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Home range sizes of Nankeen kestrels in South Australia across the annual cycle

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Abstract

Raptors are declining worldwide at a fast pace, especially in the Southern Hemisphere. Conservation efforts require an understanding of how species are coping with a rapidly urbanizing environment, yet there is a paucity of studies investigating raptors in the Southern Hemisphere. This study aims to determine, for the first time, the space use of Nankeen kestrels *Falco cenchroides* in different degrees of urban habitat across a whole annual cycle. We tagged twelve Nankeen kestrels with GPS loggers, providing robust and fine-scale data for ten individuals. This allowed us to compare individual space use (based on kernel density estimators; hereafter "home range") between Nankeen kestrels in relation to the urbanization gradient, but also seasonal changes and between sexes. Our results indicate no correlation between home range size and urbanization gradient, possible foray flights for five individuals and a slight indication that males roam wider than females (albeit not statistically significant). Nankeen kestrels in Australia seem to have relatively large home range sizes compared to similar-sized kestrel species on other continents. This phenomenon may be due to new and more accurate tracking technology in the form of high resolution spatio-temporal GPS data and longer tracking periods, which might allow the detection of more extensive spatial behavior, such as possible foray flights.

Keywords: Urban raptor, Falco cenchroides, home range, utilization distribution, breeding season, non-breeding season, urbanization, artificial light at night, ALAN, GPS, foray behavior, conservation buffers.

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Introduction

Natural habitats are rapidly and globally changing due to human activity and land transformation which highly affects wildlife (Sodhi & Ehrlich, 2010). Raptors, situated in high trophic levels, are especially affected (Kettel et al., 2018) and declining worldwide (McClure et al., 2018). In general, smaller raptors seem to have greater urban tolerance than larger species (Cooper et al., 2022; Headland et al., 2023). The focus species of this study, the Nankeen kestrel *Falco cenchroides* shows a slight displacement response towards urbanization but can inhabit urban areas in low population numbers (Headland et al., 2023). To protect and conserve wildlife in human modified landscapes, there is a need to understand its ability to cope with the relatively new urban habitat and whether it provides a suitable living space or not. The use of GPS data allows for the precise tracing of a raptor's movement within a temporal time frame (Kolowski et al., 2023). This helps to understand what specific environmental characteristics and resources a raptor needs (Horne et al., 2008). With enough GPS data a home range size can be calculated, which is a proper starting point for determining what area a bird will probably use during its lifespan, which should include resources, the need to secure a territory and successfully raising offspring (Horne et al., 2008) to ensure population viability.

What is a home range and why is it important?

A home range is originally described as:

> …that area traversed by the individual in its normal activities of food gathering, mating, and caring for young. Occasional ventures outside the area, perhaps exploratory in nature, should not be considered part of the home range. (Burt, 1943).

Therefore, the home range of an animal can only be calculated if it shows range residency behavior (Spencer et al., 1990). A fully fledged kestrel first needs to explore different sites until it finds a suitable territory (Village, 1990). During this period of dispersal, the space used by an individual does not fit the definition of a home range. Instead, the term 'utilization distribution' is more appropriate, which describes space use as a probability distribution (Powell & Mitchell, 2012). The utilization distribution can provide insights into an animal's resource selection and indicates core areas of usage depending on visitation frequencies (Powell & Mitchell, 2012). By combining this information with randomized landscape data its preferences and needs can be derived and thus generalized (Horne et al., 2008). If the location-time series underlying the utilization distribution become long enough and incorporates different stages in the annual or life cycle, a utilization distribution can fulfil the criteria to be termed home range (Powell & Mitchell, 2012). Due to technical and/or logistic limitations, the term home range nonetheless remains widely used and is often understood in a loose reference to the area a GPS tagged individual has been observed in during the time of the study period (Casagrande et al., 2008; Cunningham, 2013; Løken, 2009).

Challenges and limitations of home range studies

To date, there has not yet been a study quantifying home range sizes or utilization distributions of Nankeen kestrels. In general, there is a paucity of data on urban raptors, and on raptors in the Southern Hemisphere, especially concerning smaller species (Table 1). Most studies work with fewer than 100 fixed positions per individual and a relatively short time frame, typically capturing (part of) the breeding season (Cunningham, 2013; Kang et al., 2015; Løken, 2009; Riegert et al., 2007). This is due to methodological constraints:

I. The power-to-weight ratio limits tracking studies to larger species and shorter tracking periods (White & Garrott, 1990). This limitation is slowly changing due to the development of smaller units and batteries powered by solar panels on the tracker (e.g. Milsar Nano Tags). For example a recent study conducted in North Virginia has used solar powered GPS loggers to track female American kestrels *Falco sparverius* throughout their annual activities, whereby data has been collected via a remote base station (Kolowski et al., 2023). This technology facilitates a more accurate understanding of the bird's movements. Its results have shown that some female kestrels exhibit nonresident behavior during the breeding season while others shift their home range to another location after breeding season (Kolowski et al., 2023)

II. Reflections of radio signals from buildings and other infrastructure make radio-tracking in urban areas unreliable and labor intense, as these VHF-based methods require visual confirmation of the target animal ('homing in') or a triangulation of the signal to locate the target (Gerber et al., 2018; Millspaugh & Marzluff, 2001; White & Garrott, 1990). On-board data collection where location time-series are either downloaded via a base station (as above mention study by Kolowski et al., 2023) or transmitted via satellite or GSM network are creating the opportunity to track smaller raptor species in urban areas (Beck, 2024).

There are several methods established to quantify home range sizes and utilization distributions, most used are Minimum Convex Polygons (Mohr, 1947) and Kernel-Density Estimations (Seaman et al., 1998; Worton, 1989). The Minimum Convex Polygon (MCP) creates a polygon with the minimum area containing a certain percentage of GPS points, some authors use 100%, others 95% or even lower (Boyle et al., 2008; Cunningham, 2013; Mitchell, 2006). This is a very simple approach that assumes independence between observations and loses any information on the intensity of space use (Boyle et al., 2008). The Kernel-Density Estimation (KDE) calculates density of locations and then estimates the probability of encountering the animal at a given location (Worton, 1989), whereby 95% KDEs are commonly referred to as home ranges (Powell, 2000; Powell & Mitchell, 2012; Stewart, 2021), and 50% as core areas (Cunningham, 2013; Mitchell, 2006; Watson et al., 2014). The method assumes independence between observations and regular sampling and auto-correlation can result in underestimating the area (Fleming et al., 2015). Lately, the AKDE, an Autocorrelated Kernel Density Estimator, has received increasing attention as the method accounts for spatio-temporal autocorrelation (Fleming et al., 2015).

Table 1 presents data from published studies that are most likely comparable to what might be expected from home range sizes of Nankeen kestrels due to the close relatedness of the study species.

Table 1: Home range sizes and general data of kestrels similar to Nankeen kestrels regarding prey preferences and nest requirements.

Location / Environment	Species	Male / Female	Breeding status	No. of Ani-mals	Days recorded per animal	Data points per bird	Method used to quantify "home range size" in km2	Method	References
Southeastern Norway / Boreal forest	Falco tinnunculus	Female	Pre-fledging	6	2-6	49-141	0.39-3.88 / median 0.72 (95% MCP) 0.48-4.69 / median 0.98 (95% KDE)	Radio tracking VHF telemetry	(Cunningham, 2013)
Southeastern Norway / Boreal forest	Falco tinnunculus	Male	Chicks at least 14 days old	3	13-18	32-52	0.71, 1.9, 3.01 (95% MCP of 3)	Radio tracking VHF - Homing in then visual confirmation	(Løken, 2009)
South Korea / suburban environment	Falco tinnunculus	Mixed	Wintering and breeding season	6f. 8m	5-23 (in 6 months)	31-105	0.0354 - 0.3950 / mean = 0.1855 (Female 95% KDE) 0.2168–0.9902 / mean = 0.5845 (Male 95% KDE)	Visual identification with camera and natural features of the bird	(Kang et al., 2015)
North Virginia, USA / mostly agricultural and forestry area	Falco sparverius	Female	Breeding season (April to August)	12	39- 140	521- 2258	0.06-0.91 / mean = 0.32 (95% AKDE)	Solar powered GPS loggers with remote data download via base station	(Kolowski et al., 2023)
South of Czech Republic / mostly agricultural and ruderal areas around the city Budějovice including nests in the city	Falco tinnunculus	Male	Chick rearing (May to July)	34	?	12-38	0.8-25 / mean = 7.2 (100% MCP – calculated hunting range size, nest site in city center was excluded)	Visual verification with 7x binoculars of all locations – wing tagged birds and some with radio telemetry	(Riegert et al., 2007)
North of Italy / mostly grasslands and intensive agricultural fields	Falco tinnunculus	Male	Breeding season (starting end of March)	15	At least 45h of hunting of each Bird	?	0.28-1.42 / mean = 0.74 (100% MCP)	Radio transmitter on tail feathers. Only visual confirmation included in data	(Casagrande et al., 2008)

Although some studies have investigated home range sizes of kestrels similar to the Nankeen kestrel, there is a paucity on this subject for urban living kestrels.

Relations of raptors to the urban environment

Urban areas are often seen as deprived environments with great loss in biodiversity (Solaro, 2018). The composition of species in urban areas is subject to change, primarily as a consequence of alterations in the availability of resources through humans (Solaro, 2018). The changed composition and abundance of prey species, and therefore prey availability, largely determines the success of raptors (Kettel et al., 2018). For instance, high densities of pigeons support high numbers of avian specialists, such as Peregrine falcons (*Falco peregrinus*; Kettel et al., 2018), Black sparrowhawks (*Accipiter melanoleucus*; Suri et al., 2017), or Northern goshawks (*Accipiter gentilis*; Rutz, 2006), while low numbers of diurnal mammals might create an ecological trap or habitat sink for mammalian specialists (Kettel et al., 2018; Sumasgutner et al., 2014). Because of the rapidly changing environment, adaptability seems to be particularly valuable for urban raptors (Dykstra, 2018), either in a flexibility of prey type (Kübler et al., 2005; Solaro, 2018; Sumasgutner et al., 2013), or in flexibility in their daily or seasonal movement patterns (Riegert et al., 2007). The utilization distribution of the animal might consist of a breeding and a hunting area with a larger commute in between (Riegert et al., 2007). This has been documented for example in Eurasian kestrels in České Budějovice, where urban breeding males commute daily to a rural hunting site (Riegert et al., 2007). Another option is partial migration, whereby the urban breeding population is migratory whereas the rural breeding population remains largely resident in an area all-year-round (Warkentin et al., 1990). This is suspected of Eurasian kestrels in Vienna, where the city is only occupied during the breeding season, with little knowledge where urban kestrels migrate to during the non-breeding season (Huchler et al., 2020).

Breeding seasons on the Southern Hemisphere

The timing of breeding seasons in the Northern Hemisphere works differently from that in the Southern Hemisphere. Generally, the two most important factors determining the breeding onset are weather conditions (Charmantier et al., 2008; Visser et al., 2009) and food abundance (Verboven et al., 2001). Due to the strong seasonality of the environment, there might be only a very short and synchronized window for breeding onset in the far north (Dickey et al., 2008). On the other hand, a less pronounced seasonality enables birds to breed within a longer, less synchronized timeframe (Robb et al., 2008). Compared to the Northern

Hemisphere, breeding attempts in the Southern Hemisphere are more widely dispersed over time, especially in coastal regions where environmental conditions tend to be less variable (Garcia-Heras et al., 2016). For example, Black harriers (*Circus maurus*) in coastal regions of South Africa start their brood between May and December, although most breeding onsets happen between July and October (Garcia-Heras et al., 2016). For the Nankeen kestrel recorded clutch initiation dates are not that far spread, but data is limited to a few individuals and areas only (Bollen, 1990; Paull, 1991; Stewart, 2021). Clutch initiation has been observed at 28th September (Bollen, 1990) and otherwise guessed through appearance of nestlings or behavior of the female between early October and early November (Bollen, 1990; Mo, 2019; Paull, 1991; Stewart, 2021). Incubation time is between 28 and 31 days (Olsen & Baker, 2001; Paull, 1991) and nestling period is approximately 26 to 35 days (Stewart, 2021). Although breeding onset is temporally wider spread on the Southern Hemisphere compared to the Northern Hemisphere (Dickey et al., 2008; Garcia-Heras et al., 2016; Lof et al., 2012; Robb et al., 2008), Nankeen kestrels seem to have a relatively short breeding period with clutch initiation spread within one month (Bollen, 1990; Mo, 2019; Olsen & Baker, 2001; Paull, 1991; Stewart, 2021). With regard to the differences in home range size between the breeding and non-breeding seasons of the Nankeen kestrel, the only viable approach is to consider studies of raptors in the Northern Hemisphere due to the paucity of studies on the Southern Hemisphere. The mean home range size of some raptors seems to be similar or slightly smaller during the energy demanding breeding season (Kolowski et al., 2023; Perona et al., 2019; Sumasgutner et al., 2016), while other studies have found smaller home range sizes only for females, and larger home range sizes for males (Kang et al., 2015), or generally larger home range sizes during breeding season compared to non-breeding season (Chiang et al., 2019).

Aim of this study

Firstly, the aim of this study is to generate, for the first time, high-resolution location data for Nankeen kestrels in Australia and then compare home range sizes between rural and urban Nankeen kestrels to understand their space requirements in the urbanizing world of the Global South. We hypothesize that the home range sizes of urban Nankeen kestrels are smaller or similar compared to rural ones albeit to date only studies of similar kestrels on the Northern Hemisphere exist supporting this hypothesis (Casagrande et al., 2008; Cunningham, 2013; Kang et al., 2015; Løken, 2009; Riegert et al., 2007). In order to further utilize the urbanization calculations of our study design, we also intend to assess the efficacy of the method of utilizing mean circular buffers to calculate specific characteristics on a population level, which is a common practice in conservation efforts (Murgatroyd et al., 2021; Venter et al., 2019; Watson et al., 2014).

Secondly, this study aims to shed light on how the utilization distribution of Nankeen kestrels changes across the annual cycle, between breeding and non-breeding season, as well as between females and males. Reviewing the literature results most likely comparable to the Nankeen kestrel, we hypothesize that utilization distributions of female Nankeen kestrels are smaller in size during breeding season and males utilization distribution sizes remain at similar sizes. During the breeding season, it is typical for male kestrels to provide the majority of the food for the females and chicks, while the female remains largely bound to the nest during the incubation and early nestling period (Balgooyen, 1976; Riegert et al., 2007) – what we also expect to see in Nankeen kestrels. To test our hypotheses, we collected high-resolution spatio-temporal GPS data from tagged male and female kestrels over a whole year to determine home range sizes, seasonal differences in utilization distribution sizes and differences between sexes.

Methods

Study species

The Nankeen kestrel is a relatively small raptor (Olsen & Olsen, 1987). Its diet includes a large number of invertebrates. However, vertebrates account for approximately 70% to 85% of the biomass (Fuentes et al., 2024; Olsen et al., 1978) of its prey, which is particularly pronounced during breeding season (Stewart, 2021). Birds represent between 22% and 67% of the biomass of its diet (Fuentes et al., 2024; Olsen et al., 1978). Nankeen kestrels show a slight displacement response to urbanization (Headland et al., 2023). For these reasons, the Nankeen kestrel is an ideal subject for this study.

Study area and tagging

Adelaide is the capital city of South Australia and is home to around 1.37 million people. Twelve Nankeen kestrels were captured with Bal-chatri traps in and around Adelaide and the nest sites were categorized as rural, suburban and urban by a rough estimation of the surrounding area. Both females and males were tagged with GPS loggers “Milsar Nano Tags”, which weigh 3.4 grams. Loggers were mounted on leg loop harnesses for females and backpack harnesses for males. The combined weight of GPS loggers with either a leg loop harness or a backpack harness is approximately 5.05 g and 4.62 g, respectively. The mean weight of female Nankeen kestrels is 181.5 ± 1.1 g; n=135, while that of male Nankeen kestrels is 161.1 ± 0.6 g; n=180 (Olsen & Olsen, 1987). The attachment weight represents approximately 2.8% of body weight for females and 2.9% for males, respectively. This is well below the recommended maximum weight of 5% (White & Garrott, 1990). Harnesses are expected to stay on the bird for two to three years and then fall off, releasing the entire unit as a whole. The loggers provided data in form of GPS locations for space use, which were collected and stored throughout the whole carrying time because of solar recharge. Download of the data required approaching the tagged Nankeen kestrel with a download base station which connected to the logger via radio signal from up to 500 m in open landscapes. Data download was done on territory on a regular basis (approx. monthly; Table 2). All data are stored on the Movebank repository (www.movebank.org), Movebank ID 3416661275, Project "Movement Ecology of Nankeen kestrels in South Australia".

On the following Table 2 a summary of the basic data collection is displayed. We captured four female and eight male Nankeen kestrels and downloaded between five and 6032 GPS fixes of mounted loggers. Nankeen kestrel Animal ID 3 got hit by a car shortly after the logger was mounted and its female Animal ID 2 abandoned the nest thereafter, why we do not have any data of these Nankeen kestrels after November 13th, 2022. Nankeen kestrel Animal ID 8 was seen copulating multiple times, but then left the territory, so there is no data. Nankeen kestrel Animal ID 10 was recaptured and the logger was removed due to a malfunction of the backpack harness, which could have posed a potential risk to the kestrel. In order to avoid any further stress to the animal during the sensitive nestling phase we decided against remounting the logger.

Table 2: Basic deployment data of monitored Nankeen kestrels.
**Estimated back from hatching.*
***Estimated back from chick appearance.*

Animal ID	Sex	Habitat	Catch date	Latest GPS location	Number of GPS locations	Breeding status
1	Male	Rural	2022.10.25.	2022.11.10.	218	Unknown
2	Female	Rural	2022.10.23.	2022.11.13.	5 / left nest	Unknown
3	Male	Rural	2022.10.27.	2022.11.10.	313 / deceased	Unknown
4	Male	Rural	2022.11.09.	2023.06.24.	1589	Unknown
5	Male	Rural	2022.11.09.	2023.07.10.	4728	Unknown
6	Female	Rural	2022.11.02.	2023.12.16.	2710	Unknown
7	Male	Suburban	2022.11.04.	2023.12.16.	4968	Clutch initiation mid to late September*
8	Female	Rural	2022.10.26.	-	Left nest	Unknown
9	Male	Rural	2022.10.26.	2022.11.10.	216	Unknown
10	Male	Suburban	2022.11.01.	2023.02.21.	1863 / tag removed	Clutch initiation mid to late October
11	Male	Urban	2022.10.20.	2023.12.19	6032	Clutch initiation late September**
12	Female	Urban	2022.11.07.	2023.12.19	1740	Clutch initiation late September**

Data analysis in R

During our work with R version 4.3.2 (R Core Team, 2023), we used several packages for a variety of purposes beside its basic functions. All packages are listed in Table 3 below including use cases.

Table 3: All R packages used in this study with a short description of use cases.

Used Packages	Short description of use case	Citation
car	This was used with the anova function for confirmation of model fitting.	(Fox & Weisberg, 2019)
CTMM	This was used for most the calculations described below.	(Calabrese et al., 2016)
dplyr	This was used in the process of saving our weighted Autocorrelation Kernel Density Estimation (wAKDE) files as an sf object.	(Wickham et al., 2023)
effects	This was used to visualize regression models.	(Fox & Weisberg, 2018)
exactextractr	This was used to intersect home range shapefiles and circular buffers with the Artificial Light At Night (ALAN) map.	(Baston, 2023)
ggplot2	This was used to visualize several objects throughout the process	(Wickham, 2016)
lme4	This was used as linear mixed model to control for repeated measures of territory.	(Bates et al., 2015)
rcartocolor	This was used to fill color in spat raster files of the shape files of home ranges.	(Nowosad, 2018)
sf	This was used to convert and save home range shapefiles of our calculated wAKDE files and to establish circular buffers for further calculations.	(Pebesma, 2018; Pebesma & Bivand, 2023)
terra	This was used to import the ALAN map in R and to save spat raster files.	(Hijmans, 2024)
units	This was used to set units to km in buffer calculations.	(Pebesma, 2018)

Analysis with CTMM package

Data was downloaded from Movebank (www.movebank.org) and then analyzed with the CTMM package in R (Calabrese et al., 2016). For best results the common method of calculating a KDE requires independent and evenly distributed GPS data (Fleming et al., 2015). However, modern GPS tags allow for very short location intervals, which leads to strong autocorrelated data and thus biased estimates (Fleming & Calabrese, 2017). To realize their full potential without thinning data, new methods are needed to calculate KDEs (Fleming et al., 2015) that correct for this increasing autocorrelation. The CTMM package (Calabrese et al., 2016) accounts for spatio-temporal autocorrelation and therefore it is possible to calculate an AKDE with high-resolution GPS data (Fleming et al., 2015). Furthermore, this method not only improves accuracy of the area estimate, but at the same time establishes more reliable confidence intervals than with previous methods (Fleming & Calabrese, 2017).

After removing invalid data entries from the .csv file containing the GPS data set, the .csv file was uploaded to Movebank. While outliers usually can be ignored with coarsely sampled data, it gets increasingly more important to remove outliers the more fine-scaled the data is (Fleming et al., 2021). Therefore, outliers were detected with the following Figures 1 and 3 and later removed, which is represented in Figures 2 and 4.

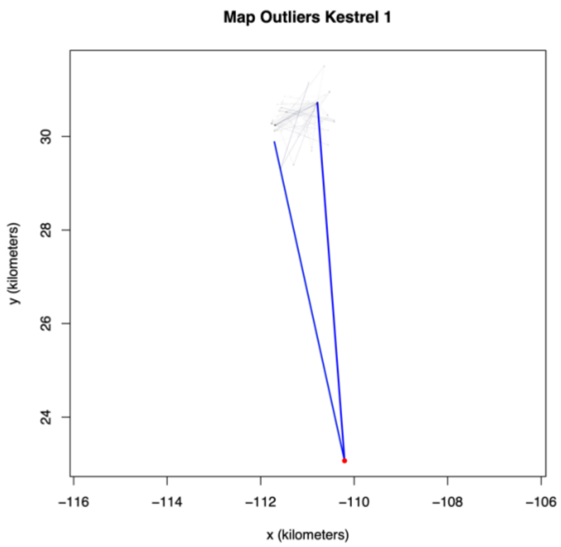

Figure 1

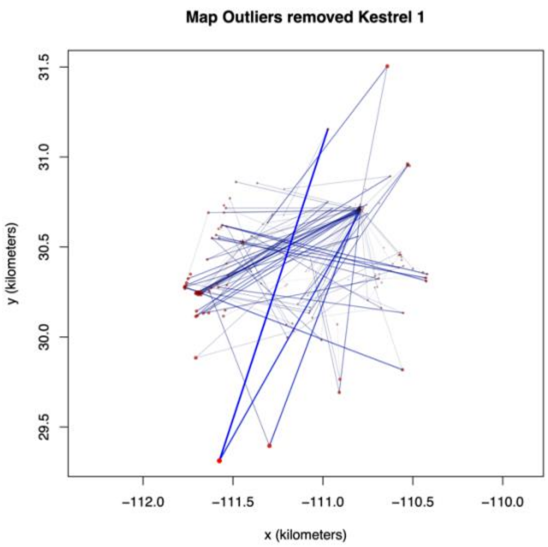

Figure 2

Figures 1 and 2, illustrated with the function outlie of the CTMM package (Calabrese et al., 2016), show a graphical representation of all GPS locations, highlighting possible outliers . Figure 1 shows an outlier that has been removed and Figure 2 serves as a control.

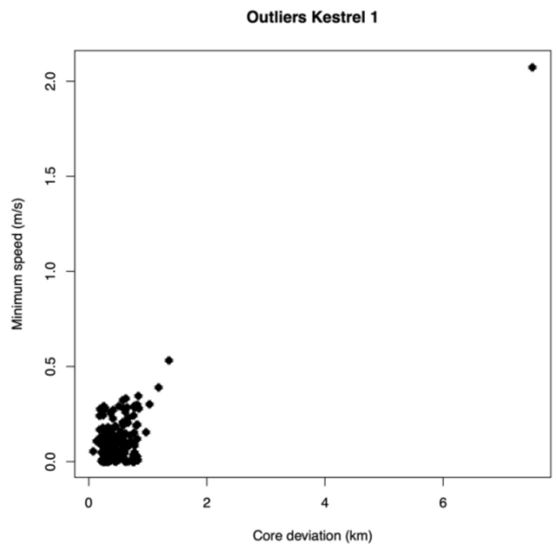

Figure 3

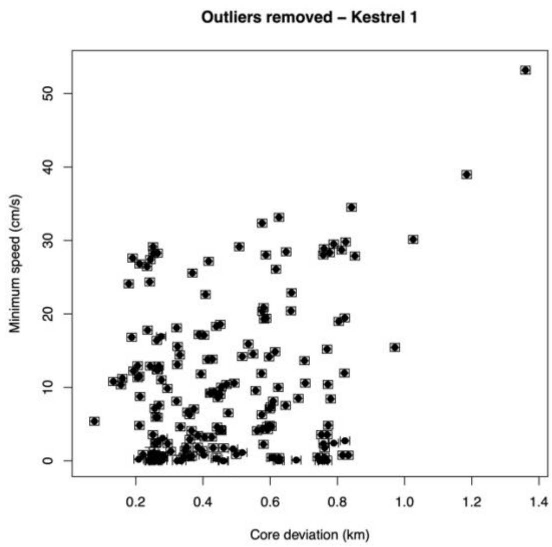

Figure 4

Figures 3 and 4, a plotted version of the function outlie of the CTMM package (Calabrese et al., 2016), show another graphical representation of all GPS locations. Outliers can be identified by speed and distance. Figure 3 shows the same outlier as above that has been removed and Figure 4 serves again as a control.

To derive a home range estimate, the animal needs to exhibit range residency, which means it uses certain areas consistently and repeatedly (Fleming & Calabrese, 2017). To analyze if that is the case, we examined the so-called variogram. It not only indicates if the animal is exhibiting range residency behavior, but also after which period of time this is the case, i.e., when the variogram stabilizes (Fleming et al., 2014). Range residency is stated in variograms in which the asymptote of the curve is horizontal (Fleming et al., 2014), which is the case for Figures 6 and 7. On the other hand, Figure 5 displays that Nankeen kestrel Animal ID 5 does not exhibit range residency behavior yet, because the asymptote to the curve does not flatten like in Figures 6 and 7. In case of a longer monitoring period, range residency behavior might establish itself and would then become visible as such.

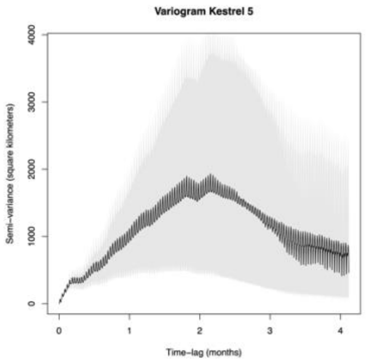

Figure 5

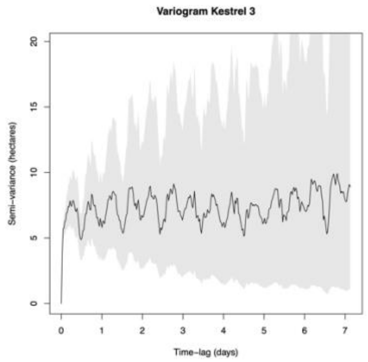

Figure 6

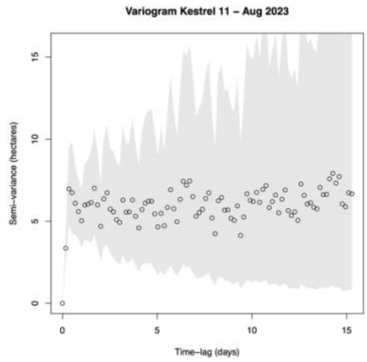

Figure 7

With the variogram, a function of the CTMM package (Calabrese et al., 2016), we can determine if the studied animal exhibits range residency behavior. Range residency behavior is displayed after a few days in Figures 6 and 7. Figures 5, 6 and 7 can be found in the Appendix in full size.

The subsequent step was to identify the most appropriate model for describing the data set and to determine the utilization distribution. The CTMM package (Calabrese et al., 2016) performs this function automatically. The optimal fitting models were selected from a set of five movement models: namely Independent Identically Distributed (IID), Brownian motion (BM), Ornstein-Uhlenbeck (OU), Integrated Ornstein-Uhlenbeck (IOU) and Ornstein-Uhlenbeck foraging (OUF) (Calabrese et al., 2016) – of which two models were applied. The IID model assumes independent and therefore uncorrelated data (Calabrese et al., 2016), whereas the OU model, similarly to the BM model, expresses a randomly searching animal in a uniform area but within a limited area (Fleming et al., 2014). Sampling irregularities and missing data can lead to wrong results if not accounted for (Fleming et al., 2018). To address this issue, an optimally weighted Autocorrelation Kernel Density Estimation (wAKDE) simulation was used, which resulted in a 95% wAKDE with confidence intervals (Fleming et al., 2018). The following examples of Figure 8 and Figure 9 illustrate a plotted version of the results with different extent of confidence intervals due to different amount of location data.

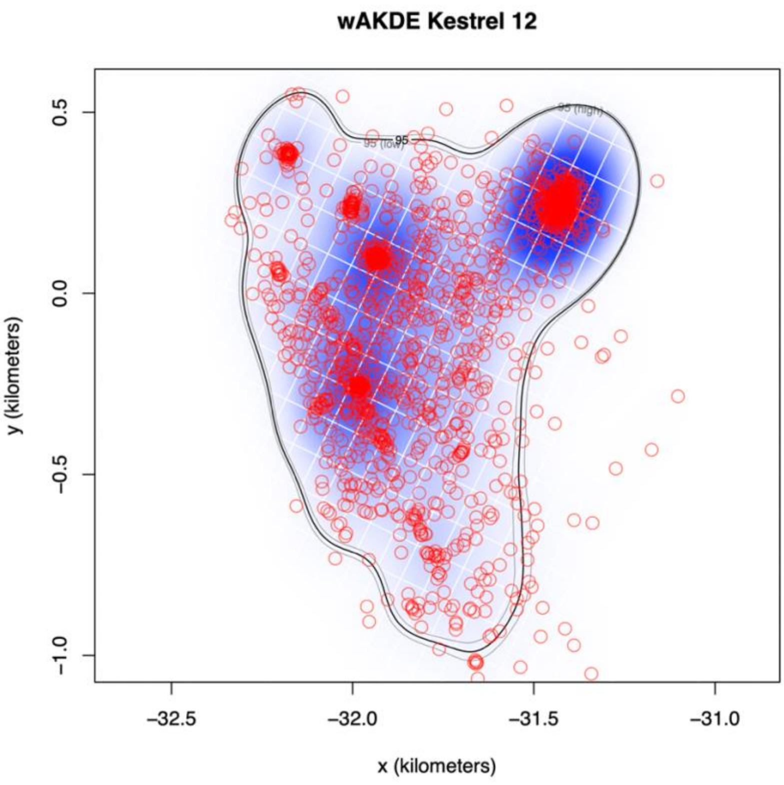

Figure 8

Figure 8 displays a wAKDE, a function of the CTMM package (Calabrese et al., 2016), of Nankeen kestrel Animal ID 12 with a high amount of fixed GPS location and therefore narrow confidence interval.

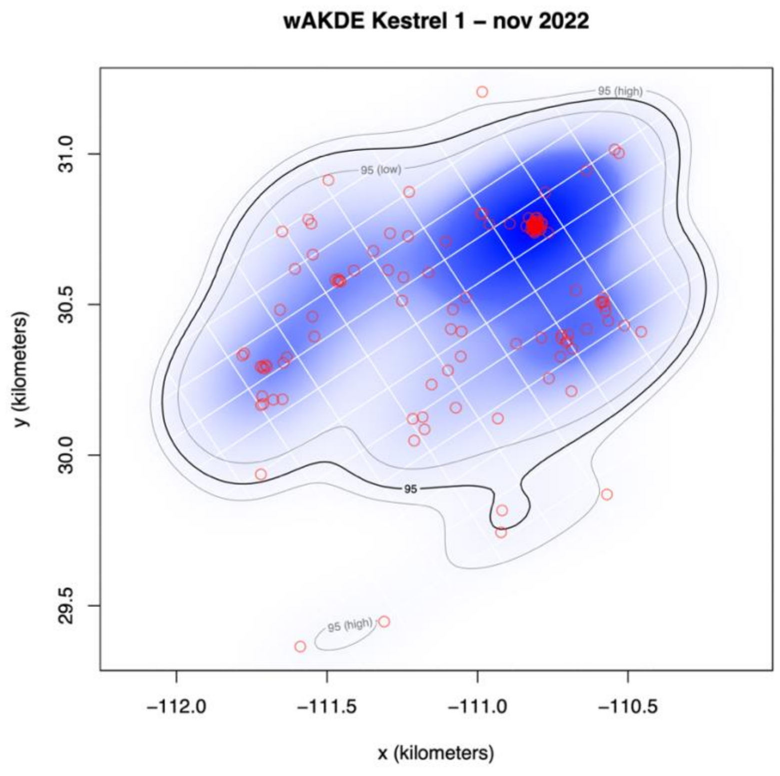

Figure 9

Figure 9 displays a wAKDE, a function of the CTMM package (Calabrese et al., 2016), of Nankeen kestrel Animal ID 1 in November 2022. Confidence intervals are much wider compared to Figure 8 due to less GPS data of a single month.

Modelling

We tried different models testing for correlations between wAKDE and either urbanization gradient – approximated using Artificial Light At Night (ALAN) calculation – or sex. The wAKDE was calculated with all data available for each Nankeen kestrel separately. Since we have two confound pairs sharing the same nest site, we had to correct for similarities in urbanization gradient and therefore used a linear mixed model with nest site ID as random factor.

Urbanization approximation through ALAN

Last but not least, the derived polygon of each wAKDE was saved in a raster file and intersected with Visible Infrared Imaging Radiometer Suite (VIIRS) night-time lights data (Elvidge et al., 2017) extracted from Google Earth Engine (Gorelick et al., 2017). We received digits measuring how much mean ALAN the areas of our Nankeen kestrels' home range estimates emitted in nanowatts per square centimeter per steradian (nW/cm2/sr). Several studies have demonstrated that ALAN can be used to quantify levels of urbanization (Elvidge et al., 2021; Pandey et al., 2013; Stathakis et al., 2015; Zhang & Seto, 2013) to a high level of 93% accuracy around the world (Zhang & Seto, 2013). Furthermore, we calculated a circular buffer equal to the mean home range size of all our Nankeen kestrels and derived ALAN values of the mean circular buffer around each nest site. We then compared the ALAN values from each polygon with the derived mean circular buffers with a linear regression function.

Changes in utilization distribution sizes over the course of a year

Given the uncertainty surrounding the precise timing of clutch initiation (Bollen, 1990; Mo, 2019; Olsen & Baker, 2001; Paull, 1991; Stewart, 2021), we opted to refrain from the conventional approach of calculating utilization distributions for the respective breeding season and non-breeding season in its entirety (Casagrande et al., 2008; Cunningham, 2013; Løken, 2009; Riegert et al., 2007). To gain better understanding of the changes in utilization distribution size over the course of the year, we instead split the data into chunks of months. While a month is an arbitrary period of time, it proofed to be long enough to capture sufficient GPS points (while two-weeks periods did not), and hence allowed to illustrate a finer-scale variation of space use across the annual cycle.

Exclusions of data

Nankeen kestrel Animal ID 5 was excluded from all home range analysis related topics due to its wandering behavior, which does not fit the definition of a home range (Burt, 1943). This was obvious when plotting GPS data and during the process of analyzing its variogram (Figure 5) with the CTMM-package (Calabrese et al., 2016). Furthermore, we excluded data of four months in the utilization distribution calculations over the course of the year due to the variogram indicating slight non-resident behavior and one additional month due to a lack of GPS data with only three locations available. All data – except for the cases noted above – were validated and included in the presented estimates. However, the confidence intervals of utilization distributions in five independent months are relatively wide, since the GPS data considered had less than 30 fixes per month. Exact sample sizes can be seen in the appendix in Table 7.

Results

Home range size – How much space do Nankeen kestrels use?

We gathered sufficient GPS fixes from nine out of twelve GPS tagged Nankeen kestrels. The best movement model underlying the resulting home range estimate was the OU anisotropic model, except for one female (Animal ID 12, IID anisotropic model). The home range sizes of males ranged from 0.858 km² to 14.577 km² and for females from 1.074 km² to 1.189 km². The mean and the median 95% wAKDE estimates were 4.138 km² and 1.637 km² respectively. In Table 4 further detail is displayed.

Table 4: Results from our GPS data calculations with the CTMM package (Calabrese et al., 2016) in R.

Animal ID	Sex	Optimal Model	95% wAKDE area in km²			Habitat
			Low	Estimated	High	
1	Male	OU anisotropic	1.409	1.637	1.881	Rural
3	Male	OU anisotropic	0.756	0.858	0.966	Rural
4	Male	OU anisotropic	3.727	3.955	4.189	Rural
6	Female	OU anisotropic	1.133	1.189	1.247	Rural
7	Male	OU anisotropic	13.891	14.577	15.279	Suburban
9	Male	OU anisotropic	7.435	8.644	9.941	Rural
10	Male	OU anisotropic	3.637	3.870	4.109	Suburban
11	Male	OU anisotropic	1.397	1.438	1.479	Urban
12	Female	IID anisotropic	1.024	1.074	1.125	Urban

For better understanding we illustrated the results from Table 4 in the following Figure 10. It displays the 95% wAKDE calculated with CTMM package including confidence intervals (Calabrese et al., 2016).

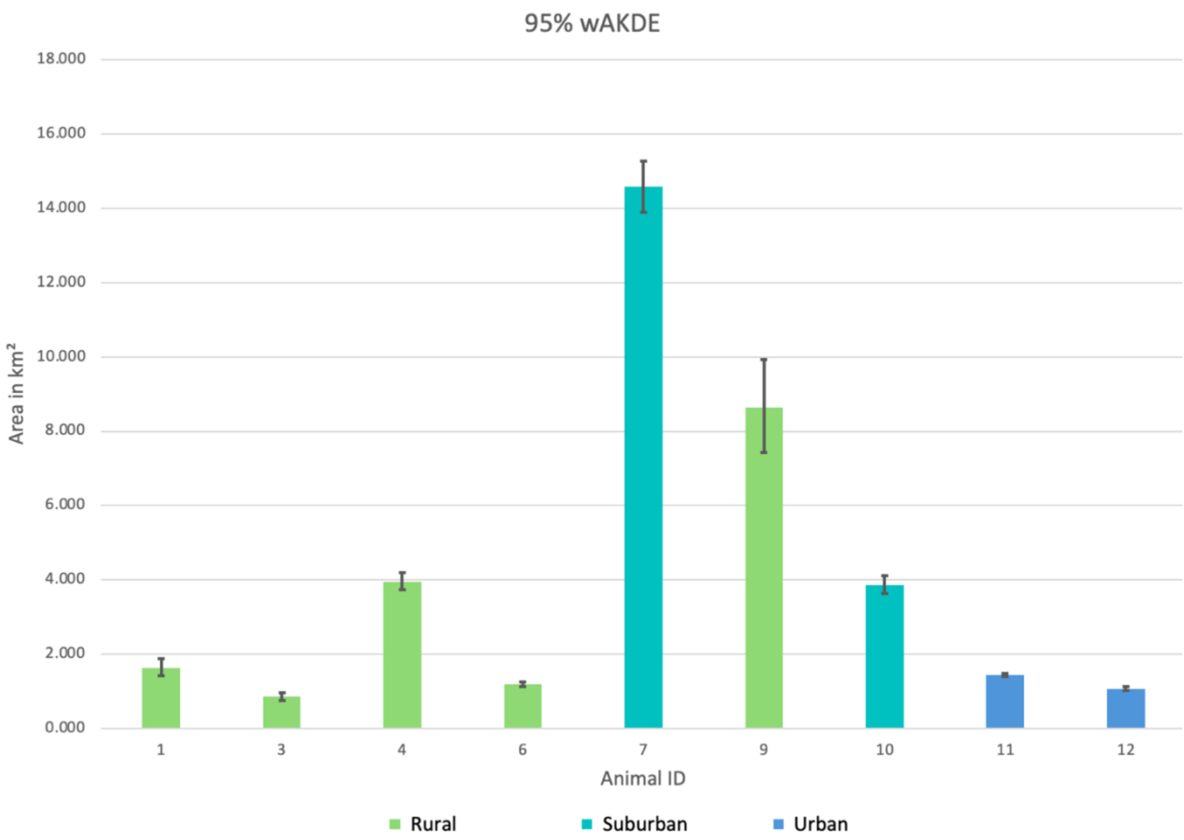

Figure 10
Graphical illustration of 95% wAKDE in km² with confidence intervals. Exact values can be found in Table 4.

Correlation between home range size, sexes and urbanization

Table 5 displays results we received from calculations with a linear mixed model. Values are a combination of the "Summary" and "Anova" function. Results indicate a tendency to larger home range sizes in males compared to females, although not significantly. Furthermore, no correlation between home range size and ALAN was found.

Table 5

Calculations with a linear mixed model (Bates et al., 2015). Values obtained from the Summary and Anova function (Fox & Weisberg, 2019).

**sex "female" was used as a reference category*

Fixed effects:	**Estimate**	**SE**	**t-value**	**Chi2**	**p-value**
(intercept)	3.74	2.63	1.42		
ALAN	-0.16	0.53	-0.31	0.09	0.7588
Sex (male)*	1.71	1.16	1.47	2.17	0.1410
Random effects:					
Groups	**Variance**	**SD**			
Territory	27.71	5.26			
Residual	1.36	1.17			

As displayed in Figure 11, results suggest that home range sizes of male Nankeen kestrels tend to be larger compared to females', but differences were not significant. Results, as shown in Figure 12, indicate no evidence of a correlation between home range size and ALAN, thus the urbanization gradient.

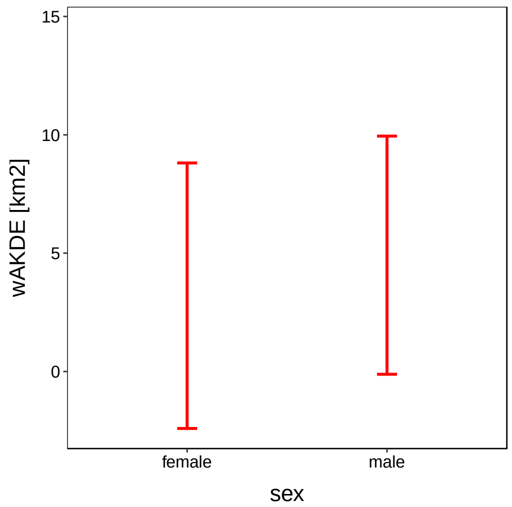

Figure 11

Home range sizes of males tend to be larger in size. Differences are not significant. Plotted with ggplot2 (Wickham, 2016).

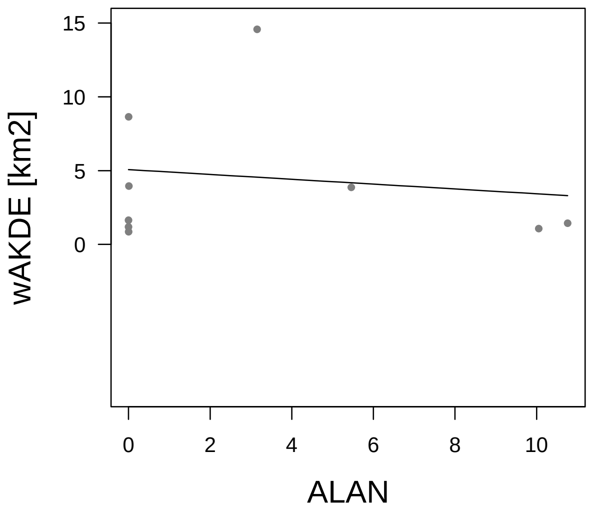

Figure 12

Results from calculations with a linear mixed model in R which concludes no correlation between home range sizes and urbanization gradient. Plotted with ggplot2 (Wickham, 2016).

Can mean circular buffers represent home range polygons?

Table 6 presents the results of the analysis conducted on the intersections between either wAKDE polygons or a mean circular buffer around each nest site with VIIRS night-time lights data (Elvidge et al., 2017). These values correspond to the mean amount of ALAN emitted from the respective area. As shown in Figure 13, results of a linear regression model stated 91% correlation of calculated ALAN values corresponding to either mean circular buffers or wAKDE polygons.

Table 6:
ALAN wAKDE polygon: *ALAN values calculated with the wAKDE polygon.*
ALAN Mean circular buffer: *ALAN values calculated with a circular buffer with mean size of wAKDE polygons. The dplyr, exactextractr, sf, terra and units packages were used in calculations for displayed results (Baston, 2023; Hijmans, 2024; Pebesma, 2018; Pebesma et al., 2016; Pebesma & Bivand, 2023; Wickham et al., 2023).*

Animal ID	Sex	wAKDE area in km² (Estimated 95%)	ALAN (nW/cm2/sr) wAKDE polygon	ALAN (nW/cm2/sr) Mean circular buffer (rad=1.018km)	Habitat
1	Male	1.637	0	0	Rural
3	Male	0.858	0	0.31	Rural
4	Male	3.955	0.0065	0	Rural
6	Female	1.189	0	0	Rural
7	Male	14.577	3.1513	1.52	Suburban
9	Male	8.644	0.0014	0.164	Rural
10	Male	3.870	5.4579	2.43	Suburban
11	Male	1.438	10.759	13.3	Urban
12	Female	1.074	10.053	13.3	Urban

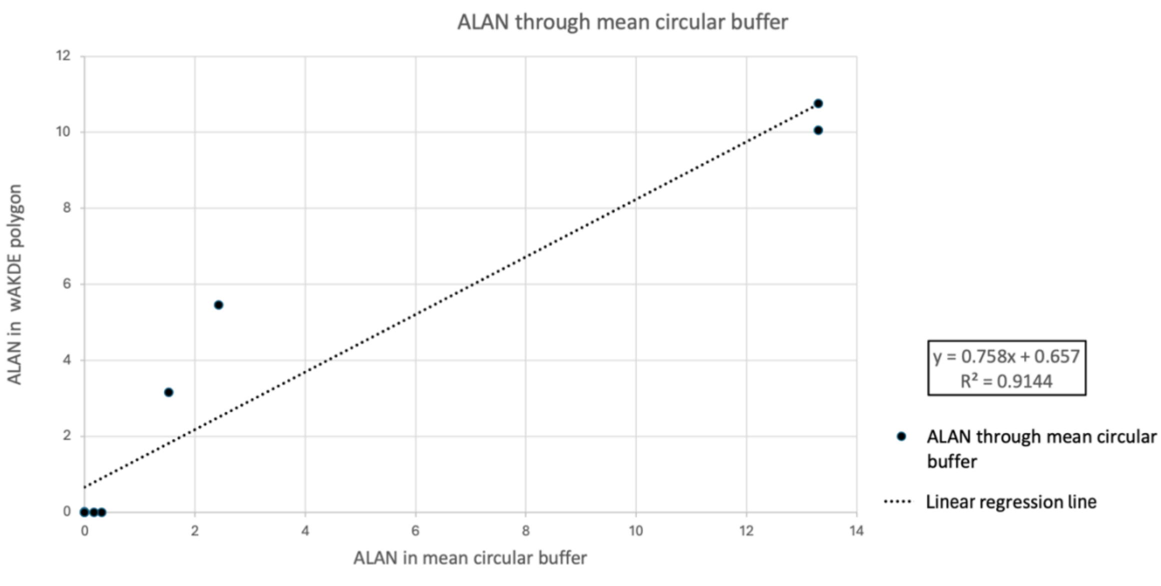

Figure 13
Correlation between ALAN values of mean circular buffers around each nest site and wAKDE polygons.

Possible patterns over the course of a year

Figure 14 shows that monthly utilization distributions were distinctly different in size over time. Figure 15 displays a visual representation of four Nankeen kestrels, with data spanning a year, in order to facilitate a more comprehensive understanding of the seasonal fluctuations observed. A Table with monthly split data is available in the Appendix (Table 7).

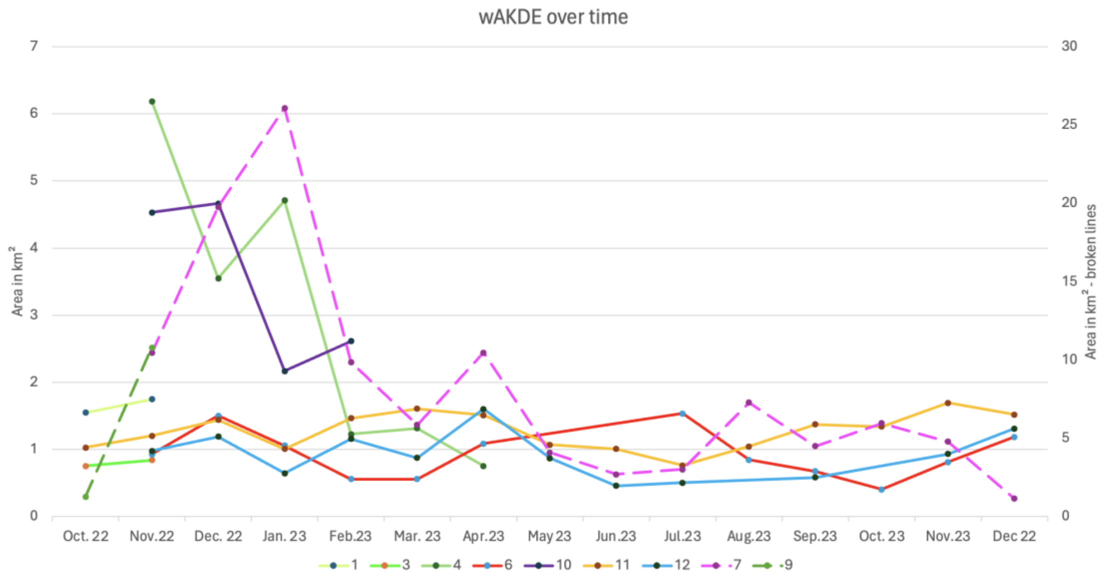

Figure 14

This Figure displays all utilization distributions of the included Nankeen kestrels. Broken lines belong to the second scale on the right side. Utilization distributions were calculated per month. Some months were excluded as shown in Table 7 in the Appendix due to the variogram indicating non-resident behavior or lack of sufficient GPS locations.

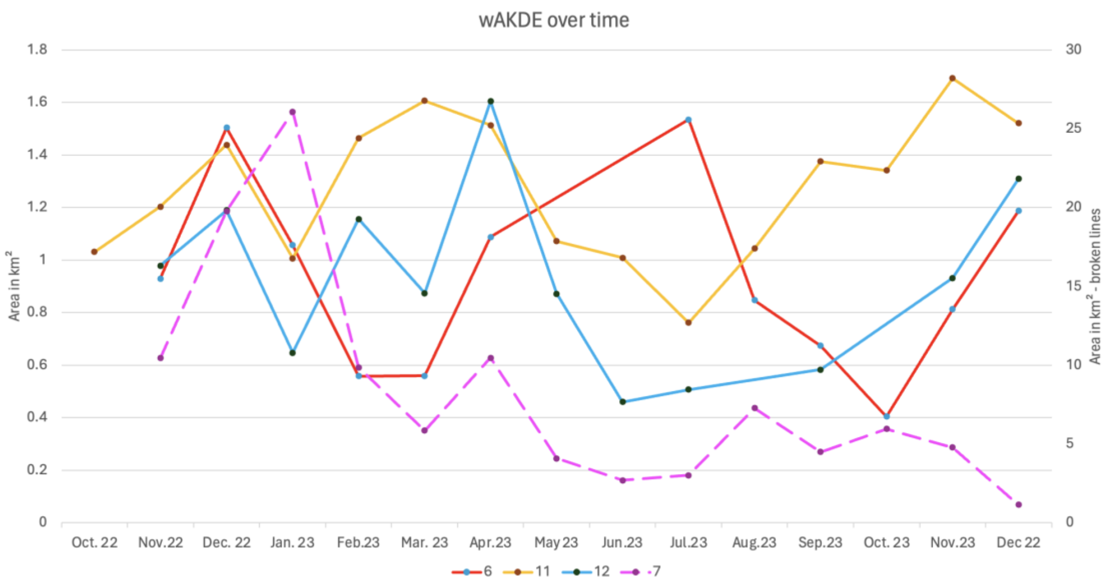

Figure 15

This Figure displays all utilization distributions of the Nankeen kestrels tracked throughout a whole year. Broken lines belong to the second scale on the right side. Utilization distributions were calculated per month. Some months were excluded as shown in Table 7 in the Appendix due to the variogram indicating non-resident behavior or lack of sufficient GPS locations.

Discussion

The sampling time frame of tracked Nankeen kestrels started on 23rd October 2022 and ended on 19th December 2024, therefore spanning more than a year. The home range sizes calculated with all available data (Table 4) ranged between 0.86 and 14.58 km². Following our results in Table 5 a possible correlation between home range size and sex was analyzed and results indicate that male home range sizes tend to be larger compared to females' (Figure 11, Table 5). Although all values in Table 5 support the tendency of larger home range sizes for males, these effects were not statistically significant. Furthermore, results in Figure 12 display that there was no correlation between wAKDE size and ALAN, which we used as a proxy to quantify urbanization. The linear regression model indicates a correlation of 91% between ALAN values calculated either with wAKDE polygons or mean circular buffers. At last, higher utilization distribution sizes between November and February suggest possible foray flights, which have been recorded in a similar-sized species that can occur in urban areas, the American kestrel (Kolowski et al., 2023).

Larger home range sizes for Nankeen kestrels?

Comparing the results of this study in Table 4 with results displayed in Table 1, it seems like the Nankeen kestrels had distinctly larger home range sizes compared to similar-sized kestrels in the Northern Hemisphere. The mean and median home range size for Nankeen kestrels was 4.138 and 1.637 km² respectively, which exceeds the home range sizes of each study reviewed: mean values in km² of 1.87 (Løken, 2009); f = 0.1855 and m = 0.5845 (Kang et al., 2015); 0.32 (Kolowski et al., 2023); 0.74 (Casagrande et al., 2008) and a median value in km² of 0.98 (Cunningham, 2013). There could be numerous, not mutually exclusive, explanations for this. For example, methodological differences allow for higher data accuracy and longer tracking periods, which tend to result in larger home range estimates (Morollón et al., 2022). Our applied method was able to capture more extensive movement behavior compared to previous studies that relied on less powerful tracking tools. However, Kolowski et al., (2023) have also worked with high-resolution GPS data, resulting in relatively small home range sizes, and have concluded that their home range estimates speak for a high-quality habitat. Study limitations have included a sex biased tracking effort (only female American kestrels were included) and the need to exclude longer foray flights from home range size calculations (Kolowski et al., 2023) – both might explain the smaller home range sizes reported for American kestrels than for Nankeen kestrels. These findings indicate that new state of the art

GPS tracking methods might lead to a more nuanced and precise understanding of spatio-temporal movement of relatively small raptors, which were previously unable to be tracked in such detail due to weight limitations. The high-resolution tracking technologies enable a more realistic utilization distribution estimation, which in turn allows for a more accurate assessment of space use and habitat within urbanized areas (Kolowski et al., 2023).

Urbanization – not a clear matter

Based on our literature search, we expected that urban Nankeen kestrels have smaller or similar home range sizes compared to rural conspecifics (Casagrande et al., 2008; Cunningham, 2013; Kang et al., 2015; Løken, 2009; Riegert et al., 2007). Our study showed however no such directional relationship between wAKDE size and ALAN. It is possible – albeit quite unlikely given the body of literature showing strong correlations between ALAN and other urban metrices (Elvidge et al., 2021; Pandey et al., 2013; Stathakis et al., 2015; Zhang & Seto, 2013) – that ALAN was a too coarse categorization to detect individual variance. Finer-scaled measures of light, or urban metrices closer related to specific resources that Nankeen kestrels use, might be more suitable. It was not possible to find better referenced ALAN values to categorize rural, suburban and urban landscapes. Instead, a combination of the on-site assessment and the calculated ALAN values to form the three categories above were used. The home range estimates with the highest ALAN values were those of a breeding pair (Animal IDs 11 and 12) living close to an airport in the city, and most of their activity took place on the large meadows of the airport area (Appendix Figure 16 and 17). Perhaps high ALAN values of aircraft runways are overestimating urbanization, thus compromising the corresponding results. On the other hand, lower home range sizes for urban living raptors have been determined mostly for avian specialists, such as Cooper hawks (Chiang et al., 2019; Mannan & Boal, 2000), Northern goshawks (Rutz, 2006) and Black sparrowhawks (Sumasgutner et al., 2016), which might be linked to their avian based diet and high pigeon density in built-up areas (Boal, 1997; Kettel et al., 2018). This might therefore also explain the seen discrepancies between our predictions and the presented results. Although it is possible to calculate the urbanization gradient of several individual Nankeen kestrels, it is a time-consuming process, therefore an alternative method is required to estimate the entire population.

Estimating urbanization of entire populations

It is unrealistic to tag and monitor an entire population in order to make completely informed conservational decisions. For this reason, it has been a common practice to calculate mean circular buffers and then apply these buffers with the nest representing the center point of an individual's territory (Murgatroyd et al., 2021; Venter et al., 2019; Watson et al., 2014). However, the question remains how accurate these mean circular buffers represent each individual in an entire population. To evaluate this idea for Nankeen kestrels specifically, we used mean circular buffers with a radius of r = 1.018 km, and intersected the resulting area with VIIRS night-time lights data (Elvidge et al., 2017). The results in Figure 13 indicate a 91% correlation between the ALAN values estimated for the mean circular buffers and the ALAN values quantified for the actual home rages based on wAKDE polygons. This high correlation supports the common method, whereby mean circular buffers are used to assess the degree of urbanization in an individual's territory. However, with an area of 3.256 km² within the circular buffer, only 56% of the included Nankeen kestrels wAKDE areas were accounted for. To cover at least 77% or 88% of sampled Nankeen kestrels regarding home range size it would be necessary to increase the mean buffer size of 3.256 m² by 22% or 166% respectively. Another aspect is the shape of the circular buffer versus the wAKDE's polygon. The real home range estimates were typically non-circular (Figure 8 and 9, Appendix Figure 18 and 19), and thus a circular buffer with an identical area only encompassed a portion of the home range's polygon, depending on its shape. It is therefore necessary to consider this factor when calculating circular buffers, which has to result in larger buffer sizes - to counteract the limitations imposed on the usable area of the Nankeen kestrel by smaller buffers. Furthermore, the habitat requirements of the species in question may vary over the course of the year.

Seasonal differences between sexes

Four individuals were successfully monitored throughout the entire sampling period spanning over a year. Thus, we examined potential temporal patterns in utilization distribution size across the breeding and non-breeding seasons (Table 13 and Table 14). The breeding season of Nankeen kestrel Animal IDs 7, 11 and 12 started in mid to late September with clutch initiation, whereas Nankeen kestrel Animal ID 6's clutch initiation was estimated between late September and early October, in line with existing literature (Bollen, 1990; Mo, 2019; Paull, 1991; Stewart, 2021). Collectively the incubation period (Olsen & Baker, 2001; Paull, 1991) and nestling period (Stewart, 2021) spans over approximately 60 days, changing ecological requirements during these times should thus be visible in changing utilization distribution sizes across the months of September, October and November.

Nankeen kestrel Animal ID 6 is a female and had its lowest utilization distribution in October. Although it was not possible to calculate the utilization distribution from our second female, Nankeen kestrel Animal ID 12, it is probable that it was occupying the breeding cavity throughout October, which would have prevented the GPS tag from establishing a connection with satellites and thus explains the lack of data. An increased activity of its male mating partner in October was validated with the visualization software "Dynamovis" (Dodge et al., 2021), and supports above made assumptions. Male kestrels provide most of the food during the egg laying period, (Riegert et al., 2007). Our findings are therefore supported by the existing literature. Concluding, our hypothesis that utilization distributions of female Nankeen kestrels are smaller in size during the breeding season, while utilization distributions of males remain similar or larger in size across the year, is thus supported by our findings. With regard to the entire investigation period, our findings indicate a tendency towards larger home range sizes in male Nankeen kestrels. However, the results were not statistically significant, which was likely a sample size effect given that we only had comprehensive data for two female individuals. Acquiring further data will be necessary to increase statistical power. In addition to the observed differences between the sexes during the breeding season, some Nankeen kestrels appeared to exhibit exceptionally high utilization distribution sizes at a synchronized time frame.

Possible foray flights of Nankeen kestrels

It has been documented that American kestrels engage in foray flights with the potential purpose of locating more suitable foraging or nesting sites (Kolowski et al., 2023). The highest frequency of such potential foray flights has been observed during nestling period (Kolowski et al., 2023), which in case of the Nankeen kestrel typically occurs from early November to early December (Table 2; Bollen, 1990; Mo, 2019; Paull, 1991; Stewart, 2021; Olsen & Baker, 2001) and lasts up to 35 days (Stewart, 2021). We assume that five of the sampled ten Nankeen kestrels undertook foray flights between November 2022 and February 2023, which would explain excessively larger utilization distribution sizes.

Looking at Nankeen kestrel Animal ID 7's utilization distribution sizes in chronological order, it seems like the kestrel was retracting its home range around its nest site (Appendix Figure 20). We speculate that it was exploring a large area in November and December 2022 for a nest site and then in January 2023 established its home range. It is possible that the behavior of Nankeen kestrels Animal IDs 4 and 10 exhibited similar patterns. The peak in utilization distribution size of Nankeen kestrel Animal ID 4 was between November 2022 and January 2023 and reduced dramatically in February (Figure 14). Nankeen kestrel Animal ID 10 had its largest utilization distributions in November and December 2022 and retracted to approximately 50% of its utilization distribution in January and February 2023 (Figure 14). A noteworthy expansion in the size of the utilization distribution in November was observed for Nankeen kestrel Animal ID 9 as well (Figure 14). Concluding from this descriptive evidence, it might be possible to assess Nankeen kestrel Animal ID 5's behavior more accurately, if we assume foray flights for this individual. We have, however, excluded the individual from home range analyses because of its wandering behavior – as the variogram did not stabilize for the location-time data series available – which violated the underlying assumption of a wAKDE and the definition of a home range (Burt, 1943). It traveled between two main locations for at least six times between December 2022 and February 2023 (Appendix Figure 21). Before and after that period it exhibited range residency behavior.

Study limitations

Given the information that five out of ten (nine of them included in home range analyses) Nankeen kestrels might have displayed foray behavior, which has been documented in a similar way in American kestrels (Kolowski et al., 2023), it could be assumed that the methodology of this study may not have been an optimal approach to assess home range sizes, as it solely utilized variograms (Calabrese et al., 2016) as an inclusion factor. Home range size calculations including multiple foray flights might have led to an overestimation of home range sizes, given the definition of a home range (Burt, 1943). There are alternative models available that can deal with nomadic behavior, like dynamic Brownian bridge movement model (Walter et al., 2015), which might be a promising avenue for additional analyses. Another opportunity is offered by the solar recharge of the applied tags, where data could possibly be collected for some more years. With longer time-series, one could ascertain whether the behavior is a repeating pattern and thus fits the definition of a home range or not.

Conclusion

This study of Nankeen kestrels provided, for the first time, high-resolution spatio-temporal GPS data, allowing insights into their spatial behavior over the course of a year. No correlation was found between wAKDE sizes and urbanization. Compared to similar species in the Northern Hemisphere, home range sizes were larger, which could be due to possible foray flights of five Nankeen kestrels. The investigation of such behavior was made possible by the use of new and lightweight GPS loggers. We think it is of great importance to further use similar solar-powered devices but with the improvement that they can connect to satellites for data transmission to establish representative home range estimates. In this study, it was not possible to collect GPS data for six out of twelve Nankeen kestrels throughout the entire sampling period. This was due to Nankeen kestrels bound to a breeding cavity (applicable to females), individuals leaving the study site, or for unknown reasons. It is possible that some Nankeen kestrels exhibited foray behavior, which could lead to shifting their home range after the breeding season, as has been the case with some American kestrels (Kolowski et al., 2023), or to partially migrating as has been suggested for Eurasian kestrels in Vienna (Huchler et al., 2020). In such instances, it would be possible to gather further data due to the satellite connection. Recurrent foray behavior might be a reason to re-evaluate and re-define the definition of a home range (Burt, 1943), which could lead to a very different understanding of space use of raptors. As expected, male Nankeen kestrels tended to have slightly larger home range sizes than females, which may be related to the fact that the male is the sole provider of food for the female and chicks for most of the breeding season (Balgooyen, 1976; Riegert et al., 2007). This is particularly important for conservation reasons. As the needs of whole populations are estimated on the basis of a few individuals (Murgatroyd et al., 2021), it is of paramount importance that these individuals are assessed as accurately as possible. Subsequently calculating mean circular buffers and applying them to each nest site to estimate urbanization appeared to be an adequate method, as 91% of the ALAN values calculated using either wAKDE polygons or mean circular buffers correlated. However, only 56% of the Nankeen kestrels' home range size were correctly estimated with an area of 3.256 km^2 when represented by the mean circular buffer. Further recalculations of a mean circular buffer are recommended to properly assess Nankeen kestrels' home range sizes with different shapes of real, non-circular home range polygons.

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Appendix

Inhaltszusammenfassung

Die Zahl der Greifvögel und Falken nimmt weltweit und insbesondere auf der Südhalbkugel in rasantem Tempo ab. Um diese schützen zu können, ist es von entscheidender Bedeutung, die Anpassungsfähigkeit von Arten an eine sich rasch urbanisierende Umwelt zu verstehen, jedoch gibt es kaum Studien, die sich zu diesem Thema mit Greifvögeln und Falken auf der Südhalbkugel befassen. Diese Studie zielt darauf ab, zum ersten Mal die Nutzungsverteilung (Utilization Distribution) und Größe des beanspruchten Lebensraums (Home Range) des Graubartfalken *Falco cenchroides* im Verlauf eines Jahres in verschieden urbanisierten Lebensräumen zu ermitteln. Wir haben 12 Graubartfalken mit GPS-Loggern versehen, die hochauflösende Daten für 10 Individuen liefern. Diese ermöglichen die Größe der Nutzungsverteilung und des beanspruchen Lebensraums von Graubartfalken bezüglich des Urbanisierungsgradienten, möglicher saisonaler Veränderungen und des Geschlechtes zu vergleichen. Unsere Ergebnisse zeigen keine Korrelation zwischen der Größe des beanspruchten Lebensraums und dem Urbanisierungsgradienten, mögliche Erkundungsflüge für 5 Individuen und eine nicht signifikante Tendenz zu größeren beanspruchten Lebensräumen für Männchen im Vergleich zu Weibchen. Graubartfalken scheinen im Vergleich zu ähnlichen Falken einen relativ großen Aktionsradius zu haben. Dieses Phänomen kann möglicherweise auf neuartige und präzisere Technologie in Form von hochauflösenden räumlich-zeitlichen GPS-Daten zurückgeführt werden, die es ermöglicht hat, ein geographisch ausschweifendes Verhalten, wie etwa mögliche Erkundungsflüge, zu erkennen.

Additional Figures and Tables

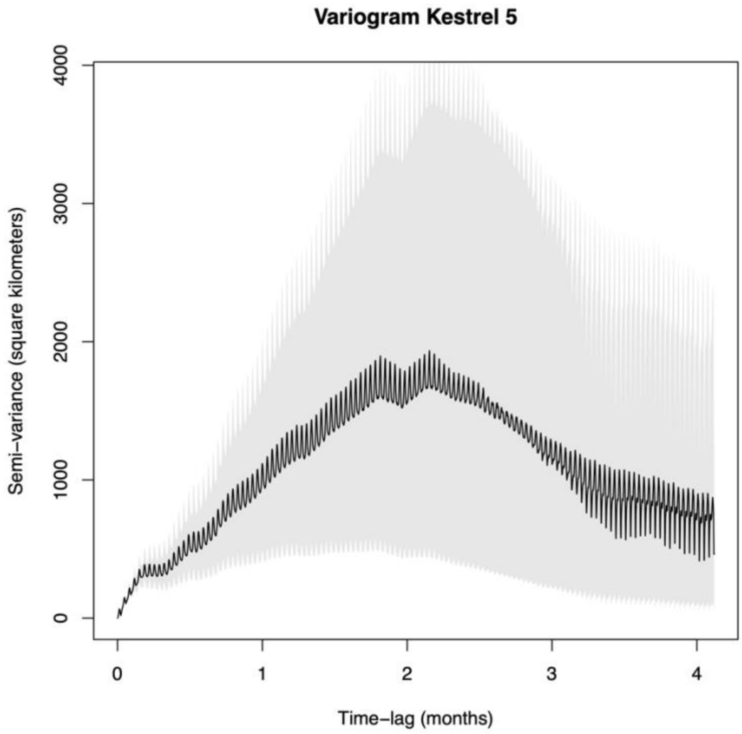


Figure 5

The variogram (Calabrese et al., 2016) of Nankeen kestrel Animal ID 5 displays its non-resident site behavior.

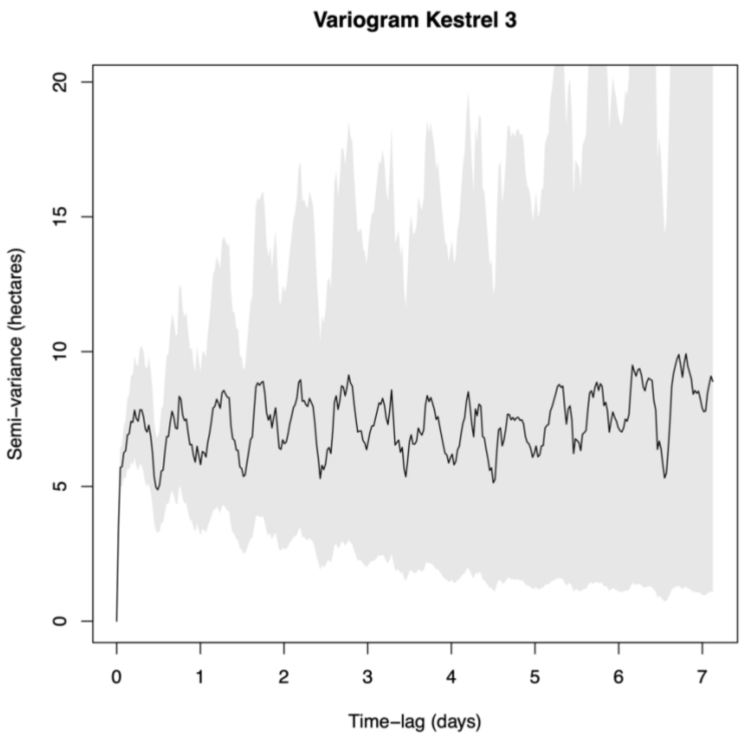


Figure 6

The variogram (Calabrese et al., 2016) of Nankeen kestrel Animal ID 3 displays its site residency behavior.

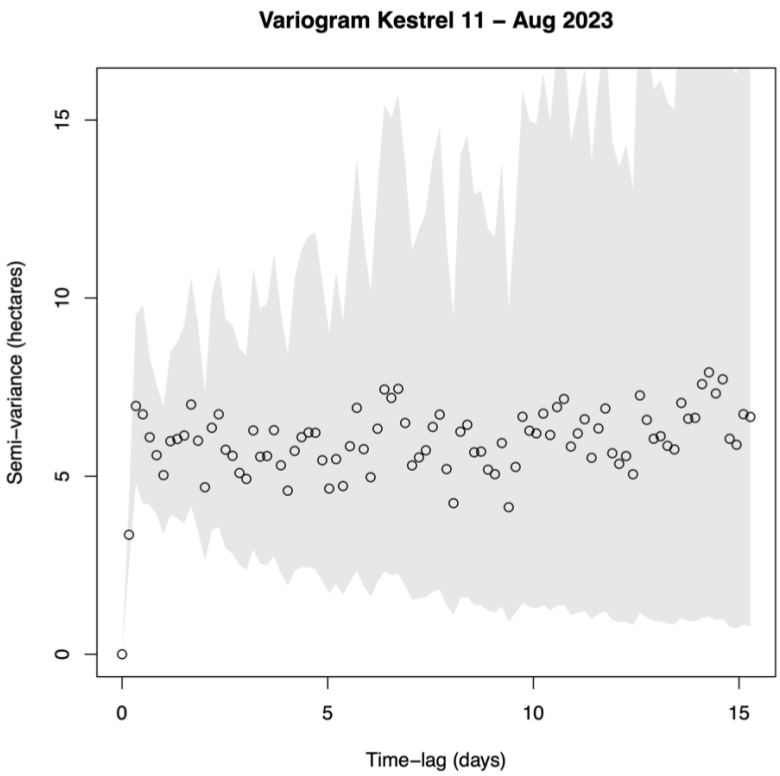


Figure 7
The variogram (Calabrese et al., 2016) of Nankeen kestrel Animal ID 11 displays its site residency behavior in Aug. 2023.

Table 7: All used locations per month, which were used to calculated low and high confidence intervals and the estimated 95% wAKDE area in km². Red and crossed out values indicate months in which the respective Nankeen kestrel did not exhibit range residency. Values were calculated with the wAKDE function of the CTMM package (Calabrese et al., 2016).

	Animal ID 1				**Animal ID 3**				**Animal ID 4**				**Animal ID 6**				**Animal ID 7**			
	Loca-tions	**95% wAKDE area in km²**			**Loca-tions**	**95% wAKDE area in km²**			**Loca-tions**	**95% wAKDE area in km²**			**Loca-tions**	**95% wAKDE area in km²**			**Loca-tions**	**95% wAKDE area in km²**		
		Low	Est.	High		Low	Est.	High		Low	Est.	High		Low	Est.	High		Low	Est.	High
Oct. 22	-	-	-	-	63	0.567	0.756	0.970	-	-	-	-	-	-	-	-	-	-	-	-
Nov.22	87	1.207	1.551	1.938	247	0.727	0.843	0.966	318	5.298	6.187	7.143	259	0.809	0.930	1.060	494	9.403	10.449	11.549
Dec. 22	130	1.438	1.748	2.088	-	-	-	-	357	3.156	3.549	3.965	251	1.296	1.504	1.729	1614	17.978	19.777	21.661
Jan. 23	-	-	-	-	-	-	-	-	357	4.097	4.709	5.362	197	0.891	1.057	1.237	878	22.641	26.075	29.748
Feb.23	-	-	-	-	-	-	-	-	222	1.056	1.229	1.414	103	0.452	0.559	0.677	674	8.037	9.869	11.886
Mar. 23	-	-	-	-	-	-	-	-	172	1.105	1.315	1.542	80	0.443	0.560	0.690	586	4.845	5.854	6.957
Apr.23	-	-	-	-	-	-	-	-	109	0.619	0.755	0.904	102	0.886	1.088	1.311	256	8.157	10.470	13.067
May 23	-	-	-	-	-	-	-	-	~~28~~	~~1.439~~	~~2.183~~	~~3.081~~	~~50~~	~~1.514~~	~~2.046~~	~~2.657~~	56	2.785	4.094	5.651
Jun.23	-	-	-	-	-	-	-	-	~~12~~	~~2.378~~	~~4.764~~	~~7.965~~	~~37~~	~~1.140~~	~~1.628~~	~~2.201~~	25	1.729	2.699	3.881
Jul.23	-	-	-	-	-	-	-	-	-	-	-	-	38	1.081	1.535	2.068	46	2.199	3.015	3.957
Aug.23	-	-	-	-	-	-	-	-	-	-	-	-	43	0.611	0.848	1.123	66	5.624	7.287	9.162
Sep.23	-	-	-	-	-	-	-	-	-	-	-	-	376	0.579	0.675	0.777	83	3.576	4.496	5.520
Oct. 23	-	-	-	-	-	-	-	-	-	-	-	-	44	0.280	0.405	0.552	62	4.566	5.969	7.557
Nov.23	-	-	-	-	-	-	-	-	-	-	-	-	638	0.744	0.813	0.886	52	3.218	4.777	6.639
Dec. 23	-	-	-	-	-	-	-	-	-	-	-	-	485	1.043	1.188	1.342	27	0.747	1.143	1.623

Table 7: All used locations per month which were used to calculated low and high confidence intervals and the estimated 95% wAKDE area in km². Red and crossed out values indicate months in which the respective Nankeen kestrel did not exhibit range residency. Values were calculated with the wAKDE function of the CTMM package (Calabrese et al., 2016)

	Animal ID 9				**Animal ID 10**				**Animal ID 11**				**Animal ID 12**			
	Locations	**95% wAKDE area in km²**			**Locations**	**95% wAKDE area in km²**			**Locations**	**95% wAKDE area in km²**			**Locations**	**95% wAKDE area in km²**		
		Low	**Est.**	**High**		**Low**	**Est.**	**High**		**Low**	**Est.**	**High**		**Low**	**Est.**	**High**
Oct. 22	74	0.978	1.265	1.588	-	-	-	-	155	0.875	1.031	1.200	-	-	-	-
Nov.22	141	8.991	10.792	12.755	348	4.049	4.531	5.040	805	1.116	1.204	1.295	258	0.858	0.979	1.108
Dec. 22	-	-	-	-	594	4.190	4.665	5.165	1486	1.346	1.439	1.536	572	1.077	1.189	1.308
Jan. 23	-	-	-	-	676	1.962	2.169	2.386	557	0.896	1.006	1.123	86	0.512	0.648	0.799
Feb.23	-	-	-	-	242	2.048	2.613	3.246	484	1.282	1.465	1.660	70	0.859	1.1567	1.498
Mar. 23	-	-	-	-	-	-	-	-	583	1.442	1.606	1.779	127	0.728	0.874	1.033
Apr.23	-	-	-	-	-	-	-	-	290	1.319	1.514	1.721	90	1.289	1.605	1.955
May 23	-	-	-	-	-	-	-	-	79	0.840	1.072	1.332	31	0.588	0.872	1.210
Jun.23	-	-	-	-	-	-	-	-	54	0.755	1.008	1.298	14	0.245	0.460	0.742
Jul.23	-	-	-	-	-	-	-	-	62	0.583	0.762	0.965	17	0.290	0.509	0.784
Aug.23	-	-	-	-	-	-	-	-	90	0.838	1.044	1.272	~~37~~	~~0.665~~	~~0.950~~	~~1.284~~
Sep.23	-	-	-	-	-	-	-	-	268	1.215	1.375	1.545	127	0.485	0.584	0.692
Oct. 23	-	-	-	-	-	-	-	-	409	1.214	1.341	1.475	~~3~~	-	-	-
Nov.23	-	-	-	-	-	-	-	-	429	1.535	1.693	1.857	171	0.794	0.932	1.081
Dec. 23	-	-	-	-	-	-	-	-	271	1.343	1.521	1.709	133	1.096	1.310	1.543

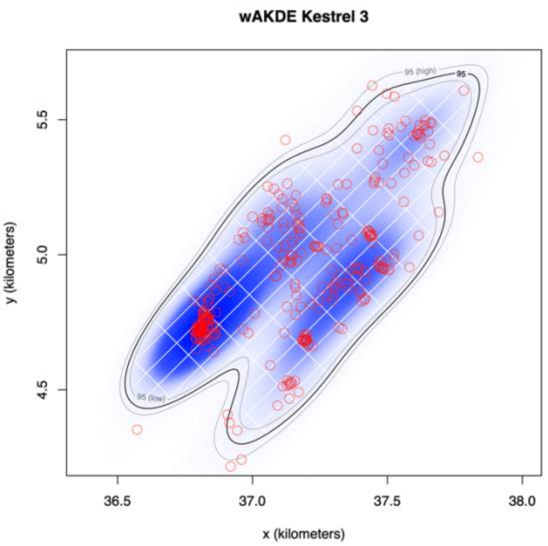
Figure 16

Male Nankeen kestrel Animal ID 11

Figure 17

Female Nankeen kestrel Animal ID 12

Although both Nankeen kestrels live in a space circled by an urban living space they mostly use extensive green sites on the airport and therefore do not fit the category “Urban” perfectly. Images extracted from www.movebank.org



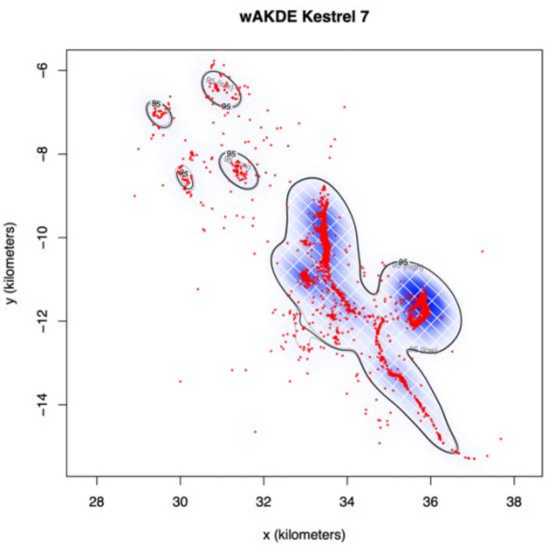


Figure 18

wAKDE of Nankeen kestrel Animal ID 3

Figure 19

wAKDE of Nankeen kestrel Animal ID 7

Both Figure 18 and 19 show elongated home range estimates and a circular buffer would not represent most their actual used space. Figures were plotted with the wAKDE function of the CTMM package (Calabrese et al., 2016)

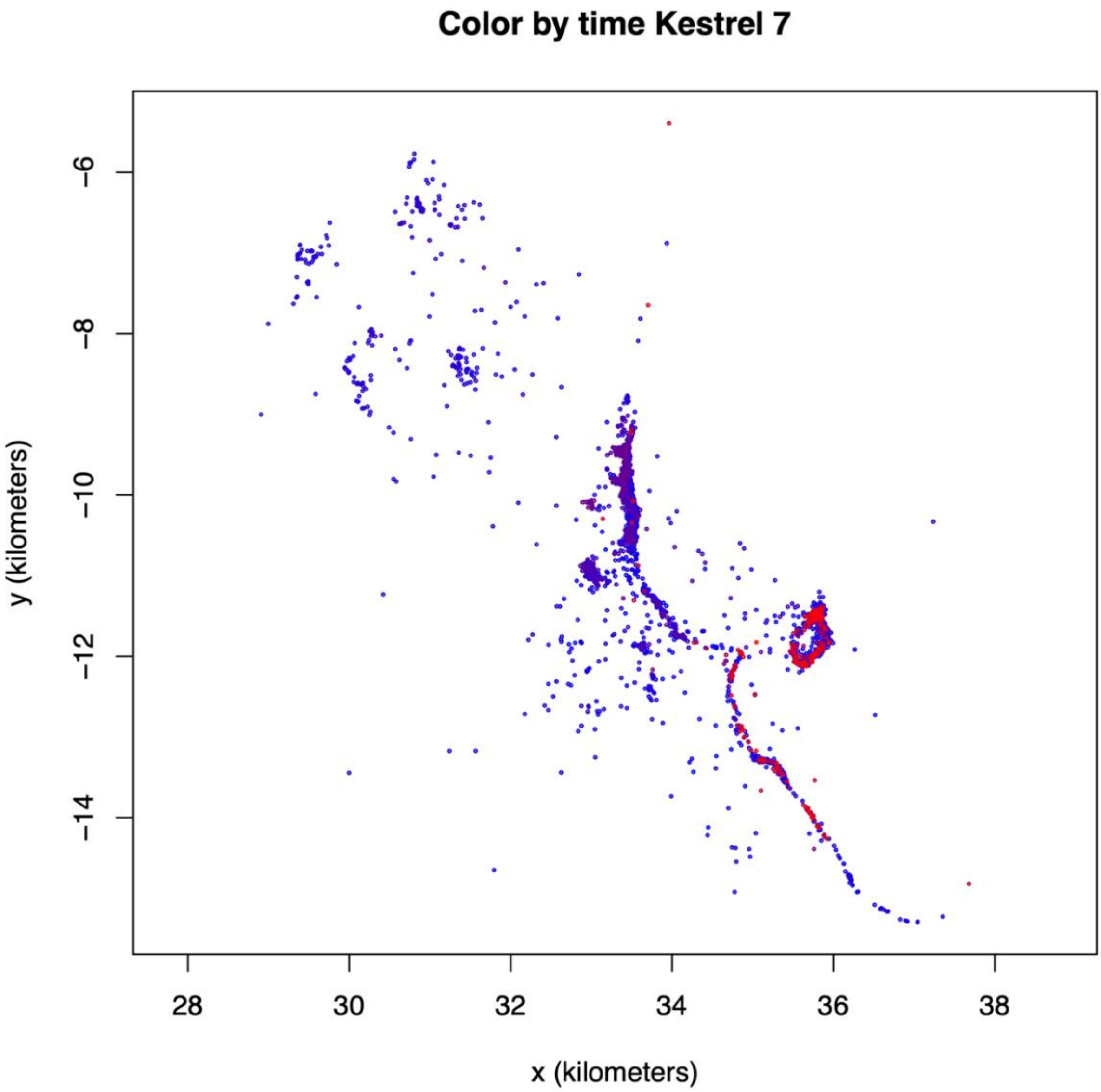


Figure 20

Blue dots and red dots represent relatively early and relatively late time stamps in this data set. It is visible that Nankeen kestrel Animal ID 7 was logged more often in the early tracking period in the upper left corner and the center of the Figure, symbolized through blue dots. Later on, it was logged more in the lower right corner, symbolized through bright red dots. It appears that the Nankeen kestrel Animal ID 7 retracted its home range to sites closer to its nest over time. This Figure was plotted Figures were plotted with the color function of the CTMM package (Calabrese et al., 2016)

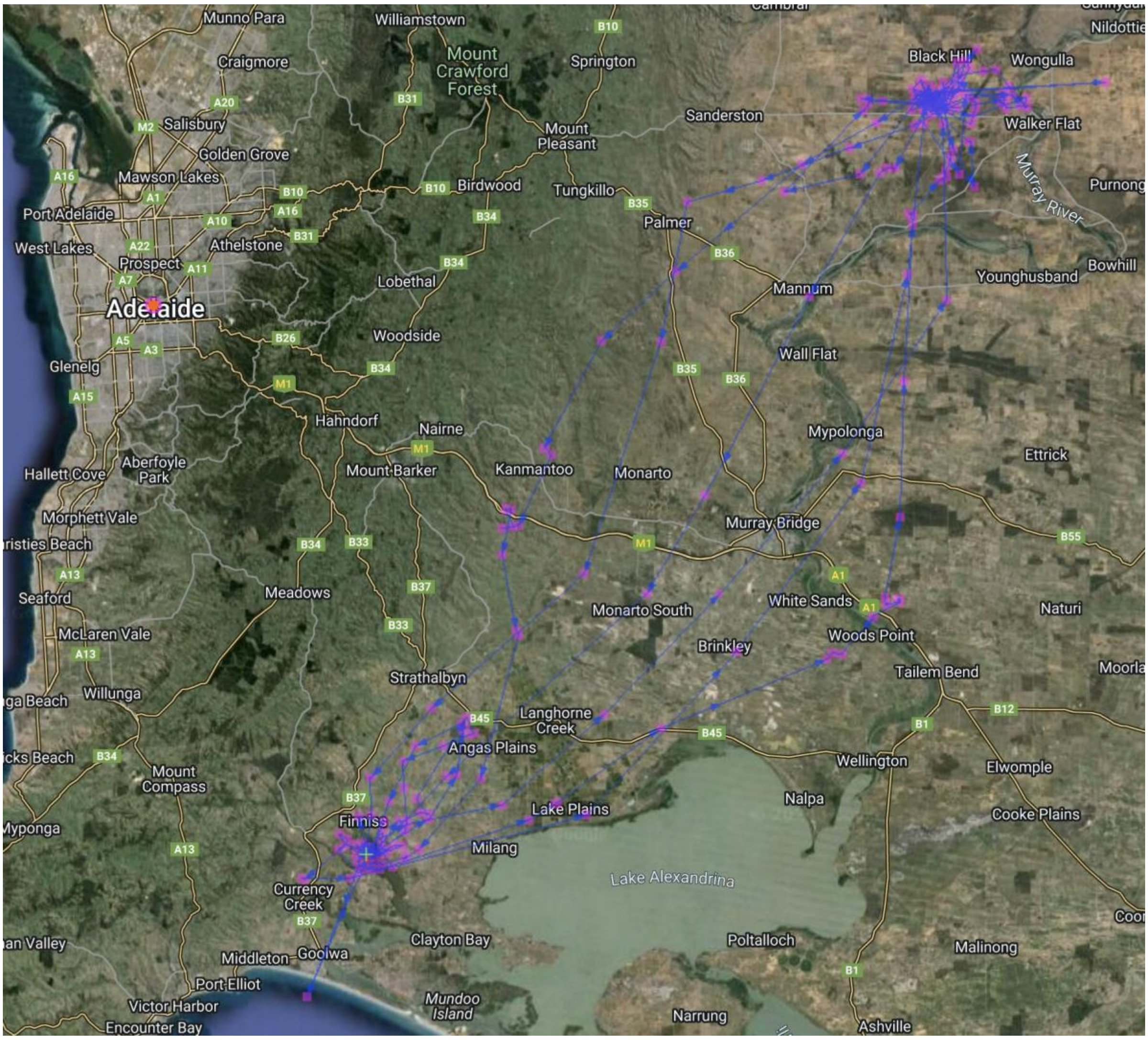


Figure 21

Nankeen kestrel Animal ID 5 with connections and travel direction between subsequent GPS locations. Image extracted from www.movebank.org.