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Flying through the forest canopy: Movement patterns and habitat selection of rescued and wild Harpy Eagles in the Brazilian Amazon

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Flying through the forest canopy: Movement patterns and habitat selection of rescued and wild Harpy Eagles in the Brazilian Amazon

Abstract: We tracked six Harpy Eagles (*Harpia harpyja*) by satellite telemetry from 2011 to 2021 in the Brazilian Amazonia, analyzing the used area, movements parameters and habitat selection functions for three of them: one adult within its breeding site, one translocated adult, and a four-years old floating subadult. We used the first-passage time to assess the scale at which these individuals respond to the environment, and the behavioral change point analysis to determine behavioral states parameters across trajectories. We fitted a logistic linear regression model with used-available locations and environmental covariates: slope, Terrain Ruggedness Index (TRI), Normalized Difference Vegetation Index (NDVI), land cover, and habitat edge as predictor variables. Harpy Eagle locations were highly related with “Forest” land cover and high NDVI values. The subadult and the translocated adult selected for “Secondary Forest” within their home ranges, which highlights the importance of this type of habitat in fragmented landscapes. In addition, we found behavioural differences in the movement paths of rehabilitated individuals of Harpy Eagle that are subsequently released to the wild. In conclusion, we suggest including in conservation management not only the nest tree and its immediately surrounding but also an area over landscape scale to optimize and promote the functional connectivity, with a safe and efficient dispersion of immatures. Linking Harpy Eagle´s movement locations to resources (land cover, NDVI), risks (forested habitat edge) and environmental conditions (slope, terrain ruggedness) is an opportunity to learn about habitat selection by this large canopy predator. The Harpy Eagle movement ecology has a potential relationship with the spatial dynamics of prey in the forest canopy, which needs to be further addressed in future research.

Keywords: behavioral change points analysis; birds of prey; *Harpia harpyja*; movement ecology; Neotropics; satellite telemetry

Volando a través del dosel del bosque: Patrones de movimiento y selección de hábitat de Águilas Arpías rescatadas y silvestres en la Amazonía brasileña

Resumen: Seis águilas arpías fueron monitoreadas mediante telemetría satelital desde 2011 a 2016 en la Amazonía brasileña, analizando el área utilizada, los parámetros de movimiento y las funciones de selección de hábitat de tres de ellas: un adulto en su sitio de reproducción, un adulto translocado y un inmaduro “flotante” de cuatro años. Utilizamos el *first passage time* para evaluar la escala en la que estos individuos responden al entorno y el *behavioral change point analysis* para determinar los parámetros del estado de comportamiento a lo largo de las trayectorias. Ajustamos un modelo de regresión lineal logística con ubicaciones disponibles utilizadas por Águila Arpía y covariables ambientales: pendiente, Índice de Rugosidad del Terreno, Índice de Vegetación de Diferencia Normalizada (NDVI), cobertura terrestre, y distancia al borde antropogénico como variables predictoras. Las ubicaciones de águila arpía estuvieron altamente relacionadas con la cobertura de suelo de "bosque" y valores altos de NDVI. El subadulto y el adulto translocado seleccionaron “Bosque Secundario” dentro de sus áreas de distribución, lo que resalta la importancia de este tipo de hábitat en paisajes fragmentados. Además, encontramos diferencias de comportamiento en las trayectorias de movimiento de individuos rehabilitados de águila arpía que posteriormente son liberados en la naturaleza. En conclusión, sugerimos incluir en la conservación y manejo de esta especie no solo el árbol del nido y su entorno inmediato, sino también un área a escala de paisaje para optimizar y promover la conectividad funcional, que permita una dispersión segura y eficiente de los inmaduros. Vincular las ubicaciones de movimiento del águila arpía con los recursos (cobertura terrestre, NDVI), los riesgos (borde del hábitat boscoso) y las condiciones ambientales (pendiente, rugosidad del terreno) es una oportunidad para aprender sobre la selección de hábitat de este gran depredador del dosel. La ecología del movimiento del águila arpía tiene una relación potencial con la dinámica espacial de sus presas en el dosel del bosque, que debe abordarse más en futuras investigaciones.

Palabras clave: análisis de puntos de cambio de comportamiento; aves de presa; ecología del movimiento; *Harpia harpyja*; Neotrópico; telemetría satelital

Introduction

Thirty years ago, Manly and his colleagues uncovered a mathematical equation that translated the complexities of resource selection by animals, describing their utilization in direct proportion to the abundance of available quality (Manly et al. 1993). Understanding the complexities of animal resource selection, as described by the equation, requires consideration of the underlying behavioral mechanisms that govern animal movement (Ims 1995; Nathan et al. 2008; Avgar et al. 2013; Gossens et al. 2020), a crucial aspect affected by habitat fragmentation and human disturbances.

The effects of forest fragmentation and habitat loss have been reported acting on the population and community levels of different taxa at Neotropical forests (Rocha et al. 2020; Miranda, Awade, et al. 2021). To measure the functional connectivity to wildlife, besides the structural configuration of the landscape, information on the animal movement, by remote tracking, for example, needs to be included in the analyses. Balancing the benefits and risks of moving through a matrix of non-habitat looking for resources (Fahrig 2007), has been reported as a challenge for animals (Zuluaga et al. 2022; McPherson et al. 2019). Understanding the animal movement is essential for the development of conservation strategies (Allen and Singh 2016) because disturbance by human activities has widespread impacts on the different movement types across diverse taxa (Doherty et al. 2021). Advances in animal tracking have improved studies into species biology and spatial ecology and have been used to promote wildlife conservation (Cogan et al. 2012; Naveda-Rodríguez et al. 2022).

The Harpy Eagle (*Harpia harpyja*) is one of the largest eagles worldwide (Voous 1969). It is indeed a long-lived monogamous raptor with a projection to reduce its distribution across the Americas (Sutton et al. 2021). As a species of conservation concern (BirdLife International 2021), the Harpy Eagle is globally listed as Vulnerable (VU) to extinction (BirdLife International 2021) mainly due to habitat loss, hunting, and persecution pressures (Trinca et al. 2008; DeLuca 2012; Giraldo-Amaya et al. 2021; Miranda, Peres et al. 2021). A pioneering study of wild Harpy Eagles using satellite transmitters, captured in their nests, documented the dependency period, post-fledgling survival, and dispersal biology in Venezuela and Panama (Álvarez-Cordero 1996). Recently, dispersal and space use were described also to Harpy Eagles from Central American landscapes (Naveda-Rodríguez et al. 2022).

Here, we present the results of six tracked Harpy Eagles by satellite telemetry in the Brazilian Amazonia, analyzing the used area, trajectories, and movement parameters. We also used habitat selection functions (HSF) to estimate the relative probability of environmental covariates used and selected by the three of them.

Material and Methods

Study area

This study was carried out between 2011 and 2021 in three geographical regions of the Brazilian Amazon: central (Amazonas state), southwestern (Rondonia state), and east (Para state), within heterogeneous vegetation formation with dense forest, savannas, floodplains and bamboo forests, grasslands, and swamps. Across this region, the Amazon lowland is composed of sedimentary basins marked by smooth and low topography (below c. 250 m) (USGS 2022). Despite the dominance of dense moist forested areas, there are deforested landscapes due to human activities such as roads, cattle ranch, intensive farming, grazing, human settlement, hydroelectric power plant and mining (Garret et al. 2021; Nunes et al. 2022). In 2022, this biome suffers 12 481 km^2 of forest loss (INPE 2023).

Harpy Eagle tagging

Six Harpy Eagles (*Harpia harpyja* Aves: Accipitridae) were tracked by satellite telemetry. These eagles came from rescued events (n = 4) and captured at a nesting tree (n = 2). The individuals had different ages, origins, and circumstances: an adult female within its breeding site (Adult1), a translocated adult (Adult2), an immature male floating (Subadult - four-year-old), and three immatures living at the nesting tree (< 2 years old – Juvenile1, Juvenile2, Juvenile3). These individuals were rescued injured in the wild due to collision with a powerline (Adult1), gunshot (Adult2 and Subadult), and falling from the nest (Juvenile 3). The nesting trees were climbed to install a 2 m diameter radio-controlled Bow Net trap (Bloom et al. 2015) to capture two juveniles (six and nine months old), that would be captured by hand by the climber. The third juvenile was rescued on the forest floor near the nesting tree. Eagles were weighed, measured for biometric parameters, sexed by body mass and tarsus dimensions, and their age was estimated by color plumages: as juveniles (first plumage ~5 months to 1 year old), subadults (2 to 4 years old), and adults (>5 years old) (Projeto Harpia, unpublished data). A platform transmitter terminal (hereafter PTT) was attached to their backpack with a harness made of 17-mm wide natural tubular Teflon (Bally Ribbon Mills, Bally, PA, USA) (Kenward 2001). All birds were ringed with a specific banding from ICMBio/CEMAVE (alphanumeric id) (Sousa and Serafini 2020), Projeto Harpia (alphabetic id), and a subcutaneous microchip was injected into the inner side of the tarsus. An Argos satellite Doppler-based positions (Argos) attached to a VHF (Very High Frequency) 85 g battery-powered (Sirtrack), and an Argos/GPS 70 g solar powered (+VHF) (NorthStar) were installed on the harness. Transmitters with harness weighed less than three 3 % of the eagle's body weight (Kenward 2001).

Locations and data processing

A pre-programmed (P1) fix rate (location acquisition) and transmission schedule (duty cycle) including Argos/Satellite transmitter to sample locations once a day, set to a 3 hours on/ every day, between 0600 am to 0900 am, while Argos/GPS satellite transmitters (average error < 26 m) sample locations four times a day, set to 8 hours on/48 hours off (P2), 8 hours on/75 hours off (P3), 10 hours on/75 hours off (P4). Two PTT record 4 GPS fixes and one 6 GPS fixes per day during the daylight hours between 0600am and 0600pm. In GMT: 1100 am, 0200 pm, 0700 pm, 1000 pm (P2, P3); 1000 am, 1200 pm, 0200 pm, 0400 pm, 0700 pm, 1000 pm (P4). These programs allow transmitters to last between 3 and 4 years as suggested by manufacturers. Data from Argos Doppler satellite transmitter were filtered to quality LC (Location Class) 3, which comprise estimated errors > 250 m (CLS 2016).

The four rescued individuals were subjected to a hard release after undergoing rehabilitation, which varied in duration depending on the circumstances of their injuries. The rehabilitation process lasted for a few days for Adult1 and Juvenile3, and a few months for Subadult and Adult2. These eagles were post-release monitored by tracking *in locus* for at least 15 days by radio-tracking VHF signals using a TR4 receiver and a handheld directional VHF antenna. This time is needed to record at least three successful predation events carried out by the eagles (successfully recorded predation every 3.6 days: Touchton et al. 2002). This can ensures that the birds had been successfully reintegrated into the wild in a healthy state. The two individuals, captured at nesting trees, were released at the same location after being handled for one hour.

This study made rehabilitation releases, not conservation translocations as defined by IUCN (2013), because the intentionally relocated individuals from one site to another, will provide only benefits to translocated individuals.

Space use estimates

To estimate the space used by the Harpy Eagles we performed two different estimators; the minimum convex polygon (MCP) (White and Garrot 1990) and the 95% Kernel density estimation (KDE) (Worton 1989). The use of MCP allowed for comparison with previous data that only used VHF telemetry and triangulation to collect locations. Only the locations of quality LC3 from PTT Argos Doppler were used in the analyses.

Trajectories and movement parameters

To explore the Harpy Eagle movements patterns the trajectories were analyzed for both adults and the subadult. Trajectories are composed of a series of steps (locations), each with a length and a direction between each location over time (Calenge et al. 2009; McLean and Volponi 2018). These movements parameter was used in the First-Passage Time analysis (FPT), defined as the time required for an animal to cross a circle with a given radius (Fauchald and Tveraa 2003; McLean and Volponi 2018), which allows studying the scale of search effort and habitat used by Harpy Eagle. The plotted variogram of FPT was used in function of the range of 100 m radii and then plotted the mean FPT at that scale to detect bouts of behaviour changes. Furthermore, we used the pattern of net squared displacement (NSD) over time to identify which of the five movement patterns was exhibited by the Harpy Eagles (Bunnefeld et al. 2011).

In addition, to investigate patterns of behaviour within the movement trajectories of the three rehabilitated Harpy Eagles, we applied the Behavioural Change Point Analysis method (BCPA) (Gurarie et al. 2009). BCPA is a statistical approach that detects structural changes in movement parameters, indicating transitions between different behavioral states (Gurarie et al. 2009). BCPA models exhibit robustness in handling data gaps and to measurement errors commonly found in telemetry data (Gurarie et al. 2016). The algorithm utilizes location data obtained from the PTTs to calculate persistence velocity (i.e., movement rate) as the representative movement metric. Persistence velocity (Vp) decomposes an animal's movement into the velocity (V is speed = step length/duration of step) and turning angle (θ) between subsequent locations, and then estimates the mean (μ), standard deviation (σ), and degree of autocorrelation (ρ) for these factors for each step of a movement trajectory (Gurarie et al. 2009; 2016). We established window sweep sizes of 30 and 50 (representing the number of data points, equivalent to considering a time interval of 15 days) to capture behavioural state changes along the time series. We utilized a K sensitivity of 2 to identify the parsimonious model based on an adjusted BIC (Bayesian Information Criteria). Lower values of K lead to less sensitive model selection, increasing the likelihood of selecting the null model (Gurarie et al. 2009).

Habitat selection

We assessed the habitat selection by the tracked Harpy Eagles on the second and third-order scales (Johnson 1980), estimating selection functions by contrasting used points versus available points (a "point selection" analysis) (Fletcher and Fortin 2018). The location data were combined with available points sampled randomly from within the MCP. The used and available locations were transformed into a projected coordinate reference system. We included 10 available points per used point, recommended as sufficient for interpreting the slope coefficients (Fieberg et al. 2021).

We assumed the following logistic regression models fit, to use-availability data to characterize the influence of covariates on relative use, w(x): exp $(\beta_0 + \beta_1\chi_1 + ... + \beta_i\chi_i)$, where w(x) is the relative probability of a covariate being selected, β0 is the intercept, β_i is the estimated coefficient for each covariate, x_i, for i = 1, 2, ... p (Johnson et al. 2006). If β > 1, a selection for that resource is indicated, and a β < 1 indicates avoidance of that resource (Manly et al. 1993; 2002). Harpy Eagle relocations represented used sites, and we assigned them a value of 1, while available points were coded as 0. The model included all additive covariates: slope, elevation, NDVI, 30-m land use and land cover (Projeto MapBiomas, Souza et al. 2020), and habitat edge, as a distance inside 150m buffer zone.

Considering that Argos Doppler locations of class LC3 have an estimated error of < 250m (CLS 2016), which may lead to overestimating/sub-estimating the number of points in forest edge areas, and even assuming that the locations were as accurate as possible considering the monthly VHF tracking, we did not analyse the habitat edge for Argos Doppler locations.

Since the habitat is not equally available on the landscape, we adjusted for differences in availability of the categorical predictors (land cover classes) within the MCP home range calculated with Harpy Eagle's locations. To do this, the result of the selection coefficients was multiplied by the ratio of habitat availability: exp(coefficient)*(availability SecondaryForest) / (availability Forest) (Fieberg et al. 2021). Finally, we estimated ŵ by integrating the spatial intensities (utilization distribution) over all habitats, "Forest" and "Secondary Forest" habitats including only available locations, coded as 1 when locations were in "Forest" or "Secondary Forest" and 0 otherwise (Fieberg et al. 2021). Analyses were performed in R 4.2.3 software (R Development Core Team 2022) using adehabitat (Calenge 2006), adehabitatHR (Calenge et al. 2009), trajr (Calenge et al. 2009; McLean and Volponi 2018), bcpa (Gurarie et al. 2014) and amt (Signer et al. 2019) packages.

Environmental covariates

The environmental covariates analysed includes a 30-m resolution slope and Terrain Ruggedness Index (TRI) data from a Digital Elevation Model (SRTM Raster) (USGS 2022), a 30-m resolution Normalized Difference Vegetation Index (NDVI) (Landsat 8 images from USGS 2022), a 30-m land use and land cover product from the Brazilian Annual Land Use and Land Cover Mapping Project from Projeto MapBiomas (MapBiomas 2022; Souza et al. 2020). The age of the secondary forest was derived from a dataset that includes the ages of secondary forests (Silva Junior et al. 2020).

The NDVI is the most common proxy for primary productivity and quality of vegetation, and it was calculated by: NDVI=(NIR−RED) / (NIR+RED), where NIR = Near InfraRed, RED = Red. Raster layers of the covariables and spatial data analysis were performed using the desktop GIS software (QGIS 2022). As forested areas are considered a preferred habitat for the Harpy Eagle, unlike non-forested areas, we used habitat edge, defined as a distance inside a 150 m buffer zone from the pasture, or other non-forested area. This distance has been reported as a zone with a high density of some primate species in Brazilian Amazonia and Costa Rican forests, used by howler monkeys, capuchin monkeys, and saki monkeys (Lenz et al. 2014; Bolt et al. 2020), species reported as Harpy Eagle prey (Touchton et al. 2002; Aguiar-Silva et al. 2014; 2015).

The TRI considers the vertical variation of the terrain at a local scale, which provides a better representation of habitat complexity considering the elevation difference between neighboring cells or a defined neighborhood (Riley et al. 1999). This enables the identification of micro-habitats, small variations in topography, and terrain irregularities that may be crucial for fauna. The TRI would likely be a variable related to the hunting behavior of the Harpy Eagle, a sit-and-wait forager, where the terrain irregularity would favor the detection of prey moving within the forest.

Results

Six individuals of the Harpy Eagle (2 males, 4 females) were tracked with satellite transmitters for 10 years (2011 – 2021) in the Amazon forests. Two juveniles (1 nine-months-old female, and 1 six-months-old male) were captured at their nesting site, and four individuals (2 adult females > 5 years old, 1 four-years-old male, and 1 seven-months-old female) came from rescue events. After being successfully rehabilitated *ex situ*, two were released by translocation and two at the rescued site (**Table 1**). The Subadult four-years-old male (**Fig. 1a**) was translocated about 12 km from rescued the site, the adult female (Adult1) (**Fig. 1b**) was translocated 60 km, and another adult female (Adult2) and the juvenile (Juvenile 3) were released back into its rescued site.

While conducting VHF tracking of Adult1 and Adult2 using GPS locations recorded by the PTT that we downloaded, we recorded an adult male and a one-year-old individual with first plumage (**Fig. 1c**). Moreover, we found remains (bones and fur) of a Red-handed Howler monkey (*Alouatta belzebul*) and Harpy Eagle feces at a GPS location we were searching for. Although the satellite

Table 1*. Used area of five wild Harpy Eagles tracked at Brazilian Amazon. ID Banding is the number of the CEMAVE/ICMBio´s ring (https://www.icmbio.gov.br/cemave/) and Projeto Harpia ring (F3). 95% MCP (Minimum Convex Polygon) and 95% KDE (Kernel Density Estimator). * Analyzing locations between 01 November 2014 to 04 February 2015.*

Tabla 1*.Área usada por cinco águilas harpías silvestres monitoreadas en la Amazonía brasileña. ID Banding es el número de anilla de CEMAVE/ICMBio (https://www.icmbio.gov.br/cemave/) y la anilla de Projeto Harpia (F3). MCP es el Mínimo Polígono Convexo al 95% y KDE es el Estimador de Densidad de Kernel al 95%. * Localizaciones analizadas entre el 1 de noviembre de 2014 y el 4 de febrero de 2015.*

ID Banding	Sex	Age	Capture site	Weight (kg)	Releasing site	Transmitter Type	Tagging Date	Signal Date	Transmitting time (days)	Number Locations	km²	
											MCP	KDE
Z01073	♂	Subadult 4-year	Rescued Injured by gunshot	4.15	Translocated 12 km	Battery powered Satellite	Dec. 2011	Dec. 2012	348	239	199	331
Z01018	♀	Adult1	Rescued injured by powerline collision	6	Rescue site	Solar powered GPS	Jul. 2014	Nov. 2014 + (Mar.-Apr. 2016)	115	391	9	14
Z01019	♀	Adult2	Rescued injured by gunshot	5.8	Translocated 60 km	Solar powered GPS	Aug. 2014	Feb. 2015	171	501	50 (11*)	126 (17*)
Z01020	♀	Juvenile1 9-month	Nesting tree	5.5	Nesting tree	Solar powered GPS/	Sep. 2015	Oct. 2015	10	53	0.002	0.008
Z01075	♂	Juvenile2 6-month	Nesting tree	2.9	Nesting tree	Solar powered GPS	Dec. 2015	Apr. 2016	139	195	0.01	0.02
F3	♀	Juvenile3 1-year	Rescued	5.3	Rescue site	Solar powered GPS	Sep. 2020	Mar. 2021	170	99	0.10	0.21

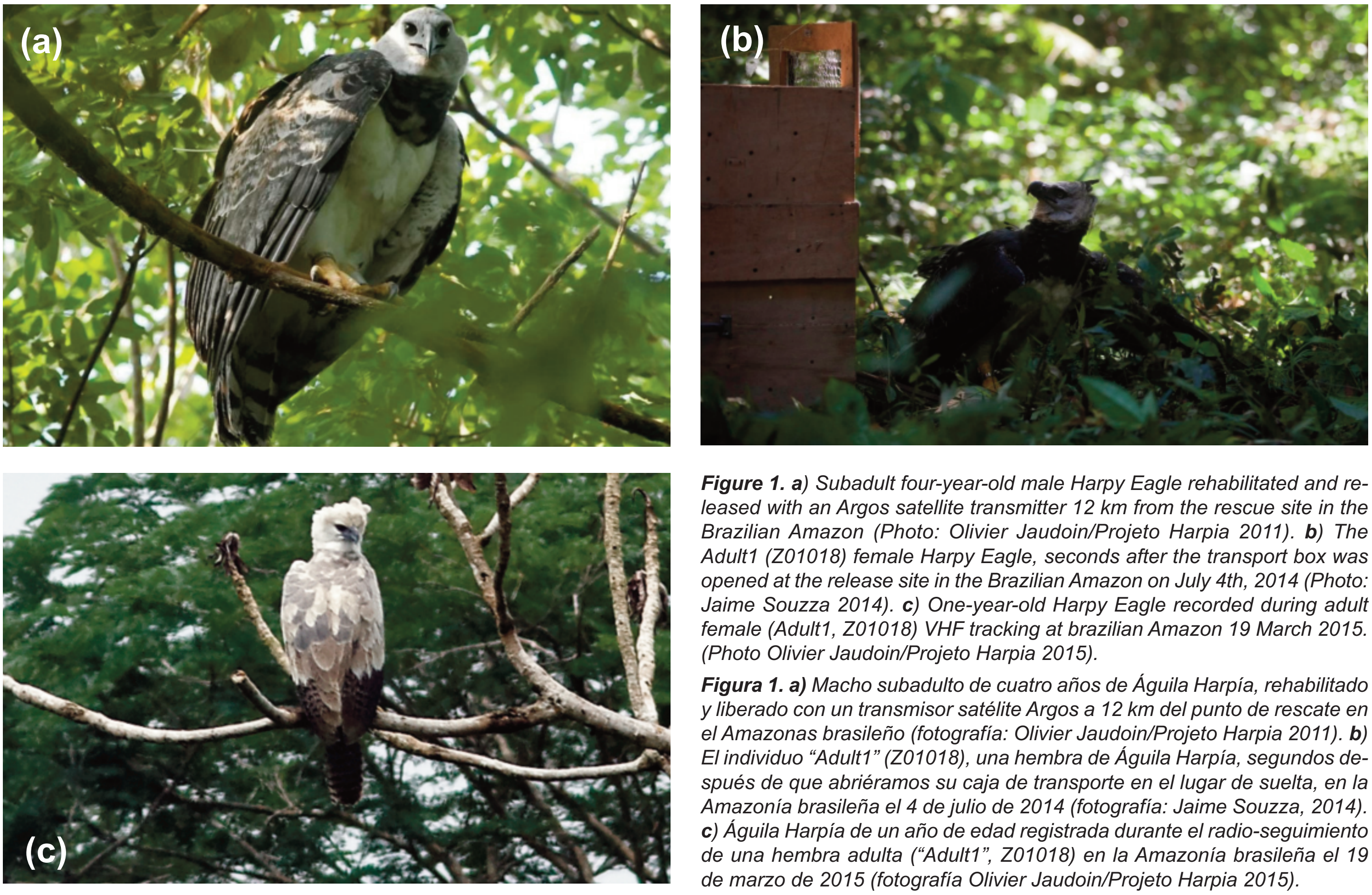


Figure 1. a*) Subadult four-year-old male Harpy Eagle rehabilitated and released with an Argos satellite transmitter 12 km from the rescue site in the Brazilian Amazon (Photo: Olivier Jaudoin/Projeto Harpia 2011).* ***b****) The Adult1 (Z01018) female Harpy Eagle, seconds after the transport box was opened at the release site in the Brazilian Amazon on July 4th, 2014 (Photo: Jaime Souzza 2014).* ***c****) One-year-old Harpy Eagle recorded during adult female (Adult1, Z01018) VHF tracking at brazilian Amazon 19 March 2015. (Photo Olivier Jaudoin/Projeto Harpia 2015).*

Figura 1. a) *Macho subadulto de cuatro años de Águila Harpía, rehabilitado y liberado con un transmisor satélite Argos a 12 km del punto de rescate en el Amazonas brasileño (fotografía: Olivier Jaudoin/Projeto Harpia 2011).* ***b)*** *El individuo "Adult1" (Z01018), una hembra de Águila Harpía, segundos después de que abriéramos su caja de transporte en el lugar de suelta, en la Amazonía brasileña el 4 de julio de 2014 (fotografía: Jaime Souzza, 2014).* ***c)*** *Águila Harpía de un año de edad registrada durante el radio-seguimiento de una hembra adulta ("Adult1", Z01018) en la Amazonía brasileña el 19 de marzo de 2015 (fotografía Olivier Jaudoin/Projeto Harpia 2015).*

equipment's stopped sending locations, the VHF transmitters continued to work for a few months, which allowed the confirmation that the birds were still alive and using the same area as the location points recorded by the satellites.

Space use

A total of 1658 locations were obtained from these six wild Harpy Eagles. Three of them had a large variation in the amount of area used, ranging from 14 (Adult1 female > 5-year-old) to 331 km² (Subadult male four-year-old) (**Table 1**) (**Fig. 2a**, **3a** and **4a**). The male traveled in a straight line 24 km in six months and returned the same distance to a region 9 km from the point of its release, while the Adult2 (> 5-year-old) traveled 20 km also in six months. Considering changes in the movement parameters of the translocated adult female, moving with slow persistence velocity and short step length for four months, like an exploitation movement (Lewis et al. 2021), we analyzed the home range specifically for this scale, which comprises 17 km². Due to the lowest number of locations, we could not estimate the used area for the three juveniles, however, we quantified the distances flown from nesting trees, which ranged from 153 m (at 10 months old) to 800m (at 16 months old).

Movement patterns

The pattern of movement behaviour identified based on NSD was sedentary (home range) for Adult1, mixed dispersal-migratory for Adult2 and migratory for the Subadult (**Fig. 2b**, **3b** and **4b**). The step lengths of the three Harpy Eagles displacements were in most cases ranging from 0 to 500 m, and some steps between 500 and 1000 m (**Fig. A1a**). The estimated mean step length for the Adult1 was 541 m (± 459 m), and median of 457 m, with -1° (± 92°) of relative turning angle (**Fig. A1b**). For the other female, the estimated mean step length was 313 m (± 309 m), and median of 224 m. The relative turning angle distribution had an estimated mean of 6° (±92°). The subadult moved in a tortuous trajectory with mean of step lengths of 1121m (± 1036 m) and median of 743 m. Its relative turning angle was 4°. The three Harpy Eagles moved in tortuous trajectories, in which the Straightness index (Benhamou 2004) was equal to 0.03 to Adult1 (Z01018) and Subadult (Z01073), and 0.3 to Adult2 (Z01019). In general, all directions of movement were selected in an equivalent way of relative turning angles (**Fig. 2c**, **3c**, **4c**, and **A1b**).

The trajectories were composed of three (Subadult), five (Adult1) and fourteen segments (Adult 2) corresponding to low FPT values (fast/directed movement) and high FPT values (slow/localized movement) (**Fig. A2**). This pattern could be interpreted as a movement searching for food, followed by several phases of sit-and-wait places used to scan the environment, locate prey, catch and to ingest them.

Behavioural states

BCPA analyses revealed that Harpy Eagle movement patterns are described mainly by two behavioural states: (1) resting (short step-lengths and large relative turning angles); (2) exploratory (long step-lengths and small relative turning angles) (**Fig. 5**). The subadult exhibited four behavioural changes, primarily characterized by very low persistence velocity and high autocorrelation in phases 1, 2, and 4 (**Fig. 5a**). In contrast, the adult female demonstrated five changing points in the time series, and the selected model considered changes in all three parameters (μ, σ, and ρ) (**Fig. 5b**). The first trajectory (phase 1) showed the highest value for μ (0.0005 ± 0.0005) and the lowest value for ρ (0.12), while the fourth trajectory displayed the lowest value for μ (0.0001 ± 0.0005) and a high value for ρ (1.8). The translocated female exhibits two change points along movement trajectories. While the mean persistence velocity and standard deviation in phase 1 (0.00008 ± 0.0004) were quite similar to phase 2 (0.00007 ± 0.0004), the ρ values were significantly different (1.3 versus 0.05, respectively) (**Fig. 5c**).

Habitat use and selection

The tracked Harpy Eagles spent on average 83% of their time in the forest, despite using two other classes of land cover: "Forest" ranging from 72% to 97% of all locations used; "Secondary Forest", 2% to 21%; and a non-forest land cover "Pasture" from 1% to 8% (**Fig. A8**). For all individuals, "Forest" was predominant in the landscape, however, "Forest" and all other land cover are not equally available (**Fig. A8**). TRI values were on average 8.17 (± 4.93), ranging from 0.65 to 27.6 (**Fig. A3**); The slope was on average 3% (± 3.5) (flat relief) but with some locations varying from 3 to 8% (smooth wavy) and 8 to 14% (wavy) (**Fig. A4**). The NDVI used in most of the cases had high values ranging from 0.8 to 0.9 (**Fig. A5**). Distance from the habitat edge used by the three Harpy Eagles was on average 90 m (**Fig. A6**).

Regarding the four adjusted models, the independent variables had inconsistent results across the models. The coefficients for "Secondary forest" and "Pasture" were negative because the Use:Availability ratio for both classes was less than the Use:Availability for the reference class ("Forest") (**Fig. A8**). For subadult Model1, no evidence of a significant relationship was found between the variables Slope, TRI, NDVI and Habitat Edge with the dependent variable (**Table 2**). Likewise, none of the land cover categories ("Secondary Forest" and "Pasture") showed a significant association. In the fitted model2 (with interaction TRI versus land cover), only the interactions between TRI and "Pasture" were significant ($\beta = 0.77$, $p = 0.000$). The model suggests that the subadult would be 0.83 times more likely to choose the locations with high TRI values, while the interaction has resulted in a positive association, which the relative intensity of use of two equally available locations that differ by 1 unit of TRI is equal to 1.23 when the locations are in "Secondary Forest", and 1.81 when the locations are in "Pasture". Thus, Harpy Eagle selects for higher TRI when in "Forest", "Secondary Forest" and "Pasture" (**Fig. 6**).

In the model adjusted for Adult1, no evidence of a significant relationship was found between Slope and TRI with the dependent variable. However, the "Secondary Forest" showed a significant association ($\beta = -1.55$, $p = 0.000$), indicating a significant difference in relation to the reference category "Forest". Likewise, the "Pasture" was negatively associated ($\beta = -1.10$, $p = 0.050$). The NDVI ($\beta = 0.29$, $p = 0.021$) and the Habitat edge ($\beta = 0.26$, $p = 0.000$) also showed a significant association with the dependent variable. In the model adjusted for Adult2, none of the variables were associated with the use of locations, except for the "Pasture" that was negatively associated ($\beta = -1.01$, $p = 0.000$), indicating avoidance. The NDVI ($\beta = 0.35$, $p = 0.000$) and the Habitat edge ($\beta = -0.28$, $p = 0.000$) also showed significant associations with habitat selection. These results suggest that land cover and topographic features may play a varying role in determining the resource use by Harpy Eagle, with some variables showing significant associations and others not. NDVI was a good predictor for habitat selection, when increasing one unit on the NDVI values, increasing between 1.34 and 1.42 times the changes for both adults respectively at different landscape contexts to select locations with high NDVI values (**Fig. 6**).

Integrating the spatial utilization distribution over "Forest" and "Secondary Forest", the translocated female had 3.5 times more chances to select "Forest" than "Secondary Forest", instead having used "Secondary Forest" more than availability (**Fig. A8**), while the subadult male was 9.7 times more likely to choose "Forest" than "Secondary Forest". The Harpy Eagle was found to be between 1.05 and 1.42 times more likely to choose forested areas with the highest NDVI values, which probably includes location where the age of the "Secondary Forest" used by the adult Harpy Eagle was 15 (± 8) years, and 19 years (± 11) per subadult (**Fig. A7**).

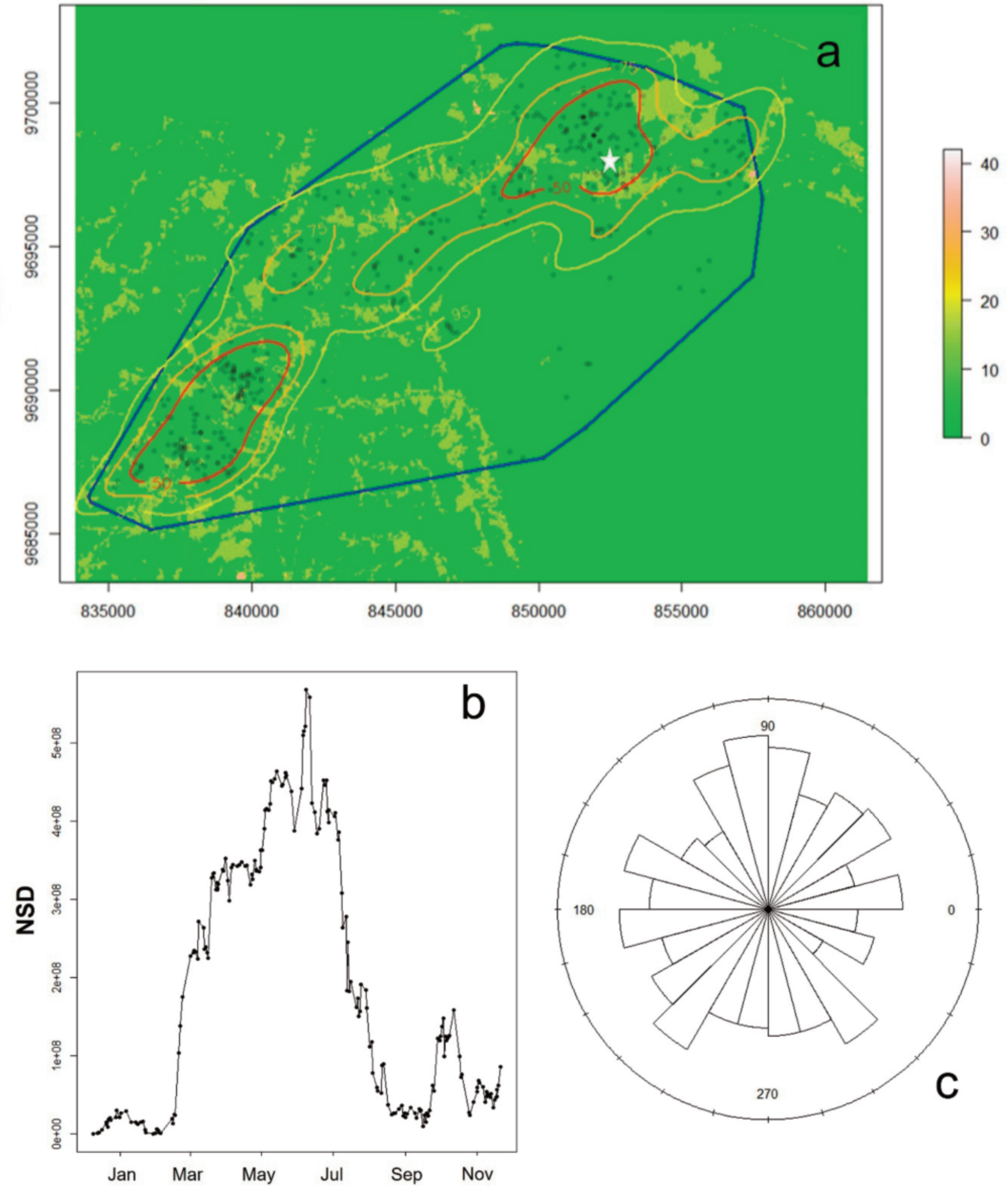


***Figure 2. a)** Isopleths of the Subadult four-year-old male Harpy Eagle locations (LC3 Argos) (black dots) released 12 km from recued site (Manaus municipality, Amazonas state) and tracked by Argos satellite telemetry during Dec 2011 to Nov 2012, at Amazon forests. White star represents release site. Polygons surrounding locations represent levels of KDE 50% (red), 75% (orange), 95% (yellow) and MCP 100% (blue). Land cover classes: 3 – Forest (green), 4 – Secondary Forest (light green), 11 – Wetlands, 12 – Grassland, 13 – Other non-forest formation 15 – Pasture, 41 – Agriculture (MapBiomas 2012); **b**) Variation of Net Squared Displacement (NSD) over time showing a migration movement; **c**) Rose diagram of relative turning angles (degrees) of 198 locations through trajectory.*

***Figura 2. a)** Isopletas de las localizaciones (LC3 Argos) del macho subadulto de cuatro años de edad de Águila Harpía (puntos negros) liberado a 12 km del punto de rescate (municipio de Manaus, estado de Amazonas) y monitoreado mediante telemetría satélite Argos desde diciembre de 2011 a noviembre de 2012 en los bosques de la Amazonía brasileña. La estrella blanca representa el lugar de suelta. Los polígonos que rodean las localizaciones representan los niveles del KDE 50% (rojo), 75% (naranja), 95% (amarillo) y el MCP 100% (azul). Las clases de cobertura del terreno son: 3 – Bosque (verde), 4 – Bosque Secundario (verde claro), 11 – Humedal, 12 – Pradera, 13 – Otra formación no forestal, 15 – Pasto, 41 – Zona Agrícola (MapBiomas 2012); **b**) Variación de la métrica Desplazamiento Neto Cuadrado (Net Squared Displacement, NSD) a lo largo del tiempo, mostrando un patrón de movimiento de migración; **c**) Diagrama de Rose de los ángulos de giro relativos (en grados) de 198 localizaciones de una trayectoria.*

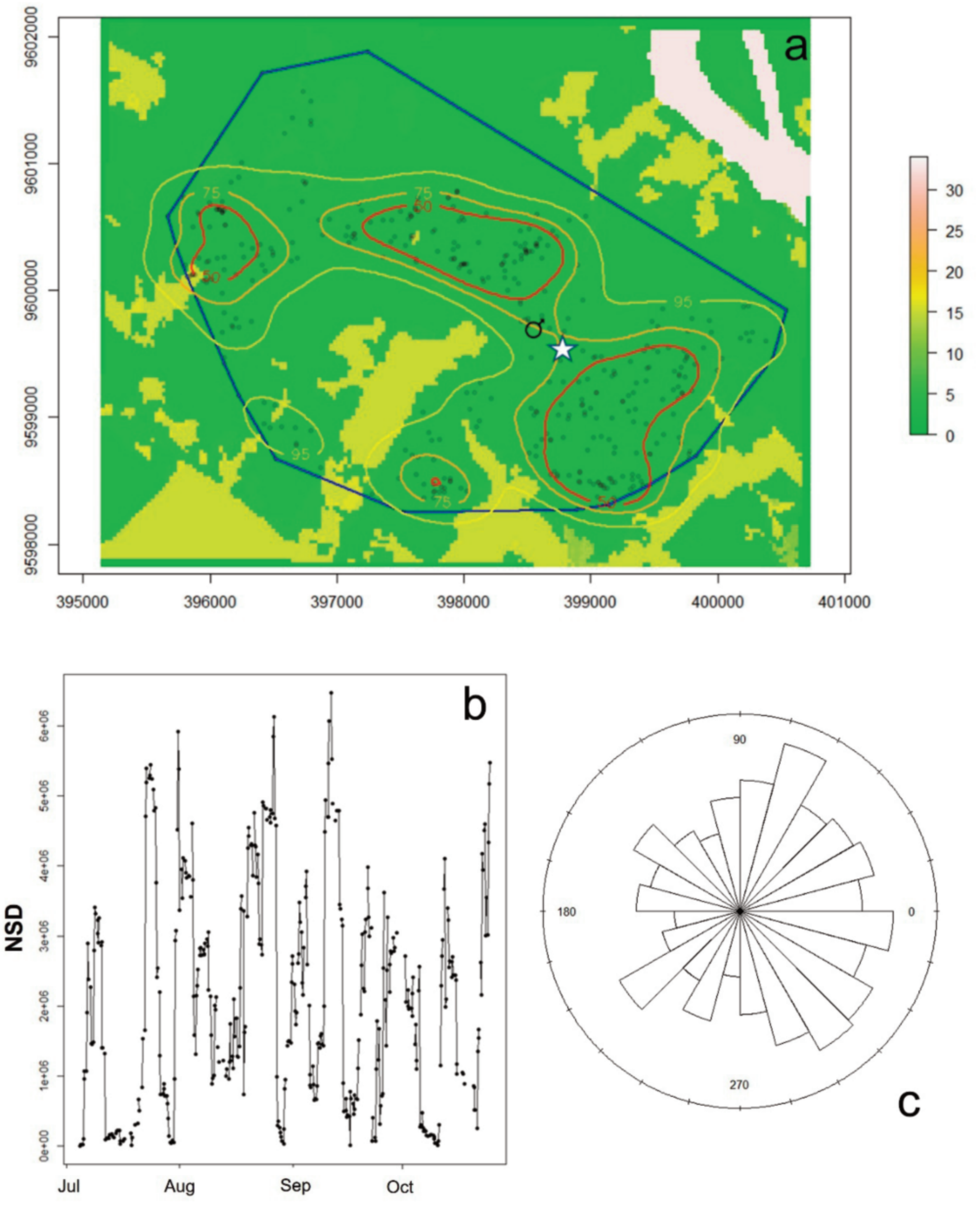


Figure 3. a) *Isopleths of the Adult1 female Harpy Eagle locations (black dots) released back into recued site (Senador José Porfírio municipality, Para state) tracked by GPS satellite telemetry during July 2014 to November 2015, at Brazilian Amazon Forest. White star represents release site. Polygons surrounding locations represent levels of KDE 50% (red), 75% (orange), 95% (yellow) and MCP 100% (blue). Land cover classes: 3 – Forest, 4 – Secondary Forest, 15 - Pasture (MapBiomas 2014). ♂ represents the adult male Harpy Eagle recorded during the female VHF tracking (4 July 2014); White star represents the juvenile recorded (**Fig. 2**) during the female VHF tracking (19 March 2015).* ***b****) Variation of Net Squared Displacement (NSD) over time showing a home range movement;* ***c****) Rose diagram of relative turning angles (degrees) of 163 locations through trajectory.*

Figura 3. a) *Isopletas de las localizaciones de la hembra de Águila Harpía "Adult1", liberada su lugar de rescate (municipio Senador José Porfírio, estado de Pará) y monitoreada mediante GPS satélite desde julio de 2014 a noviembre de 2015 en la Amazonía brasileña. La estrella blanca representa el lugar de suelta. Los polígonos que rodean las localizaciones representan los niveles del KDE 50% (rojo), 75% (naranja), 95% (amarillo) y el MCP 100% (azul). Las clases de cobertura del terreno son: 3 – Bosque (verde), 4 – Bosque Secundario (verde claro), 15 – Pasto, (MapBiomas 2014); ♂ representa el macho adulto de águila hapía registrado durante el radio-seguimiento de esta hembra (4 de julio de 2014); La estrella blanca representa el juvenil registrado (**Fig. 2**) durante el radio-seguimiento de la hembra (19 de marzo de 2015).* ***b****) Variación de la métrica Desplazamiento Neto Cuadrado (Net Squared Displacement, NSD) a lo largo del tiempo, mostrando un patrón de movimiento de área de campeo;* ***c****) Diagrama de Rose de los ángulos de giro relativos (en grados) de 163 localizaciones de una trayectoria.*

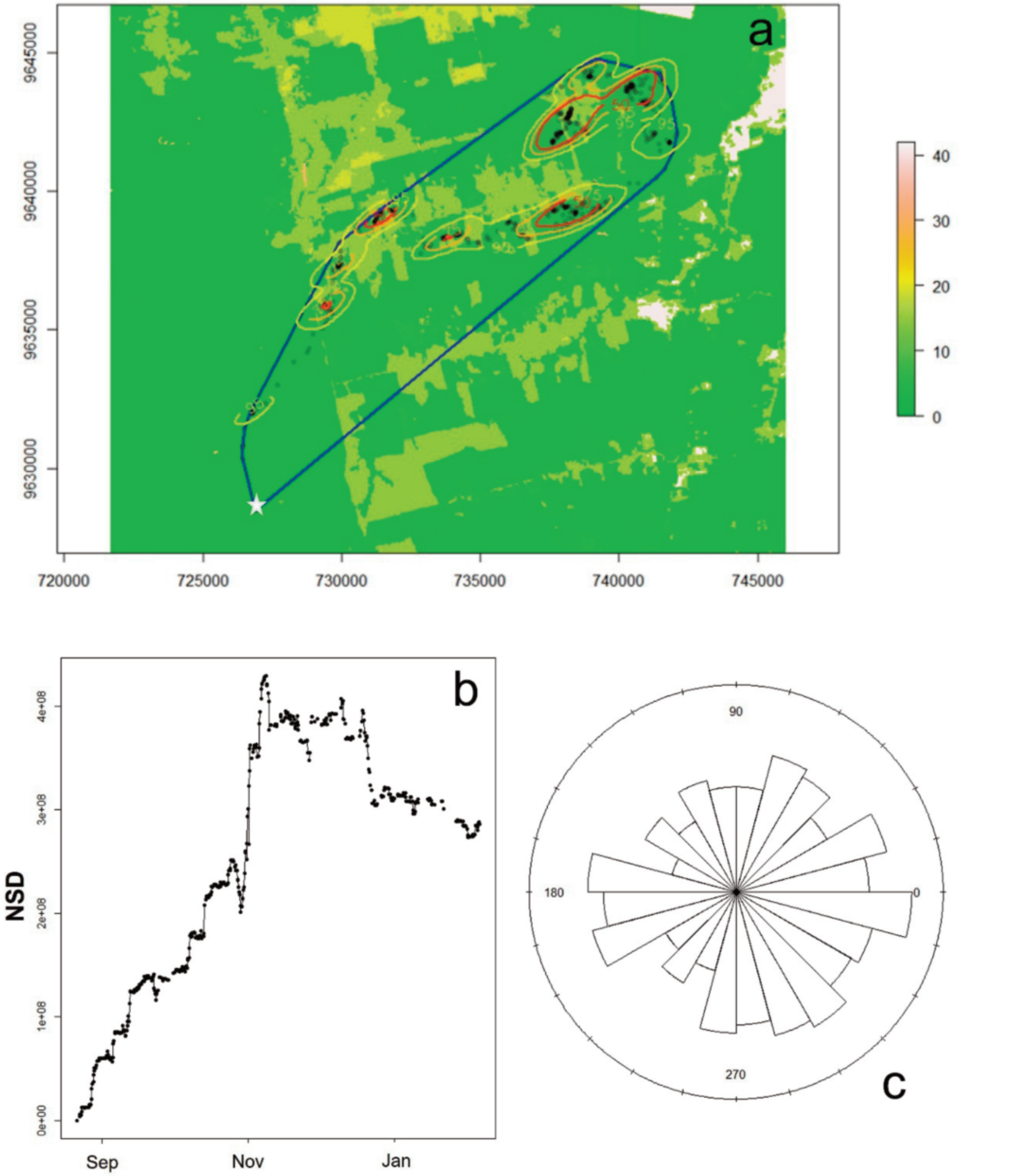
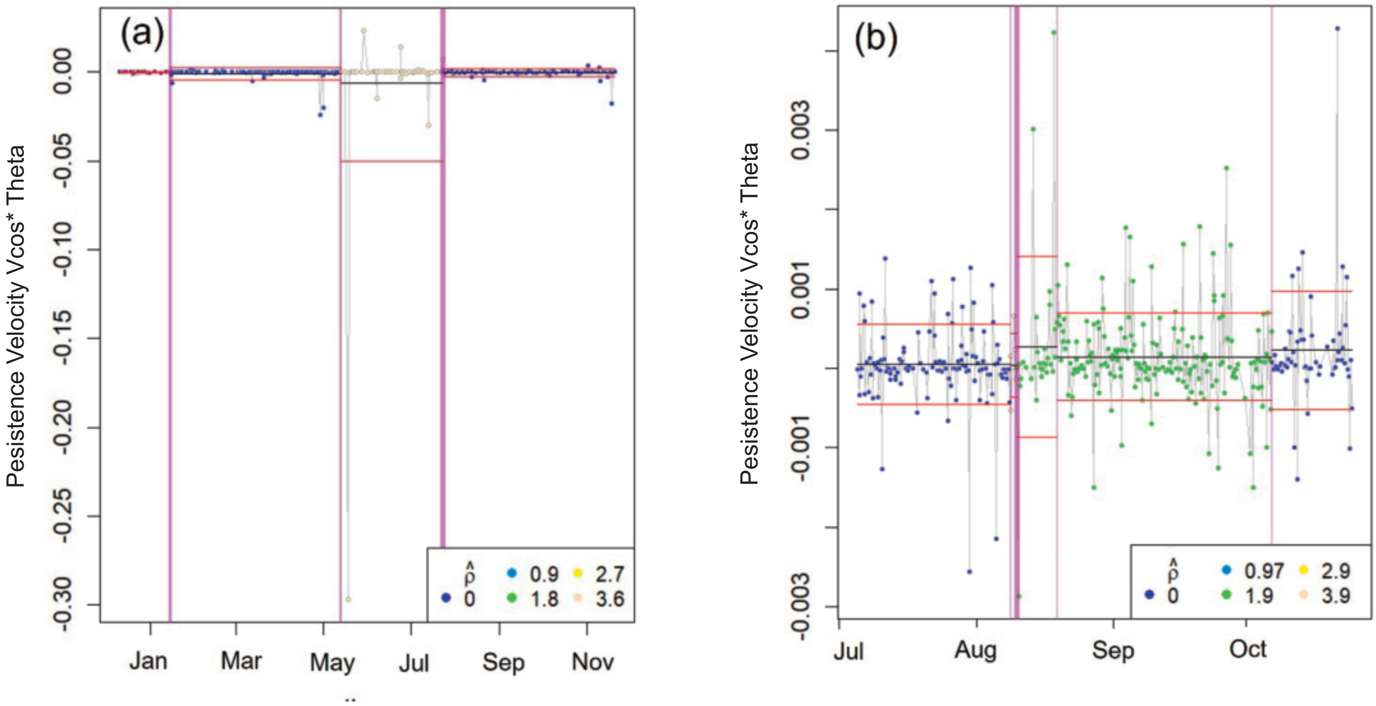


*Figure 4. **a)** Isopleths of the Adult2 female Harpy Eagle locations (black dots) tracked by GPS satellite telemetry at Belterra municipality (Para State) during August 2014 to February 2015, at Brazilian Amazon Forest. This individual was translocated 60 km from rescue site. White star represents release site. Polygons surrounding locations represent levels of KDE 50% (red), 75% (orange), 95% (yellow) and MCP 100% (blue). Land cover classes: 3 – Forest, 4 – Secondary Forest, 15 – Pasture, 19 – Monoculture, 33 – Water (MapBiomas 2014). **b**) Variation of Net Squared Displacement (NSD) over time showing a mixed dispersal-migration movement; **c**) Rose diagram of relative turning angles (degrees) of 175 locations through trajectory.*

*Figura 4. **a)** Isopletas de las localizaciones de la hembra adulta "Adult2" de Águila Harpía (puntos negros) monitoreada mediante GPS satélite en el municipio de Belterra (estado de Pará) desde agosto de 2014 a febrero de 2015, en la Amazonía brasileña. Este individuo fue traslocado 60 km desde su lugar de rescate. La estrella blanca representa el lugar de suelta. Los polígonos que rodean a las localizaciones representan los niveles de KDE al 50% (rojo), 75% (naranja), 95% (amarillo) y el MCP 100% (azul). Las clases de cobertura del terreno son: 3 – Bosque (verde), 4 – Bosque Secundario (verde claro), 15 – Pasto, 19 – Monocultivo, 33 – Agua (MapBiomas 2012); **b**) Variación de la métrica Desplazamiento Neto Cuadrado (Net Squared Displacement, NSD) a lo largo del tiempo, mostrando un patrón de movimiento mixto entre dispersión y migración; **c**) Diagrama de Rose de los ángulos de giro relativos (en grados) de 175 localizaciones de una trayectoria.*



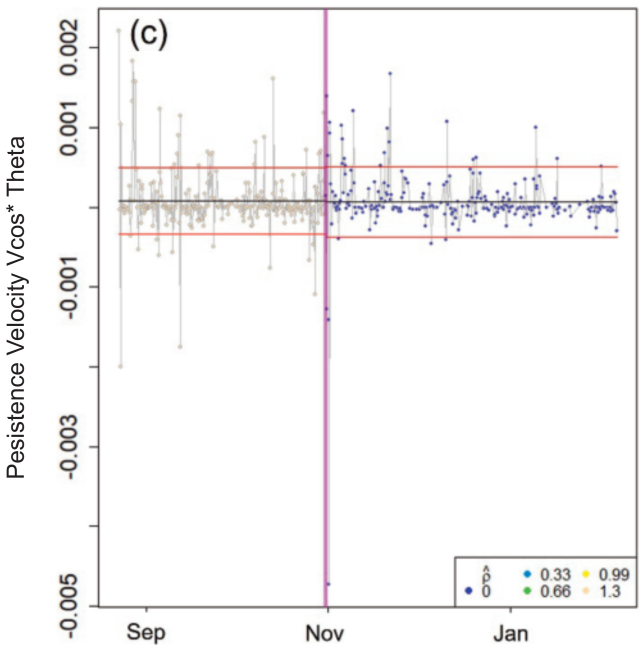


Figure 5. *Flat behavioural change point analysis (BCPA) for the translocated subadult male (**a**), adult female (Adult1) (**b**), and translocated adult female (Adult2) (**c**). Each point refers to one location. Vertical purple lines indicate behaviour change points. Horizontal black lines represent average persistence velocity for the behaviour phase, red lines represent the 95% prediction intervals. The colours indicate the time scale of temporal autocorrelation (ρ), with cooler (blue) and warmer (orange) colours indicating smaller and larger values, respectively. Low autocorrelation (blue) means that there is change in movement patterns and indicates a feeding behaviour whereas high autocorrelation emphasizes a more dispersal behaviour.*

Figura 5. *Análisis de puntos de cambio comportamental (behavioural change point analysis, BCPA) para el macho subadulto traslocado. (**a**), la hembra adulta (Adult1) (**b**), y la hembra adulta traslocada (Adult2) (**c**). Cada punto se refiere a una localización. Las líneas moradas verticales indican los puntos de cambio de comportamiento. Las líneas negras horizontales representan la persistencia promedio de la velocidad para esa fase de comportamiento, las líneas rojas representan los intervalos de predicción al 95%. Los colores indican la escala temporal de la autocorrelación temporal (ρ), con colores más fríos (azul) y cálidos (naranja) indicando valores pequeños y grandes, respectivamente. Una autocorrelación baja (azul) significa que hay un cambio en los patrones de movimiento e indica un evento de alimentación, mientras que una autocorrelación elevada indica un comportamiento más dispersivo.*

Discussion

Space use

In this study, we were able to rehabilitate four individuals and allow the establishment of the ecological function this predator performs into the wild. These individuals were rescued injured in the wild due to a collision with a powerline (Adult1 female) and gunshot (Adult2 female and Subadult male), threats recorded previously for other individuals during local and dispersal movements (Gusmão et al. 2020; Giraldo-Amaya et al. 2021). Male traveled 24 km in six months and returned the same distance to the point of its release, while the Adult1 traveled 20 km also in six months. Comparing these two individuals, the movement of the subadult was like that of the adult. Both wild individuals underwent a rehabilitation and translocation process. Its capability to travel large areas was also recorded in several individuals in Panama and Belize, where the mean post-release dispersal was 14.6 km (10.4 - 19.8) for adult wild-rehabilitated and 43.8 km (22.7 - 78.8) for captive-reared subadult > 30 months old (Naveda-Rodríguez et al. 2022). It is widely recorded worldwide that large eagles could travel large distances and back to their original breeding sites, even non-migrant species (Boshoff and Vernon 1988; Martínez-Miranzo et al. 2016).

The four-year-old individual utilized a large area (331 km²) (KDE95). At this age, the acquisition of information by exploration imposes movements across a larger area, rather than the smaller areas typically used by individuals in the established reproductive stage. Floaters, as is the case of subadults, will invest most of the time in information acquisition (Eliassen et al. 2007), then, after knowledge accumulation, the movements will become an exploitation performance through repeated visitation to patches of resources (Lewis et al. 2021). This could be observed in an adult female (Adult2, **Fig. 4a**). Harpy Eagle must have the ability for this learning shift before establishing its breeding site, investing time in learning about resources. This could probably be an advantage for

***Table 2**. Regression coefficients of four fitted models to data from three Harpy Eagle tracked at the Brazilian Amazon landscapes, 2011–2015. Model 1 (Subadult); Model 2 (Subadult) includes interaction between TRI and land cover; Model 3 (Adult 1 - released at rescued site); Model 4 (Translocated Adult). All models use "Forest" as the reference level.*

***Tabla 2.** Coeficientes de regresión de los cuatro modelos ajustados a los datos de tres Águilas Harpías monitoreadas en los paisajes de la Amazonía brasileña entre 2011 y 2015. Modelo 1 (Subadulto); Modelo 2 (Subadulto) incluye la interacción entre TRI y cobertura del terreno; Modelo 2 (Adulto 1 – liberado en el lugar de rescate); Modelo 4 (Adulto Traslocado). Todos los modelos utilizan bosque ("Forest") como categoría de referencia..*

Variables	β	Std. Error	p	OR	IC 95%	Model
(Intercept)	-10.75	0.07	0.000	0.00	0.00 – 0.00	Model 1
Slope	-0.04	0.07	0.567	0.96	0.84 – 1.09	
TRI	-0.09	0.07	0.174	0.91	0.79 – 1.04	
Secondary forest	-0.41	0.23	0.074	0.66	0.42 – 1.04	
Pasture	-0.45	0.33	0.170	0.64	0.33 – 1.21	
NDVI	0.05	0.09	0.600	1.05	0.87 – 1.26	
Habitat edge	0.11	0.06	0.074	1.11	0.99 – 1.25	AIC 5651.2
(Intercept)	-10.75	0.07	0.000	0.00	0.00 – 0.00	Model 2
Slope	0.03	0.07	0.640	0.97	0.85 – 1.11	
TRI	**-0.18**	**0.07**	**0.016**	**0.83**	**0.71 – 0.96**	
Secondary forest	-0.42	0.24	0.070	0.65	0.41 – 1.03	
Pasture	-0.30	0.32	0.347	0.74	0.39 – 1.39	
NDVI	0.03	0.09	0.761	1.03	0.86 – 1.22	
Habitat edge	0.11	0.06	0.065	1.12	0.99 – 1.25	
TRI:SecondaryForest	0.39	0.20	0.054	1.47	0.99 – 2.18	
TRI:Pasture	**0.77**	**0.25**	**0.002**	**2.17**	**1.32 – 3.55**	AIC 5644.8
(Intercept)	-10.81	0.06	0.000	0.00	0.00 – 0.00	Model 3
Slope	-0.05	0.05	0.307	0.95	0.85 – 1.05	
TRI	0.09	0.05	0.078	1.09	0.99 – 1.20	
Secondary forest	**-1.55**	**0.41**	**0.000**	**2.12**	**0.09 – 0.47**	
Pasture	-1.10	0.56	0.050	0.33	0.11 – 1.00	
NDVI	**0.29**	**0.12**	**0.021**	**1.34**	**1.04 – 1.71**	
Habitat edge	**0.26**	**0.08**	**0.000**	**1.29**	**1.11 – 1.51**	AIC 9155.6
(Intercept)	-10.71	0.06	0.000	2.23	0.00 – 0.00	Model 4
Slope	-0.09	0.05	0.047	0.91	0.83 – 0.99	
TRI	-0.05	0.04	0.304	0.95	0.87 – 1.04	
Secondary forest	-0.13	0.12	0.276	0.88	0.69 – 1.11	
Monoculture	-9.16	142.98	0.949	0.00	0.00 – 5.32	
Pasture	**-1.01**	**0.21**	**0.000**	**0.36**	**0.24 – 0.55**	
NDVI	**0.35**	**0.09**	**0.000**	**1.42**	**1.17 – 1.71**	
Habitat edge	**-0.28**	**0.05**	**0.000**	**0.76**	**0.68 – 0.84**	AIC 11762

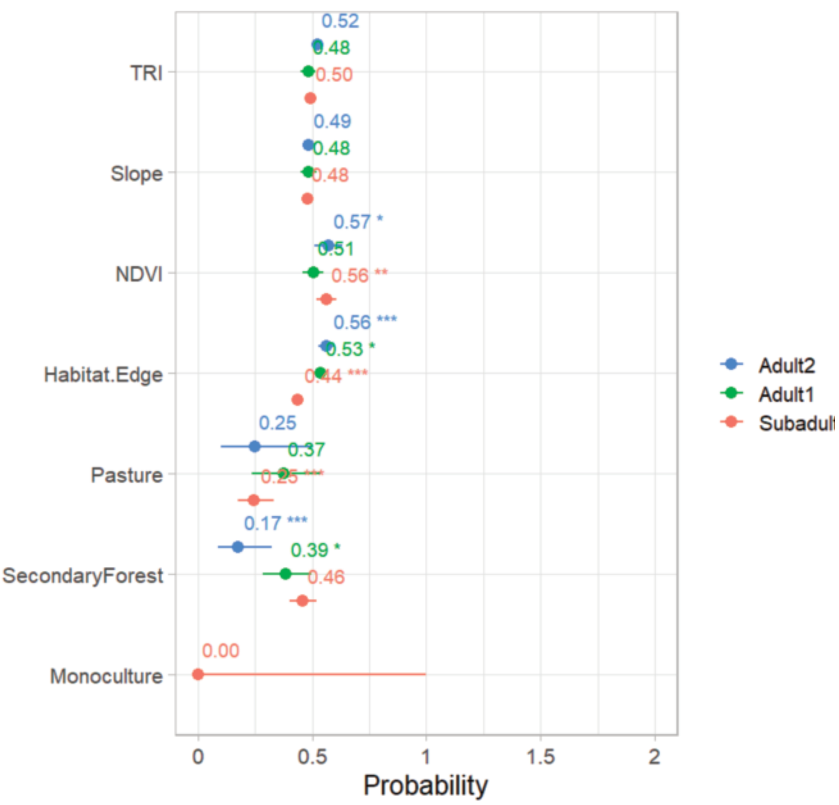


***Figure 6.** Selection probability of covariables by a subadult and two adults of Harpy Eagle tracked in Brazilian Amazon Forest.*

***Figura 6.** Probabilidad de selección de las covariables para una subadulto y dos adultos de Águila Harpía monitoreados en la selva amazónica de Brasil.*

this species, considering that it consumes a wide variety of prey on a biogeographic scale (Álvarez-Cordero 1996; Touchton et al. 2002; Aguiar-Silva et al. 2014; 2015; Miranda, Peres, et al. 2021).

Exploring large areas before establishing a breeding site can benefit in recognizing resource sites for when to start breeding and searching for prey to feed the female that does not hunt for at least two months during incubation (55 days in Rettig 1978), nestling and female for next two months after hatching, which the eaglet growth demands (at least one prey every 1 to 3.5 day (Projeto Harpia unpublished data, Rettig 1978) especially when exposed to habitat changes and consequently resources reduction by anthropogenic actions.

The three individuals tracked in their natal area between 10 and 16 months old, flew 153 m (at 10 months old) and 800m (at 16 months old) surrounding the nesting tree. This behavior reflects the dependence on parental care, during the post-fledging dependence (Soutullo et al. 2006), which on average occurs for three years, until dispersal movements. Juveniles Harpy Eagle tracked in Venezuela and Ecuador in their first two years after hatching, moved around 600 and 1300 m from nesting tree, without any signals of dispersal movements, one of them flew only 296 m from the nest when 13 months old (Álvarez-Cordero 1996; Muñiz-López et al. 2012). After the onset of dispersal, a juvenile with 39 months old, flew 35 km far from its nesting tree, using 386 km² (Urios et al. 2017). In Venezuela a juvenile Harpy Eagle was relocated three years later in <10 km from its native nest site (Álvarez-Cordero 1996). This range of area used by Harpy Eagle indicates that a movement pattern may depend not only on the landscape or resource availability but also on individual performance by internal state and response of individuals to the perceived risk while moving (Revilla and Wiegand 2008).

Translocated individuals (Subadult and Adult1) injured by gunshot, that came from fragmented landscape, were released inside protected areas. However, both eagles transposed the borders of these sites moving near the edge of the forest (**Fig. 2a** and **4a**), or in a mosaic of land anthropogenic uses. This situation where these eagles can approach human settlements, increases the chances of them being gunshot or poached. Shooting was an important cause of wild-born Harpy Eagle mortality (Sanaiotti et al. 2015; Muñiz-López 2017; Giraldo-Amaya et al. 2020). Translocations may be considered only if it is not possible to maintain the eagle´s safety due to reduced habitat and high levels of threats of anthropogenic origins. For adult translocations, the effect of translocating a member of the established couple in the area must be assessed.

The translocated female moved in the direction of its rescued site and the translocated subadult moved back and forward to the rescue and released sites. Unfortunately, the transmitter stopped sending data so we could not confirm that this individual's movement would be in the direction of its original place. It is important to be cautious in interpreting homing with only two individuals. However, the Harpy Eagle´s homing ability is a behavior that should be examined, mainly for initiatives that includes translocations of captive-reared individuals. Translocation drawbacks need to be managed, for example, a released eagle inside an occupied Harpy Eagle territory, should be immatures (Pullins et al. 2018), which will be a floater until a territory becomes vacant (Boshoff and Vernon 1988). Several studies reported homing to breeding sites even without techniques to encourage this behavior (Boshoff and Vernon 1988, Martínez-Miranzo et al. 2016). However, in our study we could not analyze this due to few data and available replicas. Translocation strategy as a management decision of Harpy Eagle has drawbacks, such as their long-distance displacement capability reported in this study and in Panama and Belize (Naveda-Rodríguez et al. 2022). This was also reported for other large eagles with a good homing ability that even 200 km may not be enough distance of translocation (Boshoff and Vernon 1988). Maintenance of home range size and fidelity across years assures that the adoption of any conservation management plan would have a lasting impact over time.

As reported from Belize, Harpy Eagle has a high capacity for long-distance displacement, when a subadult (> 30 months) dispersed 150 and 179.7 km from the release site (Matola 2006 and Naveda-Rodríguez et al. 2022 respectively). A good homing ability was reported for some large eagles, such as Black Eagles, *Aquila verreauxii* and Crowned Eagles, *Stephanoetus coronatus*, which travels 105 km to the capture sites (Boshoff and Vernon 1988). These authors suggest that releases should be at least 200 km from the original capture site. However, there are reasons that the translocation strategy needs to be used with caution due to various drawbacks, e.g., translocating an eagle to an occupied territory, imposing them to an interspecific conflict (Boshoff and Vernon 1988; Berger-Tal et al. 2019). It is a well-known fact that eagles have excellent homing ability and can get back to their home ranges even after 400km translocation. Harpy Eagles probably cannot disperse that far since they do not soar. Anyways, a 12 km translocation is trivial, obviously it would not work.

The adult female used 14 km² consistently for nine months (**Fig. 3a**; **Table 1**). The nest tree of this tracked adult has not yet been found. This individual was probably flying along its breeding site, as during *in situ* VHF tracking, an adult male carrying a sloth and an immature (one year old) were recorded within the area used by the tracked female. The area used by this adult is within the home range estimates based on inter-nests distance in Panama (10 to 63 km^2), but much smaller than estimated for pairs in Venezuela (45 to 79 km²) (Álvarez-Cordero 1996). This can probably reflect a performance associated with the composition and configuration of the landscape. This female, which was utilizing its breeding site, had the smallest home range (14 km²) when compared to the translocated individuals (126 and 331 km²) (**Table 1**). For central-place foragers (Orians and Pearson 1979), such as the most of diurnal raptors (Sonerud 1992), it is evident that reproduction imposes constraints on movement, leading to home range behavior.

A large variation in the size areas of movement for Harpy Eagle in the Brazilian Amazonia may reflect the age (immature versus adult) and release situation (around the nesting tree, releases back to the rescued site, or translocations). However, it seems that the home ranges performed by the adult Harpy Eagles are much smaller than the 100 Km² estimated previously for a primary forest in French Guiana (Thiollay 1989). A pattern that may depend on the landscape composition, resource availability, and ecological interactions.

We reinforce the recommendation to include in conservation management an area over the landscape scale to optimize and provide connectivity as subadults disperse, beside the nest tree itself. The dependence of juveniles on the nesting tree highlights the importance of managing this area cautiously for at least the first two years after a hatchling has been recorded.

Habitat selection

The higher availability of forest habitat (**Fig. A8**) implies that Harpy Eagle is more likely to be in forest; however, an individual (Adult2 translocated 60 km from the rescued site) used "Secondary Forest" more than its availability (**Fig. A8**). Despite using other habitats, the probability of using forests is always higher even if their habitat availability is lower. For example, it was eight times more likely for the subadult for choose the "Forest" than the "Secondary Forest" habitat (**Table 2**). Additionally, the land cover type "Pasture", which is not considered habitat for the Harpy Eagle, was used in a smaller proportion than that available in the landscapes of the three individuals tracked. It is likely that the Harpy Eagle was perched on the edge of its habitat, as documented in a photographic record (Junqueira 2016). A Red-handed Howler monkey (*Alouatta belzebul*) remains (hair, fur, pelvis, femur, and foot bones) were recorded near the Harpy Eagle faeces during adult female (Adult2, Z01019 ID banding) VHF tracking about 10 m from the habitat edge. We also have several records of adults and juveniles using pasture areas being about 150 m from the forest edge. The individuals were perched in a group of three/four trees isolated by pasture.

A positive association between adult Harpy Eagle in selecting "Forest" cover over other classes of vegetation cover and high NDVI values, and negative in relation to "Secondary Forest" for the adult flying in its reproductive site with low impact from deforestation, report the high dependency of this species with high qualities of resources strictly from forest habitats. Despite this, an adult female used the "Secondary Forest" more than its availability (**Fig. A8b**). Probably, this individual used this habitat to travel and hunt, as the predation record during VHF tracking, where we found a monkey remains (bones and fur) and Harpy Eagle faeces, at a GPS location that we were looking for. For the central-place foragers, the probability of use is expected to decline with distance from the nest site (Rosenberg and McKelvey 1999).

Perhaps the secondary forest, depending on the use that the eagles have had in it, is important as a place of communication between better-preserved forests where it remains longer (hours). The number of locations in limited times can skew the origin of the behaviour, which means that in fragmented landscapes this habitat is highly important to Harpy Eagle as a selected habitat and indicates its value to biodiversity conservation. Even though secondary forest is not like as the original old-growth forest, mainly in terms of structure of trees, biomass and species diversity, this ecosystem has a high value to biodiversity in human-modified tropical landscapes, allowing the connectivity of forest fragments (Rozendaal et al. 2019; Souza et al. 2020; Rosenfield et al. 2022). The secondary forests, an important carbon sink in the Amazonia, have been identified as a potential nature-based solutions to the climate crisis (Heinrich et al. 2021).

In addition, there is a negative association with "Pasture" and "Monoculture" (soybean in the region of Adult2, for example), open areas without stratified vegetation, which means that the Harpy Eagle avoids this anthropogenic land uses, in respect to use relative to availability. The subadult moved by 24 km crossing several times a pavemented road that connects a metropolis (municipality of Manaus) with 2 063 547 inhabitants to another city on the banks of the Amazon River (municipality of Itacoatiara) with 103 598 inhabitants (IBGE 2020). These covariables would also be a threat factor due to the probability of encounters and negative interactions with humans or anthropogenic infrastructures, as previously reported gunshot and electrocution threaten the Harpy Eagle (Gusmão et al. 2020; Giraldo-Amaya et al. 2021). Electrocution for example was reported as the main cause of mortality to the Bonelli's Eagle, Hieraaetus fasciatus in Spain (Real et al. 2001). Considering that the Harpy Eagle uses the forest edge and may be in contact with human-wildlife conflicts, awareness campaigns are strongly recommended to reduce the shooting risks (by lack of knowledge, myths, and curiosity) this species during dispersal movements or dependence of nesting trees.

The TRI (Terrain Ruggedness Index) had no general importance for habitat selection among the three individuals, except when considering the interaction with land cover (**Table 2**). Nevertheless, this covariate was among the three associated predictors in a model used to estimate the distribution of the Harpy Eagle, employing a spatial resolution of approximately ~4.5 km (Sutton et al. 2021). In contrast, our study's spatial scale was 30 m. We were uncertain whether the absence of recorded associations with habitat selection, as observed in the aforementioned study utilizing a spatial scale 150 times larger, may have resulted from a spatial scale bias.

The mechanisms involved in Harpy Eagle movements probably include memory, and it is oriented towards the spatial heterogeneity of the resource (Mueller and Fagan 2008). Probably the limitations to the Harpy Eagle are a combination of the resources used, such as the arboreal prey species, forest structure, and temperature (Moreira et al. 2014). Sloths, known as the main prey for Harpy Eagle are poor body temperature regulators due to their low capacity to increase their metabolism (Gilmore et al. 2000), being intolerant to large temperature variations (McNab 1985; Lopes et al. 2023). To cope with this limitation, sloths have adapted to seeking refuge in the forest canopy, where they can thermoregulate more effectively (Montgomery and Sunquist 1978). The dossel provides them with a stable microclimate, allowing sloths to conserve body heat during cooler periods and avoid overheating in warmer conditions. However, this strategy makes them vulnerable to canopy predators, becoming the most frequent food intake for Harpy Eagles (Aguiar-Silva et al. 2014; Miranda, Peres, et al. 2021).

Even using secondary forests, Harpy Eagle selected for forests more than other type of land cover. For two individuals the "Secondary Forest" was also used more than its availability, which means that in fragmented landscapes this habitat is highly important for the conservation for translocated individuals of Harpy Eagle. We suggest including in conservation management not only to protect the nesting trees and its immediate surroundings but also an area at the landscape scale to optimize and provide connectivity process as subadults dispersal. The dependence of the juveniles on the nesting tree, highlights the importance of managing this area during at least the first two years after a hatch has been recorded.

Conclusion

This study is a part of a larger ongoing effort to provide data for Harpy Eagle conservation strategies in Brazil. Despite providing important information about the behavioral ecology of this large and highly vulnerable eagle during its movements through the forest in the Brazilian Amazon, these results are not worthy of generalizations due to the low number of replicates. We could demonstrate behavioural differences in the movement patterns of rehabilitated individuals, as well as confirm their successful integration into the wild. Even using secondary forests, Harpy Eagle selected for forests more than any other land cover type. We suggest that the Harpy Eagle movement ecology reflects the spatial dynamics of its prey in the forest canopy, which needs to be further addressed in future research.

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Author's contributions

Francisca Helena Aguiar-Silva: Conceptualization, Data curation, Investigation, Formal analysis, Writing - Original draft. Tânia Margarete Sanaiotti: Investigation, Writing – Review and Editing. Thiago Bicudo: Investigation, Writing – Review and Editing. Rogerio Martins Sanches: Data collection. Carlos Augusto Tuyama: Data collection. Tiago Guimarães Junqueira: Data collection. Ana Luiza Kerti Mangabeira Albernaz: Writing – Review and Editing.

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Appendix/Apéndice

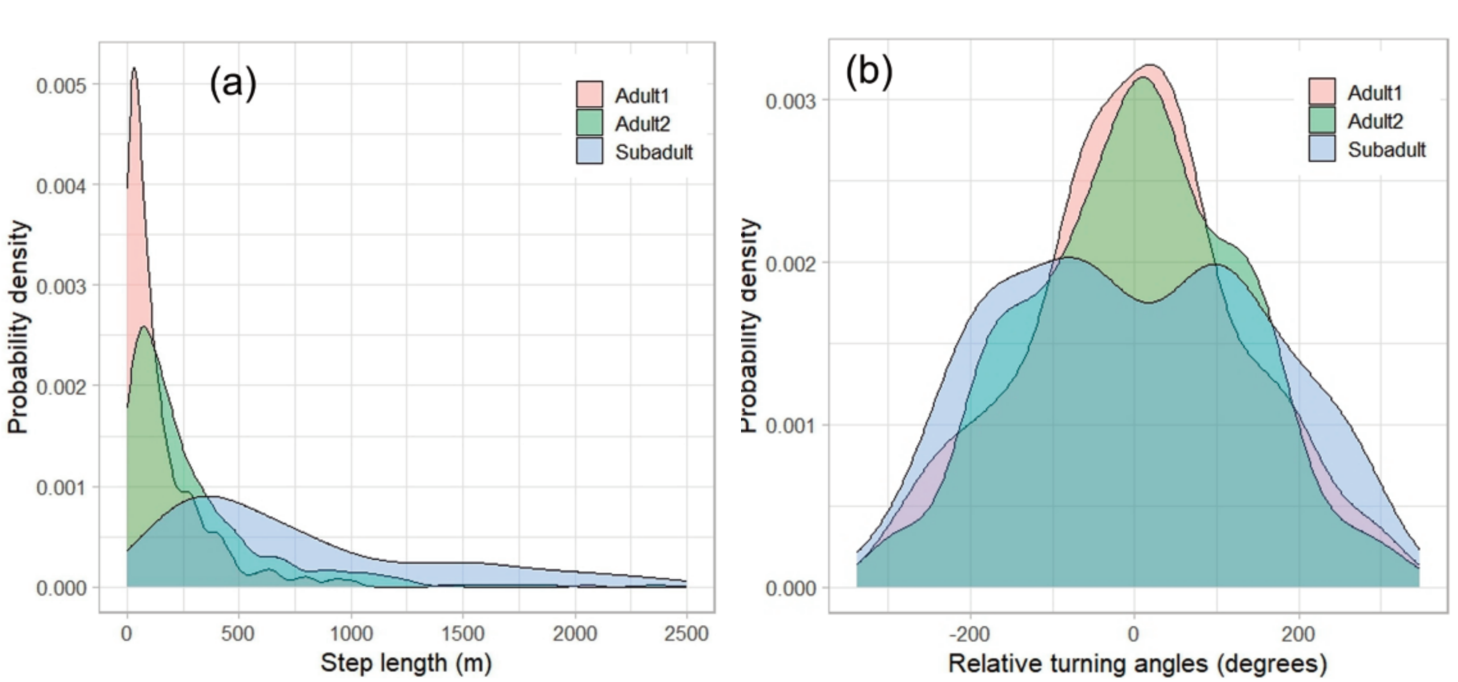

Figure A1. *Probability density of the observed step length (**a**) and relative turning angles (degrees) (**b**) of the three Harpy Eagles tracked on the Brazilian Amazon.*

Figura A1. *Densidad de probabilidad de la longitud de paso observada (**a**) y los ángulos de giro relativos (en grados) (**b**) para las tres Águilas Harpías monitoreadas en la Amazonía brasileña.*

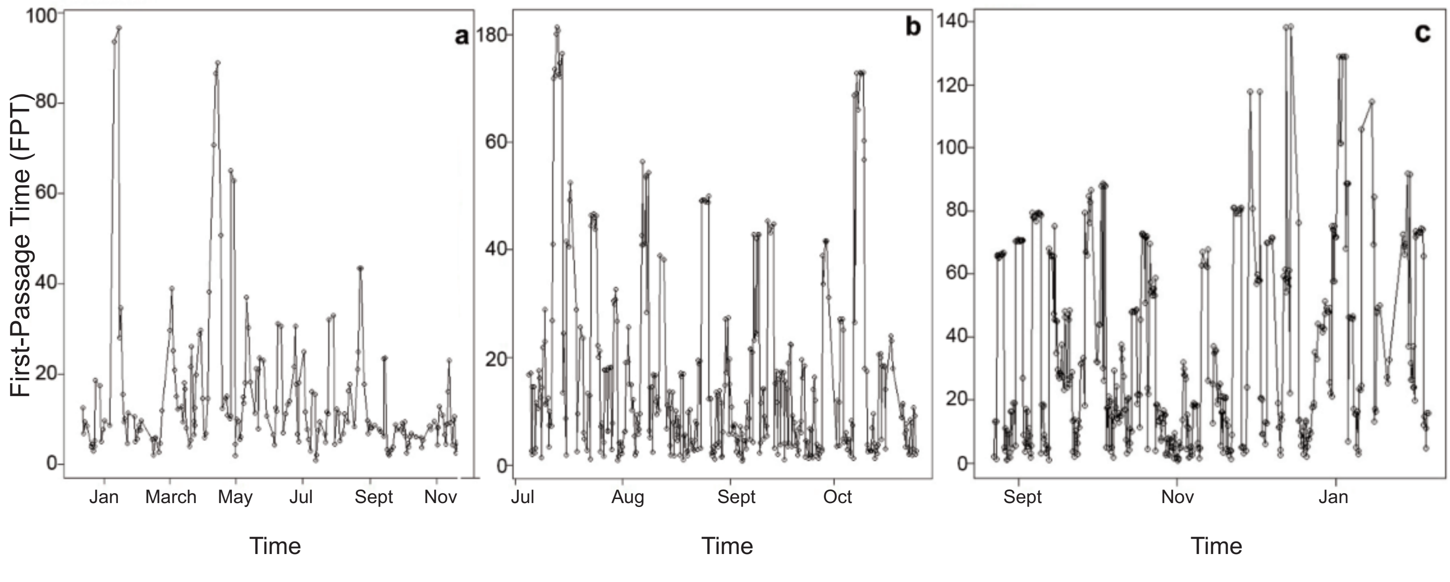

Figure A2. *First-Passage Time (FPT) over time for the Subadult, Adult1, and Adult2 Harpy Eagle movements.*

Figura A2. *Hora del primer pasaje (First-Passage Time, FPT) a lo largo del tiempo para los movimientos de el Subadulto, el Adulto1 y el Adulto2 de Águila Harpía.*

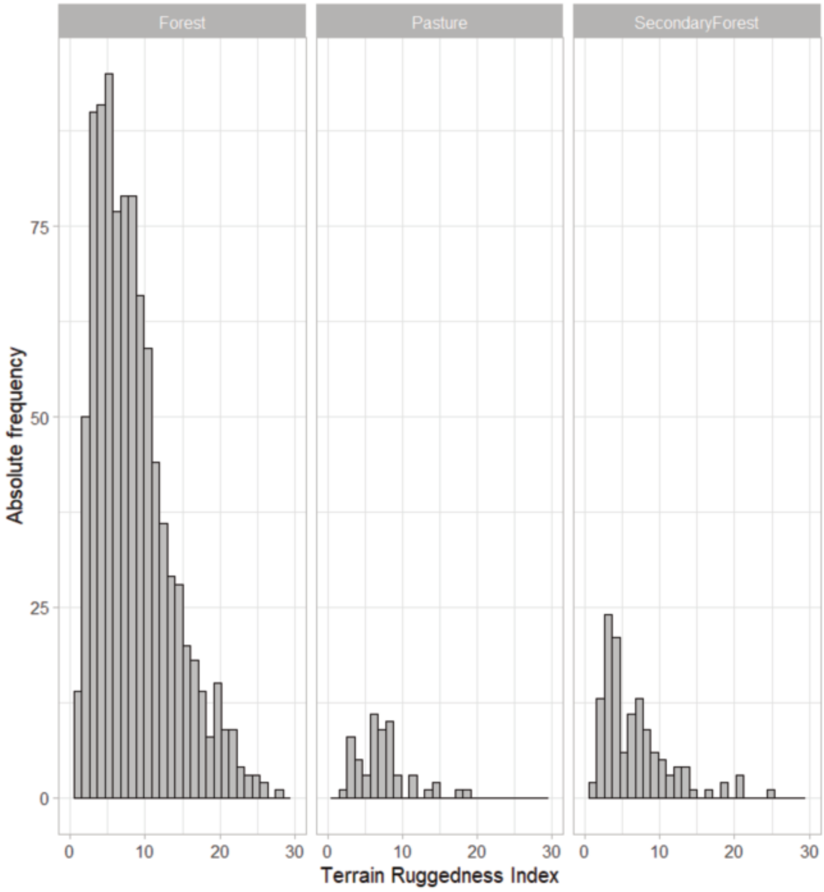

Figure A3. *Absolute frequency of TRI values used by three Harpy Eagles tracked in the Brazilian Amazon.*
Figura A3. *Frecuencia absoluta de valores de TRI usados por las tres Águilas Harpías monitoreadas en la Amazonía brasileña.*

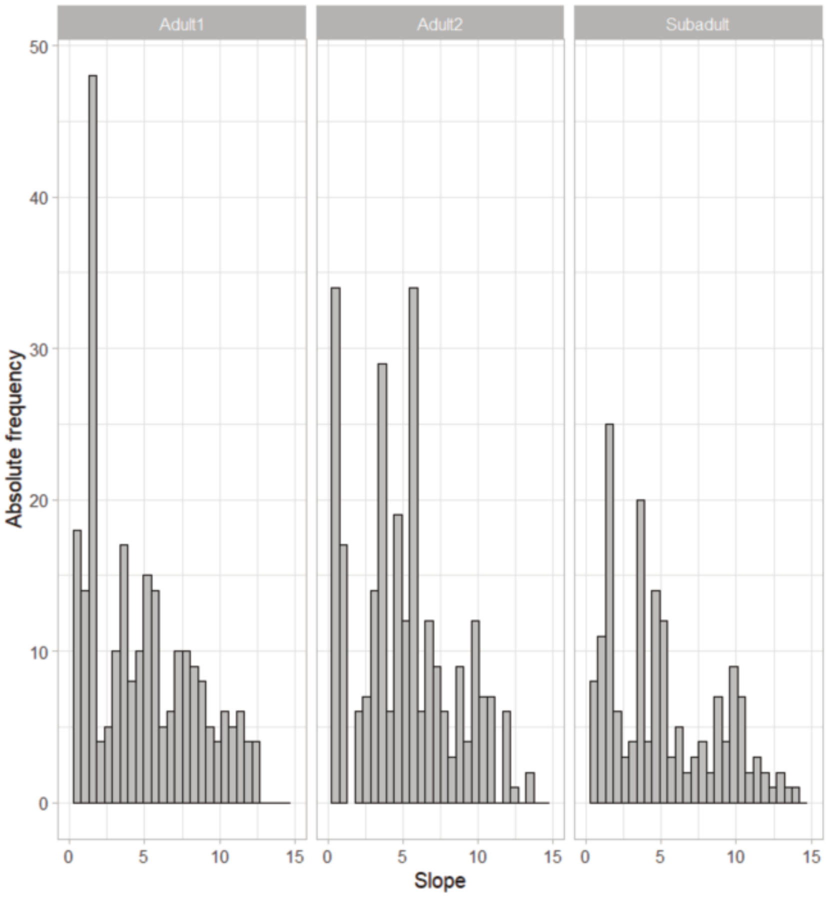

Figure A4. *Absolute frequency of slope values used by three Harpy Eagles tracked in the Brazilian Amazon.*
Figura A4. *Frecuencia absoluta de valores de pendiente usados por las tres Águilas Harpías monitoreadas en la Amazonía brasileña.*

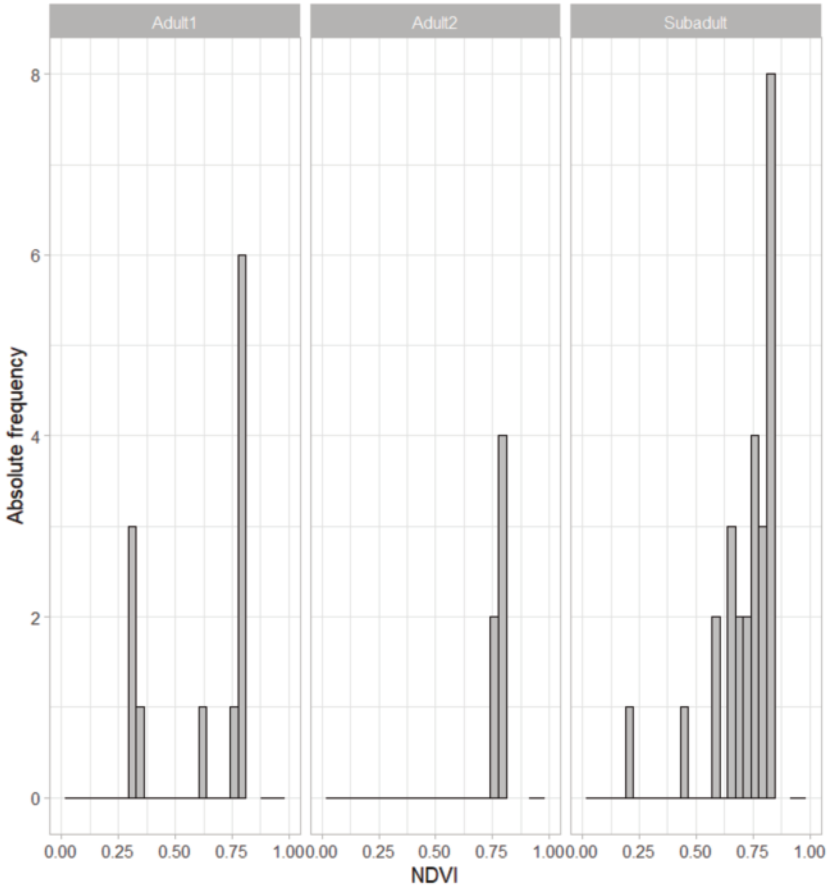

Figure A5. *Absolute Frequency of NDVI values used by three Harpy Eagles tracked in the Brazilian Amazon.*
Figura A5. *Frecuencia absoluta de valores de NDVI usadas por las tres Águilas Harpías monitoreadas en la Amazonía brasileña.*

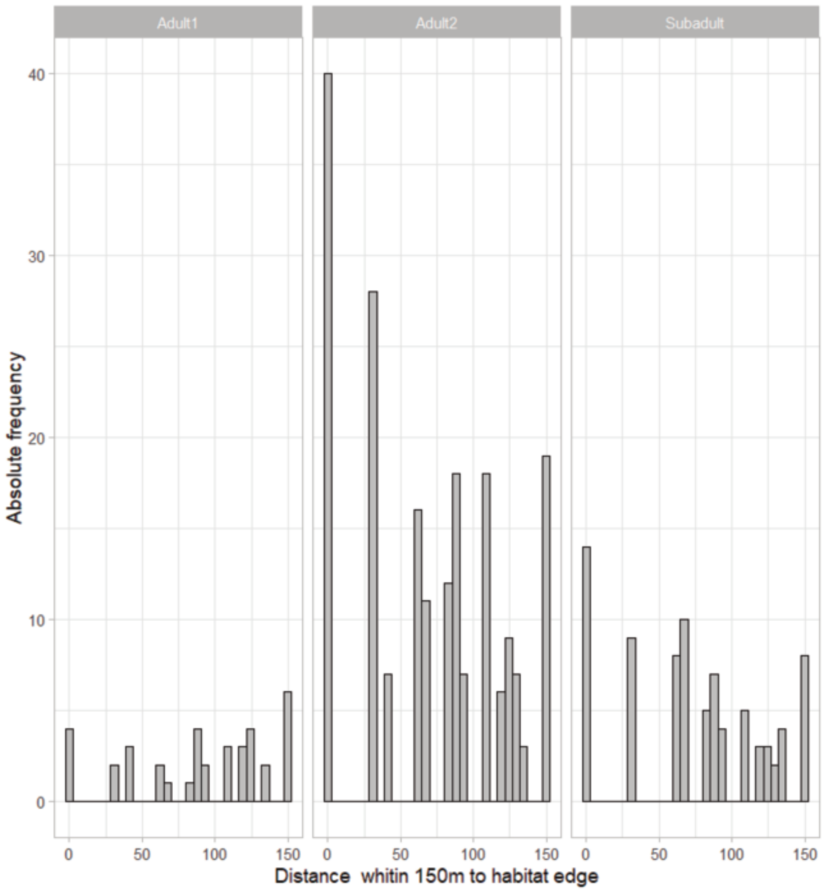

Figure A6. *Absolute frequency of distance to habitat edge used by three Harpy Eagles tracked in the Brazilian Amazon.*
Figura A6. *Frecuencia absoluta de valores de "distancia al borde del hábitat" usadas por las tres Águilas Harpías monitoreadas en la Amazonía brasileña.*

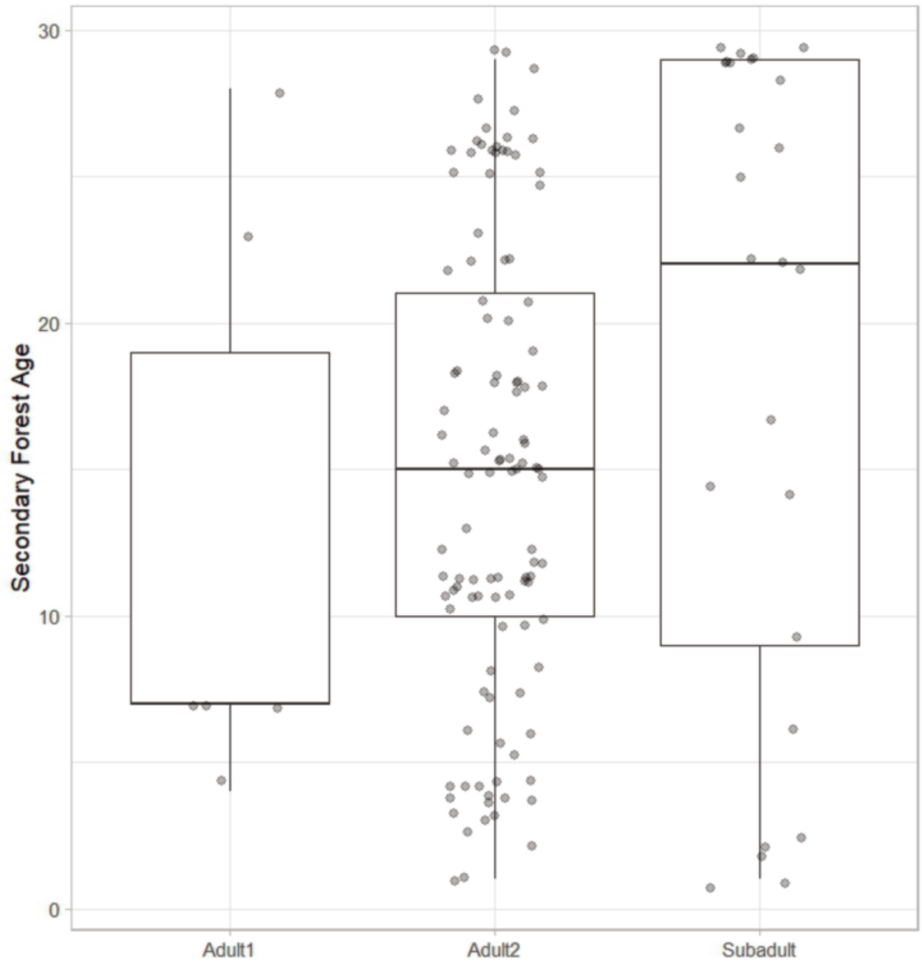

Figure A7. *Secondary forest age used by Adult2 and Subadult four-year-old Harpy Eagle.*
Figura A7. *Edad del bosque secundario usado por el Adulto2 y el Subadulto de cuatro años de Águila Harpía.*

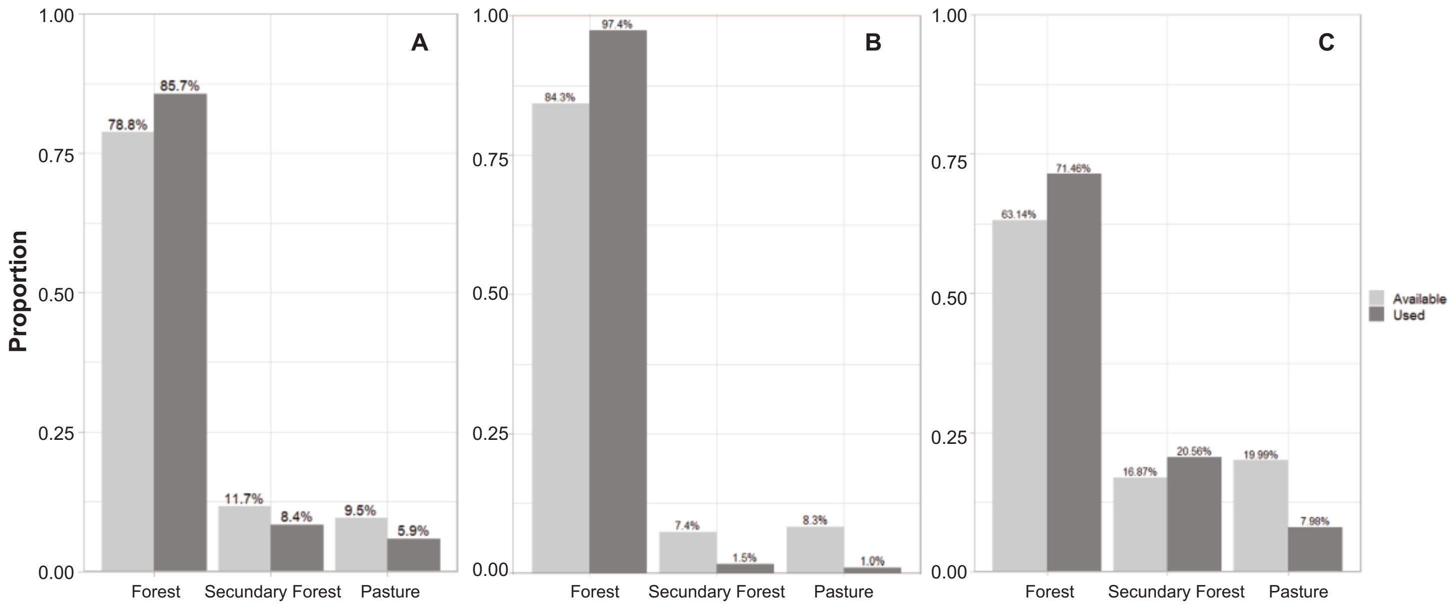

Figure A8. *Used and available of land cover classes by three Harpy Eagle in the Brazilian Amazonia.* ***A)*** *Subadult four-year-old male translocated 12 km from rescue site;* ***B)*** *Adult1 female released back at the rescued site;* ***C)*** *Adult2 female translocated 60 km from rescue site.*

Figura A8. *Clases de cobertura del terreno utilizadas y disponibles para las tres Águilas Harpías estudiadas en la Amazonía brasileña.* ***A)*** *Subadulto de cuatro años traslocado a 12 km de su lugar de rescate;* ***B)*** *"Adult1", hembra vuelta a liberar en su lugar de rescate;* ***C)****"Adult2", hembra traslocada 60 km desde el lugar de rescate.*