vultures which are wide ranging this approach might be impractical since it would cover such a large area.

Territorial adult Bearded Vultures were found to have an average home range area of 286 km^2 (Krüger et al. 2014); while the breeding Lappet-faced Vulture had an average home range area of 16,968 km^2 inside their breeding season and 70,207 km^2 in the non-breeding season (Garbett et al. Unpublished data). Thus, buffer circles might be a practical approach for the solitary nesting Bearded Vulture, but probably not so useful for the Lappet-faced vulture.

In the only other study similar to ours, Watson et al. (2014) found that the best buffer circle for Golden Eagles, in order to captures 95% of their home range, was 12.8 km (Watson et al. 2014). Another study also looked at Booted Eagles *Aquila pennata* in Spain during the breeding season and found an average home range of 27.8 km^2 at 95% KDE (López-López et al. 2016), suggesting a radius of 2.97 km. Another group of authors however, found an average home range area of 146.0 km^2 (Martínez et al. 2007), which suggests a buffer radius of 6.82 km. Both studies fitted their buffer circles according to the 95% KDE polygon, but this study implies that the buffer circle would need to have a radius that is 2.0 – 3.0 times their suggested size to actually capture 95% of the home range area.

A study on Cape Vultures *Gyps coprotheres* in South Africa suggested that a buffer radius of 50 km should be used around the core area of the colony; however, this was calculated using only the 50% KDE of the species population (Venter et al. 2019). With the literature indicating such large home ranges, the practice of using a buffer circle with a radius that is three times the size of one fitted for the 95% KDE polygon, as seen in this study, would be very difficult to do if protected areas are already constrained and cannot be expanded on.

Study Limitations

While the analyses have revealed some useful results, there are still some limitations to my study. One of these is the small sample size of tagged individuals – all of the species had less than 10 tagged individuals. This is often a limitation of GPS studies because the tags themselves are very expensive. The tagged individuals also consisted of a mixture of both sexes, which could alter the home range area and GPS fixes if the sexes have different movements at certain times of the year. With raptors, the male provides nesting materials to the female, who remains at the nest and is most involved in its construction and repair (Brown 1971). The female is also the most involved in incubation and would either be the sole incubator, or have the greater share between the sexes (Brown 1971). With respect to the tracking data, a tagged female would provide a lot of GPS fixes that would be either at, or in close proximity to the nest during the pre-laying and incubation periods of the breeding season – which could result in a smaller home range area. We did not examine the patterns differently for the different sexes, because such an approach would reduce the sample size further. However, this does represent a limitation in this study.

Another concern from this study is the large CI values associated, which occurred for the home range size for all of the species (Table 2). This is likely due to the number of sampled individuals and the number of years that each individual was tagged. Much like with a greater number of individuals to sample, a greater number of years would also provide a better estimation of the results and a narrower CI. In the seminal paper by Watson et al. (2014), the Golden Eagles used in their study were tagged for at least 2 years from 2004 to 2013; which allowed for multiple years to be used in their study. My study used all years that were available, which included a partial or single year for some individuals. The use of half of the length of both seasons as a minimum requirement to include a partial year and viable season could also produce inaccurate results. The reasons for using this limit were explained under 'Data Structure and Processing'.

Conclusion

In this study, I found that buffer circles, when applied as they usually are by land developers, do not adequately cover the ranging movements of multiple southern African raptors during both the breeding and non-breeding season as they would need to be 2.0 – 3.0X larger to consistency cover 95% of the home ranges. The data regarding the proportion of captured GPS fixes and KDE area captured by their respective 95% buffers are favourable with regards to the capture of GPD fixes; but are inadequate in consistently capturing 95% of the home range and need to be increased in order to do so efficiently. Overall, this study showed that developers should be applying buffer circles that are between 1.5 – 2.0X the size that they are currently applying; with vultures possibly needing buffer circles that are 3X their current size. Alternatively, while this study has found the use of buffer circles to be a viable approach when scaled appropriately, recent research has aimed to move away from buffer circles and instead apply prediction of home range usage based on habitat models; which link the distance from nest site, and topography to predict the most likely areas that will be used (Reid et al. 2015; Tikkanen et al. 2018; Murgatroyd et al. In Prep). This approach may provide better and more accurate results whilst minimising the area in which development is excluded.

Appendix

Appendix Table 1: The number of viable years, breeding and non-breeding seasons provided by tagged individuals to calculate the Average Species Home Range and Buffer Circle radii. The values in brackets indicate the total number of years and seasons provided by the individual, while the value outside indicate how many were viable and used in the analyses.

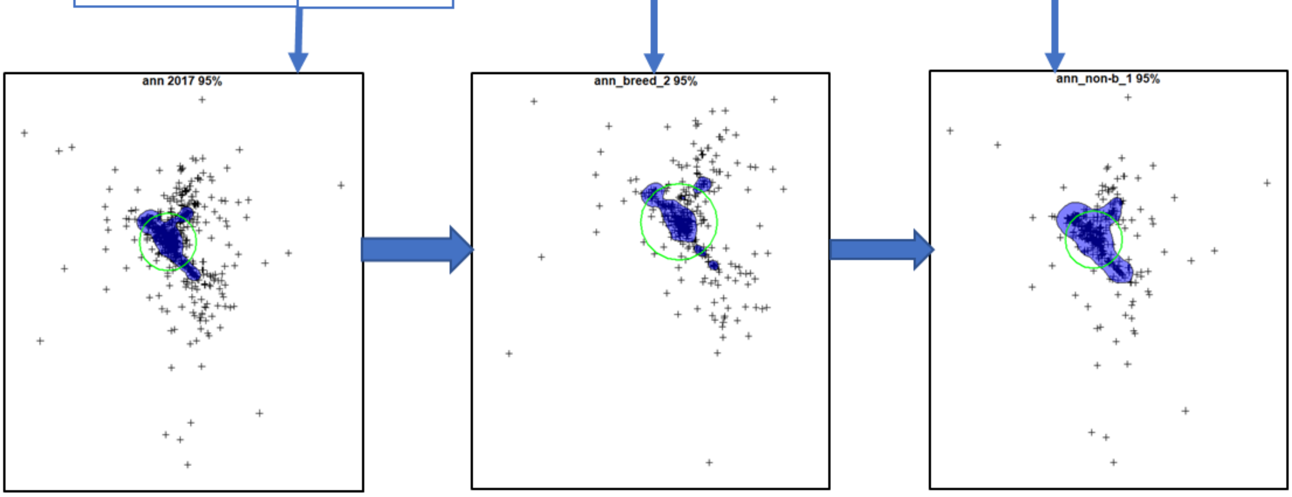
* Individual was not used in the study due to the time that the individual spent tagged was too short at the time of data processing

Species	Individual	Total no. of GPS fixes	No. of Years used	No. of Breeding seasons used	No. of Non-breeding seasons used
African crowned eagle	COTSWOLD	3072	1 (2)	1 (2)	1 (1)
African crowned eagle	MT MORELAND	2903	1 (1)	1 (2)	1 (1)
African crowned eagle	SPRINGSIDE	2731	1 (2)	0 (2)	1 (1)
African crowned eagle	TANGLEWOOD	3331	1 (3)	0 (1)	1 (1)
Black Sparrowhawk	IMH	1764	0 (2)	1 (1)	0 (2)
Black Sparrowhawk	SC	3154	1 (2)	0 (1)	1 (1)
Black Sparrowhawk	SP	5716	1 (2)	1 (1)	1 (1)
Black Sparrowhawk	TA	3375	1 (2)	1 (1)	1 (1)
Black Sparrowhawk	TP	1799	0 (2)	0 (1)	0 (1)
Black Sparrowhawk	ZS	7993	3 (4)	1 (2)	2 (2)
Bearded Vulture	Carmella	1007	0 (1)	1 (1)	0 (0)
Bearded Vulture	Inkosi	9227	2 (3)	3 (3)	2 (2)
Bearded Vulture	Jeremia	18051	5 (8)	4 (5)	7 (7)
Bearded Vulture	Lefuma	1401	0 (1)	1 (1)	0 (0)

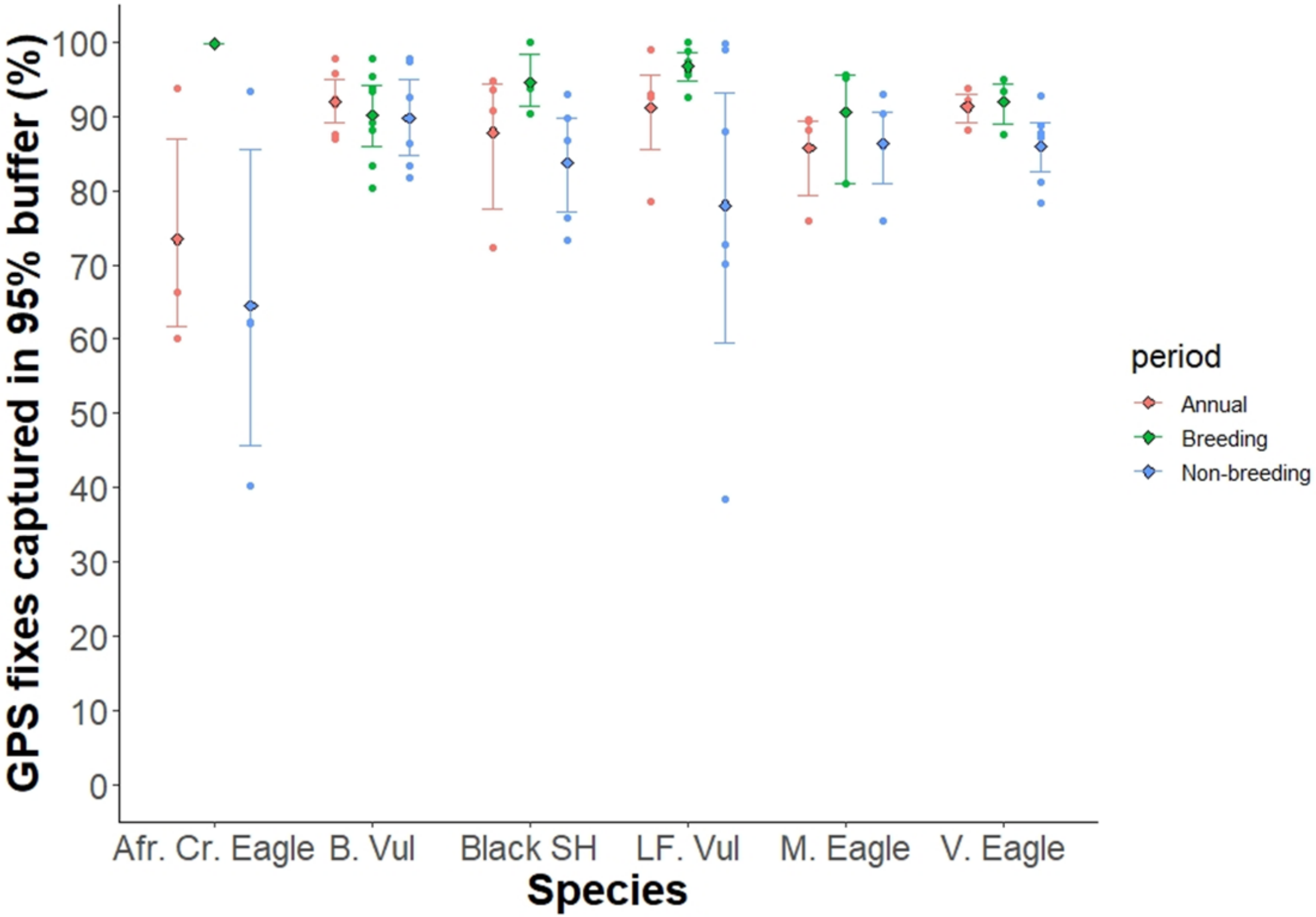
Bearded Vulture	Lehlwa	13370	1 (3)	4 (4)	3 (3)
Bearded Vulture	Pharoah	21114	7 (7)	5 (5)	5 (5)
Bearded Vulture	Sphinx	3498	1 (2)	2 (2)	1 (1)
Bearded Vulture	Springbok	16457	5 (6)	6 (6)	6 (6)
Lappet-faced Vulture	BK1LF	2179	1 (3)	1 (2)	2 (2)
Lappet-faced Vulture	BK2LF	2207	1 (3)	2 (2)	2 (2)
Lappet-faced Vulture	BK3LF	2214	1 (2)	1 (1)	1 (2)
Lappet-faced Vulture	GR1LF	4193	2 (2)	2 (2)	1 (2)
Lappet-faced Vulture	LE1LF	3890	2 (3)	1 (2)	2 (2)
Lappet-faced Vulture	SA1LF	9618	2 (2)	2 (2)	2 (2)
Martial Eagle	G32519	18792	4 (4)	2 (2)	2 (3)
Martial Eagle	G32554	11475	5 (5)	3 (3)	3 (4)
Martial Eagle*	G32555*	2416*	0 (2) *	0 (1) *	0 (1) *
Martial Eagle	G34491	12275	3 (3)	1 (1)	2 (2)
Martial Eagle	G34492	6782	2 (2)	0 (1)	1 (1)
Martial Eagle*	G34495*	398*	0 (1) *	0 (1) *	0(1) *
Verreaux's eagle	ann	8577	2 (2)	1 (2)	1 (2)
Verreaux's eagle	ber	3264	0 (2)	0 (1)	1 (1)
Verreaux's eagle*	cas*	1579*	0 (1) *	0 (1) *	0 (0) *
Verreaux's eagle	kat	3232	0 (2)	0 (1)	1 (1)
Verreaux's eagle	mag	5394	2 (2)	2 (2)	1 (1)
Verreaux's eagle	sto	5248	2 (2)	2 (2)	2 (2)
Verreaux's eagle	tre	8240	2 (3)	2 (3)	2 (2)

Verreaux's eagle	uil	1620	1 (1)	0 (1)	1 (1)

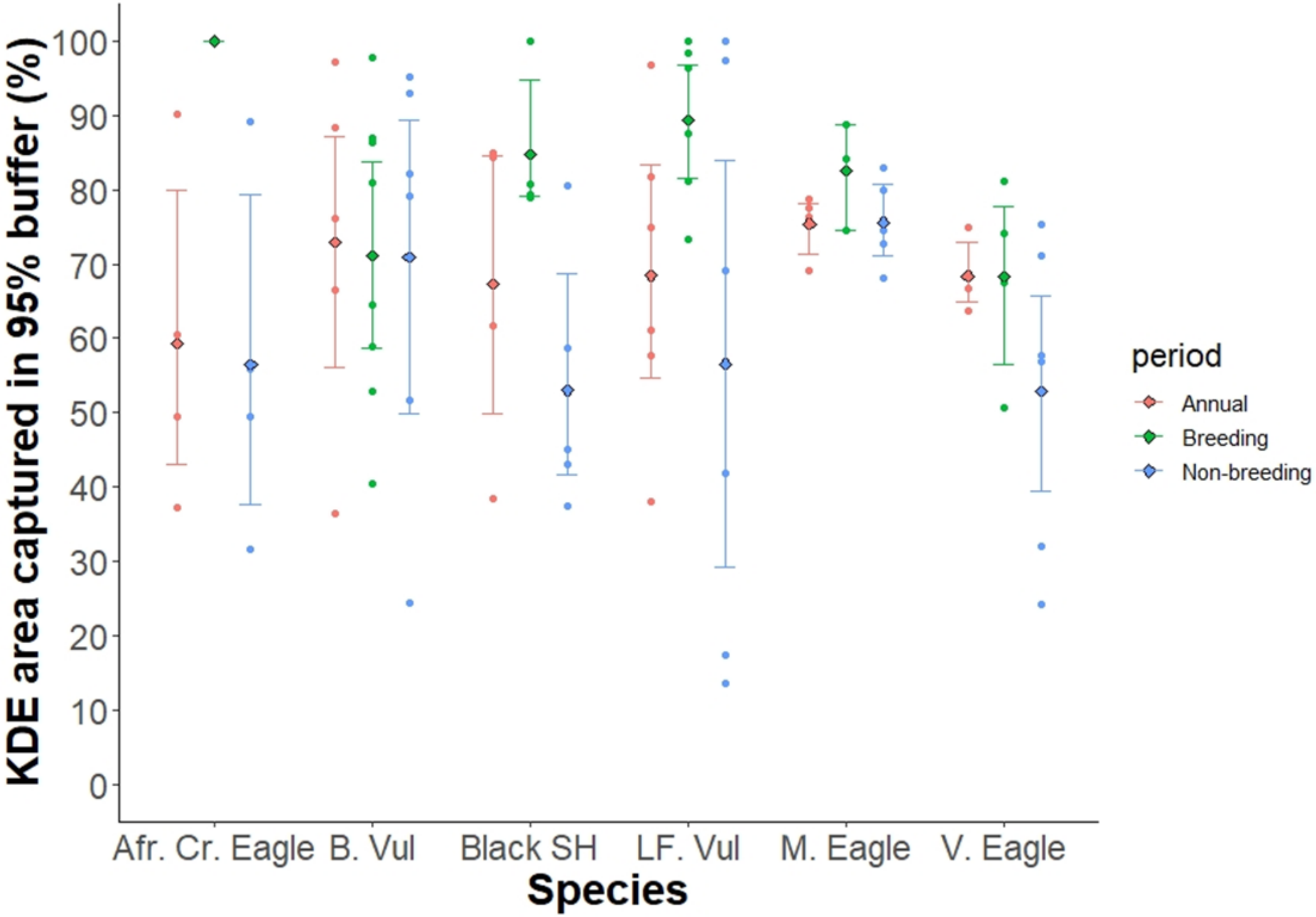
ID	YEAR	YEAR HR	INDIV. MEAN YEAR	BREEDING SEASON	MEAN BREEDING SEASON	NON-BREEDING SEASON	MEAN NON-BREEDING SEASON
A	1	1a	mean A	br		nb	
	2	2a		br		nb	
	3	3a		br		nb	
	4	4a		br		nb	
	5	5a		br	mean.br A	nb	mean.nb A
B	1	1b	mean B	br		nb	
	2	2b		-		nb	
	3	3b		br	mean.br B	-	mean.nb B
C	1	1c	mean C	br	mean.br C	nb	mean.nb C
D	1	1d	mean D	-		nb	
	2	2d		br		nb	
	3	3d		br	mean.br D	nb	mean.nb D
	Ave. HR		**km2**	**Ave. BR**	**Mean.BR**	**Ave. NB**	**Mean.NB**
	Buffer radius		**km**				



Appendix figure 1: A simplified version of the methodology of the construction of the Average Species Home Range and Buffer circle. The buffer circle used for the annual, breeding season and non-breeding season were the same size and species-specific. The differences in the size of the buffer in the demonstrated image is due to scaling when applied to the time period.



Appendix figure 2: The comparison of the three different breeding statuses and the proportion of GPS fixes that was captured by each species' 95% buffer circle. The mean proportion of the fixes captured is indicated by the black-lined diamond, with the 95% confidence interval present as error bars on both sides.



Appendix Figure 3: The comparison of the three different breeding statuses and the proportion of the 95% kernel area that was captured by each species' 95% buffer circle. The mean proportion of the fixes captured is indicated by the black-lined diamond, with the 95% confidence interval present as error bars on both sides.

Appendix Table 2: The mean area and 95% confidence interval of the 95% kernel captured by the 95% buffer (1.0) and other buffer circles relative to it in size (0.0 – 3.0). Each species was given an average area with the relative buffer circle, which was used to create the graphs that depict at which point the buffer circle captures 95% of the home range of the species (Figure 3a – c).

Species	Relative Buffer Radius	Area in Buffer (%)	Confidence Interval (95%)
African Crowned Eagle	0	0	0
African Crowned Eagle	0.1	1	1
African Crowned Eagle	0.25	7	5
African Crowned Eagle	0.5	24	14
African Crowned Eagle	0.75	41	27
African Crowned Eagle	1	59	36
African Crowned Eagle	1.5	85	26
African Crowned Eagle	2	96	11
African Crowned Eagle	2.5	99	2
African Crowned Eagle	3	100	0
Bearded Vulture	0	0	0
Bearded Vulture	0.1	1	1
Bearded Vulture	0.25	9	4
Bearded Vulture	0.5	33	15
Bearded Vulture	0.75	56	21
Bearded Vulture	1	73	22
Bearded Vulture	1.5	89	15
Bearded Vulture	2	96	8
Bearded Vulture	2.5	98	5
Bearded Vulture	3	98	4
Black Sparrowhawk	0	0	0
Black Sparrowhawk	0.1	2	2
Black Sparrowhawk	0.25	11	15
Black Sparrowhawk	0.5	37	41

Black Sparrowhawk	0.75	55	41
Black Sparrowhawk	1	67	35
Black Sparrowhawk	1.5	83	26
Black Sparrowhawk	2	94	17
Black Sparrowhawk	2.5	98	5
Black Sparrowhawk	3	100	1
Lappet-faced Vulture	0	0	0
Lappet-faced Vulture	0.1	3	3
Lappet-faced Vulture	0.25	13	11
Lappet-faced Vulture	0.5	35	19
Lappet-faced Vulture	0.75	54	23
Lappet-faced Vulture	1	68	22
Lappet-faced Vulture	1.5	77	18
Lappet-faced Vulture	2	81	18
Lappet-faced Vulture	2.5	84	17
Lappet-faced Vulture	3	85	16
Martial Eagle	0	0	0
Martial Eagle	0.1	1	0
Martial Eagle	0.25	7	1
Martial Eagle	0.5	26	4
Martial Eagle	0.75	52	5
Martial Eagle	1	75	7
Martial Eagle	1.5	97	4
Martial Eagle	2	100	0
Martial Eagle	2.5	100	0
Martial Eagle	3	100	0
Verreaux's Eagle	0	0	0
Verreaux's Eagle	0.1	1	0
Verreaux's Eagle	0.25	7	3
Verreaux's Eagle	0.5	26	10
Verreaux's Eagle	0.75	48	9

Verreaux's Eagle	1	68	8
Verreaux's Eagle	1.5	97	4
Verreaux's Eagle	2	100	0
Verreaux's Eagle	2.5	100	0
Verreaux's Eagle	3	100	0

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