

Jaguar (*Panthera onca*) density and population size across protected areas and indigenous lands in the Amazon biome, its largest stronghold

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ABSTRACT

Protected areas, including Indigenous Lands, play a critical role in protecting natural habitats and wildlife. The Amazon has a remarkable network of protected areas and is home to the largest population of the Neotropics' largest felid, the jaguar (*Panthera onca*). Yet, knowledge of the population status of jaguars across the biome is scarce. In this article, we use camera trap data combined with multi-session spatial capture-recapture models to estimate site-independent jaguar densities in 22 protected areas. Additionally, we tested for density spatial variation based on anthropogenic and biological variables, predicting approximate jaguar population size for

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each protected area sampled. The estimated average density of jaguars across our sites was 3.08 ± 1.13 individuals per 100 km^2 but density estimates varied more than 20-fold from 0.60 ± 0.50 ind./ 100 km^2 in the Lower Negro River (Cuieiras Biological Reserve) to 9.97 ± 2.48 ind./ 100 km^2 in the várzea floodplains of the Amazon River (Sustainable Development Reserve Mamirauá). Our results revealed that the highest densities of jaguars occur in regions with higher primary productivity and that all 22 protected areas combined harbour an estimated jaguar population size of 6389 individuals (95 % CI: 4664–7986), highlighting the importance that protected areas have for the conservation of this emblematic species. We contend that implementing continuous monitoring programs across Amazonian protected areas and curbing escalating anthropogenic pressures is paramount to ensure these areas remain as a stronghold for the species.

1. Introduction

The establishment of protected areas (hereafter PAs) stands as the main global strategy for conserving natural habitats, biodiversity, and ecosystem services (IUCN, 2010). While PAs alone do not guarantee absolute protection, their effectiveness in mitigating land cover transformation is widely acknowledged (Pessôa et al., 2023). Similarly, Indigenous Lands have repeatedly proven their efficacy to guarantee protection of natural habitats (for simplification hereafter PAs) (Qin et al., 2023). Given the escalating human impact on natural habitats, monitoring the population size of key species becomes a crucial tool for guiding management and conservation efforts. Population size or abundance is a basic ecological measure commonly used to characterize population trends over time and to assess the status of endangered species. To estimate densities of elusive species with distinctive marks, camera-traps associated with capture-recapture models have been successfully applied worldwide for over two decades (Green et al., 2020; Karanth, 1998).

The jaguar (*Panthera onca*) is a secretive and solitary predator, relying on camouflage to ambush prey. Like other top carnivores, it naturally occurs at low densities, has a large home range, and requires healthy prey populations to thrive (Sunquist and Sunquist, 2002). Currently considered as Near Threatened by the IUCN, its ecological requirements make the jaguar especially sensitive to anthropogenic pressures, such as habitat loss, fragmentation and degradation, prey depletion, and direct persecution (Quigley et al., 2017). Historically, jaguars ranged from the southern USA to central Argentina, but they have lost half of their range over the last century (Quigley et al., 2017). Across the remaining area, most populations are isolated and likely decreasing, with the Amazon, the Pantanal, and the tropical forests of the Yucatan Peninsula in southeast Mexico still holding stable populations (Ceballos et al., 2021; de la Torre et al., 2018; Jędrzejewski et al., 2018). Due to its vast extent and a large network of PAs, the Amazon is considered the main stronghold for the species (Quigley et al., 2017; Sollmann et al., 2008).

The Amazon is of enormous importance to humanity due to the vast biological resources it harbours, its role in local and global climate regulation, carbon storage, as well as a home to many traditional and indigenous groups (Science Panel for the Amazon, 2021). Yet, the biome has been increasingly threatened by anthropogenic activities (Flores et al., 2024; Lapola et al., 2023). From 2001 to 2021, deforestation cleared nearly 10 % of the forest (Zanon, 2023), contributing directly to local and global climate changes. Extreme droughts and rising temperatures have become more frequent (Flores et al., 2024), directly affecting all those who depend on the rivers to survive, including humans (Grossman, 2024). In addition, such dry conditions exacerbated the Amazonia's fire crises that has continuously increased since 2019, reaching alarming levels now in 2024 (INPE, 2024; Machado et al., 2024). The combination of all these threats imposes great pressure on the Amazon biodiversity and a recent study suggested that approximately 1500 jaguars were displaced or killed due to habitat loss and degradation in the last four years, in the Brazilian portion of the Amazon alone (Menezes et al., 2021). Hunting of jaguar prey species and jaguar killings are widespread in the biome (Benítez-López et al., 2017; El Bizri

et al., 2020; Valsecchi et al., 2022) and, more recently, concerning reports on the illegal trade of jaguar parts have emerged (Arias, 2021; Charity and Ferreira, 2020; IUCN NL, 2020; Morcatty et al., 2020; Polisar et al., 2023).

Over the past two decades, several studies have developed local estimates of jaguar population sizes across the Amazon, revealing significant variation in densities, ranging from 0.29 to 17.80 ind./ 100 km^2 (Ayala et al., 2022; Duarte et al., 2021; Mena et al., 2020; Ramalho, 2012; Silver et al., 2004; Tobler et al., 2013). The Amazon is indeed not homogeneous; it represents a complex mosaic of ecosystems largely heterogenic in soil composition, hydrological features, and climatic conditions, as well as in their levels of anthropogenic pressure (Fearnside, 2005; Junk et al., 2011; Quesada et al., 2011; Salati et al., 2012). Such heterogeneity over this vast area affects the abundance and distribution of jaguars, however, most studies present population estimates for only one or a few sites, making it challenging to assess what is driving the variation across broader areas. The few studies that extrapolated densities across the Amazon and over, either assumed a single value for the entire biome (de la Torre et al., 2018) or used published density estimates obtained with inconsistent methodological approaches (Berzins et al., 2023; Jędrzejewski et al., 2023a; Jędrzejewski et al., 2018). Furthermore, published density estimates from the Amazon are scarce and even range wide estimates of jaguar numbers were produced with few data points from the Amazon, which represents ca 70 % of the species distribution (Jędrzejewski et al., 2018). In this study, we compiled 40 camera trap datasets in 22 PAs across the Amazon biome to produce standardized estimates of jaguar population densities using multi-session spatial capture-recapture models while assessing which variable influence densities and associated model parameters. This represents an unprecedented effort for the biome, filling important knowledge gaps and furthering knowledge of jaguar densities in the species main stronghold. Furthermore, we estimated the approximate jaguar population size for the sampled PAs, accounting for spatial variation in environmental and anthropogenic factors.

2. Methods

2.1. Study area

The Amazon is the largest tropical forest biome in the world, encompassing 8,414,085 km^2 across nine countries, with 60 % of the area in Brazil (RAISG, 2020). The biome is formed by an intricate system of large rivers, intertwined by a mosaic of over 50 different habitats, all directly influenced by the physical-chemical properties of water and soils and by the climatic variations along its extension (Salati et al., 2012). Along the borders of the rivers and lakes are the floodplain habitats that cover around 14–30 % of the biome and can be flooded for up to 230 days/year (Junk et al., 2011; Junk et al., 1989; Melack and Hess, 2010). Amazonian floodplains are mainly divided between the highly productive várzea forests flooded by nutrient-rich white-water rivers (e.g. Amazon River) and the igapó forests with low-fertility soils that are flooded by nutrient-poor blackwater and clearwater rivers (e. g. Negro and Xingu Rivers respectively). Most of the biome is made up of unflooded upland or terra firme forest, encompassing a wide variety of

habitats. Lowland areas with an average elevation of 100 m are dominant, however, along the biome's borders, rainforests can extend up to 1500 m, followed by montane cloud forests that reach a maximum elevation of 3000 m in the Andes and in the Guiana Shield (Lujan, 2010). Rainfall, the driving force behind the seasonal flood-pulse, is unevenly distributed across the biome, ranging from 1500 to 3000 mm annually with the highest rainfall in the extreme West in the Andean Amazon (Junk et al., 2011; Salati and Vose, 1984). Our dataset consists of 22 survey locations in PAs from Brazil, Colombia, Ecuador, and Peru, covering coastal Amazonian environments, and distinct *terra firme*, *igapó* and *várzea* forests (Fig. 1). The surveys were conducted in areas under different formal protection levels (e.g. strictly protected National Parks, Sustainable Use Extractive Reserves, and Indigenous Lands), covering a wide range of areas with varying anthropogenic pressures (full description in the Appendices section).

2.2. Data collection

The study sites ($N = 22$) were assessed between 2005 and 2020 with some sites sampled across different years, totalling 40 camera-trap surveys with varying grid sizes (median: 183 km²; min: 34 km², max: 4349 km²) and number of camera-trap stations (median: 43 stations; min: 24 stations, max: 119 stations) (Table A1). Some surveys had double cameras at each station, while others had single cameras. These stations were deployed within grids with an average distance of 1700 m $\pm$ 700 m ($\pm$ SD; min: 700 m, max: 3300 m) and were set to work

continuously for approximately 110 d $\pm$ 50 d ($\pm$ SD, min: 61, max: 276 d). Most surveys covered areas considered large enough for robust jaguar density estimation with low biases (Tobler and Powell, 2013), and the distance between camera station was lower than the diameter of the smaller jaguar home range recorded for the Amazon (Morato et al., 2016).

2.3. Density estimation with covariates

We identified individual jaguars by their unique rosette patterns and their sex through photographic evidence. For single-station surveys we identified individuals based on one flank only (left or right) - considering the flank with more captures. We then built individual capture histories for adult individuals and analyzed the datasets with spatial capture-recapture (SCR) models (Efford, 2004) using the R package *secr* (version 4.5.8 - Efford, 2023). We used multi-session models that combined all datasets into a single model. This allowed us to model parameters as functions of covariates across surveys, increasing estimate precisions, especially for surveys with few jaguar records or small grid sizes.

For the detection model we used the alternative formulation proposed by Efford and Mowat (2014), assuming an inverse relationship between σ , a spatial parameter related to home range size, and λ_0 , the detection probability for a camera at the center of a home range. This model introduces a new parameter a_0 , the “single-detector sampling area”, that is defined as $a_0 = 2\pi\lambda_0\sigma$ and therefore $\lambda_0 = \frac{a_0}{2\pi\sigma}$. Under this

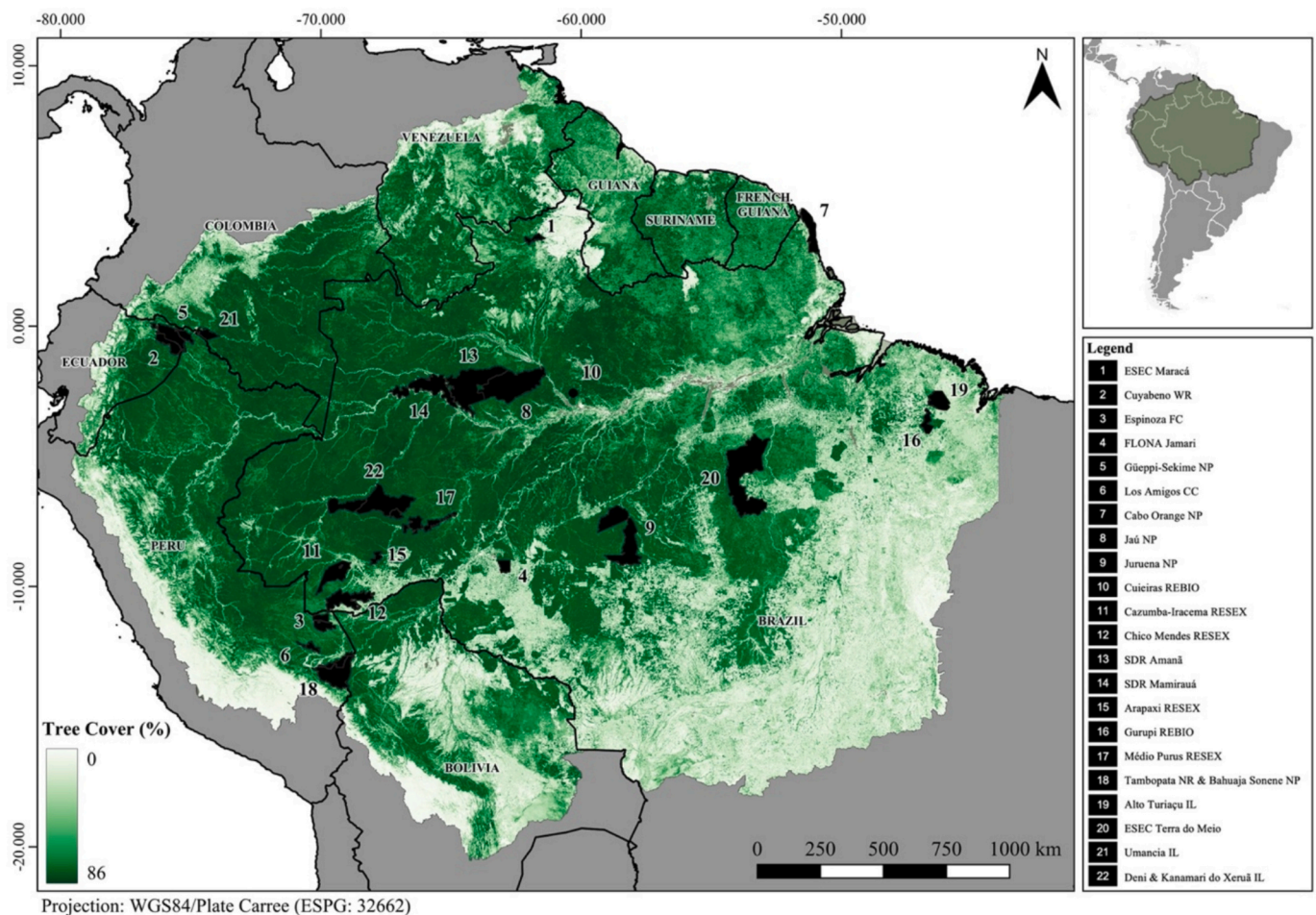


Fig. 1. (2-column image). Study area map. The Amazon basis borders (RAISG, 2020) and the distribution of the 22 protected areas sampled. ESEC: Ecological Station; WR: Wildlife Reserve; FC: Forestry Concession; FLONA: National Forest; NP: National Park; CC: Conservation Concession; REBIO: Biological Reserve; RESEX: Extractive Reserve; SDR: Sustainable Development Reserve; NR: National Reserve; IL: Indigenous Land. The central map depicts the percentage of tree cover in 2020 (Hansen et al., 2013).

formulation, an increase in the movement parameter σ leads to a reduction in λ_0 , which is what we would expect assuming a constant movement speed. If an animal moves over a larger area, we expect it to spend less time close to each camera, reducing the detection probability at that camera. The advantage of this formulation is that we can include covariates for σ that we assume to affect home range size and λ_0 is automatically adjusted for these changes in σ . However, we can still include a different set of detection covariates for a_0 (Efford and Mowat, 2014).

Jaguars generally have higher detection probabilities on trails and unpaved roads, and males have both a higher detection probability as well as a larger home range sizes than females (de Azevedo et al., 2022; Harmsen et al., 2017; Tobler et al., 2018). We therefore included sex as a covariate for a_0 and σ , and we included trap location (on a road, trail or in the forest) as a covariate interacting with sex for a_0 . Since we had many individuals for which the sex could not reliably be determined (22 %), we used a hybrid mixture model (*hcov* parameter in *secr*) for sex that allows the inclusion of individuals with known and unknown sex. Given the low number of individuals for many surveys we were not able to estimate individual mixing parameters for each survey and therefore assumed that the average sex ratio was the same across all surveys. Furthermore, as we had varying sampling designs, we included single versus paired camera-stations for a_0 .

We evaluated additional covariates on sigma (σ) and density based on factors known to influence jaguar home range size, movement, and density (Jędrzejewski et al., 2018; Thompson et al., 2021). Jaguar presence, for instance, has been reported to increase in response to mean temperature and annual precipitation, across the entire species range (Jędrzejewski et al., 2018). We included three climatic covariates (annual mean temperature, annual mean precipitation, and precipitation seasonality) and the first three components of a principal component analysis (PCA) summarizing the 19 BIOCLIM variables (Karger et al., 2017). PC1 was driven by temperature measures, such as temperature variation over time (BIO2 and BIO7) and minimum temperatures (BIO6, BIO9 and BIO11). PC2 was mostly influenced by two variables related to warmer temperatures (BIO5 and BIO10), while PC3 had humidity-related variables as the most important (BIO16, BIO8 and BIO19) (Table A4). As jaguars have consistently shown a preference for forested habitats and tend to exhibit higher densities in productive environments (Alvarenga et al., 2021; Jędrzejewski et al., 2018; Morato et al., 2018), we tested gross primary productivity (GPP – mean [NASA EOSDIS Land Processes DAAC]) (Running et al., 2015), the normalized difference vegetation index (NDVI – mean [NASA EOSDIS Land Processes DAAC]) (Didan, 2021), net primary productivity (NPP – mean [MODIS MOD17A3] and standard deviation [MODIS MOD17A4]) (Running et al., 2004) and percentage of tree cover (Hansen et al., 2013). The Amazon biome, although often referred to as a lowland forest, presents considerable topographic variation, which determines, for instance, which portions of the biome will be submerged during the flooded season. The flood pulse is the most powerful driver of change in the Amazon, directly influencing the distribution of both, plants and animals (Alvarenga et al., 2018; Assis and Wittmann, 2011). To evaluate its potential effect on jaguars, we tested the compound topographic index (CTI) (Amatulli et al., 2020). Finally, since human-altered landscapes are known to negatively impact jaguars (Paviolo et al., 2016; Romero-Muñoz et al., 2019), we included the Human Footprint Index (HFI – Venter et al., 2016), the Human Modification Index (Kennedy et al., 2019), and forest degradation ([EC JRC] – Vancutsem et al., 2021). Covariates were compiled in a raster format at a resolution of 1 km² for the entire biome. Then, at a survey-level, we averaged the spatial covariates across the area using a buffer of 10 km around the camera trap grids. To run the spatial capture-recapture model, we used a state-space with a buffer of 25 km around camera trap grids.

We explored different combinations of covariates for σ and a_0 while estimating independent densities for each survey using the survey-level covariates mentioned above. Given the large number of covariates, we

selected covariates in multiple steps. We first identified significant covariates for a_0 and in a second step selected covariates for σ . We used a forward variable selection strategy, where we first built models with a single covariate and then added additional covariates to the highest-ranking model. We used model selection based on the Akaike's Information Criterion (AIC) to select the most parsimonious model (Table A2). Based on the most parsimonious model, we produced independent density estimates for each survey in each site (hereafter: site-independent model). We then fixed the covariates selected from the best model for σ and a_0 , and tested which covariates influence density at a biome-scale using spatial covariates at a 1 km resolution for density (Table A3). This biome-wide model, combines the capture-recapture data from all PAs and identifies the variables influencing variation of density in space. It then generates density estimates across the biome based on the spatial distribution of these selected variables, which allows for interpretation at a broader scale as well as extrapolation to sites with no survey data. Using density estimates from the biome-wide model, we also produced density estimates for each PA sampled (hereafter: biome-wide model).

To explore the jaguar population size within PAs, we applied three different approaches. In the first and second approaches we assumed a homogeneous jaguar density across the PAs, therefore we multiplied the predicted density of each PA by the PA's size, repeating the process for both models (site-independent and biome-wide). In our third approach, we multiplied the coefficient values of the final covariates selected in the biome-wide model by their respective layers to produce an extrapolated density estimate across the entire biome. We then clipped this density map to the boundaries of the 22 PAs and calculated the expected jaguar population size for each PA. To compare the results, we run a Pearson correlation test between the three extrapolations. For simplicity, we opted to present only the two extrapolations that assumed a homogeneous density across PAs, as the correlation between the second and third approach was very strong ($r = 0.99$). To test the robustness of our predictions, after estimating the jaguar population size for the 22 PAs, we compared our results with the predictions made by Jędrzejewski et al. (2018). To do this, we first clipped the density-adjusted map from Jędrzejewski et al. (2018) to match the boundaries of the 22 PAs and then calculated the jaguar population for each PA. We then compared the expected jaguar population for each PA, based on our biome-wide model, with the results from Jędrzejewski et al. (2018) using a Pearson correlation test.

3. Results

We recorded a total of 389 individual jaguars across all study areas, with an average of 9.73 (± 7.64 ind., range: 2–43) individuals per site (Table A1). The minimum number of records was 2 individuals at three different sites – FLONA Jamari (2016 survey); Jaú NP (2016–2017a survey); and Cuieiras REBIO (2018 and 2020 surveys). The maximum number of records was 43 individuals in Espinoza FC (2014 survey). We recorded a total of 116 females and 188 males and 85 individuals of unknown sex across all sites for an observed sex ratio of 1.62:1 male to female. The estimated sex ratio based on the hybrid mixture model was 0.51:1 male to female, indicating a female bias in adult jaguars.

The best model showed that cameras deployed on unpaved roads had the highest detection probability, followed by cameras on trails, with cameras placed in the forest without trails having the lowest detection probability regardless of sex. Males had a higher detection probability than females and a stronger preference for roads and trails as indicated by the interaction term (Table 1). As expected, paired-cameras stations were more likely to detect jaguars than single-cameras. No spatial covariates were significant for a_0 . For the most parsimonious model, PC1 and GPP had a negative effect on σ , while human footprint had a positive effect and σ was larger for males than for females. PC1 was highly correlated with bioclimatic variables measuring temperature fluctuation throughout the year (BIO2 and BIO7) as well as minimum temperatures

Table 1

Coefficients from the most parsimonious Spatial Capture-Recapture Model of jaguar density, based on data from 40 camera-trap surveys conducted across 22 protected areas within the Amazon biome. D: Density parameter; a0: Detection parameter – “single detector sampling area”, sigma: Movement parameter, pmix Male: the probability that a random individual is a male based on the hybrid mixture model. SE: Standard Error; LCI: Lower Confidence Interval; UCI: Upper Confidence Interval. NPP Mean: mean net primary productivity; NPP SD: net primary productivity standard deviation; PC1: first bioclimatic component; GPP: gross primary productivity; Paired: paired camera stations.

Parameter	Beta value $\pm$ SE (95 % LCI - 95 % UCI)	Link Function
D	-8.25 ± 0.08 (-8.41 - -8.09)	log
D NPP Mean	0.47 ± 0.15 (0.17 - 0.78)	log
D NPP SD	0.18 ± 0.12 (-0.06 - 0.42)	log
D Precipitation Seasonality	-0.12 ± 0.09 (-0.29 - 0.05)	log
D Precipitation Total	0.08 ± 0.07 (-0.05 - 0.22)	log
a0	1.74 ± 0.16 (1.43 - 2.04)	log
a0 Males	0.71 ± 0.18 (0.35 - 1.06)	log
a0 Road	2.1 ± 0.19 (1.72 - 2.47)	log
a0 Trail	0.69 ± 0.19 (0.33 - 1.05)	log
a0 Males: Road	0.41 ± 0.11 (0.19 - 0.62)	log
a0 Males: Trail	1.14 ± 0.25 (0.66 - 1.63)	log
a0 Paired	1.11 ± 0.23 (0.65 - 1.57)	–
sigma	7.86 ± 0.08 (7.71 - 8.02)	log
sigma Males	0.45 ± 0.08 (0.3 - 0.6)	log
sigma PC1	-0.34 ± 0.04 (-0.43 - -0.25)	log
sigma Human Footprint	0.41 ± 0.13 (0.15 - 0.67)	log
sigma GPP	-0.36 ± 0.11 (-0.58 - -0.15)	log
pmix Male	-0.62 ± 0.16 (-0.92 - -0.31)	logit

(BIO6, BIO9 and BIO11). This indicates that jaguar home ranges are larger in areas with lower seasonality, warmer temperatures, lower productivity and under high human pressure. Considering the above-mentioned covariates, we produced independent density estimates for each survey in the 22 PAs. The estimated average density of jaguars across sites was 3.08 ± 1.13 individuals per 100 km² with a large variation from 0.60 ± 0.50 ind./100 km² (95 % CI: 0.14–2.51) in the Cuieiras REBIO to 9.97 ± 2.48 ind./100 km² (95 % CI: 6.17–16.11) in the SDR Mamirauá (Table 2).

Once covariates that most influenced σ and a_0 were known, we fixed them and applied a model selection to investigate which covariates best fitted the density parameter at a biome-scale. For this biome-wide model, we found a positive effect for mean NPP as well as the standard deviation of NPP. Total precipitation (BIO12) and seasonality of precipitation (BIO15) were also selected although their effect on density was not clear as their confidence intervals varied from negative to positive values (Table 1). Considering such covariates, the estimated average density of jaguars was 2.99 ± 0.36 individuals per 100 km². Following this approach, we gained a general view of the biome, but lost sight of local differences, observing less variation between sites, with density estimates ranging from 1.74 ± 0.34 ind./100 km² (95 % CI: 1.20–2.53) in ESEC Maracá to 4.30 ± 0.62 ind./100 km² (95 % CI: 3.24–5.70) in Cabo Orange NP (Table 2).

The expected jaguar population size for the sampled PAs that was produced with the two models was strongly correlated ($r = 0.87$); nevertheless, some variation can be detected between the models. Overall, we estimated a total of 7050 individuals (95 % CI: 3615–14,140) when the site-independent model was applied, while 6389 jaguars (95 % CI: 4664–7986) were predicted when based on the biome-wide model. Considering the site-independent model, ESEC Terra do Meio, followed by SDR Amanã and SDR Mamirauá had the largest jaguar populations estimates with 1204, 1191 and 1180 individuals respectively. According to the biome-wide extrapolations, though, the largest jaguar populations were found at ESEC Terra do Meio, SDR Amanã and Deni & Kanamari do Xerua IL with 951, 765 and 648 individuals respectively (Table 3). Our biome-wide extrapolation within the 22 PAs was highly correlated ($r =$

0.95) with the previous prediction available (Jędrzejewski et al., 2018), which produced an estimate of 4873 jaguars for the 22 areas.

4. Discussion

Using a multi-session spatial capture-recapture model we estimated jaguar densities across 22 sites in the Amazon basin. In accordance with other studies (Boron et al., 2016; Jędrzejewski et al., 2017; Mena et al., 2020; Tobler et al., 2018), we found a positive effect of trails and roads on detection probability, as well as sexual heterogeneity in detection and home range sizes. The preference for roads and trails is probably linked to ease of movement, allowing individuals to cover large areas in less time, especially in a densely forested environment such as the Amazon; while the difference in the effect size of road and trail between sexes has been attributed to cub protection and a stronger risk aversion (Foster et al., 2010; Harmsen et al., 2017). Males had larger home range (approximated by the σ parameter in the SCR model) and higher probability of detection, a pattern expected as they have been widely described by camera-trapping studies (Foster et al., 2020; Tobler et al., 2018) and confirmed by telemetry (Morato et al., 2016; Thompson et al., 2021). Home ranges increased in areas with lower productivity and under high human footprint (HFI), which is consistent with research in different biomes (Jędrzejewski et al., 2018; Morato et al., 2016; Paviolo et al., 2016; Thompson et al., 2021). This pattern suggests that such areas have suboptimal conditions (e.g., less prey availability) and therefore individuals would need larger areas to fulfil their metabolic requirements. Regarding the bioclimatic covariates, jaguar home ranges were larger in warmer and less seasonal regions. When compared with habitats at higher latitudes, the Amazon has relatively small fluctuations in its temperature, both daily as well as seasonally. These fluctuations increase with seasonality along the slopes of the Andes and with temperature in deforested areas, indicating that smaller home ranges would be found in the seasonal, less-disturbed habitats of the central-west Amazon.

Density estimates were highly variable across the biome, evidencing the high habitat heterogeneity found in the Amazon. Overall, our results indicated that jaguar density is best predicted by NPP, corroborating the range-wide analysis of Jędrzejewski et al. (2018). Productive habitats can support high diversity of animal species (Khamila et al., 2023), and carnivores tend to benefit from the abundance of prey (Karanth et al., 2004). In the Amazon, this high productivity is associated with the fertile fluvial soils of its western region and the várzea habitats, while low productive regions from white sand soils are found mainly in the lowlands of the Brazilian and Guyana shields - eastern, southern and northern regions (Malhi et al., 2004). To some extent, our models reflected this pattern. For instance, several sites under geological influence of floodplain várzea forests, either currently or historically – such as Mamirauá, Los Amigos and Médio-Purus – were among the highest density estimates regardless of the model (whether site-independent or biome-wide). Conversely, PAs located in regions with poorer soils, such as Jaú, Cuieiras and Maracá, tended to fall within the lower range of our density estimates. The averaged values further support this trend, with mean estimates of 3.63 ind./100km² (3.25 ind./100km² considering the biome-wide model) in sites under influence of white-water rivers with intermediate-rich soils, compared to 2.22 ind./100km² (2.52 ind./100km² considering the biome-wide model) in PAs along black or clear-water rivers with intermediate-poor soils (Table 2).

While both models (site-independent and biome-wide) preserved the general patterns across the biome, clear differences were observed for some protected areas. Such variation, however, is not surprising. Both models share the variables selected to estimate a_0 and σ , which is useful to predict density in sites with suboptimal data. However, when the density parameter is estimated independently for each PA, the model relies solely on the capture-recapture data from that specific PA. This approach is expected to yield reliable estimates at a local scale, provided requirements are met – in other words, when a sufficient number of

Table 2

Jaguar (*Panthera onca*) density estimate (individuals/100 km²) comparison between the independent and biome-wide models across 40 camera-trap surveys and 22 protected areas across the Amazon biome. Both spatial capture-recapture models were based in the best fitting anthropogenic and environmental variables. Site-independent estimates: $D \sim \text{session } a_0 \sim h_2 * \text{Trail} + \text{Paired } \sigma \sim h_2 + \text{sc_PC1} + \text{sc_HumFP} + \text{sc_GPP2021_mean } \text{pmix} \sim h_2$. Biome-wide estimates: $D \sim \text{sc_NPP_mean} + \text{sc_NPP_sd} + \text{sc_BIO15_PercSeason} + \text{sc_BIO12_PercTot } a_0 \sim h_2 * \text{Trail} + \text{Paired } \sigma \sim h_2 + \text{sc_PC1} + \text{sc_HumFP} + \text{sc_GPP2021_mean } \text{pmix} \sim h_2$. Paired: paired camera stations; Trail: camera stations on trails or roads. BIO12_PercTot: Annual Precipitation; BIO15_PercSeason: Precipitation Seasonality (Coefficient of Variation); GPP2021_mean: mean gross primary productivity in 2021; HumFP: human footprint index; NPP mean and sd: mean and standard deviation net primary productivity; PC1: First component of a principal component analysis (PCA). CC: Conservation Concession; ESEC: Ecological Station; FC: Forestry Concession; FLONA: National Forest; IL: Indigenous Land; NP: National Park; NR: National Reserve; REBIO: Biological Reserve; RESEX: Extractive Reserve; SDR: Sustainable Development Reserve; WR: Wildlife Reserve. SE: Standard Error; LCI: Lower Confidence Interval; UCI: Upper Confidence Interval.

Survey	Density estimate $\pm$ SE (95 % LCI - 95 % UCI)		River Type ¹	Soil Fertility ²
	Site-independent model	Biome-wide model		
Alto Turiaçu IL	2.30 $\pm$ 0.63 (1.36–3.91)	3.06 $\pm$ 0.38 (2.40–3.90)	–	Poor
Arapaxi RESEX	1.61 $\pm$ 0.72 (0.70–3.73)	2.53 $\pm$ 0.23 (2.12–3.02)	White	Intermediate
Cabo Orange NP	3.22 $\pm$ 1.41 (1.41–7.31)	4.30 $\pm$ 0.62 (3.24–5.70)	–	Rich
Cazumbá-Iracema RESEX	2.00 $\pm$ 0.73 (1.00–4.00)	2.57 $\pm$ 0.23 (2.16–3.06)	White	Intermediate
Chico Mendes RESEX	2.92 $\pm$ 1.30 (1.27–6.72)	2.31 $\pm$ 0.30 (1.79–2.97)	White	Intermediate
Cuieiras REBIO 2018	1.09 $\pm$ 0.91 (0.26–4.52)	2.57 $\pm$ 0.26 (2.10–3.14)	Black	Poor
Cuieiras REBIO 2019a	1.73 $\pm$ 1.13 (0.54–5.58)	2.57 $\pm$ 0.26 (2.10–3.14)	Black	Poor
Cuieiras REBIO 2019b	3.70 $\pm$ 1.68 (1.58–8.66)	2.57 $\pm$ 0.26 (2.10–3.14)	Black	Poor
Cuieiras REBIO 2020	0.60 $\pm$ 0.50 (0.14–2.51)	2.57 $\pm$ 0.26 (2.10–3.14)	Black	Poor
Cuyabeno WR 2017–2018	2.68 $\pm$ 1.06 (1.27–5.67)	3.74 $\pm$ 0.42 (3.01–4.65)	White	Intermediate
Cuyabeno WR 2018	2.59 $\pm$ 1.12 (1.15–5.82)	3.85 $\pm$ 0.42 (3.10–4.78)	White	Intermediate
Cuyabeno WR 2019	3.55 $\pm$ 1.07 (2.00–6.31)	3.69 $\pm$ 0.41 (2.98–4.58)	White	Intermediate
Deni & Kanamari do Xerua IL	2.39 $\pm$ 0.61 (1.46–3.91)	2.84 $\pm$ 0.23 (2.43–3.32)	White	Intermediate
ESEC Maracá	2.58 $\pm$ 0.75 (1.48–4.49)	1.74 $\pm$ 0.34 (1.20–2.53)	Clear	Poor
ESEC Terra do Meio 2016	2.74 $\pm$ 1.33 (1.12–6.73)	2.82 $\pm$ 0.32 (2.26–3.52)	Clear	Poor
ESEC Terra do Meio 2017	4.39 $\pm$ 1.67 (2.13–9.04)	2.82 $\pm$ 0.32 (2.26–3.53)	Clear	Poor
Espinoza FC 2009–2010	3.61 $\pm$ 0.70 (2.48–5.26)	2.81 $\pm$ 0.26 (2.34–3.37)	White	Rich
Espinoza FC 2014	3.17 $\pm$ 0.51 (2.32–4.33)	2.69 $\pm$ 0.26 (2.23–3.24)	White	Rich
FLONA Jamari 2016	1.75 $\pm$ 1.44 (0.43–7.15)	1.98 $\pm$ 0.37 (1.38–2.84)	–	Poor
FLONA Jamari 2017	1.27 $\pm$ 0.70 (0.46–3.48)	1.98 $\pm$ 0.36 (1.38–2.83)	–	Poor
FLONA Jamari 2018	3.08 $\pm$ 1.3 (1.40–6.80)	1.98 $\pm$ 0.36 (1.39–2.83)	–	Poor
FLONA Jamari 2019	1.97 $\pm$ 0.97 (0.80–4.89)	2.00 $\pm$ 0.36 (1.41–2.85)	–	Poor
Güepi-Sekime NP 2017–2018	2.57 $\pm$ 0.78 (1.44–4.60)	3.36 $\pm$ 0.34 (2.77–4.09)	White	Rich
Güepi-Sekime NP 2019	2.88 $\pm$ 1.01 (1.48–5.61)	3.40 $\pm$ 0.34 (2.80–4.14)	White	Rich
Gurupi REBIO	2.82 $\pm$ 0.74 (1.71–4.67)	3.00 $\pm$ 0.41 (2.29–3.92)	–	Poor
Jaú NP 2016–2017a	0.64 $\pm$ 0.52 (0.16–2.59)	2.53 $\pm$ 0.34 (1.95–3.28)	Black	Intermediate
Jaú NP 2016–2017b	1.51 $\pm$ 0.83 (0.55–4.14)	2.53 $\pm$ 0.34 (1.95–3.28)	Black	Intermediate
Juruena NP	3.26 $\pm$ 1.10 (1.71–6.20)	2.57 $\pm$ 0.27 (2.10–3.15)	Clear	Poor
Los Amigos 2005	4.61 $\pm$ 1.55 (2.43–8.76)	3.73 $\pm$ 0.54 (2.81–4.94)	–	Rich
Los Amigos 2006	3.94 $\pm$ 1.32 (2.08–7.46)	3.73 $\pm$ 0.54 (2.81–4.95)	–	Rich
Los Amigos 2007	3.72 $\pm$ 1.18 (2.02–6.83)	3.73 $\pm$ 0.54 (2.81–4.95)	–	Rich
Los Amigos CC 2010	5.21 $\pm$ 1.62 (2.88–9.45)	3.30 $\pm$ 0.47 (2.50–4.35)	–	Rich
Médio Purus RESEX	3.23 $\pm$ 1.08 (1.71–6.12)	2.94 $\pm$ 0.23 (2.52–3.43)	White	Intermediate
SDR Amanã 2013	7.11 $\pm$ 2.72 (3.44–14.68)	3.32 $\pm$ 0.45 (2.55–4.32)	White	Intermediate
SDR Amanã 2013–2014	3.22 $\pm$ 1.39 (1.43–7.26)	3.32 $\pm$ 0.45 (2.55–4.32)	White	Intermediate
SDR Mamirauá 2013	7.90 $\pm$ 2.18 (4.64–13.45)	3.93 $\pm$ 0.46 (3.14–4.93)	White	Rich
SDR Mamirauá 2014	9.97 $\pm$ 2.48 (6.17–16.11)	3.93 $\pm$ 0.46 (3.14–4.93)	White	Rich
Tambopata NR & Bahuaja Sonene NP	1.82 $\pm$ 0.73 (0.85–3.89)	3.13 $\pm$ 0.33 (2.55–3.85)	–	Rich
Umancia IL 2018	1.87 $\pm$ 0.81 (0.83–4.21)	3.66 $\pm$ 0.34 (3.06–4.37)	White	Intermediate
Umancia IL 2019	2.16 $\pm$ 1.03 (0.89–5.26)	3.67 $\pm$ 0.34 (3.07–4.40)	White	Intermediate

¹ Junk et al., 2011² EMBRAPA, 1966; Quesada et al., 2011.

captures and individuals are recorded, and both effort and grid size are appropriately defined. The biome-wide model, on the other hand, generates density estimates based on the spatial distribution of selected variables, however, as with any regression model, not all the variance is captured by the covariates.

Considering our site-independent models – better suited for local evaluations – some estimates deserve closer examination. Notably, the two highest jaguar densities among all sites were found in the várzea forests of SDR Mamirauá with impressive figures of 7.90 and 9.97 ind./100km². Mamirauá estimations are comparable with jaguar densities from northern Pantanal, the highest one published to date (12.4 ind./100 km²; Eriksson et al., 2021), but lower than estimations of a previous study in the same area (17.8 $\pm$ 8.0 ind./100 km² - Ramalho, 2012). As the area has not undergone major changes between studies, we assume that differences in predictions are due to variations in methodologies and analytical approaches, such as the fact we considered spatial variables to estimate a_0 and σ which in turn influence density. At the lower

end of our predictions, Cuieiras REBIO and Jaú NP each had one survey with values at or below 1 ind./100 km² and average densities of 1.78 and 1.07 ind./100 km², respectively. These numbers are comparable to recent estimates (1.6–1.9 ind./100 km²) from the Guyana Shield in the northern Amazon region (Berzins et al., 2023). While Cuieiras and Jaú are not located in the Guyana shield, both lie near its southern border and are primarily covered by *terra firme* forests adjacent to *igapó* floodplain forests – forests flooded by sediment-poor black-water rivers (FVA; IBAMA, 1998). This composition seems to be driving the observed pattern, despite the low anthropogenic impact within their borders. As previously discussed, forests with low productivity have reduced carrying capacities for herbivores, and by extension, for large carnivores (Gonçalves et al., 2022; Junk et al., 2015).

According to the biome-wide model – better suited for extrapolation – we predicted a population of 6389 jaguars (95 % CI: 4664–7986) across an area of over 200,000 km² within the 22 sampled PAs. This figure is particularly noteworthy given that our study area covers only

Table 3

Expected jaguar (*Panthera onca*) population size (number of adults) in 22 protected areas sampled using camera-trapping across the Amazon biome. Population extrapolations derived from the most parsimonious spatial capture-recapture models, considering anthropogenic and environmental variables. Site-independent estimates: $D \sim \text{session } a0 \sim h2 * \text{Trail} + \text{Paired } \sigma \sim h2 + \text{sc_PC1} + \text{sc_HumFP} + \text{sc_GPP2021_mean } \text{pmix} \sim h2$. Biome-wide estimates: $D \sim \text{sc_NPP_mean} + \text{sc_NPP_sd} + \text{sc_BIO15_PercSeason} + \text{sc_BIO12_PercTot } a0 \sim h2 * \text{Trail} + \text{Paired } \sigma \sim h2 + \text{sc_PC1} + \text{sc_HumFP} + \text{sc_GPP2021_mean } \text{pmix} \sim h2$. Paired: paired camera stations; Trail: camera stations on trails or roads. BIO12_PercTot: Annual Precipitation; BIO15_PercSeason: Precipitation Seasonality (Coefficient of Variation); GPP2021_mean: mean gross primary productivity in 2021; HumFP: human footprint index; NPP mean and sd: mean and standard deviation net primary productivity; PC1: First component of a principal component analysis (PCA). CC: Conservation Concession; ESEC: Ecological Station; FC: Forestry Concession; FLONA: National Forest; IL: Indigenous Land; NP: National Park; NR: National Reserve; REBIO: Biological Reserve; RESEX: Extractive Reserve; SDR: Sustainable Development Reserve; WR: Wildlife Reserve. LCI: Lower Confidence Interval; UCI: Upper Confidence Interval.

Protected Areas	Adult population (95 % LCI - 95 % UCI)		Size (km ²)		Major Habitats
	Independent estimates	Biome-wide estimates	PA	Grid	
Alto Turiaçu IL	122 (72–207)	162 (20–207)	5295	293	Terra Firme
Arapaxi RESEX	22 (9–50)	34 (28–40)	1337	1001	Terra Firme & Várzea
Cabo Orange NP	138 (60–313)	184 (139–244)	4281 ²	226	Mangroves & Restinga
Cazumba-Iracema RESEX	151 (76–302)	194 (163–231)	7554	1296	Terra Firme & Várzea
Chico Mendes RESEX	272 (118–626)	215 (167–277)	9315	164	Terra Firme
Cuieiras REBIO	4 (1–12)	6 (5–7)	227	34	Terra Firme
Cuyabeno WR	400 (200–807)	512 (57–636)	13,607	147	Terra Firme & Igapó
Deni & Kanamari do Xeruá IL ¹	545 (333–892)	648 (554–757)	22,808	1813	Terra Firme & Várzea
ESEC Maracá	40 (23–69)	27 (19–39)	1542	164	Terra Firme
ESEC Terra do Meio	1204 (550–2661)	951 (762–1191)	33,732	192	Terra Firme
Espinoza FC	151 (107–214)	123 (105–148)	4464	864	Terra Firme
FLONA Jamari	45 (17–124)	44 (31–63)	2222	662	Terra Firme
Güepi-Sekime NP	56 (30–104)	69 (57–84)	2038	312	Terra Firme & Várzea
Gurupi REBIO	77 (46–127)	81 (62–106)	2712	1546	Terra Firme
Jaú NP	256 (85–798)	599 (462–777)	23,673	429	Terra Firme & Campinarana
Juruena NP	638 (335–1213)	503 (411–617)	19,570	432	Terra Firme & Savannah
Los Amigos CC	64 (34–119)	53 (40–70)	1457	196	Terra Firme & Várzea
Médio Purus RESEX	194 (103–368)	177 (151–206)	6006	4347	Terra Firme & Várzea
SDR Amanã	1191 (562–2527)	765 (587–995)	23,035	135	Terra Firme
SDR Mamirauá	1180 (714–1951)	519 (415–651)	13,199	216	Várzea
Tambopata NR & Bahuaja Sonene NP ¹	250 (117–534)	429 (350–528)	13,720	57	Terra Firme & Várzea
Umancia IL	52 (22–123)	95 (80–114)	2595	145	Terra Firme & Várzea
TOTAL	7050 (3615–14,140)	6389 (4664–7986)	214,392	14,671	–

¹sum of both PAs; ²area of land.

2.5 % of the Amazon Basin, and jaguars are expected to remain in approximately 79 % of their historic range in this biome, from which approximately 54 % are covered by protected areas and Indigenous Lands (Berzins et al., 2023; Jędrzejewski et al., 2023a, 2023b). This supports high population estimates recently projected for the Amazon (Berzins et al., 2023; Jędrzejewski et al., 2023a) and highlights the crucial role the biome plays in jaguar conservation. We acknowledge the limitations of extrapolating density estimates to entire PAs, especially considering the large extent that PAs generally have in the Amazon. Yet, our total population estimates are consistent across both models (site-independent and biome-wide) and aligned with previous jaguar population estimates (Pearson Correlation: $r = 0.95$) (Jędrzejewski et al., 2018). Absolute values, though, differ between our biome-wide model and the estimates from Jędrzejewski et al. (2018), with the latter predicting a total population of 4873 jaguars in the same 22 PAs, which is at the lower end of our confidence interval.

Although our estimates were based on robust statistical analysis, it is important to point out some limitations of our study. Certain factors not included in our models are likely influencing jaguar densities, which can explain the difference between the site-independent and biome-wide model. For example, anthropogenic pressures, like prey overhunting and jaguar killings, are known to have a strong negative impact on jaguars (Jędrzejewski et al., 2023b), nevertheless they only appeared indirectly through the Human Footprint Index (HFI). Additional sources of variation may stem from differences in local governance, enforcement and protection, such as financial resources, staffing, and the type of protected area. These factors undoubtedly influence the effectiveness of protected areas in safeguarding their species (Herrera et al., 2019). As for the sampling design, among the 40 datasets analyzed we had great variation in number of camera-trap stations, sampled days and covered area (polygon size), which can potentially influence local estimations

(Tobler and Powell, 2013). Nevertheless, we found no correlation between survey duration, study area size, number of cameras and density estimates, which is partly because we jointly modelled parameters across sites, helping to reduce some of these issues. Another aspect to consider is the large temporal window among surveys (2005–2020), which makes temporal correspondence between covariates and surveys imperfect. Ideally, survey designs and sampling efforts would have been standardized and surveys would have been conducted over the same period, however, coordinating such a large survey effort simultaneously is virtually impossible. By jointly analysing all the data in a multi-session model with shared parameters we can address some of the issues of non-standardized survey designs and low sampling efforts and obtain density estimates that are comparable across many sites.

5. Conclusions and recommendations

Our study provides novel information on jaguar populations across the Amazon, reinforcing the biome's importance for the species' conservation and highlighting the value of Amazonian PAs in safeguarding jaguars. The 22 PAs alone host an astonishing population size, surpassing even estimates for entire countries highly relevant for jaguar conservation such as Mexico (Ceballos et al., 2021). Considering the critical state of most jaguar populations outside of the Amazon (de la Torre et al., 2018; Espinosa et al., 2022), and the continued advance of human pressure on the biome (Menezes et al., 2021), we emphasize the need for more conservation initiatives, particularly in areas that host large jaguar populations and are under greater threats (Bogoni et al., 2023). Specifically, our study highlights that many sites, such as the Chico Mendes RESEX, Juruena NP, and ESEC Terra do Meio, still have high jaguar densities but are located along the “arc of deforestation”, where deforestation is increasing especially in untitled public lands

(INPE, 2022; Moutinho and Azevedo-Ramos, 2023). This is concerning and we recommend increasing funding to these areas to guarantee management effectiveness. In addition, countering political pressure to downsize, downgrade and degazette PAs as well as implementing policies and incentives to reduce deforestation outside protected areas is urgently needed. We recommend careful attention to the Andes-Amazon interface and the white-water floodplains due to their ecological importance for the species and for biodiversity – the former under increasing threat from illegal gold mining (Asner and Tupayachi, 2017; Hidalgo and Dargent, 2020), and the latter with historic high levels of human occupancy (Antunes et al., 2016; Clement et al., 2015). Finally, we underline the importance of large-scale jaguar monitoring programs inside and outside PAs to ensure timely adaptive management.

CRediT authorship contribution statement

Guilherme Costa Alvarenga: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Mathias W. Tobler:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Valeria Boron:** Writing – review & editing, Validation, Methodology, Funding acquisition, Conceptualization. **Elido Alves Ribeiro de Carvalho Jr:** Writing – review & editing, Validation. **Ronaldo Gonçalves Morato:** Writing – review & editing, Validation. **Whaldener Endo:** Writing – review & editing, Validation. **Eloisa Neves Mendonça:** Writing – review & editing, Validation. **Ricardo Sampaio:** Writing – review & editing, Validation. **Carlos César Durigan:** Writing – review & editing, Validation. **André Luis Sousa Gonçalves:** Writing – review & editing, Validation. **Emiliano Esterici Ramalho:** Writing – review & editing, Validation. **Juarez Carlos Brito Pezzuti:** Writing – review & editing, Validation. **Milton José de Paula:** Writing – review & editing, Validation. **André Pinassi Antunes:** Writing – review & editing, Validation. **José Luis Mena:** Writing – review &

editing, Validation. **Gates Dupont:** Formal analysis. **Wilson Spironello:** Writing – review & editing. **Jessica Pacheco:** Writing – review & editing. **Fabiola La Rosa-Camino:** Writing – review & editing. **Jaime Cabrera:** Writing – review & editing. **Anelise Montanarin:** Writing – review & editing. **Marcelo Oliveira da Costa:** Writing – review & editing, Validation, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Appendix A. Study area description

In Brazil, in the northeast Amazonian coast, the Cabo Orange National Park (NP) is characterized by coastal environments, such as mangroves, and flooded fields (MMA, ICMBio, 2017). In the eastern Amazon, the Gurupi Biological Reserve (REBIO, in Portuguese) and the Alto Turiaçu Indigenous Lands (ILs) represent expansive terra firme forest fragments surrounded by a matrix of high anthropogenic pressure within the “arc of deforestation” (Almeida et al., 2022; Oliveira, 2011). Meanwhile, in the interfluvium between Xingu and Iriri Rivers, the Terra do Meio ESEC is part of a mosaic of PAs and ILs comprising over 27 million ha and forming the largest block of protected tropical forests in the world (Pérez, 2015). However, this area constantly faces the threat of expansion of deforestation driven by the highways BR 163 (Cuiabá-Santarém) and BR 230 (Transamazônica) (Silva, 2013). In the southern Amazon, in a transition zone between the Amazon and the Brazilian savannah, we sampled the Juruena National Park (NP) that hosts both biome features (MMA, ICMBio, 2011).

In central-north and central Amazonia, the ESEC Maracá, the Cuieiras REBIO, the Jaú NP and the Sustainable Development Reserve (SDR) Amanã are composed mainly by terra firme forest (FVA, ICMBio, 2011; Oliveira et al., 2008; MMA, ICMBio, 2015; SEMA, IDSM, 2019). SDR Mamirauá together with the latter two form the Central Amazon Corridor, a conservation zone of 5746,000 ha (MCT, IDSM, 2010; Queiroz, 2005). SDR Mamirauá is delimited by the Amazonas and the Japurá Rivers, establishing the largest area exclusively dedicated to the protection of white-water floodplain forests (MCT, IDSM, 2010). In the western portion of the biome, the Chico Mendes Extractive Reserve (RESEX, in Portuguese) and the Cazumba-Iracema RESEX were surveyed, both located in the lowland forests surrounding the tributaries of Purus River (Acre, 2010; Brasil, 1976). Along the Juruá River, surveys were conducted in the Deni and Kanamari do Xerua ILs. Both territories have fertile soils of Andean origin and are covered by terra firme and white-water floodplains forests (Pezzuti and Chaves, 2009). Similarly, the Arapixi and Médio Purus RESEXs, located along the Purus River, feature terra firme and white-water floodplains forests (MMA, ICMBio, 2020; 2010). In the southwest Amazon, near the Madeira River, the National Forest (FLONA, in Portuguese) of Jamari is covered mainly by terra firme forest (Kerber et al., 2021; MMA, IBAMA, 2005).

In Peru, camera-trap grids were deployed in four different areas, three of which were in the Madre de Dios department, and one in the Putumayo Province within the Loreto department. In Madre de Dios the Tambopata National Reserve (NR) and Bahuaja Sonene NP, along with the Los Amigos Conservation Concession (CC), featured a combination of terra firme and white-water floodplain forest whilst the Espinoza Forestry Concession (FC) (legally not a protected area but FSC certified with strict control of hunting as well as carbon credits) was purely *terra firme* forest, characterized by a significant presence of bamboo forest (Tobler et al., 2013). In Putumayo Province, we sampled Güepi-Sekime NP. Located at the extreme north of the country, this protected area is part of the Trinational Program for Conservation and Sustainable Development of the Protected Areas Corridor, a mosaic of protected areas distributed along the borders of Peru, Ecuador, and Colombia encompassing ~40,000 km² (Usma et al., 2016). This entire region is renowned for its high levels of biodiversity, earning recognition as a biodiversity hotspot (Bass et al., 2010). Within this tri-national corridor, we conducted sampling in the Cuyabeno Wildlife Reserve (WR) in Ecuador and Umancia IL in Colombia. The latter area is within the expansive indigenous land known as the Predio Putumayo Indigenous Reserve. For the sake of comparison, we will maintain consistency with the name utilized in a prior study.

Table A1

Study sites summary. Description of each study site and their sampling design. ESEC: Ecological Station; WR: Wildlife Reserve; FC: Forestry Concession; FLONA: National Forest; NP: National Park; CC: Conservation Concession; REBIO: Biological Reserve; RESEX: Extractive Reserve; SDR: Sustainable Development Reserve; NR: National Reserve; IL: Indigenous Land.

Survey Name	Sampled Period	Latitude	Longitude	Country	Stations	Paired cameras	Days	Camera Days	Area (km ²)	Captures	Individuals
Alto Turiaçu IL	02/2020–08/2020	−3.042000	−46.415700	Brazil	18	Yes	162	2288	293	55	15
Arapaxi RESEX	04/2019–06/2019	−8.842683	−67.840581	Brazil	96	No	68	5026	1002	6	6
Cabo Orange NP	10/2019–01/2020	2.936570	−51.199910	Brazil	33	Yes	88	2501	226	6	6
Cazumba-Iracema RESEX	05/2018–09/2018	−9.449309	−68.907706	Brazil	119	No	108	6554	1296	11	9
Chico Mendes RESEX	04/2019–08/2019	−10.288559	−68.173210	Brazil	23	Yes	122	2473	164	13	6
Cuieiras REBIO	06/2018–10/2018	−2.574010	−60.304320	Brazil	40	No	110	3587	34	3	2
Cuieiras REBIO	04/2019–06/2019	−2.574010	−60.304320	Brazil	40	No	73	2646	34	3	3
Cuieiras REBIO	07/2019–09/2019	−2.574010	−60.304320	Brazil	40	No	68	2426	34	9	6
Cuieiras REBIO	02/2020–05/2020	−2.574010	−60.304320	Brazil	40	No	104	3850	34	8	2
Cuyabeno WR	12/2017–04/2018	−0.325916	−75.785472	Ecuador	29	Yes	126	3309	87	8	7
Cuyabeno WR	07/2018–10/2018	−0.325916	−75.785472	Ecuador	43	Yes	145	4199	147	15	12
Cuyabeno WR	01/2019–06/2019	−0.325916	−75.785472	Ecuador	25	Yes	98	1676	95	9	6
Deni & Kanamari do Xerua IL	07/2011–04/2012	−6.609180	−68.235440	Brazil	41	No	276	5746	1813	40	19
ESEC Maracá	02/2019–05/2019	3.395130	−61.542020	Brazil	28	Yes	83	1802	164	39	13
ESEC Terra do Meio	06/2016–08/2016	−4.685691	−53.580800	Brazil	60	No	70	3438	192	5	5
ESEC Terra do Meio	05/2017–08/2017	−4.685691	−53.580800	Brazil	53	No	91	4022	174	8	8
Espinoza FC	10/2009–03/2010	−11.480000	−69.840000	Peru	38	Yes	140	3460	335	82	29
Espinoza FC	06/2014–10/2014	−11.460000	−69.700000	Peru	89	Yes	121	8780	864	481	43
FLONA Jamari	08/2016–11/2016	−9.346536	−62.966493	Brazil	41	No	90	1610	156	2	2
FLONA Jamari	09/2017–12/2017	−9.346536	−62.966493	Brazil	105	No	111	4803	662	4	4
FLONA Jamari	08/2018–12/2018	−9.346536	−62.966493	Brazil	109	No	128	4111	580	8	7
FLONA Jamari	07/2019–12/2019	−9.346536	−62.966493	Brazil	94	No	135	3857	526	6	5
Güepi-Sekime NP	11/2017–02/2018	−0.370944	−75.214722	Peru	50	Yes	94	4248	313	76	12
Güepi-Sekime NP	02/2019–04/2019	−0.370944	−75.214722	Peru	44	Yes	70	2863	140	58	9
Gurupi REBIO	02/2020–06/2020	−3.656000	−46.809000	Brazil	19	No	109	1401	1548	63	17
Jaú NP	09/2016–01/2017	−1.857490	−61.691670	Brazil	48	No	125	4272	429	4	2
Jaú NP	12/2016–07/2017	−1.857490	−61.691670	Brazil	40	No	228	5857	413	6	4
Juruena NP	06/2019–08/2019	−8.985254	−58.577000	Brazil	76	Yes	75	4648	432	24	10
Los Amigos CC	09/2005–11/2005	−12.540000	−70.060000	Peru	24	Yes	63	1478	63	14	10
Los Amigos CC	08/2006–10/2006	−12.540000	−70.060000	Peru	40	Yes	65	2509	62	36	10
Los Amigos CC	09/2007–11/2007	−12.540000	−70.060000	Peru	40	Yes	69	2510	62	48	11
Los Amigos CC	03/2010–12/2010	−12.430000	−70.210000	Peru	30	Yes	269	3131	196	17	12
Médio Purus RESEX	07/2019–08/2019	−7.752370	−65.649433	Brazil	102	No	61	5089	4349	15	11
SDR Amanã	01/2013–04/2013	−2.474850	−64.620420	Brazil	49	Yes	83	1866	131	11	8
SDR Amanã	12/2013–04/2014	−2.474850	−64.620420	Brazil	63	Yes	121	2948	135	7	6

(continued on next page)

Table A1 (continued)

Survey Name	Sampled Period	Latitude	Longitude	Country	Stations	Paired cameras	Days	Camera Days	Area (km ²)	Captures	Individuals
SDR Mamirauá	09/2013–12/2013	−3.045530	−64.861880	Brazil	54	Yes	87	2225	216	22	15
SDR Mamirauá	09/2014–12/2014	−3.045530	−64.861880	Brazil	53	Yes	93	2294	216	25	19
Tambopata NR & Bahuaja Sonene NP	04/2007–06/2007	−12.990000	−69.460000	Peru	43	Yes	68	2663	58	12	7
Umancia IL	01/2018–04/2018	−0.314944	−74.375805	Colombia	50	No	68	3030	144	26	6
Umancia IL	02/2019–06/2019	−0.314944	−74.375805	Colombia	48	No	113	4352	146	8	5

Table A2

Model selection for sigma (σ) and a_0 . D: density; a_0 : Detection parameter – “single detector sampling area”; CTI: compound topographic index; Degradation2021: forest degradation in 2021; GPP2021_mean: mean gross primary productivity in 2021; HumFP: human footprint index; HumModif: human modification index; NDVI2021_mean: mean normalized difference vegetation index in 2021; NPP_mean: mean net primary productivity; PC1, PC2 and PC3: the three first bioclimatic components; BIO1_TempMean: annual mean temperature; BIO12_PercTot: annual mean precipitation; BIO15_PercSeason: precipitation seasonality; TreeCover_mean: mean percentage of tree cover; Paired: paired camera stations; Trail: camera stations on trails or roads.

Model	AICc	dAICc
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5175.84	0
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean + sc_GPP2021_mean pmix~h2	5178.39	2.55
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP pmix~h2	5180.14	4.30
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_HumFP pmix~h2	5182.23	6.39
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean pmix~h2	5182.48	6.64
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_humModif pmix~h2	5182.60	6.76
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_CTI pmix~h2	5182.69	6.85
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_degradation2021 pmix~h2	5182.81	6.97
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_HumFP pmix~h2	5182.82	6.98
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 + sc_HumFP pmix~h2	5184.92	9.08
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean + sc_degradation2021 pmix~h2	5185.15	9.31
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean + sc_CTI pmix~h2	5185.16	9.32
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 + sc_HumFP + sc_NPP_mean pmix~h2	5187.22	11.38
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_humModif + sc_NPP_mean pmix~h2	5192.57	16.73
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 pmix~h2	5191.40	15.56
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_humModif pmix~h2	5192.24	16.40
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_humModif + sc_NPP_mean pmix~h2	5194.34	18.50
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 pmix~h2	5194.06	18.22
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 pmix~h2	5194.06	18.22
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_humModif pmix~h2	5194.85	19.01
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_humModif pmix~h2	5194.91	19.07
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_NPP_mean pmix~h2	5195.40	19.56
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_NPP_mean pmix~h2	5195.54	19.70
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 pmix~h2	5196.73	20.89
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 + sc_humModif pmix~h2	5197.52	21.68
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_humModif pmix~h2	5202.10	26.26
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_HumFP pmix~h2	5204.35	28.51
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_NDVI2021_mean pmix~h2	5206.77	30.93
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_NPP_mean + sc_HumFP + sc_TreeCover_mean pmix~h2	5209.44	33.60
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_BIO1_TempMean pmix~h2	5211.92	36.08
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_CTI pmix~h2	5215.43	39.59
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_BIO15_PercSeason pmix~h2	5222.97	47.13
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_degradation2021 pmix~h2	5223.68	47.84
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_GPP2021_mean pmix~h2	5223.94	48.10
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_BIO12_PercTot pmix~h2	5225.25	49.41
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC2 + sc_PC3 pmix~h2	5230.31	54.47
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC2 + sc_PC3 + sc_NPP_mean pmix~h2	5232.04	56.20
D ~ session a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC3 pmix~h2	5230.78	54.94

Table A3

Model selection for density. D: density; a0: Detection parameter – “single detector sampling area”; Degradation2021: forest degradation in 2021; GPP2021_mean: mean gross primary productivity in 2021; HumFP: human footprint index; NPP_mean: mean net primary productivity; NPP_sd: net primary productivity standard deviation; PC1, PC2 and PC3: the three first bioclimatic components; BIO1_TempMean: annual mean temperature; BIO12_PercTot: annual mean precipitation; BIO15_PercSeason: precipitation seasonality; TreeCover_mean: mean percentage of tree cover; Paired: paired camera stations; Trail: camera stations on trails or roads.

Model	AICc	dAICc
D ~ sc_NPP_mean + sc_NPP_sd + sc_BIO15_PercSeason + sc_BIO12_PercTot a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5146.5	0
D ~ sc_NPP_mean + sc_NPP_sd + sc_BIO12_PercTot a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5146.5	0.03
D ~ sc_NPP_mean + sc_BIO15_PercSeason + sc_BIO12_PercTot a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5146.7	0.18
D ~ sc_NPP_mean + sc_NPP_sd + sc_HumFP + sc_BIO15_PercSeason a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5147.3	0.81
D ~ sc_NPP_mean + sc_NPP_sd + sc_PC1 + sc_PC2 a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5147.6	1.07
D ~ sc_NPP_mean + sc_NPP_sd + sc_PC1 + sc_PC2 + sc_HumFP a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5149.2	2.74
D ~ sc_NPP_mean + sc_NPP_sd + sc_HumFP + sc_BIO15_PercSeason + sc_PC2 a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5149.3	2.77
D ~ sc_NPP_mean a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5149.7	3.18
D ~ sc_BIO12_PercTot a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5150.5	3.98
D ~ sc_NPP_mean + sc_NPP_sd a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5151.3	4.83
D ~ sc_NPP_mean + sc_NPP_sd + sc_PC2 a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5151.4	4.86
D ~ sc_BIO12_PercTot + sc_HumFP a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5151.4	4.89
D ~ sc_NPP_mean + sc_NPP_sd + sc_HumFP a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5151.7	5.22
D ~ sc_BIO12_PercTot + sc_GPP2021_mean a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5152.0	5.46
D ~ sc_NPP_mean + sc_NPP_sd + sc_PC2 + sc_HumFP a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5152.1	5.56
D ~ sc_GPP2021_mean a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5152.1	5.59
D ~ sc_BIO12_PercTot + sc_BIO15_PercSeason a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5152.4	5.85
D ~ sc_BIO12_PercTot + sc_PC2 a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5152.4	5.89
D ~ sc_BIO15_PercSeason a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5153.0	6.50
D ~ sc_PC2 a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5153.8	7.29
D ~ sc_HumFP a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5153.9	7.39
D ~ sc_BIO12_PercTot + sc_GPP2021_mean + sc_BIO15_PercSeason a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5154.0	7.45
D ~ sc_BIO12_PercTot + sc_GPP2021_mean + sc_BIO15_PercSeason + sc_HumFP a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5154.9	8.35
D ~ sc_PC1 a0 ~ h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2	5155.0	8.47

Table A4

First three components of a principal component analysis (PCA). BIO1: Annual Mean Temperature; BIO2: Mean Diurnal Range (Mean of monthly (max temp - min temp)); BIO3: Isothermality (BIO2/BIO7) ($\times 100$); BIO4: Temperature Seasonality (standard deviation $\times 100$); BIO5: Max Temperature of Warmest Month; BIO6: Min Temperature of Coldest Month; BIO7: Temperature Annual Range (BIO5-BIO6); BIO8: Mean Temperature of Wettest Quarter; BIO9: Mean Temperature of Driest Quarter; BIO10: Mean Temperature of Warmest Quarter; BIO11: Mean Temperature of Coldest Quarter; BIO12: Annual Precipitation; BIO13: Precipitation of Wettest Month; BIO14: Precipitation of Driest Month; BIO15: Precipitation Seasonality (Coefficient of Variation); BIO16: Precipitation of Wettest Quarter; BIO17: Precipitation of Driest Quarter; BIO18: Precipitation of Warmest Quarter; BIO19: Precipitation of Coldest Quarter.

Bioclimatic variables	PC1	PC2	PC3
BIO1_TempMean	0.235	-0.326	-0.124
BIO2_TempRangeDay	-0.280	0.029	0.090
BIO3_Isotherm	0.268	0.180	-0.026
BIO4_TempSeason	-0.205	-0.030	-0.187
BIO5_TempMax	-0.092	-0.381	0.094
BIO6_TempMin	0.326	-0.122	-0.025
BIO7_TempRangeYear	-0.314	-0.056	0.061
BIO8_TempMeanWet	0.113	-0.278	-0.359
BIO9_TempMeanDry	0.285	-0.251	0.073
BIO10_TempMeanWarm	0.171	-0.367	-0.168
BIO11_TempMeanCold	0.273	-0.248	0.005
BIO12_PercTot	0.247	0.217	0.184
BIO13_PercWetMonth	0.150	0.038	0.490
BIO14_PercDryMonth	0.248	0.271	-0.167
BIO15_PercSeason	-0.233	-0.242	0.285
BIO16_PercWetQuater	0.147	0.055	0.489
BIO17_PercDryQuater	0.255	0.269	-0.156
BIO18_PercWarmQuater	0.010	0.320	-0.200
BIO19_PercColdQuater	0.234	-0.053	0.279

Table A5

Estimates of the movement parameter σ for male and female jaguars (*Panthera onca*) using the highest-ranking multi-session spatial capture-recapture model with independent density estimates for each site.

Survey	Female σ	Male σ
Alto Turiaçu IL	1853 $\pm$ 211 (1483–2314)	3029 $\pm$ 265 (2553–3593)
Arapaxi RESEX	2895 $\pm$ 222 (2491–3365)	4733 $\pm$ 327 (4134–5419)
Cabo Orange NP	1338 $\pm$ 142 (1088–1646)	2188 $\pm$ 178 (1865–2566)
Cazumbá-Iracema RESEX	2908 $\pm$ 221 (2506–3374)	4754 $\pm$ 307 (4189–5396)
Chico Mendes RESEX	3885 $\pm$ 401 (3175–4753)	6351 $\pm$ 586 (5302–7608)
Cuieiras REBIO 2018	3506 $\pm$ 784 (2274–5407)	5732 $\pm$ 1245 (3763–8730)
Cuieiras REBIO 2019a	3506 $\pm$ 784 (2274–5407)	5732 $\pm$ 1245 (3763–8730)
Cuieiras REBIO 2019b	3506 $\pm$ 784 (2274–5407)	5732 $\pm$ 1245 (3763–8730)
Cuieiras REBIO 2020	3506 $\pm$ 784 (2274–5407)	5732 $\pm$ 1245 (3763–8730)
Cuyabeno WR 2017–2018	1894 $\pm$ 135 (1647–2179)	3096 $\pm$ 179 (2764–3468)
Cuyabeno WR 2018	1736 $\pm$ 127 (1504–2003)	2838 $\pm$ 165 (2533–3179)
Cuyabeno WR 2019	1857 $\pm$ 132 (1616–2135)	3037 $\pm$ 173 (2716–3395)
Deni & Kanamari do Xerua IL	1957 $\pm$ 142 (1699–2255)	3200 $\pm$ 180 (2866–3572)
ESEC Maracá-Jipioca	2098 $\pm$ 171 (1788–2462)	3430 $\pm$ 262 (2954–3983)
ESEC Terra do Meio 2016	1932 $\pm$ 171 (1625–2297)	3159 $\pm$ 238 (2726–3659)
ESEC Terra do Meio 2017	1932 $\pm$ 171 (1626–2296)	3159 $\pm$ 238 (2726–3659)
Espinoza FC 2009–2010	3017 $\pm$ 223 (2611–3486)	4932 $\pm$ 254 (4459–5455)
Espinoza FC 2014	3207 $\pm$ 236 (2777–3703)	5243 $\pm$ 272 (4737–5803)
FLONA Jamari 2016	3238 $\pm$ 325 (2661–3939)	5293 $\pm$ 539 (4338–6458)
FLONA Jamari 2017	3239 $\pm$ 318 (2674–3925)	5296 $\pm$ 525 (4363–6427)
FLONA Jamari 2018	3095 $\pm$ 291 (2575–3720)	5060 $\pm$ 476 (4210–6082)
FLONA Jamari 2019	3102 $\pm$ 284 (2593–3711)	5071 $\pm$ 461 (4244–6059)
Güepi-Sekime NP 2017–2018	1658 $\pm$ 125 (1431–1920)	2710 $\pm$ 157 (2420–3035)
Güepi-Sekime NP 2019	1578 $\pm$ 127 (1348–1847)	2580 $\pm$ 168 (2272–2930)
Gurupi REBIO	1768 $\pm$ 158 (1485–2105)	2891 $\pm$ 174 (2570–3252)
Jaú NP 2016–2017a	1580 $\pm$ 153 (1308–1910)	2584 $\pm$ 246 (2145–3112)
Jaú NP 2016–2017b	1582 $\pm$ 153 (1309–1913)	2587 $\pm$ 247 (2147–3117)
Juruena NP	2490 $\pm$ 199 (2129–2911)	4070 $\pm$ 288 (3543–4676)
Los Amigos 2005	2489 $\pm$ 185 (2152–2878)	4068 $\pm$ 268 (3576–4629)
Los Amigos 2006	2490 $\pm$ 185 (2153–2881)	4071 $\pm$ 269 (3577–4634)
Los Amigos 2007	2490 $\pm$ 185 (2153–2881)	4071 $\pm$ 269 (3577–4634)
Los Amigos CC 2010	2122 $\pm$ 141 (1864–2416)	3469 $\pm$ 139 (3208–3752)
Médio Purus RESEX	2335 $\pm$ 213 (1954–2790)	3817 $\pm$ 347 (3196–4559)
SDR Amanã 2013	1480 $\pm$ 134 (1240–1766)	2419 $\pm$ 196 (2064–2835)
SDR Amanã 2013–2014	1479 $\pm$ 134 (1239–1765)	2418 $\pm$ 196 (2064–2833)
SDR Mamirauá 2013	1988 $\pm$ 256 (1546–2557)	3251 $\pm$ 435 (2504–4220)
SDR Mamirauá 2014	1991 $\pm$ 257 (1548–2561)	3255 $\pm$ 436 (2506–4228)
Tambopata NR & Bahuaja Sonene NP	2733 $\pm$ 209 (2352–3175)	4467 $\pm$ 308 (3903–5113)
Umancia IL 2018	1967 $\pm$ 147 (1700–2276)	3215 $\pm$ 199 (2848–3630)
Umancia IL 2019	1972 $\pm$ 148 (1704–2283)	3225 $\pm$ 201 (2855–3642)

Appendix B. Appendices references

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Data availability

The authors do not have permission to share data.

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