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Fifteen days are enough to estimate home-range size in some long-lived resident eagles.

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Abstract

In this paper we show how many fixes are enough to define the territory of two long-lived resident raptors marked by GPS transmitters. To this end, we analyzed high-resolution GPS data from 50 territorial Bonelli's eagles (*Aquila fasciata*) and 9 territorial Golden eagles (*Aquila chrysaetos*) equipped with GPS/GSM dataloggers. Our results show that between 2200 and 2800 fixes are enough to define the territory. This is interesting for movement ecology works where long-term GPS data series are not available.

Key words: *Aquila fasciata*; *Aquila chrysaetos;* accumulation curve; breakpoint regression; GPS; kernel density; telemetry; territory.

Authors' contribution

S.M., V.U. and P.L.L conceived the ideas, designed methodology and collected the data. S.M., P.L.L. analysed the data and wrote the manuscript. V.U. and P.L.L. contributed critically to the drafts and gave final approval for publication.

Conflict of interest

Authors declare that no conflict of interest exists.

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Data Availability Statement

All data used in this study are publicly available upon request to data managers in the online data repository Movebank (www.movebank.org). The projects are: “Bonelli's eagle University of Alicante Spain” (project ID = 58923588), “Bonelli's eagle Alicante Spain” (ID = 430140799), “Bonelli's eagle University of Valencia Spain” (ID =

193515984), “Bonelli's eagle and Golden eagle GVA Spain” (ID = 1140247354), and “Movement ecology of large raptors in Spain” (ID = 640908212).

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Introduction

Movement ecology has emerged as a transdisciplinary discipline with an exponential increase of studies including many different taxa worldwide (Nathan et al. 2008; Kays et al., 2015; Tucker et al. 2018). Estimating how many locations are needed for territorial species to define their home-range is key for spatial ecology studies, particularly of long-lived resident raptors, for which obtaining a large dataset of marked animals becomes difficult in economic and logistical terms. Difficulty in capturing and handling individuals, the pressure of working with charismatic and/or endangered species, and the limitations in financial budget, particularly in countries of the global South, among others, make often difficult to work with a large amount of individuals. In addition, in some cases transmitters stop emitting a few days after tagging for different reasons including natural and unnatural mortality. After almost twenty years of experience with large eagles tracked by different telemetry technologies (i.e., radio-tracking, Argos satellite, GPS and current GPS/GSM telemetry) we have observed that after a certain number of days eagles of both sexes define their territory and maintain its extension and topology with little variation in successive years.

Materials and Methods

The study area is located in eastern Spain including Albacete, Alicante, Castellón, Cuenca and Valencia provinces. The area covers approximately 8000 km^2 with an average altitude ranging from 100 to 1500 m above sea level. The climate is Mediterranean with an average annual temperature varying between 17°C in the coastal areas and 8°C in the inland mountains. The dominant landscape is composed by Mediterranean evergreen forests (*Pinus halepensis, P. nigra*), oak forests (*Quercus rotundifolia, Q. suber)* and Mediterranean scrublands.

In this study we used a current dataset of 50 adult and subadult Bonelli's eagles (*Aquila fasciata*), 25 males and 25 females, and 9 adult Golden eagles (*Aquila chrysaetos*), 5 males and 4 females. All of the individuals were captured and tagged in their territory with GPS/GSM solar energy dataloggers manufactured by e-obs GmbH (Munich, Germany) and Ornitela (Vilnius, Lithuania) using a backpack configuration. Transmitters weights were 48 and 50 g, respectively, and represented 1.66 to 2.86% (mean = 2.25%, SD = 0.38%) of the eagles' body mass, below the 3% threshold established to avoid negative effects on behavior (Kenward, 2001; García et al. 2021). Tagging details are available in detail in Perona *et al.* (2019). Trapping and tagging activities were authorized and conducted under permissions issued by regional authorities (Conselleria de Agricultura, Medio Ambiente, Cambio climático y Desarrollo Rural, Generalitat Valenciana, Spain) and all efforts were made to minimize handling time to avoid any suffering to eagles. Transmitters were programmed to obtain GPS fixes with a sampling frequency of five minutes during daytime (e.g., López-López et al. 2021). All eagles were territorial according to field observations and GPS information.

To determine the amount of GPS fixes or days needed to delimit and define an individual's territory, home-range indicators were computed using kernel density methods (KDE) (Worton, 1989). For this, we obtained the 95% daily accumulative kernel (K95%) from the day of tagging to the 30^{th} day of data transmission using the "reproducible home-range" (*rhr*) R package (Signer and Balkenhol, 2015). The 95% kernel was considered as the home-range area (Samuel et al., 1985) and is the most common metric in spatial ecology studies for home-range delineation within territories. Kernel surface tends to increase from the first GPS locations after tagging until the animal delineates its home range area. Mathematically, this results in an asymptote of the daily K95% accumulation curve. To check this, we plotted the K95% area versus the number of accumulation fixes, and also the K95% area versus time. Since there is a non-linear relationship between both variables, we computed data breakpoints to assess when the home-range size has already been fully defined. Breakpoints were calculated using the piecewise regression method (Neter et al., 1985; Toms and Lesperance, 2003) implemented in the "*segmented*" R package (Muggeo, 2017). This method splits the independent variable (i.e., number of locations or number of days after tagging) into different intervals with different slopes calculating separate line segments that fit to each interval. A linear model was calculated using the data after the last breakpoint to determine when there is no increase in the home-range area (i.e., when the slope tends to zero). The breakpoints were used to estimate when eagles had reached the asymptote and thus when they had delimited their home-range. We also repeated this analysis using monthly and seasonal data (i.e., breeding and non-breeding seasons) in order to check if the general pattern of stabilization of the home range size after a given number of locations or time period is consistent. To this end we verified it with six individuals with the longest tracking time redoing the analyses instead from the first day after tagging, by taking data month by month and by breeding and non-breeding season. Differences in the number of fixes per month and/or period were tested by means of a one-way ANOVA and a *post hoc* Tukey test (Figures and data in Supplementary Material). Finally, to test if there are differences in the number of locations between species and sexes (only in Bonelli's eagle because the data is representative enough), a one-way ANOVA was performed. Statistical significance was set at $P < 0.05$.

Results

Our results showed that the mean minimum number of fixes to define the territory was 2209 ± 538 and 2795 ± 50 fixes in the Bonelli's eagle and the Golden eagle, respectively, and in our case it corresponds to 15.64 ± 6.74 and 13.72 ± 4.98 days. The mean slope of the linear model after the data breakpoint of all individuals was 0.008 ± 0.028 (0.495 ± 0.523 for minimum number of days) (Figs 1-2). There were neither differences in the number of locations between species (F = 2.746; p = 0.103) nor between sexes in Bonelli's eagle (F = 0.037; p = 0.849).

Discussion

According to our results, we propose that in studies with long-lived resident raptors we can consider that between 2200 and 2800 fixes after tagging would be enough to define the extent of their home-range based on the 95% kernel. In fact, this is a common metric used in movement ecology studies and, in contrast to other more sophisticated metrics, is easily calculated by researchers and specialists that use GPS telemetry.

Since no differences were found between species, it would be interesting to check whether these results could be extrapolated to other similar long-lived resident eagles. We hypothesize that this could be true taking into account that long-lived raptors need to fly over their entire territory in a few days both to hunting and to defend it from other territorial pairs in the neighborhood. Regarding the absence of sex differences in Bonelli's eagle home-ranges, this is to be expected due to the cooperative hunting behavior typical of this species.

Our results can be extrapolated to other large eagles that have a similar hunting behavior to the Golden eagle and the Bonelli's eagle, which explore their territories from the air to attack their prey. Since our data sampling frequency is very high (one location every five minutes) and that these two species have a continuous flight, the number of locations needed to define the home-range size is achieved in just 15 days. in the case of slower species or for species sampled with lower time resolution, the lower number of locations would be compensated by the larger territory covered by them.

The capture and tagging of individuals is carried out outside the breeding season so as not to interfere with the breeding season. For this reason we do not consider the 15-day period of total exploration of the home-range for breeding individuals, as during the breeding season long-lived eagle species tend to have unusual behavior (Meyburg et al., 2006; Meyburg et al., 2007)

Finally, this study shows that the combination of a simple metric (i.e., 95% kernel density contour) and a standard statistical technique (i.e., piecewise regression) are a simple but a powerful tool for assessing how long takes eagles to delineate their home range, which is ultimately important for management and decision-taking in conservation actions.

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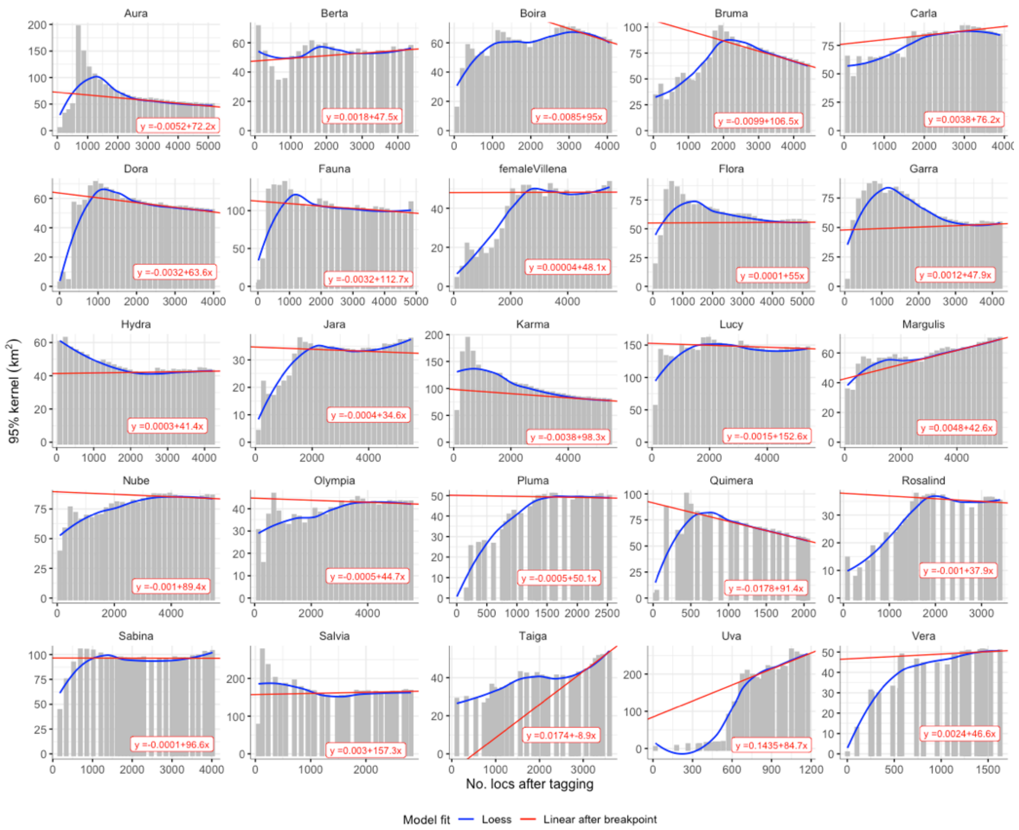
Supplementary Online Material (SOM)

The data referring to the values of the breakpoints and the formula of each graph is shown in the supplementary online material. Also the complementary monthly and seasonal analysis, both results and figures are shown in this section.

Figures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Boira
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Bruma
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Carla
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Dora
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Fauna
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femaleVillena
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Flora
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Garra
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Hydra
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Jara
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Karma
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Margulis
y =0.0048+42.6x
Nube
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Olympia
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Pluma
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Quimera
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Rosalind
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Sabina
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Salvia
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Taiga
y =0.0174+-8.9x
Uva
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Vera
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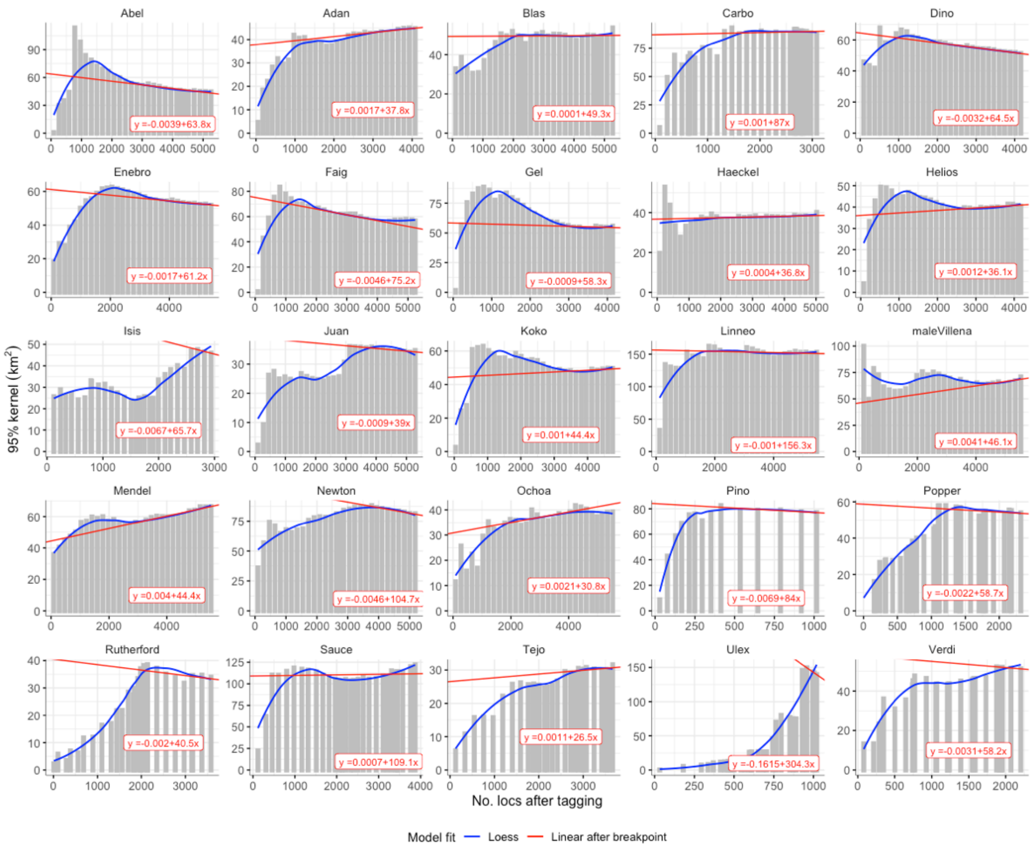
95% kernel (km²)
No. locs after tagging
Model fit — Loess — Linear after breakpoint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Dino
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Enebro
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Faig
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Gel
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Helios
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Isis
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Juan
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Koko
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Linneo
y =-0.001+156.3x
maleVillena
y =0.0041+46.1x
Mendel
y =0.004+44.4x
Newton
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Ochoa
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Pino
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Popper
y =-0.0022+58.7x
Rutherford
y =-0.002+40.5x
Sauce
y =0.0007+109.1x
Tejo
y =0.0011+26.5x
Ulex
y =-0.1615+304.3x
Verdi
y =-0.0031+58.2x
95% kernel (km²)
No. locs after tagging
Model fit — Loess — Linear after breakpoint

Figure 1: A) Accumulation daily 95% kernel surface of 25 female Bonelli's eagle tracked with GPS/GSM transmitters by the accumulation number of fixes during the first 30 days after tagging. Linear regression fit after the breakpoint (red line) and smoothed fitting line (blue line) are shown. B) Accumulation daily 95% kernel surface of 25 male Bonelli's eagle tracked with GPS/GSM transmitters by the accumulation number of fixes during the first 30 days after tagging. Linear regression fit after the breakpoint (red line) and smoothed fitting line (blue line) are shown

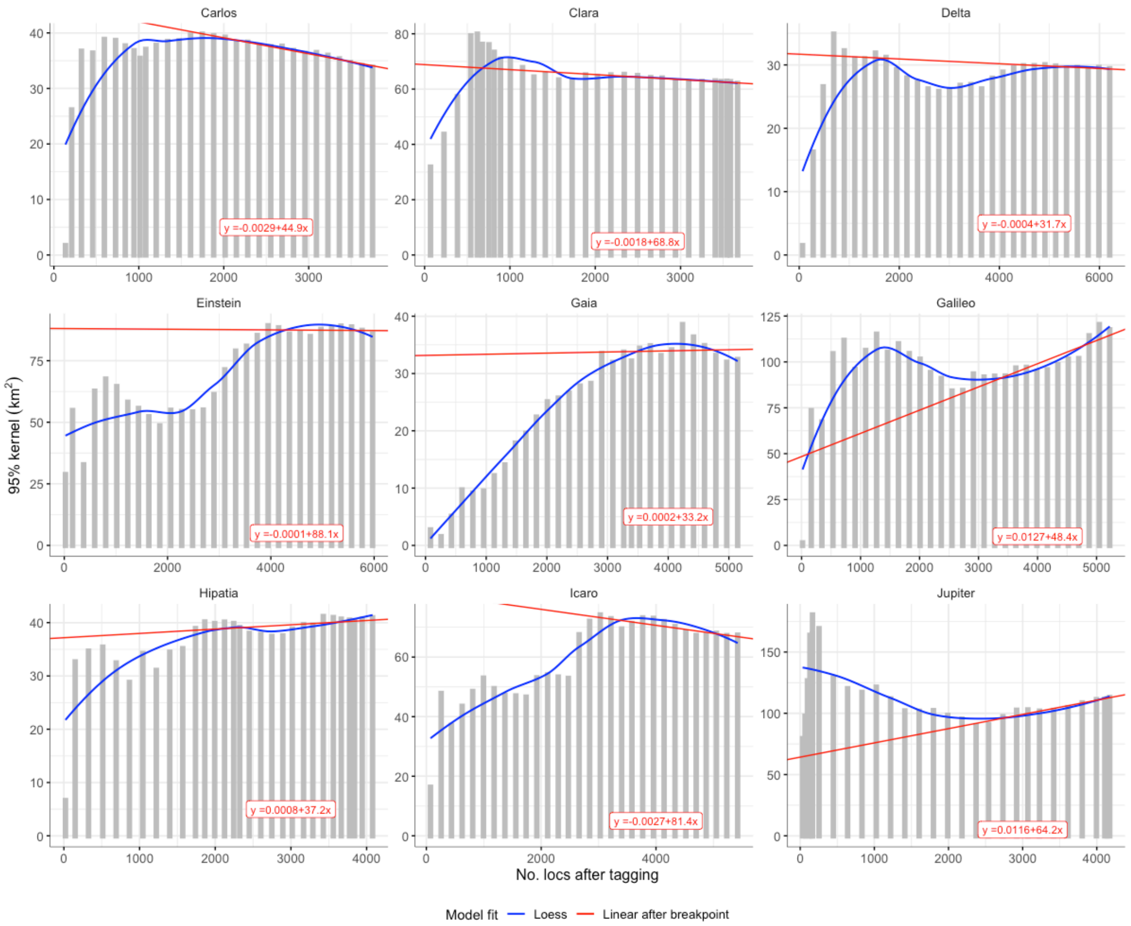

Figure 2.- Accumulation daily 95% kernel surface of nine Golden eagles tracked with GPS/GSM transmitters by the accumulation number of fixes during the first 30 days after tagging. Linear regression fit after the breakpoint (red line) and smoothed fitting line (blue line) are shown.