Range-wide analysis of jaguar (*Panthera onca*) population connectivity



Guilherme Costa Alvarenga
Lady Margaret Hall
University of Oxford

A thesis submitted for the degree of
Doctor of Philosophy

Michaelmas Term 2025

Acknowledgments

As I grew up, I never thought I would have the opportunity to know another country beyond Brazil, for work or leisure, and I certainly – not even in my wildest dreams – imagined I would do so as a doctoral researcher and student at the University of Oxford. I feel very privileged, but I am also deeply grateful for having lived this life-changing opportunity. This thesis, although led by me, is certainly the product of many hands and, as such, requires due acknowledgement of all those involved in its development.

First and more important than all I thank my family. My father, Flavio, and my mother, Goretti, have done absolutely everything they could to proportionate me this incredible privilege to focus entirely on my academic career for so many years. The same extends to my sister, Lorena, who is my inspiration in life and without her support nothing of this would ever been possible. I do not believe there are words to express my gratitude to you three, I just know I am extremely lucky to have you in my life, and I am grateful for it. Thank you very much.

Over the years, many professionals crossed my academic path, believing in my potential and opening doors through their teaching, guidance, supervision, care, corrections, and, at times, reprimands. The *Universidade Federal de Lavras* (UFLA) and the *Laboratório de Diversidade e Sistemática de Mamíferos* (LADISMA), led by Prof. Renato Gregorin for presenting me sciences for the first time – the first door. The Mamirauá Institute for Sustainable Development and the Felid Ecology and Conservation in Amazonia research group, led by Dr. Emiliano E. Ramalho for introducing me to the Amazon, its brilliant and generous people and to the jaguars – the second door. The National Institute for Amazonian Research (INPA) and my masters' supervisors Prof. Paulo Bobrowiec, Prof. Fabricio Baccaro and Dr. Emiliano E. Ramalho for teaching me how to do sciences – the third door. The University of Oxford and the Wildlife Conservation Research Unit (WildCRU), funded by Prof. David Macdonald for

widening my view and showing me that conservation and research can reach the world – the fourth door. Thank you all as well as to all my colleagues over the years; you helped to build the researcher I have become, and I am very grateful for it.

As the following pages show, this doctorate is the fruit of several collaborations, and I am very proud of them. Over 50 institutions and researchers have been directly involved in different phases of this thesis. For this reason, I will not list them all here, although their names can be found at the beginning of each chapter. I feel extremely lucky to have built such an incredible network of collaborators, and I am very grateful to all of you.

I am also deeply grateful to my doctoral supervisors. Formally, Prof. Żaneta Kaszta (Żan), Dr. Samuel A. Cushman (Sam), Prof. Alexandra Zimmermann, and Prof. Yadvinder Malhi; and informally, Dr. Caroline Sartor (Carol) and Prof. David W. Macdonald (David). Thank you for opening doors, for believing in my potential, for sharing your knowledge, and for dedicating your time, patience, and energy to me. This thesis is a team accomplishment, and you are the core of this team. Thank you.

In particular, I would like to thank Żan for being with me since the very beginning of this project, back in 2018, still during my Diploma years. Thank you, Żan, for becoming much more than a supervisor over the years, and for going above and beyond even with so much on your plate – two kids are no joke. Haha. Sam and Carol, thank you very much for your guidance and for working closely with me – sometimes almost on a daily basis – when I most needed it. And David, thank you, thank you very much, for your kindness, inspiration, and for giving me this incredible opportunity to develop my doctorate as a member of WildCRU at the University of Oxford.

I am very proud to be part of WildCRU, Lady Margaret Hall (LMH), the Department of Biology, and the University of Oxford, and I would like to thank all the professionals who

make these institutions work every day. At WildCRU, where I spent most of my doctorate, I would like to thank – beyond Żan, Sam, Carol, and David – Dr. Darragh Hare, Dr. Dawn Burnham, Amanda Adams, Sarah Markes, Emma Stewart-Wood, Prof. Amy Dickman, Dr. Sandra Lai, Dr. Jan Kamler, Dr. Diogo Veríssimo, Dr. Egil Dröge, Dr. Paul Johnson, Dr. Luciano Atzeni, Prof. Claudio Sillero-Zubiri, Dr. Jorgelina Marino, Dr. Lauren Harrington, and all my WildCRU colleagues who were present during my doctorate and helped transform the work environment into a family.

Last, but definitely not least, a very special thank you to all my friends. You have been present in both bad and good times, have seen my best and worst versions, and helped me grow – thank you. In Oxford, despite being so far from home and so different, you somehow managed to make it feel like home, and I am deeply grateful for that; namely Aline, Leo, Felipe, Vivi, Luca, Jenny, Elisa & Antonio, Meshach (in memoriam), Carol, Erika, André V., Chrishen, Emily M., Sandra, Mele & Jaime, Nicole, Alfredo, Tom & Bill, Dominik & Lydia, Holly, Claire P., Audrey, Lila, Sho, Hasita, Emily O., Jas, Jess T., Tyler & Amanda, Dylan, Ella, and Esme. A special thank you as well to my friends in Brazil, who, even from afar, never stopped supporting me – to name just a few: KK, Heitor, Brenin, Samu, Felipe, Tenaz, Dioguin, Fanny, Diego, PG, Thiaguin, Kinder, Caetas (in memoriam), Arthur, Dedé, Ferrel, Milo, Matheus, Nana, Gab, Bela, Danidani, Isão, Livia, Norminha, Losa, Ciro, Gabriel, Bê, Pedrinho, Dino & Livia, Mendigo, Bambino, Thaís, Hani, Alininha, Marina & Fred, Diogo Piracatinga, Diogo Peregrino, Dadá, Lou, and many more.

My most sincere gratitude. Thank you.

Range-wide analysis of jaguar (*Panthera onca*) population connectivity

Guilherme Costa Alvarenga, Lady Margaret Hall, University of Oxford
Doctor of Philosophy, Michaelmas Term 2025

Abstract

Rapid anthropogenic habitat transformation has caused widespread population declines and fragmentation, particularly for large carnivores whose persistence depends on extensive, connected landscapes. Jaguars (*Panthera onca*), the largest felid in the Neotropics, have lost approximately half of their historical range, with most populations outside the Amazon now small, isolated, and highly threatened. This thesis provides a comprehensive, large-scale assessment of jaguar ecology and conservation by integrating demographic, ecological, spatial, and social dimensions across the species' range. First, I quantified jaguar population density and size across 22 protected areas and Indigenous Lands in the Amazon using camera-trap data and multi-session spatial capture–recapture models. Jaguar densities varied widely across sites, with the highest values associated with highly productive floodplain systems, highlighting the Amazon's protected area network as a global stronghold for the species. Second, I developed a multiscale habitat suitability model using GPS telemetry data from 172 jaguars across eight countries. Jaguars strongly selected productive habitats near water and avoided human-modified landscapes, resulting in a high-performing suitability model that identified the Amazon and Mayan Forests as core strongholds while revealing additional conservation-relevant areas under ecoregion-specific analyses. Third, I assessed population connectivity across the jaguar's range by identifying and ranking core movement areas and dispersal corridors using complementary resistance-based approaches. Results revealed a large, highly interconnected network spanning much of South America, contrasted with fragmented and discontinuous connectivity in northern portions of the range. Finally, I evaluated human–jaguar interactions and tolerance within the Pantanal–Amazon Corridor through a quantitative social survey. Despite localized conflicts, tolerance toward jaguars and conservation actions was generally high, with political orientation and perceptions of climatic change influencing attitudes. Together, these findings demonstrate that effective jaguar conservation requires integrating population status, habitat quality, landscape connectivity, and human dimensions. By identifying priority populations, habitats, corridors, and social contexts, this thesis provides an evidence-based framework to guide large-scale conservation planning and promote long-term jaguar persistence under accelerating environmental change.

Declaration of Authorship

I declare that this thesis is primarily my work. The conception was collaborative and individual author contributions are specified at the end of each chapter. All the analyses and writing are my own. Since each chapter was collaborative, I use the third person plural “we” to indicate the same. The work in part or full has not been submitted to meet the requirements of any degree or professional qualification.

Guilherme Costa Alvarenga

Funding

This DPhil was generously funded by the Robertson Foundation through a scholarship from Wildlife Conservation Research Unit (WildCRU). Additional financial support was provided by the Wildlife Conservation Network (WCN), Panthera-Brazil, Berlin World Wild, The Rufford Foundation, Lady Margaret Hall College of the University of Oxford, the OAF University of Oxford and The Wild Felid Research and Management Association (WFA).

Table of Contents

Acknowledgments....ii
Abstract....v
Declaration of Authorship....vi
Funding....vi
Chapter 1 ....***2***
General Introduction ***2***
References....11
Chapter 2 ....***27***
Jaguar (Panthera onca) density and population size across protected areas and indigenous lands in the Amazon Biome, its largest stronghold ***27***
Abstract....28
Keywords....28
Introduction....29
Methods....31
Results....38
Discussion....44
Conclusions and Recommendations....48
Acknowledgements....49
References....51
Author Contributions....65
Supplementary Material....66
References Supplementary....75
Chapter 3 ....***79***
Range-wide assessment of habitat suitability for jaguars using multiscale species distribution modelling ***79***
Abstract....80
Key words....80
Introduction....81
Results....83
Discussion....91
Methods....99
Acknowledgements....110
Data Availability Statement....110
References....112
Author Contributions....126
Supplementary Material....128
References Supplementary....143
Chapter 4 ....***147***
Jaguar range-wide connectivity: Prioritizing core areas and corridors between protected areas and Indigenous Lands ***147***
Abstract....148
Keywords....149
Introduction....150
Methods....151
Results....160
Discussion....174
Conclusions....186
Acknowledgements....187
References....188

Author Contributions 207
Supplementary Material 209
Chapter 5 ..... ***218***
Human-jaguar coexistence in the Pantanal-Amazon Corridor: attitudes and conservation implications ***218***
Abstract 219
Keywords 220
Introduction 221
Methods 224
Results 232
Discussion 238
Conclusion 245
Acknowledgments 246
References 247
Author Contributions 255
Supplementary Material 256
Chapter 6 ..... ***266***
General Discussion ***266***
Conclusion 272
References 274
Appendices ***279***
Other Publications (between 2021 and 2026) ***279***
AMAZONIA CAMTRAP: A dataset of mammal, bird, and reptile species recorded with camera traps in the Amazon forest 280
Abstract 280
Hematology and Serum Chemistry of Free-Ranging Jaguars (*Panthera onca*) from a Floodplain Forest Site in Amazonia, Brazil 282
Abstract 282
Community-based monitoring of wild felid hunting in Central Amazonia 283
Abstract 283
Divergent effects of lure on multi-species camera-trap detections and quality of photos 285
Abstract 285
Anthropogenic factors do not affect male or female jaguar habitat use in an Amazonian Sustainable Reserve 287
Abstract 287
Mammal responses to global changes in human activity vary by trophic group and landscape 289
Abstract 289
Impact of seasonal flooding on Jaguar (*Panthera onca*) home range and movements 290
Abstract 290
Gender dynamics of tropical wildmeat systems: A systematic map of women's roles and influence 292
Abstract 292



"*There's some good in this world and it's worth fighting for.*"
Samwise Gamgee, The Lord of the Rings
J.R.R. Tolkien



Bruno Kelly - Mamirauá Institute

Chapter 1

General Introduction

Organisms' movement is the ability to dislocate the whole body or the gametes in space and time – a skill widely mastered in nature, from microorganisms to large animals and even plants (Nathan et al., 2008). As a fundamental function, movement affects life at all scales. Individuals' survival, populations dynamics, communities' diversity, and ecosystems structures are all directly shaped by individuals and species capacity to move (Jeltsch et al., 2013). In turn, an endless list of biotic and abiotic factors acting at multiple spatiotemporal scales also influences the decision to move. For example, inter- and intraspecific interactions such as mate-searching, territory patrol, or predation occur practically on a daily basis for some species. Other types of movement, though, occur over the year and as a response to the habitat availability and its seasonal changes (Ferreira et al., 2017; Ramalho et al., 2021). To understand this intricate array of mechanisms influencing and being influenced by movement, researchers developed a variety of methodologies that combined became a field of study known as "spatial ecology" (Nathan et al., 2008).

As humans we investigate animals' movement since our ancestors - following tracks for hunting or scavenging in early times (Domínguez-Rodrigo, 2002). More recently, with the development of refined tools, we deepen our knowledge on movement, not for hunting but mostly to manage and protect wildlife. From the known techniques, species distribution models (SDMs) are predominant in scientific literature to predict species habitat use (Araújo et al., 2019; Briscoe et al., 2019; Guisan and Thuiller, 2005). This method has its theoretical roots in niche theory and related concepts, such as fundamental and realized niches, and has been referred to over time by a variety of terms, including "ecological niche models," "environmental niche models", and "habitat suitability models" (Fletcher and Fortin, 2018). In short, SDMs use statistical relationships between georeferenced species occurrences and spatially explicit environmental variables (e.g. elevation, land cover, precipitation) to infer and predict species distributions (Guisan and Zimmermann, 2000).

The quality of the SDMs' predictions depends mainly on reliable empirical data on species presence (and, if possible, absence), good quality spatial information on the habitat components driving species presence/absence, and correct statistical methods applied to such data. There are five different sources of animal occurrence data - (1) expert's knowledge; (2) systematic surveys (e.g.: camera traps); (3) occasional observations; (4) genetic samples; and (5) radio/GPS telemetry. Each of these data sources entails specific trade-offs in terms of spatial coverage, sampling bias, and ecological inference (Guisan and Thuiller, 2005; Rondinini and Boitani, 2012; Zeller et al., 2012).

GPS-telemetry data provides presence-only information, and the data are often limited to only few individuals since capturing animals is generally expensive and logistically difficult (Rondinini and Boitani, 2012). Presence-only data are commonly analysed using Resource Selection Functions (RSFs), which model the proportional probability of resource use rather than the absolute probability of occurrence (Fletcher and Fortin, 2018). RSFs compare the used habitat (the presences extracted from animal locations) with randomly created background points to quantify the variation in the use of resources – in other words, a comparison between used and available habitat (matrix SF is an exception, for more information see Zeller et al., 2012). A central challenge in RSF development is defining the spatial extent over which habitat is considered available, as this choice is scale-dependent and closely tied to the research question (Barbet-Massin et al., 2012; Hazen et al., 2021). Once used and available habitats were defined and properly sampled from the relevant spatial covariates, then statistical analysis, usually logistic regressions, are applied to map how species respond to the habitat (Elith and Leathwick, 2009).

Despite these limitations, telemetry data provide uniquely robust information on the spatial behaviour of individual animals and represent one of the most direct empirical descriptions of movement in real landscapes. GPS telemetry, in particular, offers fine

temporal and spatial resolution, enabling detailed and often more accurate modelling of resource selection and movement processes than coarser occurrence datasets (Zeller et al., 2018). Once GPS locations are obtained, researchers must decide how these data will be analysed statistically. A range of selection-function approaches is available, including point selection, home range selection, matrix selection, step, and path selection functions (Zeller et al., 2012). The choice among these methods depends on both the research objectives and the characteristics of the telemetry dataset. For example, datasets with large temporal gaps between consecutive locations are unsuitable for path-based selection functions, which require high-frequency tracking data to reliably capture movement trajectories (Zeller et al., 2016).

RSFs are usually the first step from which movement models are produced (except for genetic sample data - Zeller et al., 2018). Typically, habitat suitability surfaces – the outcomes of RSFs – are transformed into resistance maps, which quantifies potential permeability of the landscape to movement (Fletcher and Fortin, 2018). The idea that the level of isolation (or connectivity) between habitat patches and their populations varies according to the matrix resistance between them is a derivation of metapopulation studies (Zeller et al., 2012). This approach measures potential connectivity and defends that an intersection of space and environmental constraints drives movement capacity – commonly referred as isolation-by-resistance (McRae, 2006). Using these resistance maps as surface basis, several algorithms can be applied to identify paths that reduce the accumulated cost of movement between locations, generating potential corridors between those locations – among these algorithms, least-cost paths, resistant kernels and Circuitscape are the most prominent methods (Kumar and Cushman, 2022).

Beyond landscape resistance, however, connectivity between populations is also shaped by demographic processes, among which population size and density play a central

role (Nichols et al., 2000). Population density influences dispersal pressure, source–sink dynamics, and the probability that individuals will move across the landscape to occupy suitable habitats or join other populations (Fletcher and Fortin, 2018). Consequently, areas predicted as suitable or highly connected based solely on resistance surfaces may differ substantially in their functional and conservation value depending on whether they support viable populations capable of producing dispersers. Therefore, density estimates enable a more nuanced interpretation of landscape functionality, helping to distinguish areas that merely facilitate movement from those that actively contribute to population persistence and gene flow. Despite their importance, robust density estimates remain scarce at large spatial scales, which continues to limit the explicit incorporation of demographic processes into connectivity assessments.

Similarly, human attitudes and perceptions toward a target species can strongly influence the likelihood of effective connectivity between populations (Struebig et al., 2018). While some anthropogenic pressures (e.g. deforestation, human population density, road networks) can be spatially mapped and are therefore readily incorporated into connectivity models, more nuanced social variables are rarely available over large spatial extents, limiting their integration into landscape analyses (Titus and Jachowski, 2025). One of the main challenges to their inclusion at broad scales is that human attitudes are rarely homogeneous across large areas and are often dynamic, changing over time in response to social, economic, and ecological factors (Zimmermann et al., 2021). Capturing such variability would require intensive sampling and continuous monitoring to ensure reliability, rendering their incorporation into large-scale connectivity modelling largely impractical.

Despite their limitations, resource selection and movement models are extremely useful to answer a variety of ecological questions and/or for conservation purposes (Fraser et al., 2018; Guisan et al., 2013). To cite just a few applications, these models have been used to

predict dispersal and connectivity (Elliot et al., 2014), biodiversity hotspots (Chiaverini et al., 2022), land use change (Kaszta et al., 2019), climate change (Macdonald et al., 2020), human-wildlife conflict (Rostro-García et al., 2016; Zimmermann, 2014), invasive species (Ouko et al., 2020), creation of new protected areas (Penjor et al., 2021), and others (for more examples see Fraser et al., 2018). With human activities causing high reduction of wildlife's natural habitats throughout the world (Koh and Gardner, 2010; Pimm and Raven, 2000), SDMs and movement models come useful to track species response to these changes and to define and protect the crucial habitats (and habitats elements) for their survival.

Jaguars (*Panthera onca*), for instance, were originally distributed from southwestern United States to central Argentina (Seymour, 1989), but had their geographical range reduced by half in the last century (Quigley et al., 2017). From the remaining area, the Amazonian forest, the wetlands of Pantanal and the Mayan forest still harbour large jaguar populations, while all the others are small, isolated and highly threatened (Ceballos et al., 2021; de la Torre et al., 2018; WWF et al., 2019). Many consequences of this isolation have been already detected, for instance studies reported limited dispersal between jaguar populations and loss of genetic diversity in different regions of the species' range (Haag et al., 2010; Lorenzana et al., 2020; Srbek-Araujo et al., 2018; Wultsch et al., 2016). As a clear response to the anthropogenic threats, various initiatives have been undertaken to improve the knowledge on jaguar habitat use and movement (including long-distance dispersal movement).

As part of these initiatives, 51 areas important for jaguars' long-term survival, called Jaguar Conservation Units (JCU's), have been identified through experts-knowledge (Sanderson et al., 2002). In 2006, these areas were revised by 130 researchers, who updated the previous estimation to 90 JCU's in total (Zeller, 2007), and in 2010, a landscape connectivity model (also expert-based) was developed for the entire geographical range of the species (Rabinowitz and Zeller, 2010). Since then, with new and more accessible

technologies available, several studies updated the pioneered models – this time using jaguar occurrence data. At a large scale, Tôrres et al. (2012) and Jędrzejewski et al. (2018) combined different sources of jaguar occurrence to produce species distribution models for the entire distribution area of the species, Bernal-Escobar et al. (2015) developed dispersal models accounting for sex differences in South America, and the Brazilian National Action Plan for Jaguar Conservation produced occupancy maps for the species in Brazil (Ferraz et al., 2013). At regional and local scales, studies were developed in the Atlantic Forest (Cullen Junior et al., 2013; De Angelo et al., 2013; de Azevedo et al., 2022; Ferraz et al., 2012; Jorge et al., 2013; Paviolo et al., 2016), in the Brazilian savanna (Portugal et al., 2019; Zeilhofer et al., 2014), in the Pantanal (Alvarenga et al., 2021; de Azevedo et al., 2021), in the Caatinga Brazilian biome (Ferraz et al., 2012; Morato et al., 2014), in tropical forests of Central America (Calderón et al., 2022; Craighead et al., 2022; Meyer et al., 2019; Petracca et al., 2014; Salom-Perez et al., 2021; Salom-Pérez et al., 2010; Watkins et al., 2015; Zeller et al., 2011), in different ecosystems of Mexico (Balbuena-Serrano et al., 2022; Colchero et al., 2011; de la Torre et al., 2017; Luja et al., 2017; Petracca et al., 2018; Ramirez-Reyes et al., 2016; Rodríguez-Soto et al., 2011; Stoner et al., 2015) and in south USA (Landau et al., 2022; Sanderson et al., 2022).

Although studies on jaguar's habitat selection and landscape connectivity were based on different methodologies, scales and geographical regions, some patterns in the species' response to the landscape can be highlighted. For instance, the importance of protected areas for jaguar's populations is noticeable throughout its geographical range, especially outside the Amazonian forest, where all the remaining suitable habitats are fragmented (Ferraz et al., 2012; Figel et al., 2022; Paviolo et al., 2016; Sollmann et al., 2008; Zeilhofer et al., 2014). Among the natural resources, primary and secondary forests, as well as water bodies are probably the most frequently reported areas of high suitability, and dispersal corridors for

jaguars (Cullen Junior et al., 2013; De Angelo et al., 2013; de la Torre et al., 2017; Emmons, 1987; Rabinowitz and Jr, 1986; Schaller and Crawshaw, 1980). Forested habitats, such as riparian forests, facilitates predation as jaguars can camouflage while approaching prey on the riverbanks (Crawshaw and Quigley, 1991; Schaller and Crawshaw, 1980). On the contrary, jaguars seem to avoid anthropogenic areas, such as settlements, crop farms and roads (Colchero et al., 2011; Rodríguez-Soto et al., 2013; Rosas-Rosas and Valdez, 2010) - a pattern already expected since humans impose different types of pressure to wildlife, from direct persecution of predators and depletion of their prey to habitat loss and fragmentation (Galetti et al., 2016; Michalski et al., 2006; Zanin et al., 2015). In addition, it is well documented that males and females use their habitat differently. Home ranges' size vary widely between sexes (McBride and Thompson, 2018; Morato et al., 2016); males seem to look for trails while females avoid them (Harmsen et al., 2017), and females are more sensitive to human alterations than males (Colchero et al., 2011; Conde et al., 2010). Ignoring these differences could produce unreliable estimations of SDMs and eventual corridors (Bernal-Escobar et al., 2015; Elliot et al., 2014; Maiorano et al., 2017).

The incredible knowledge generated by these studies on jaguar habitat use is undeniable, however, some fundamental questions remain. For instance, although differences in habitat use between sexes are well known (Harmsen et al., 2017; Thompson et al., 2021), the limited amount of data available for researchers restricted their capability to develop predictions at large geographical scales. To the best of my knowledge, only Bernal-Escobar et al. (2015) considered sex differences to simulate habitat use of jaguars at a large scale but only for South America. Models covering the entire jaguar range did not consider these differences and were based either on expert-knowledge (Rabinowitz and Zeller, 2010; Sanderson et al., 2002; Zeller, 2007) or a compilation of occurrence data from varying

sources, such as museums records, publications, and online databases (Jędrzejewski et al., 2018; Tôrres et al., 2012).

In this study, I combined demographic, ecological, spatial, and social approaches to provide a comprehensive, large-scale assessment of jaguar ecology and conservation across the species' range. Specifically, I: (1) estimate jaguar population density and size across 22 protected areas and Indigenous Lands in the Amazon; (2) develop a multi-scale model of habitat suitability across the species' range; (3) model and quantify population connectivity throughout the jaguar's distribution; and (4) assess human–carnivore conflict and coexistence between jaguars and local communities within the Pantanal-Amazon Corridor identified by the connectivity analysis.

Thesis overview

This thesis is organised into six chapters. Chapter 1 provides the general introduction and theoretical background. Chapters 2–5 constitute the data chapters, each addressing a complementary component of jaguar ecology and conservation, from population demography to habitat use, connectivity, and human–carnivore interactions. These chapters (2-5) are formatted as independent manuscripts; therefore, figures and tables are numbered separately within each chapter. Chapter 6 synthesises the main findings, discusses their implications for jaguar conservation across the species' range, and outlines limitations and future research directions.

References

Alvarenga, G.C., Chiaverini, L., Cushman, S.A., Dröge, E., Macdonald, D.W., Kantek, D.L.Z., Morato, R.G., Thompson, J.J., Oscar, R.B.L.M., Abade, L., Azevedo, F.C.C. de, Ramalho, E.E., Kaszta, Ż., 2021. Multi-scale path-level analysis of jaguar habitat use in the Pantanal ecosystem. Biol Conserv 253, 108900. https://doi.org/10.1016/j.biocon.2020.108900

Araújo, M.B., Anderson, R.P., Barbosa, A.M., Beale, C.M., Dormann, C.F., Early, R., Garcia, R.A., Guisan, A., Maiorano, L., Naimi, B., O'Hara, R.B., Zimmermann, N.E., Rahbek, C., 2019. Standards for distribution models in biodiversity assessments. Sci Adv 5, 1–11. https://doi.org/10.1126/sciadv.aat4858

Balbuena-Serrano, Á., Zarco-González, M.M., Carreón-Arroyo, G., Carrera-Treviño, R., Amador-Alcalá, S., Monroy-Vilchis, O., 2022. Connectivity of priority areas for the conservation of large carnivores in northern Mexico. J Nat Conserv 65, 126116. https://doi.org/10.1016/j.jnc.2021.126116

Barbet-Massin, M., Jiguet, F., Albert, C.H., Thuiller, W., 2012. Selecting pseudo-absences for species distribution models: How, where and how many? Methods Ecol Evol 3, 327–338. https://doi.org/10.1111/j.2041-210X.2011.00172.x

Bernal-Escobar, A., Payan, E., Cordovez, J.M., 2015. Sex dependent spatially explicit stochastic dispersal modeling as a framework for the study of jaguar conservation and management in South America. Ecol Modell 299, 40–50. https://doi.org/10.1016/j.ecolmodel.2014.12.002

Briscoe, N.J., Elith, J., Salguero-Gómez, R., Lahoz-Monfort, J.J., Camac, J.S., Giljohann, K.M., Holden, M.H., Hradsky, B.A., Kearney, M.R., McMahon, S.M., Phillips, B.L., Regan, T.J., Rhodes, J.R., Vesk, P.A., Wintle, B.A., Yen, J.D.L., Guillera-Arroita, G.,

2019. Forecasting species range dynamics with process-explicit models: matching methods to applications. Ecol Lett 22, 1940–1956. https://doi.org/10.1111/ele.13348

Calderón, A.P., Louvrier, J., Planillo, A., Araya-Gamboa, D., Arroyo-Arce, S., Barrantes-Núñez, M., Carazo-Salazar, J., Corrales-Gutiérrez, D., Doncaster, C.P., Foster, R., García, M.J., Garcia-Anleu, R., Harmsen, B., Hernández-Potosme, S., Leonardo, R., Trigueros, D.M., McNab, R., Meyer, N., Moreno, R., Salom-Pérez, R., Sauma Rossi, A., Thomson, I., Thornton, D., Urbina, Y., Grimm, V., Kramer-Schadt, S., 2022. Occupancy models reveal potential of conservation prioritization for Central American jaguars. Anim Conserv 1–12. https://doi.org/10.1111/acv.12772

Ceballos, G., Zarza, H., González-Maya, J.F., de la Torre, J.A., Arias-Alzate, A., Alcerreca, C., Barcenas, H. V., Carreón-Arroyo, G., Chávez, C., Cruz, C., Medellín, D., García, A., Antonio-García, M., Lazcano-Barrero, M.A., Medellín, R.A., Moctezuma-Orozco, O., Ruiz, F., Rubio, Y., Luja, V.H., Torres-Romero, E.J., 2021. Beyond words: From jaguar population trends to conservation and public policy in Mexico. PLoS One 16, 1–22. https://doi.org/10.1371/journal.pone.0255555

Chiaverini, L., Macdonald, D.W., Bothwell, H.M., Hearn, A.J., Cheyne, S.M., Haidir, I., Hunter, L.T.B., Kaszta, Z., Macdonald, E.A., Ross, J., Cushman, S.A., 2022. Multi-scale, multivariate community models improve designation of biodiversity hotspots in the Sunda Islands. Anim Conserv 25, 660–679. https://doi.org/10.1111/acv.12771

Colchero, F., Conde, D.A., Manterola, C., Chávez, C., Rivera, A., Ceballos, G., 2011. Jaguars on the move: Modeling movement to mitigate fragmentation from road expansion in the Mayan Forest. Anim Conserv 14, 158–166. https://doi.org/10.1111/j.1469-1795.2010.00406.x

Conde, D.A., Colchero, F., Zarza, H., Christensen, N.L., Sexton, J.O., Manterola, C., Chávez, C., Rivera, A., Azuara, D., Ceballos, G., 2010. Sex matters: Modeling male and

female habitat differences for jaguar conservation. Biol Conserv 143, 1980–1988. https://doi.org/10.1016/j.biocon.2010.04.049

Craighead, K., Yacelga, M., Wan, H.Y., Vogt, R., Cushman, S.A., 2022. Scale-dependent seasonal habitat selection by jaguars (*Panthera onca*) and pumas (*Puma concolor*) in Panama. Landsc Ecol 37, 129–146. https://doi.org/10.1007/s10980-021-01335-2

Crawshaw, J.P.G., Quigley, H.B., 1991. Jaguar spacing, activity and habitat use in a seasonally flooded environment in Brazil. Journal of Zoology, London 223, 357–370.

Cullen Junior, L., Sana, D.A., Lima, F., Abreu, K.C. de, Uezu, A., 2013. Selection of habitat by the jaguar, *Panthera onca* (Carnivora: Felidae), in the upper Paraná River, Brazil. Zoologia 30, 379–387. https://doi.org/10.1590/S1984-46702013000400003

De Angelo, C., Paviolo, A., Wiegand, T., Kanagaraj, R., Di Bitetti, M.S., 2013. Understanding species persistence for defining conservation actions: A management landscape for jaguars in the Atlantic Forest. Biol Conserv 159, 422–433. https://doi.org/10.1016/j.biocon.2012.12.021

de Azevedo, F.C.C., Bastille-Rousseau, G., Murray, D.L., 2021. Habitat selection of jaguars in a seasonally flooded landscape. Mammalian Biology 101, 817–830. https://doi.org/10.1007/s42991-021-00185-4

de Azevedo, F.C.C., Pasa, J.B., Arrais, R.C., Massara, R.L., Widmer, C.E., 2022. Density and habitat use of one of the last jaguar populations of the Brazilian Atlantic Forest: Is there still hope? Ecol Evol 12, 1–15. https://doi.org/10.1002/ece3.8487

de la Torre, A.J., González-Maya, J.F., Zarza, H., Ceballos, G., Medellín, R.A., 2018. The jaguar's spots are darker than they appear: Assessing the global conservation status of the jaguar *Panthera onca*. Oryx 52, 300–315. https://doi.org/10.1017/S0030605316001046

de la Torre, J.A., Núñez, J.M., Medellín, R.A., 2017. Habitat availability and connectivity for jaguars (*Panthera onca*) in the Southern Mayan Forest: Conservation

priorities for a fragmented landscape. Biol Conserv 206, 270–282. https://doi.org/10.1016/j.biocon.2016.11.034

Domínguez-Rodrigo, M., 2002. Hunting and Scavenging by Early Humans: The State of the Debate. J World Prehist 16, 1–54.

Elith, J., Leathwick, J.R., 2009. Species distribution models: Ecological explanation and prediction across space and time. Annu Rev Ecol Evol Syst 40, 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Elliot, N.B., Cushman, S.A., Macdonald, D.W., Loveridge, A.J., 2014. The devil is in the dispersers: Predictions of landscape connectivity change with demography. Journal of Applied Ecology 51, 1169–1178. https://doi.org/10.1111/1365-2664.12282

Emmons, L.H., 1987. Feeding ecology of felids in a Neotropical rainforest. Behav Ecol Sociobiol 20, 271–283.

Ferraz, K., Beisiegel, B., de Paula, R., Sana, D., de Campos, C., de Oliveira, T., Desbiez, A., 2012. How species distribution models can improve cat conser vation - jaguars in Brazil. CATNews 38–42.

Ferraz, K.M.P.M., Paula, R.C. de, Campos, C.B., Beisiegel, B.M., Moraes Jr, E.A., Cavalcanti, S.M.C., Oliveira, T.G. de, 2013. Distribuição potencial e adequabilidade ambiental dos biomas brasileiros à ocorrência da onça-pintada, in: Paula, R.C. de, Desdiez, A., Cavalcanti., S. (Eds.), Plano Nacional Para Conservação Da Onça-Pintada. Instituto Chico Mendes de Conservação da Biodiversidade, ICMBio, Brasília, pp. 125–206.

Ferreira, D.F., Rocha, R., López-Baucells, A., Farneda, F.Z., Carreiras, J.M.B., Palmeirim, J.M., Meyer, C.F.J., 2017. Season-modulated responses of Neotropical bats to forest fragmentation. Ecol Evol 7, 4059–4071. https://doi.org/10.1002/ece3.3005

Figel, J.J., Botero-Cañola, S., Lavariega, M.C., Luna-Krauletz, M.D., 2022. Overlooked jaguar guardians: Indigenous territories and range-wide conservation of a cultural icon. Ambio. https://doi.org/10.1007/s13280-022-01754-8

Fletcher, R., Fortin, M.-J., 2018. Spatial Ecology and Conservation Modeling, Spatial Ecology and Conservation Modeling. Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-01989-1

Fraser, K.C., Davies, K.T.A., Davy, C.M., Ford, A.T., Flockhart, D.T.T., Martins, E.G., 2018. Tracking the conservation promise of movement ecology. Front Ecol Evol 6, 1–8. https://doi.org/10.3389/fevo.2018.00150

Galetti, M., Brocardo, C.R., Begotti, R.A., Hortenci, L., Rocha-Mendes, F., Bernardo, C.S.S., Bueno, R.S., Nobre, R., Bovendorp, R.S., Marques, R.M., Meirelles, F., Gobbo, S.K., Beca, G., Schmaedecke, G., Siqueira, T., 2016. Defaunation and biomass collapse of mammals in the largest Atlantic forest remnant. Anim Conserv 1–12. https://doi.org/10.1111/acv.12311

Guisan, A., Thuiller, W., 2005. Predicting species distribution: Offering more than simple habitat models. Ecol Lett 8, 993–1009. https://doi.org/10.1111/j.1461-0248.2005.00792.x

Guisan, A., Tingley, R., Baumgartner, J.B., Naujokaitis-Lewis, I., Sutcliffe, P.R., Tulloch, A.I.T., Regan, T.J., Brotons, L., Mcdonald-Madden, E., Mantyka-Pringle, C., Martin, T.G., Rhodes, J.R., Maggini, R., Setterfield, S.A., Elith, J., Schwartz, M.W., Wintle, B.A., Broennimann, O., Austin, M., Ferrier, S., Kearney, M.R., Possingham, H.P., Buckley, Y.M., 2013. Predicting species distributions for conservation decisions. Ecol Lett 16, 1424–1435. https://doi.org/10.1111/ele.12189

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecol Modell 135, 147–186. https://doi.org/10.1016/S0304-3800(00)00354-9

Haag, T., Santos, a. S., Sana, D. a., Morato, R.G., Cullen, L., Crawshaw, P.G., De Angelo, C., Di Bitetti, M.S., Salzano, F.M., Eizirik, E., 2010. The effect of habitat fragmentation on the genetic structure of a top predator: Loss of diversity and high differentiation among remnant populations of Atlantic Forest jaguars (*Panthera onca*). Mol Ecol 19, 4906–4921. https://doi.org/10.1111/j.1365-294X.2010.04856.x

Harmsen, B.J., Foster, R.J., Sanchez, E., Gutierrez-González, C.E., Silver, S.C., Ostro, L.E.T., Kelly, M.J., Kay, E., Quigley, H., 2017. Long term monitoring of jaguars in the Cockscomb Basin Wildlife Sanctuary, Belize; Implications for camera trap studies of carnivores. PLoS One 12, 1–19. https://doi.org/10.1371/journal.pone.0179505

Hazen, E.L., Abrahms, B., Brodie, S., Carroll, G., Welch, H., Bograd, S.J., 2021. Where did they not go? Considerations for generating pseudo-absences for telemetry-based habitat models. Mov Ecol 9, 1–13. https://doi.org/10.1186/s40462-021-00240-2

Jędrzejewski, W., Robinson, H.S., Abarca, M., Zeller, K.A., Velasquez, G., Paemelaere, E.A.D., Goldberg, J.F., Payan, E., Hoogesteijn, R., Boede, E.O., Schmidt, K., Lampo, M., Viloria, Á.L., Carreño, R., Robinson, N., Lukacs, P.M., Nowak, J.J., Salom-Pérez, R., Castañeda, F., Boron, V., Quigley, H., 2018. Estimating large carnivore populations at global scale based on spatial predictions of density and distribution - Application to the jaguar (*Panthera onca*). PLoS One 13, 1–25. https://doi.org/10.1371/journal.pone.0194719

Jeltsch, F., Bonte, D., Pe'er, G., Reineking, B., Leimgruber, P., Balkenhol, N., Schröder, B., Buchmann, C.M., Mueller, T., Blaum, N., Zurell, D., Böhning-Gaese, K., Wiegand, T., Eccard, J.A., Hofer, H., Reeg, J., Eggers, U., Bauer, S., 2013. Integrating movement ecology with biodiversity research - exploring new avenues to address spatiotemporal biodiversity dynamics. Mov Ecol 1, 1–13. https://doi.org/10.1186/2051-3933-1-6

Jorge, M.L.S.P., Galetti, M., Ribeiro, M.C., Ferraz, K.P.M.B., 2013. Mammal defaunation as surrogate of trophic cascades in a biodiversity hotspot. Biol Conserv 163, 49–57. https://doi.org/10.1016/j.biocon.2013.04.018

Kaszta, Ż., Cushman, S.A., Hearn, A.J., Burnham, D., Macdonald, E.A., Goossens, B., Nathan, S.K.S.S., Macdonald, D.W., 2019. Integrating Sunda clouded leopard (*Neofelis diardi*) conservation into development and restoration planning in Sabah (Borneo). Biol Conserv 235, 63–76. https://doi.org/10.1016/j.biocon.2019.04.001

Koh, L.P., Gardner, T.A., 2010. Conservation in human-modified landscapes, in: Sodhi, N.S., Ehrlich, P.R. (Eds.), Conservation Biology for All. Oxford University Press, Oxford, UK.

Kumar, S.U., Cushman, S.A., 2022. Connectivity modelling in conservation science: a comparative evaluation. Sci Rep 12, 16680. https://doi.org/10.1038/s41598-022-20370-w

Landau, V.A., Noon, B.R., Theobald, D.M., Hobbs, N.T., Nielsen, C.K., 2022. Integrating presence-only and occupancy data to model habitat use for the northernmost population of jaguars. Ecological Applications 32, 1–34. https://doi.org/10.1002/eap.2619

Lorenzana, G., Heidtmann, L., Haag, T., Ramalho, E., Dias, G., Hrbek, T., Farias, I., Eizirik, E., 2020. Large-scale assessment of genetic diversity and population connectivity of Amazonian jaguars (*Panthera onca*) provides a baseline for their conservation and monitoring in fragmented landscapes. Biol Conserv 242, 108417. https://doi.org/10.1016/j.biocon.2020.108417

Luja, V.H., Navarro, C.J., Torres Covarrubias, L.A., Cortés Hernández, M., Vallarta Chan, I.L., 2017. Small Protected Areas as Stepping-Stones for Jaguars in Western Mexico. Trop Conserv Sci 10, 194008291771705. https://doi.org/10.1177/1940082917717051

Macdonald, D.W., Chiaverini, L., Bothwell, H.M., Kaszta, Ż., Ash, E., Bolongon, G., Can, Ö.E., Campos-Arceiz, A., Channa, P., Clements, G.R., Hearn, A.J., Hedges, L., Htun,

S., Kamler, J.F., Macdonald, E.A., Moore, J., Naing, H., Onuma, M., Rasphone, A., Rayan, D.M., Ross, J., Singh, P., Tan, C.K.W., Wadey, J., Yadav, B.P., Cushman, S.A., 2020. Predicting biodiversity richness in rapidly changing landscapes: climate, low human pressure or protection as salvation? Biodivers Conserv 29, 4035–4057. https://doi.org/10.1007/s10531-020-02062-x

Maiorano, L., Boitani, L., Chiaverini, L., Ciucci, P., 2017. Uncertainties in the identification of potential dispersal corridors: The importance of behaviour, sex, and algorithm. Basic Appl Ecol 21, 66–75. https://doi.org/10.1016/j.baae.2017.02.005

McBride, R.T., Thompson, J.J., 2018. Space use and movement of jaguar (*Panthera onca*) in western Paraguay. Mammalia 82, 540–549. https://doi.org/10.1515/mammalia-2017-0040

McRae, B.H., 2006. Isolation By Resistance. Evolution (N Y) 60, 1551–1561. https://doi.org/10.1554/05-321.1

Meyer, N.F.V., Moreno, R., Sutherland, C., de la Torre, J.A., Esser, H.J., Jordan, C.A., Olmos, M., Ortega, J., Reyna-Hurtado, R., Valdes, S., Jansen, P.A., 2019. Effectiveness of Panama as an intercontinental land bridge for large mammals. Conservation Biology 0, 1–13. https://doi.org/10.1111/cobi.13384

Michalski, F., Boulhosa, R.L.P., Faria, a., Peres, C. a., 2006. Human-wildlife conflicts in a fragmented Amazonian forest landscape: Determinants of large felid depredation on livestock. Anim Conserv 9, 179–188. https://doi.org/10.1111/j.1469-1795.2006.00025.x

Morato, R.G., Ferraz, K.M.P.M.D.B., De Paula, R.C., Campos, C.B. De, 2014. Identification of priority conservation areas and potential corridors for Jaguars in the Caatinga Biome, Brazil. PLoS One 9. https://doi.org/10.1371/journal.pone.0092950

Morato, R.G., Stabach, J.A., Fleming, C.H., Calabrese, J.M., De Paula, R.C., Ferraz, K.M.P.M., Kantek, D.L.Z., Miyazaki, S.S., Pereira, T.D.C., Araujo, G.R., Paviolo, A., De

Angelo, C., Di Bitetti, M.S., Cruz, P., Lima, F., Cullen, L., Sana, D.A., Ramalho, E.E., Carvalho, M.M., Soares, F.H.S., Zimbres, B., Silva, M.X., Moraes, M.D.F., Vogliotti, A., May, J.A., Haberfeld, M., Rampim, L., Sartorello, L., Ribeiro, M.C., Leimgruber, P., 2016. Space use and movement of a neotropical top predator: The endangered jaguar. PLoS One 11, 1–17. https://doi.org/10.1371/journal.pone.0168176

Nathan, R., Getzb, W.M., Revillac, E., Holyoakd, M., Kadmona, R., Saltze, D., Smouse, P.E., 2008. A movement ecology paradigm for unifying organismal movement research. PNAS 105, 19052–19059. https://doi.org/10.4135/9781446215050.n1

Nichols, J.D., Hines, J.E., Lebreton, J.D., Pradel, R., 2000. Estimation of contributions to population growth: A reverse-time capture-recapture approach. Ecology 81, 3362–3376. https://doi.org/10.1890/0012-9658(2000)081[3362:EOCTPG]2.0.CO;2

Ouko, E., Omondi, S., Mugo, R., Wahome, A., Kasera, K., Nkurunziza, E., Kiema, J., Flores, A., Adams, E.C., Kuraru, S., Wambua, M., 2020. Modeling Invasive Plant Species in Kenya's Northern Rangelands. Front Environ Sci 8, 1–10. https://doi.org/10.3389/fenvs.2020.00069

Paviolo, A., De Angelo, C., Ferraz, K.M.P.M.B., Morato, R.G., Martinez Pardo, J., Srbek-Araujo, A.C., Beisiegel, B.D.M., Lima, F., Sana, D., Xavier Da Silva, M., Velázquez, M.C., Cullen, L., Crawshaw, P., Jorge, M.L.S.P., Galetti, P.M., Di Bitetti, M.S., De Paula, R.C., Eizirik, E., Aide, T.M., Cruz, P., Perilli, M.L.L., Souza, A.S.M.C., Quiroga, V., Nakano, E., Ramírez Pinto, F., Fernández, S., Costa, S., Moraes, E.A., Azevedo, F., 2016. A biodiversity hotspot losing its top predator: The challenge of jaguar conservation in the Atlantic Forest of South America. Sci Rep 6. https://doi.org/10.1038/srep37147

Penjor, U., Kaszta, Ż., Macdonald, D.W., Cushman, S.A., 2021. Prioritizing areas for conservation outside the existing protected area network in Bhutan: the use of multi-species,

multi-scale habitat suitability models. Landsc Ecol 36, 1281–1309. https://doi.org/10.1007/s10980-021-01225-7

Petracca, L.S., Frair, J.L., Cohen, J.B., Calderón, A.P., Carazo-Salazar, J., Castañeda, F., Corrales-Gutiérrez, D., Foster, R.J., Harmsen, B., Hernández-Potosme, S., Herrera, L., Olmos, M., Pereira, S., Robinson, H.S., Robinson, N., Salom-Pérez, R., Urbina, Y., Zeller, K.A., Quigley, H., 2018. Robust inference on large-scale species habitat use with interview data: The status of jaguars outside protected areas in Central America. Journal of Applied Ecology 55, 723–734. https://doi.org/10.1111/1365-2664.12972

Petracca, L.S., Hernández-Potosme, S., Obando-Sampson, L., Salom-Pérez, R., Quigley, H., Robinson, H.S., 2014. Agricultural encroachment and lack of enforcement threaten connectivity of range-wide jaguar (*Panthera onca*) corridor. J Nat Conserv 22, 436–444. https://doi.org/10.1016/j.jnc.2014.04.002

Pimm, S.L., Raven, P., 2000. Extiction by numbers. Nature 403, 843–845. https://doi.org/10.1038/35002708

Portugal, M.P., Morato, R.G., Ferraz, K.M.P.M.D.B., Rodrigues, F.H.G., Jacobi, C.M., 2019. Priority areas for jaguar *Panthera onca* conservation in the Cerrado. Oryx 54, 854–865. https://doi.org/10.1017/S0030605318000972

Quigley, H., Foster, R.J., Petracca, L., Payan, E., Salom, R., Harmsen, B.J., 2017. *Panthera onca*. The IUCN Red List of Threatened Species 8235, 8.

Rabinowitz, A., Zeller, K. a., 2010. A range-wide model of landscape connectivity and conservation for the jaguar, *Panthera onca*. Biol Conserv 143, 939–945. https://doi.org/10.1016/j.biocon.2010.01.002

Rabinowitz, A.R., Jr, B.G.N., 1986. Ecology and behaviour of the Jaguar (*Panthera onca*) in Belize, Central America. J Zool 210, 149–159. https://doi.org/10.1111/j.1469-7998.1986.tb03627.x

Ramalho, E.E., Main, M.B., Alvarenga, G.C., Oliveira-Santos, L.G.R., 2021. Walking on water: the unexpected evolution of arboreal lifestyle in a large top predator in the Amazon flooded forests. Ecology 102, 1–4. https://doi.org/10.1002/ecy.3286

Ramirez-Reyes, C., Bateman, B.L., Radeloff, V.C., 2016. Effects of habitat suitability and minimum patch size thresholds on the assessment of landscape connectivity for jaguars in the Sierra Gorda, Mexico. Biol Conserv 204, 296–305. https://doi.org/10.1016/j.biocon.2016.10.020

Rodríguez-Soto, C., Monroy-Vilchis, O., Maiorano, L., Boitani, L., Faller, J.C., Briones, M.Á., Núñez, R., Rosas-Rosas, O., Ceballos, G., Falcucci, A., 2011. Predicting potential distribution of the jaguar (*Panthera onca*) in Mexico: Identification of priority areas for conservation. Divers Distrib 17, 350–361. https://doi.org/10.1111/j.1472-4642.2010.00740.x

Rodríguez-Soto, C., Monroy-Vilchis, O., Zarco-González, M.M., 2013. Corridors for jaguar (*Panthera onca*) in Mexico: conservation strategies. J Nat Conserv 21, 438–443. https://doi.org/10.1016/j.jnc.2013.07.002

Rondinini, C., Boitani, L., 2012. Mind the map: trips and pitfalls in making and reading maps of carnivore distribution, in: Boitani, L., Powell, R.A. (Eds.), Carnivore Ecology and Conservation: A Handbook of Techniques. Oxford University Press, New York, USA, p. 506.

Rosas-Rosas, O.C., Valdez, R., 2010. The Role of Landowners in Jaguar Conservation in Sonora, Mexico. Conservation Biology 1–6. https://doi.org/10.1111/j.1523-1739.2009.01441.x

Rostro-García, S., Tharchen, L., Abade, L., Astaras, C., Cushman, S.A., Macdonald, D.W., 2016. Scale dependence of felid predation risk: identifying predictors of livestock kills by tiger and leopard in Bhutan. Landsc Ecol 31, 1277–1298. https://doi.org/10.1007/s10980-015-0335-9

Salom-Perez, R., Corrales-Gutierrez, D., Araya-Gamboa, D., Espinoza-Muñoz, D., Finegan, B., Petracca, L.S., 2021. Forest cover mediates large and medium-sized mammal occurrence in a critical link of the Mesoamerican Biological Corridor. PLoS One 16, 1–19. https://doi.org/10.1371/journal.pone.0249072

Salom-Pérez, R., Polisar, J., Quigley, H., Zeller, K., 2010. Iniciativa del Corredor del Jaguar: Un Corredor Biológico y un Compromiso a Largo Plazo para la Conservación. Mesoamericana 14 (3), 1–10.

Sanderson, E.W., Fisher, K., Peters, R., Beckmann, J.P., Bird, B., Bradley, C.M., Bravo, J.C., Grigione, M.M., Hatten, J.R., Lopez González, C.A., Menke, K., Miller, J.R.B., Miller, P.S., Mormorunni, C., Robinson, M.J., Thomas, R.E., Wilcox, S., 2022. A systematic review of potential habitat suitability for the jaguar *Panthera onca* in central Arizona and New Mexico, USA. Oryx 56, 116–127. https://doi.org/10.1017/S0030605320000459

Sanderson, E.W., Redford, K.H., Chetkiewicz, C.L.B., Medellin, R. a., Rabinowitz, A.R., Robinson, J.G., Taber, A.B., 2002. Planning to save a species: The jaguar as a model. Conservation Biology 16, 58–72. https://doi.org/10.1046/j.1523-1739.2002.00352.x

Schaller, G.B., Crawshaw, P.G., 1980. Movement Patterns of Jaguar. Biotropica 12, 161–168. https://doi.org/10.2307/2387967

Seymour, K.L., 1989. *Panthera onca*. Mammalian Species 340, 1–9.

Sollmann, R., Torres, N.M., Silveira, L., 2008. Jaguar conservation in Brazil: the role of Protected Areas. CAT News 4, 15–20.

Srbek-Araujo, A.C., Haag, T., Chiarello, A.G., Salzano, F.M., Eizirik, E., 2018. Worrisome isolation: Noninvasive genetic analyses shed light on the critical status of a remnant jaguar population. J Mammal 99, 397–407. https://doi.org/10.1093/jmammal/gyy007

Stoner, K.J., Hardy, A.R., Fisher, K., Sanderson, E.W., 2015. Jaguar habitat connectivity and identification of potential road mitigation locations in the Northwestern Recovery Unit for the Jaguar.

Struebig, M.J., Linkie, M., Deere, N.J., Martyr, D.J., Millyanawati, B., Faulkner, S.C., Le Comber, S.C., Mangunjaya, F.M., Leader-Williams, N., McKay, J.E., St. John, F.A.V., 2018. Addressing human-tiger conflict using socio-ecological information on tolerance and risk. Nat Commun 9, 3455. https://doi.org/10.1038/s41467-018-05983-y

Thompson, J.J., Morato, R.G., Niebuhr, B.B., Alegre, V.B., Oshima, J.E.F., de Barros, A.E., Paviolo, A., de la Torre, J.A., Lima, F., McBride, R.T., Cunha de Paula, R., Cullen, L., Silveira, L., Kantek, D.L.Z., Ramalho, E.E., Maranhão, L., Haberfeld, M., Sana, D.A., Medellin, R.A., Carrillo, E., Montalvo, V.H., Monroy-Vilchis, O., Cruz, P., Jacomo, A.T.A., Alves, G.B., Cassaigne, I., Thompson, R., Sáenz-Bolaños, C., Cruz, J.C., Alfaro, L.D., Hagnauer, I., Xavier da Silva, M., Vogliotti, A., Moraes, M.F.D., Miyazaki, S.S., Araujo, G.R., Cruz da Silva, L., Leuzinger, L., Carvalho, M.M., Rampim, L., Sartorello, L., Quigley, H., Tortato, F.R., Hoogesteijn, R., Crawshaw, P.G., Devlin, A.L., May Júnior, J.A., Powell, G.V.N., Tobler, M.W., Carrillo-Percastegui, S.E., Payán, E., Azevedo, F.C.C., Concone, H.V.B., Quiroga, V.A., Costa, S.A., Arrabal, J.P., Vanderhoeven, E., Di Blanco, Y.E., Lopes, A.M.C., Ribeiro, M.C., 2021. Environmental and anthropogenic factors synergistically affect space use of jaguars. Current Biology 31, 3457-3466.e4. https://doi.org/10.1016/j.cub.2021.06.029

Titus, K.L., Jachowski, D.S., 2025. Mapping human-carnivore coexistence: approaches to integrating anthropogenic influences on carnivore distribution and connectivity modelling. Anim Conserv 28, 185–196. https://doi.org/10.1111/acv.12966

Tôrres, N.M., De Marco, P., Santos, T., Silveira, L., de Almeida Jácomo, A.T., Diniz-Filho, J.A.F., 2012. Can species distribution modelling provide estimates of population

densities? A case study with jaguars in the Neotropics. Divers Distrib 18, 615–627. https://doi.org/10.1111/j.1472-4642.2012.00892.x

Watkins, A., Noble, J., Foster, R.J., Harmsen, B.J., Doncaster, C.P., 2015. A spatially explicit agent-based model of the interactions between jaguar populations and their habitats. Ecol Modell 306, 268–277. https://doi.org/10.1016/j.ecolmodel.2014.10.038

Wultsch, C., Caragiulo, A., Dias-Freedman, I., Quigley, H., Rabinowitz, S., Amato, G., 2016. Genetic diversity and population structure of Mesoamerican jaguars (*Panthera onca*): Implications for conservation and management. PLoS One 11, 1–25. https://doi.org/10.1371/journal.pone.0162377

WWF, WCS, Panthera, UNDP, 2019. Jaguar 2030: Conservation Roadmap for the Americas.

Zanin, M., Palomares, F., Brito, D., 2015. The jaguar's patches: Viability of jaguar populations in fragmented landscapes. J Nat Conserv 23, 90–97. https://doi.org/10.1016/j.jnc.2014.06.003

Zeilhofer, P., Cezar, A., Torres, N.M., Jacomo, A.T.A., Silveira, L., 2014. Jaguar Panthera onca Habitat Modeling in Landscapes Facing High Land-use Transformation Pressure—Findings from Mato Grosso, Brazil. Biotropica 46, 98–105.

Zeller, K., 2007. Jaguars in the new millennium data set update: The state of the jaguar in 2006. Wildlife Conservation Society, Bronx, New York 1–77.

Zeller, K.A., Jennings, M.K., Vickers, T.W., Ernest, H.B., Cushman, S.A., Boyce, W.M., 2018. Are all data types and connectivity models created equal? Validating common connectivity approaches with dispersal data. Divers Distrib 24, 868–879. https://doi.org/10.1111/ddi.12742

Zeller, K.A., McGarigal, K., Cushman, S.A., Beier, P., Vickers, T.W., Boyce, W.M., 2016. Using step and path selection functions for estimating resistance to movement: pumas as a case study. Landsc Ecol 31, 1319–1335. https://doi.org/10.1007/s10980-015-0301-6

Zeller, K.A., McGarigal, K., Whiteley, A.R., 2012. Estimating landscape resistance to movement: A review. Landsc Ecol 27, 777–797. https://doi.org/10.1007/s10980-012-9737-0

Zeller, K.A., Nijhawan, S., Salom-Pérez, R., Potosme, S.H., Hines, J.E., 2011. Integrating occupancy modeling and interview data for corridor identification: A case study for jaguars in Nicaragua. Biol Conserv 144, 892–901. https://doi.org/10.1016/j.biocon.2010.12.003

Zimmermann, A., 2014. Jaguars and people: a range-wide analysis of human-wildlife conflict. University of Oxford.

Zimmermann, A., Johnson, P., de Barros, A.E., Inskip, C., Amit, R., Soto, E.C., Lopez-Gonzalez, C.A., Sillero-Zubiri, C., de Paula, R., Marchini, S., Soto-Shoender, J., Perovic, P.G., Earle, S., Quiroga-Pacheco, C.J., Macdonald, D.W., 2021. Every case is different: Cautionary insights about generalisations in human-wildlife conflict from a range-wide study of people and jaguars. Biol Conserv 260, 109185. https://doi.org/10.1016/j.biocon.2021.109185


Mamirauá Instituto

Chapter 2

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

Guilherme Costa Alvarenga, Mathias W. Tobler, Valeria Boron, Elildo Alves Ribeiro de Carvalho Jr, Ronaldo Gonçalves Morato, Whaldener Endo, Eloisa Neves Mendonça, Ricardo Sampaio, Carlos César Durigan, André Luis Sousa Gonçalves, Emiliano Esterci Ramalho, Juarez Carlos Brito Pezzuti, Milton José de Paula, André Pinassi Antunes, José Luis Mena, Gates Dupont, Wilson Spironello, Jessica Pacheco, Fabiola La Rosa-Camino, Jaime Cabrera, Anelise Montanarin, Marcelo Oliveira da Costa

Published at Biological Conservation
https://doi.org/10.1016/j.biocon.2025.111010

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 each protected area sampled. The estimated average density of jaguars across our sites was 3.08 ± 1.13 individuals per 100 km² but density estimates varied more than 20-fold from 0.60 ± 0.50 ind./100 km² in the Lower Negro River (Cuieiras Biological Reserve) to 9.97 ± 2.48 ind./100 km² 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 6,389 individuals (95% CI: 4,664-7,986), 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.

Keywords

Density estimates; Amazonian rainforest; conservation units; spatial capture-recapture; camera traps

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 1,500 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 km² (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, 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.

Methods

Study area

The Amazon is the largest tropical forest biome in the world, encompassing 8,414,085 km² 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, 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 1,500 m, followed by montane cloud forests that reach a maximum elevation of 3,000 m in the Andes and in the Guiana Shield (Lujan and Armbruster, 2010). Rainfall, the driving force behind the seasonal flood-pulse, is unevenly distributed across the biome, ranging from 1,500 to 3,000 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 (Figure 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).

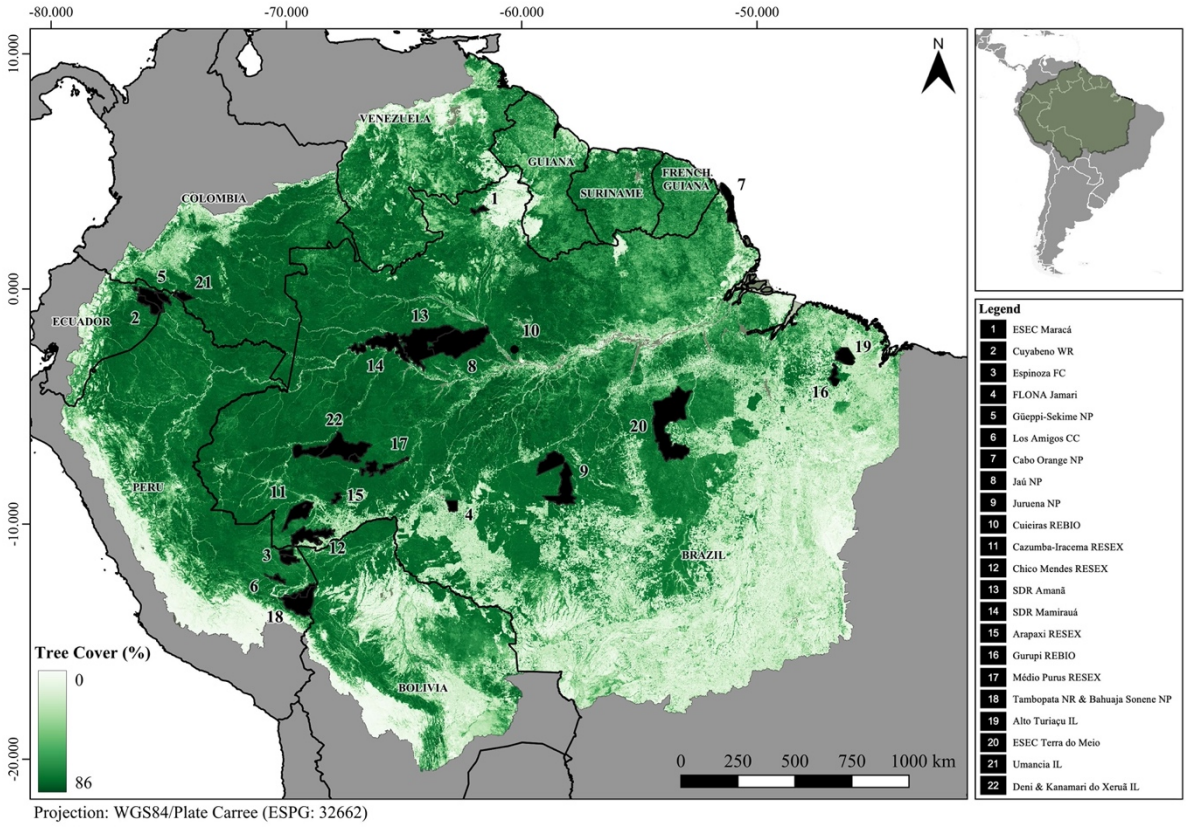


Figure 1 (2-column image). Study area map. The Amazon basis borders (RAISG, 2020) and the distribution of the 22 protected areas sampled. ESEC: Ecological Station; WR: Wildlife Reserve; FC: Forestry Concession; FLONA: National Forest; NP: National Park; CC: Conservation Concession; REBIO: Biological 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).

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: 4,349 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 ± 700 m (± SD; min: 700 m, max: 3300 m) and were set to work continuously for approximately 110 d ± 50 d (± 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).

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 λ0, the detection probability for a camera at the center of a home range. This model introduces a new parameter a0, the "single-detector sampling area", that is defined as $a_0=2\pi\lambda_0 \sigma$ and therefore $\lambda_0=a_0/2\pi\sigma$. Under this formulation, an increase in the movement parameter σ leads to a reduction in λ0, 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 λ0 is automatically adjusted for these changes in σ. However, we can still include a different set of detection covariates for a0 (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 a0 and σ, and we included trap location (on a road, trail or in the forest) as a covariate interacting with sex for a0. 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 ration was the same across all surveys. Furthermore, as we had varying sampling designs, we included single versus paired camera-stations for a0.

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 a0 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 a0 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 a0, 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.

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 unknow 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 a0. 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 (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).

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 ± 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

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~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2. Biome-wide estimates: 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. 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 ± SE (95% LCI - 95% UCI)		River Type[1]	Soil Fertility[2]
	Site-independent model	Biome-wide model		
Alto Turiaçu IL	2.30 ± 0.63 (1.36-3.91)	3.06 ± 0.38 (2.40-3.90)	-	Poor
Arapaxi RESEX	1.61 ± 0.72 (0.70-3.73)	2.53 ± 0.23 (2.12-3.02)	White	Intermediate
Cabo Orange NP	3.22 ± 1.41 (1.41-7.31)	4.30 ± 0.62 (3.24-5.70)	-	Rich
Cazumbá-Iracema RESEX	2.00 ± 0.73 (1.00-4.00)	2.57 ± 0.23 (2.16-3.06)	White	Intermediate
Chico Mendes RESEX	2.92 ± 1.30 (1.27-6.72)	2.31 ± 0.30 (1.79-2.97)	White	Intermediate
Cuieiras REBIO 2018	1.09 ± 0.91 (0.26-4.52)	2.57 ± 0.26 (2.10-3.14)	Black	Poor
Cuieiras REBIO 2019a	1.73 ± 1.13 (0.54-5.58)	2.57 ± 0.26 (2.10-3.14)	Black	Poor
Cuieiras REBIO 2019b	3.70 ± 1.68 (1.58-8.66)	2.57 ± 0.26 (2.10-3.14)	Black	Poor
Cuieiras REBIO 2020	0.60 ± 0.50 (0.14-2.51)	2.57 ± 0.26 (2.10-3.14)	Black	Poor
Cuyabeno WR 2017-2018	2.68 ± 1.06 (1.27-5.67)	3.74 ± 0.42 (3.01-4.65)	White	Intermediate
Cuyabeno WR 2018	2.59 ± 1.12 (1.15-5.82)	3.85 ± 0.42 (3.10-4.78)	White	Intermediate

Cuyabeno WR 2019	3.55 ± 1.07 (2.00-6.31)	3.69 ± 0.41 (2.98-4.58)	White	Intermediate
Deni & Kanamari do Xeruã IL	2.39 ± 0.61 (1.46-3.91)	2.84 ± 0.23 (2.43-3.32)	White	Intermediate
ESEC Maracá	2.58 ± 0.75 (1.48-4.49)	1.74 ± 0.34 (1.20-2.53)	Clear	Poor
ESEC Terra do Meio 2016	2.74 ± 1.33 (1.12-6.73)	2.82 ± 0.32 (2.26-3.52)	Clear	Poor
ESEC Terra do Meio 2017	4.39 ± 1.67 (2.13-9.04)	2.82 ± 0.32 (2.26-3.53)	Clear	Poor
Espinoza FC 2009-2010	3.61 ± 0.70 (2.48-5.26)	2.81 ± 0.26 (2.34-3.37)	White	Rich
Espinoza FC 2014	3.17 ± 0.51 (2.32-4.33)	2.69 ± 0.26 (2.23-3.24)	White	Rich
FLONA Jamari 2016	1.75 ± 1.44 (0.43-7.15)	1.98 ± 0.37 (1.38-2.84)	-	Poor
FLONA Jamari 2017	1.27 ± 0.70 (0.46-3.48)	1.98 ± 0.36 (1.38-2.83)	-	Poor
FLONA Jamari 2018	3.08 ± 1.3 (1.40-6.80)	1.98 ± 0.36 (1.39-2.83)	-	Poor
FLONA Jamari 2019	1.97 ± 0.97 (0.80-4.89)	2.00 ± 0.36 (1.41-2.85)	-	Poor
Güeppi-Sekime NP 2017-2018	2.57 ± 0.78 (1.44-4.60)	3.36 ± 0.34 (2.77-4.09)	White	Rich
Güeppi-Sekime NP 2019	2.88 ± 1.01 (1.48-5.61)	3.40 ± 0.34 (2.80-4.14)	White	Rich
Gurupi REBIO	2.82 ± 0.74 (1.71-4.67)	3.00 ± 0.41 (2.29-3.92)	-	Poor
Jaú NP 2016-2017a	0.64 ± 0.52 (0.16-2.59)	2.53 ± 0.34 (1.95-3.28)	Black	Intermediate
Jaú NP 2016-2017b	1.51 ± 0.83 (0.55-4.14)	2.53 ± 0.34 (1.95-3.28)	Black	Intermediate
Juruena NP	3.26 ± 1.10 (1.71-6.20)	2.57 ± 0.27 (2.10-3.15)	Clear	Poor
Los Amigos 2005	4.61 ± 1.55 (2.43-8.76)	3.73 ± 0.54 (2.81-4.94)	-	Rich
Los Amigos 2006	3.94 ± 1.32 (2.08-7.46)	3.73 ± 0.54 (2.81-4.95)	-	Rich
Los Amigos 2007	3.72 ± 1.18 (2.02-6.83)	3.73 ± 0.54 (2.81-4.95)	-	Rich
Los Amigos CC 2010	5.21 ± 1.62 (2.88-9.45)	3.30 ± 0.47 (2.50-4.35)	-	Rich
Médio Purus RESEX	3.23 ± 1.08 (1.71-6.12)	2.94 ± 0.23 (2.52-3.43)	White	Intermediate
SDR Amanã 2013	7.11 ± 2.72 (3.44-14.68)	3.32 ± 0.45 (2.55-4.32)	White	Intermediate
SDR Amanã 2013-2014	3.22 ± 1.39 (1.43-7.26)	3.32 ± 0.45 (2.55-4.32)	White	Intermediate
SDR Mamirauá 2013	7.90 ± 2.18 (4.64-13.45)	3.93 ± 0.46 (3.14-4.93)	White	Rich
SDR Mamirauá 2014	9.97 ± 2.48 (6.17-16.11)	3.93 ± 0.46 (3.14-4.93)	White	Rich
Tambopata NR & Bahuaja Sonene NP	1.82 ± 0.73 (0.85-3.89)	3.13 ± 0.33 (2.55-3.85)	-	Rich
Umancia IL 2018	1.87 ± 0.81 (0.83-4.21)	3.66 ± 0.34 (3.06-4.37)	White	Intermediate
Umancia IL 2019	2.16 ± 1.03 (0.89-5.26)	3.67 ± 0.34 (3.07-4.40)	White	Intermediate

[1] Junk et al., 2011; [2] EMBRAPA, 1966; Quesada et al., 2011.

Once covariates that most influenced σ and a0 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 7,050 individuals (95% CI: 3,615-14,140) when the site-independent model was applied, while 6,389 jaguars (95% CI: 4,664-7,986) 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 1,204, 1,191 and 1,180 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 Xeruã 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 4,873 jaguars for the 22 areas.

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~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_GPP2021_mean pmix~h2. Biome-wide estimates: 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. 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 (km²)		Major Habitats
	Independent estimates	Biome-wide estimates	PA	Grid	
Alto Turiaçu IL	122 (72-207)	162 (20-207)	5,295	293	Terra Firme
Arapaxi RESEX	22 (9-50)	34 (28-40)	1,337	1,001	Terra Firme & Várzea
Cabo Orange NP	138 (60-313)	184 (139-244)	4,281[2]	226	Mangroves & Restinga
Cazumba-Iracema RESEX	151 (76-302)	194 (163-231)	7,554	1,296	Terra Firme & Várzea
Chico Mendes RESEX	272 (118-626)	215 (167-277)	9,315	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 Xeruã IL[1]	545 (333-892)	648 (554-757)	22,808	1,813	Terra Firme & Várzea
ESEC Maracá	40 (23-69)	27 (19-39)	1,542	164	Terra Firme
ESEC Terra do Meio	1,204 (550-2,661)	951 (762-1,191)	33,732	192	Terra Firme
Espinoza FC	151 (107-214)	123 (105-148)	4,464	864	Terra Firme
FLONA Jamari	45 (17-124)	44 (31-63)	2,222	662	Terra Firme
Güeppi-Sekime NP	56 (30-104)	69 (57-84)	2,038	312	Terra Firme & Várzea
Gurupi REBIO	77 (46-127)	81 (62-106)	2,712	1,546	Terra Firme
Jaú NP	256 (85-798)	599 (462-777)	23,673	429	Terra Firme & Campinarana
Juruena NP	638 (335-1,213)	503 (411-617)	19,570	432	Terra Firme & Savannah

Los Amigos CC	64 (34-119)	53 (40-70)	1,457	196	Terra Firme & Várzea
Médio Purus RESEX	194 (103-368)	177 (151-206)	6,006	4,347	Terra Firme & Várzea
SDR Amanã	1,191 (562-2,527)	765 (587-995)	23,035	135	Terra Firme
SDR Mamirauá	1,180 (714-1,951)	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)	2,595	145	Terra Firme & Várzea
TOTAL	**7,050 (3,615-14,140)**	**6,389 (4,664-7,986)**	**214,392**	**14,671**	**-**

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 a0 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 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 ± 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 a0 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 6,389 jaguars (95% CI: 4,664 -7,986) 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 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 4,873 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 analysed 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.

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.

Acknowledgements

GCA doctorate is supported by a grant to David Macdonald at WildCRU from the Robertson Foundation. We thank Instituto Chico Mendes de Biodiversidade (ICMBio), notably the protected area managers and staff who supported the field work. Work at Gurupi, Jamari, Juruena, and Terra do Meio study areas in Brazil was financed by Programa ARPA and conducted as part of the National Biodiversity Monitoring Program of the ICMBio (Programa Monitora ICMBio). We are grateful for the collaboration between World Conservation Society (WCS), The Mamirauá Institute for Sustainable Development (MISD), the World Wide Fund for Nature (WWF), and the National Institute of Amazonian Research (INPA).

Funding for work in Peru came from the Gordon and Betty Moore Foundation, the Blue Moon Foundation and was carried out in collaboration between San Diego Zoo Wildlife Alliance, the Botanical Research Institute of Texas and WWF. We thank all institutions that were directly or indirectly involved with the data collection and sharing that enabled this study.

References

Alvarenga, G.C., Chiaverini, L., Cushman, S.A., Dröge, E., Macdonald, D.W., Kantek, D.L.Z., Morato, R.G., Thompson, J.J., Oscar, R.B.L.M., Abade, L., Azevedo, F.C.C. de, Ramalho, E.E., Kaszta, Ż., 2021. Multi-scale path-level analysis of jaguar habitat use in the Pantanal ecosystem. Biol Conserv 253. https://doi.org/10.1016/j.biocon.2020.108900

Alvarenga, G.C., Ramalho, E.E., Baccaro, B.F., Rocha, D.G. da, Ferreira-Ferreira, J., Bobrowiec, P.E.D., 2018. Spatial patterns of medium and large size mammal assemblages in várzea and terra firme forests, Central Amazonia, Brazil. PLoS One 13, e0198120. https://doi.org/https://doi.org/10.1371/journal.pone.0198120

Amatulli, G., McInerney, D., Sethi, T., Strobl, P., Domisch, S., 2020. Geomorpho90m, empirical evaluation and accuracy assessment of global high-resolution geomorphometric layers. Sci Data 7, 1–18. https://doi.org/10.1038/s41597-020-0479-6

Antunes, A.P., Fewster, R.M., Venticinque, E.M., Peres, C.A., Levi, T., Rohe, F., Shepard, G.H., 2016. Empty forest or empty rivers? A century of commercial hunting in Amazonia. Sci Adv 2, e1600936.

Arias, M., 2021. The Illegal Trade in Jaguars (*Panthera onca*).

Asner, G.P., Tupayachi, R., 2017. Accelerated losses of protected forests from gold mining in the Peruvian Amazon. Environmental Research Letters 12, 094004. https://doi.org/10.1088/1748-9326/aa7dab

Assis, R.L. de, Wittmann, F., 2011. Forest structure and tree species composition of the understory of two central Amazonian várzea forests of contrasting flood heights. Flora: Morphology, Distribution, Functional Ecology of Plants 206, 251–260. https://doi.org/10.1016/j.flora.2010.11.002

Ayala, G., Viscarra, M.E., Fonseca, C., Wallace, R.B., 2022. Estimates of jaguar (*Panthera onca*) population density in the South American Greater Madidi- Tambopata

Landscape. Revista de Ciencias Ambientales (Tropical Journal of Environmental Sciences) 56, 1–16.

Benítez-López, A., Alkemade, R., Schipper, A.M., Ingram, D.J., Verweij, P.A., Eikelboom, J.A.J., Huijbregts, M.A.J., 2017. The impact of hunting on tropical mammal and bird populations. Science (1979) 356, 180–183. https://doi.org/10.1126/science.aaj1891

Berzins, R., Hallet, M.T., Paemelaere, E.A.D., Cromwell, L., Ouboter, P., Kadoso, V., Ramalho, E.E., Morato, R.G., Jędrzejewski, W., 2023. Distribution and status of the jaguar in the Guiana shield. Cat News Special Issue 1–22.

Bogoni, J.A., Boron, V., Peres, C.A., Coelho, M., Morato, R.G., Oliveira-da-Costa, M., 2023. Impending anthropogenic threats and protected area prioritization for jaguars in the Brazilian Amazon. Commun Biol 1–11. https://doi.org/10.1038/s42003-023-04490-1

Boron, V., Tzanopoulos, J., Gallo, J., Barragan, J., Jaimes-Rodriguez, L., Schaller, G., Payán, E., 2016. Jaguar Densities across Human-Dominated Landscapes in Colombia: The Contribution of Unprotected Areas to Long Term Conservation. PLoS One 11, e0153973. https://doi.org/10.1371/journal.pone.0153973

Ceballos, G., Zarza, H., González-Maya, J.F., de la Torre, J.A., Arias-Alzate, A., Alcerreca, C., Barcenas, H. V., Carreón-Arroyo, G., Chávez, C., Cruz, C., Medellín, D., García, A., Antonio-García, M., Lazcano-Barrero, M.A., Medellín, R.A., Moctezuma-Orozco, O., Ruiz, F., Rubio, Y., Luja, V.H., Torres-Romero, E.J., 2021. Beyond words: From jaguar population trends to conservation and public policy in Mexico. PLoS One 16, 1–22. https://doi.org/10.1371/journal.pone.0255555

Charity, S., Ferreira, J.M., 2020. Wildlife trafficking in Brazil, TRAFFIC International. Cambridge, UK.

Clement, C.R., Denevan, W.M., Heckenberger, M.J., Junqueira, A.B., Neves, E.G., Teixeira, W.G., Woods, W.I., 2015. The domestication of Amazonia before European conquest. Proceedings Royal Society B 282, 20150813.

de Azevedo, F.C.C., Pasa, J.B., Arrais, R.C., Massara, R.L., Widmer, C.E., 2022. Density and habitat use of one of the last jaguar populations of the Brazilian Atlantic Forest: Is there still hope? Ecol Evol 12, 1–15. https://doi.org/10.1002/ece3.8487

de la Torre, A.J., González-Maya, J.F., Zarza, H., Ceballos, G., Medellín, R.A., 2018. The jaguar's spots are darker than they appear: Assessing the global conservation status of the jaguar Panthera onca. Oryx 52, 300–315. https://doi.org/10.1017/S0030605316001046

Didan, K., 2021. MODIS/Terra Vegetation Indices 16-Day L3 Global 500m SIN Grid V061. NASA EOSDIS Land Processes DAAC. URL https://doi.org/10.5067/MODIS/MOD13A1.061. (accessed 10.27.22).

Duarte, H.O.B., Boron, V., Carvalho, W.D., De Toledo, J.J., 2021. Amazon islands as predator refugia: jaguar density and temporal activity in Maracá-Jipioca. J Mammal 1–7. https://doi.org/10.1093/jmammal/gyab142

Efford, M., 2023. secr 4.5 - spatially explicit capture-recapture in R.

Efford, M., 2004. Density estimation in live-trapping studies. Oikos 106, 598–610.

Efford, M.G., Mowat, G., 2014. Compensatory heterogeneity in spatially explicit capture-recapture data. Ecology 95, 1341–1348. https://doi.org/10.1890/13-1497.1

El Bizri, H.R., Morcatty, T.Q., Ferreira, J.C., Mayor, P., Vasconcelos Neto, C.F.A., Valsecchi, J., Nijman, V., Fa, J.E., 2020. Social and Biological Correlates of Wild Meat Consumption and Trade by Rural Communities in the Jutaí River Basin, Central Amazonia. J Ethnobiol 40, 183–201. https://doi.org/10.2993/0278-0771-40.2.183

EMBRAPA, 1966. Mapa esquemático de solos: regiões Norte, Meio-Norte e Centro-Oeste do Brasil.pdf. Rio de Janeiro, Brazil.

Eriksson, C.E., Kantek, D.L.Z., Miyazaki, S.S., Morato, R.G., dos Santos-Filho, M., Ruprecht, J.S., Peres, C.A., Levi, T., 2021. Extensive aquatic subsidies lead to territorial breakdown and high density of an apex predator. Ecology e03543. https://doi.org/10.1002/ecy.3543

Espinosa, S., de la Torre, J.A., Lara, A., Morato, R.G., Paviolo, A., 2022. The Jaguar: Hope for a Brighter Future in the Americas, Imperilled: The Encyclopedia of Conservation. Elsevier Inc. https://doi.org/10.1016/b978-0-12-821139-7.00244-0

Fearnside, P.M., 2005. Deforestation in Brazilian Amazonia: history, rates, and consequences. Conservation Biology 19, 680–688.

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C., Nobre, C.A., Oliveira, R.S., Borma, L.S., Nian, D., Boers, N., Hecht, S., ter Steege, H., Arieira, J., Lucas, I., Berenguer, E., Marengo, J., Gatti, L., Mattos, C., Hirota, M., 2024. Critical transitions in the Amazon forest system. Nature 626, 555–564. https://doi.org/10.1038/s41586-023-06970-0

Foster, R.J., Harmsen, B.J., Doncaster, C.P., 2010. Habitat use by sympatric jaguars and pumas across a gradient of human disturbance in Belize. Biotropica 42, 724–731. https://doi.org/10.1111/j.1744-7429.2010.00641.x

Foster, R.J., Harmsen, B.J., Urbina, Y.L., Wooldridge, R.L., Doncaster, C.P., Quigley, H., Figueroa, O.A., 2020. Jaguar (*Panthera onca*) density and tenure in a critical biological corridor. J Mammal 101, 1622–1637. https://doi.org/10.1093/jmammal/gyaa134

FVA; IBAMA, 1998. Plano de Manejo do Parque Nacional do Jaú.

Gonçalves, A.L.S., de Oliveira, T.G., Arévalo-Sandi, A.R., Canto, L. V., Yabe, T., Spironello, W.R., 2022. Composition of terrestrial mammal assemblages and their habitat use in unflooded and flooded blackwater forests in the Central Amazon. PeerJ 10. https://doi.org/10.7717/peerj.14374

Green, A.M., Chynoweth, M.W., Şekercioğlu, Ç.H., 2020. Spatially Explicit Capture-Recapture Through Camera Trapping: A Review of Benchmark Analyses for Wildlife Density Estimation. Front Ecol Evol 8. https://doi.org/10.3389/fevo.2020.563477

Grossman, D., 2024. A River in Flux. Science (1979) 383, 692–697. https://doi.org/10.1126/science.ado6281

Hansen, M.C.C., Potapov, P. V, Moore, R., Hancher, M., Turubanova, S.A. a, Tyukavina, A., Thau, D., Stehman, S.V. V, Goetz, S.J.J., Loveland, T.R.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O.O., Townshend, J.R.G.R.G., Patapov, P.V., Moore, R., Hancher, M., Turubanova, S.A. a, Tyukavina, A., Thau, D., Stehman, S.V. V, Goetz, S.J.J., Loveland, T.R.R., Kommaredy, A., Egorov, A., Chini, L., Justice, C.O.O., Townshend, J.R.G.R.G., 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science (1979) 342, 850–854. https://doi.org/10.1126/science.1244693

Harmsen, B.J., Foster, R.J., Sanchez, E., Gutierrez-González, C.E., Silver, S.C., Ostro, L.E.T., Kelly, M.J., Kay, E., Quigley, H., 2017. Long term monitoring of jaguars in the Cockscomb Basin Wildlife Sanctuary, Belize; Implications for camera trap studies of carnivores. PLoS One 12, 1–19. https://doi.org/10.1371/journal.pone.0179505

Herrera, D., Pfaff, A., Robalino, J., 2019. Impacts of protected areas vary with the level of government: Comparing avoided deforestation across agencies in the Brazilian Amazon. Proc Natl Acad Sci U S A 116, 14916–14925. https://doi.org/10.1073/pnas.1802877116

Hidalgo, V.B., Dargent, E., 2020. State Responses to the Gold Rush in the Andes (2004–2018): The Politics of State Action (and Inaction). Stud Comp Int Dev 55, 516–537. https://doi.org/10.1007/s12116-020-09314-5

INPE, 2024. Programa Queimadas. Instituto Nacional de Pesquisas Espaciais. URL https://terrabrasilis.dpi.inpe.br/queimadas/situacao-atual/situacao_atual/ (accessed 9.7.24).

INPE, 2022. Monitoramento do Desmatamento da Floresta Amazônica Brasileira por Satélite. URL http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes

IUCN, 2010. 50 Years of Working for Protected Areas A brief history of IUCN World Commission on Protected Areas 23.

IUCN NL, 2020. Unveiling the criminal networks behind jaguar trafficking in Bolivia. Amsterdam.

Jędrzejewski, W., Maffei, L., Espinosa, S., Wallace, R.B., Negrões, N., Morato, R.G., Tobler, M., Crespo, G.M.A., Ramalho, E.E., Payán, E., Hoogesteinjn, R., Gozalez-Maya, J.F., Viscarra, M., Ferraz, K.M.P.M., Portugal, M.P., Romero, A.P., Polisar, J., Breitenmoser, C., Breitenmoser, U., 2023a. Jaguar conservation status in north-western South America. Cat News Special Issue 1–34.

Jędrzejewski, W., Morato, R.G.;, Negrões, N.;, Wallace, R.B.;, Paviolo, A.;, De Angelo, C.;, Thompson, J.J.;, Paemelaere, E., Hallett, M.T.;, Berzins, R.;, Tortato, F.;, Espinosa, S.;, Payán, E.;, Romero, A.P.;, Ouboter, P.E.;, Kadosoe, V.;, Quiroga, V.A.;, Tobler, M.;, Ferraz, K.M.P.M.;, Portugal, M.P.;, Viscarra, M.;, Crespo, G.M.A.;, Cruz, P.;, Ramalho, E.E.;, Maffei, L.;, Robinson, N.;, Breitenmoser, U.;, Breitenmoser, C.;, Polisar, J.;, Quigler, H.;, Hoogesteinjn, R.;, Guerra, N.;, Barboza, K.;, Cromwell, L.;, Gonzáles-Maya, J.F.;, Johnson, S.;, Velásquez, G., Vivas, I.;, Abarca, M., 2023b. Estimating species distribution changes due to human impacts: the 2020's status of the jaguar in South America. CATnews Special Issue 44–55.

Jędrzejewski, W., Puerto, M.F., Goldberg, J.F., Hebblewhite, M., Abarca, M., Gamarra, G., Calderón, L.E., Romero, J.F., Viloria, Á.L., Carreño, R., Robinson, H.S., Lampo, M., Boede, E.O., Biganzoli, A., Stachowicz, I., Velásquez, G., Schmidt, K., 2017. Density and population structure of the jaguar (*Panthera onca*) in a protected area of Los Llanos,

Venezuela, from 1 year of camera trap monitoring. Mamm Res 62, 9–19. https://doi.org/10.1007/s13364-016-0300-2

Jędrzejewski, W., Robinson, H.S., Abarca, M., Zeller, K.A., Velasquez, G., Paemelaere, E.A.D., Goldberg, J.F., Payan, E., Hoogesteijn, R., Boede, E.O., Schmidt, K., Lampo, M., Viloria, Á.L., Carreño, R., Robinson, N., Lukacs, P.M., Nowak, J.J., Salom-Pérez, R., Castañeda, F., Boron, V., Quigley, H., 2018. Estimating large carnivore populations at global scale based on spatial predictions of density and distribution - Application to the jaguar (*Panthera onca*). PLoS One 13, 1–25. https://doi.org/10.1371/journal.pone.0194719

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river-floodplain systems. Canadian special publication of fisheries and aquatic sciences 106, 110–127. https://doi.org/10.1371/journal.pone.0028909

Junk, W.J., Piedade, M.T.F., Schöngart, J., Cohn-Haft, M., Adeney, J.M., Wittmann, F., 2011. A classification of major naturally-occurring amazonian lowland wetlands. Wetlands 31, 623–640. https://doi.org/10.1007/s13157-011-0190-7

Junk, W.J., Wittmann, F., Schöngart, J., Piedade, M.T.F., 2015. A classification of the major habitats of Amazonian black-water river floodplains and a comparison with their white-water counterparts. Wetl Ecol Manag 23, 677–693. https://doi.org/10.1007/s11273-015-9412-8

Karanth, K.U., 1998. Estimation of Tiger Densites in India using photographic captures and recapture. Ecology 79(8), 2852–2862. https://doi.org/10.1890/0012-9658(1998)079[2852:EOTDII]2.0.CO;2

Karanth, K.U., Nichols, J.D., Kumar, N.S., Link, W.A., Hines, J.E., 2004. Tigers and their prey: Predicting carnivore densities from prey abundance. Proc Natl Acad Sci U S A 101, 4854–4858. https://doi.org/10.1073/pnas.0306210101

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, P., Kessler, M., 2017. Climatologies at high resolution for the Earth land surface areas. Sci Data 4, 170122. https://doi.org/10.1038/sdata.2017.122

Kennedy, C.M., Oakleaf, J.R., Theobald, D.M., Baurch-Murdo, S., Kiesecker., J., 2019. Managing the middle: A shift in conservation priorities based on the global human modification gradient. Glob Chang Biol 00, 1–16. https://doi.org/10.1111/gcb.14549

Khamila, C.N., Groen, T.A., Toxopeus, A.G., Santini, L., Neumann, M., Van Swaay, C., Van Swaay, H., 2023. There is a trade-off between forest productivity and animal biodiversity in Europe. Biodivers Conserv 32, 1879–1899. https://doi.org/10.1007/s10531-023-02582-2

Lapola, D.M., Pinho, P., Barlow, J., Aragão, L.E.O.C., Berenguer, E., Carmenta, R., Liddy, H.M., Seixas, H., Silva, C.V.J., Silva-Junior, C.H.L., Alencar, A.A.C., Anderson, L.O., Armenteras, D., Brovkin, V., Calders, K., Chambers, J., Chini, L., Costa, M.H., Faria, B.L., Fearnside, P.M., Ferreira, J., Gatti, L., Gutierrez-Velez, V.H., Han, Z., Hibbard, K., Koven, C., Lawrence, P., Pongratz, J., Portela, B.T.T., Rounsevell, M., Ruane, A.C., Schaldach, R., da Silva, S.S., von Randow, C., Walker, W.S., 2023. The drivers and impacts of Amazon forest degradation. Science (1979) 379. https://doi.org/10.1126/science.abp8622

Lujan, Armbruster, 2010. The Guiana Shield, in: Historical Biogeography of Neotropical Freshwater Fishes. pp. 211–225.

Machado, M.S., Berenguer, E., Brando, P.M., Alencar, A., Menor, I.O., Barlow, J., Malhi, Y., 2024. Emergency policies are not enough to resolve Amazonia' s fire crises. Nature Communications Earth & Environment 5, 1–5. https://doi.org/10.1038/s43247-024-01344-4

Malhi, Y., Baker, T.R., Phillips, O.L., Almeida, S., Alvarez, E., Arroyo, L., Chave, J., Czimczik, C.I., Di Fiore, A., Higuchi, N., Killeen, T.J., Laurance, S.G., Laurance, W.F.,

Lewis, S.L., Montoya, L.M.M., Monteagudo, A., Neill, D.A., Vargas, P.N., Patino, S., Pitman, N.C.A., Quesada, C.A., Salomao, R., Silva, J.N.M., Lezama, A.T., Martínez, R.V., Terborgh, J., Vinceti, B., Lloyd, J., 2004. The above-ground coarse wood productivity of 104 Neotropical forest plots. Glob Chang Biol 10, 563–591. https://doi.org/10.1111/j.1529-8817.2003.00778.x

Melack, J.M., Hess, L.L., 2010. Remote Sensing of the Distribution and Extent of Wetlands in the Amazon Basin, in: Junk, W.J., Piedade, M.T.F., Wittmann, F., Schöngart, J., Parolin, P. (Eds.), Amazonian Floodplain Forests: Ecophysiology, Biodiversity and Sustainable Management, Ecological Studies. Springer, New York: Berlin-Heidelberg, pp. 43–59. https://doi.org/10.1007/978-90-481-8725-6

Mena, J.L., Yagui, H., Tejeda, V., Cabrera, J., Pacheco-Esquivel, J., Rivero, J., Pastor, P., 2020. Abundance of jaguars and occupancy of medium- and large-sized vertebrates in a transboundary conservation landscape in the northwestern Amazon. Glob Ecol Conserv 23, e01079. https://doi.org/10.1016/j.gecco.2020.e01079

Menezes, J.F.S., Tortato, F.R., Oliveira-Santos, L.G.R., Roque, F.O., Morato, R.G., 2021. Deforestation, fires, and lack of governance are displacing thousands of jaguars in Brazilian Amazon. Conserv Sci Pract 3, 1–10. https://doi.org/10.1111/csp2.477

Morato, R.G., Connette, G.M., Stabach, J.A., De Paula, R.C., Ferraz, K.M.P.M., Kantek, D.L.Z., Miyazaki, S.S., Pereira, T.D.C., Silva, L.C., Paviolo, A., De Angelo, C., Di Bitetti, M.S., Cruz, P., Lima, F., Cullen, L., Sana, D.A., Ramalho, E.E., Carvalho, M.M., da Silva, M.X., Moraes, M.D.F., Vogliotti, A., May Jr., J.A., Haberfeld, M., Rampim, L., Sartorello, L., Araujo, G.R., Wittemyer, G., Ribeiro, M.C., Leimgruber, P., 2018. Resource selection in an apex predator and variation in response to local landscape characteristics. Biol Conserv 228, 233–240. https://doi.org/10.1016/j.biocon.2018.10.022

Morato, R.G., Stabach, J.A., Fleming, C.H., Calabrese, J.M., De Paula, R.C., Ferraz, K.M.P.M., Kantek, D.L.Z., Miyazaki, S.S., Pereira, T.D.C., Araujo, G.R., Paviolo, A., De Angelo, C., Di Bitetti, M.S., Cruz, P., Lima, F., Cullen, L., Sana, D.A., Ramalho, E.E., Carvalho, M.M., Soares, F.H.S., Zimbres, B., Silva, M.X., Moraes, M.D.F., Vogliotti, A., May, J.A., Haberfeld, M., Rampim, L., Sartorello, L., Ribeiro, M.C., Leimgruber, P., 2016. Space use and movement of a neotropical top predator: The endangered jaguar. PLoS One 11, 1–17. https://doi.org/10.1371/journal.pone.0168176

Morcatty, T.Q., Bausch Macedo, J.C., Nekaris, K.A.I., Ni, Q., Durigan, C.C., Svensson, M.S., Nijman, V., 2020. Illegal trade in wild cats and its link to Chinese-led development in Central and South America. Conservation Biology 34, 1525–1535. https://doi.org/10.1111/cobi.13498

Moutinho, P., Azevedo-Ramos, C., 2023. Untitled public forestlands threat Amazon conservation. Nat Commun 14, 1152. https://doi.org/10.1038/s41467-023-36427-x

Paviolo, A., De Angelo, C., Ferraz, K.M.P.M.B., Morato, R.G., Martinez Pardo, J., Srbek-Araujo, A.C., Beisiegel, B.D.M., Lima, F., Sana, D., Xavier Da Silva, M., Velázquez, M.C., Cullen, L., Crawshaw, P., Jorge, M.L.S.P., Galetti, P.M., Di Bitetti, M.S., De Paula, R.C., Eizirik, E., Aide, T.M., Cruz, P., Perilli, M.L.L., Souza, A.S.M.C., Quiroga, V., Nakano, E., Ramírez Pinto, F., Fernández, S., Costa, S., Moraes, E.A., Azevedo, F., 2016. A biodiversity hotspot losing its top predator: The challenge of jaguar conservation in the Atlantic Forest of South America. Sci Rep 6, 1–16. https://doi.org/10.1038/srep37147

Pessôa, A.C.M., Morello, T.F.R.S., Silva-Junior, C.H.L., Doblas, J., Carvalho, N.S., Aragão, L.E.O.C., Anderson, L.O., 2023. Protected areas are effective on curbing fires in the Amazon. Ecological Economics 214, 107983. https://doi.org/10.1016/j.ecolecon.2023.107983

Polisar, J., Davies, C., Morcatty, T., Da Silva, M., Zhang, S., Duchez, K., Madrid, J., Lambert, A.E., Gallegos, A., Delgado, M., Nguyen, H., Wallace, R., Arias, M., Nijman, V., Ramnarace, J., Pennell, R., Novelo, Y., Rumiz, D., Rivero, K., Murillo, Y., Salas, M.N., Kretser, H.E., Reuter, A., 2023. Multi-lingual multi-platform investigations of online trade in jaguar parts. PLoS One 18, e0280039. https://doi.org/10.1371/journal.pone.0280039

Qin, Y., Xiao, X., Liu, F., de Sa e Silva, F., Shimabukuro, Y., Arai, E., Fearnside, P.M., 2023. Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. Nat Sustain. https://doi.org/10.1038/s41893-022-01018-z

Quesada, C.A., Lloyd, J., Anderson, L.O., Fyllas, N.M., Schwarz, M., Czimczik, C.I., 2011. Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences 8, 1415–1440. https://doi.org/10.5194/bg-8-1415-2011

Quigley, H., Foster, R.J., Petracca, L., Payan, E., Salom, R., Harmsen, B.J., 2017. Pantera onca. The IUCN Red List of Threatened Species 8235, 8.

RAISG, 2020. Amazonía: límite utilizado por RAISG. Rede Amazónica de Información Socioambiental Georreferenciada. URL https://www.amazoniasocioambiental.org/en/maps/.

Ramalho, E.E., 2012. Jaguar (*Panthera onca*) population dynamics, feeding ecology, human induced mortality, and conservation in the Várzea Floodplain Forests of Amazonia.

Romero-Muñoz, A., Torres, R., Noss, A.J., Giordano, A.J., Quiroga, V., Thompson, J.J., Baumann, M., Altrichter, M., McBride, R., Velilla, M., Arispe, R., Kuemmerle, T., 2019. Habitat loss and overhunting synergistically drive the extirpation of jaguars from the Gran Chaco. Divers Distrib 25, 176–190. https://doi.org/10.1111/ddi.12843

Running, S., Mu, Q., Zhao, M., 2015. MOD17A2H MODIS/Terra Gross Primary Productivity 8-Day L4 Global 500m SIN Grid V006. NASA EOSDIS Land Processes DAAC. URL https://doi.org/10.5067/MODIS/MOD17A2H.006. (accessed 10.27.22).

Running, S., Nemani, R.R., Heinsch, F., Zhao, M., Reeves, M., Hashimoto, H., 2004. Determining the Spatial Scale of Species' Determining the Spatial Scale of Species' Response to Habitat. Bioscience 54, 547–560. https://doi.org/10.1641/0006-3568(2004)054

Salati, E., Dourojeanni, M.J., Mundim, A., Sampaio, G., Lovejoy, T., 2012. The Brazilian Amazon, in: Jody A. Hilty, Charles C. Chester, M.S.C. (Ed.), Climate and Conservation. Island Press/Center for Resource Economics, pp. 45–55.

Salati, E., Vose, P.B., 1984. Amazon Basin: A system in equilibrium. Science (1979) 225, 129–138. https://doi.org/10.1126/science.225.4658.129

Science Panel for the Amazon, 2021. Amazon Assessment Report 2021, Amazon Assessment Report 2021. United Nations Sustainable Development Solutions Network, New York, USA. https://doi.org/10.55161/rwsx6527

Silver, S.C., Ostro, L.E.T., Marsh, L.K., Maffei, L., Noss, A.J., Kelly, M.J., Wallace, R.B., Gomez, H., Ayala, G., 2004. The use of camera traps for estimating jaguar *Panthera onca* abundance and density using capture / recapture analysis. Oryx 38, 1–7. https://doi.org/10.1017/S0030605303000000

Sollmann, R., Torres, N.M., Silveira, L., 2008. Jaguar conservation in Brazil: the role of Protected Areas. CAT News 15–20.

Sunquist, M.E., Sunquist, F.C., 2002. Wild Cats of the World. University of Chicago Press, Chicago and London.

Thompson, J.J., Morato, R.G., Niebuhr, B.B., Alegre, V.B., Oshima, J.E.F., de Barros, A.E., Paviolo, A., de la Torre, J.A., Lima, F., McBride, R.T., Cunha de Paula, R., Cullen, L., Silveira, L., Kantek, D.L.Z., Ramalho, E.E., Maranhão, L., Haberfeld, M., Sana, D.A., Medellin, R.A., Carrillo, E., Montalvo, V.H., Monroy-Vilchis, O., Cruz, P., Jacomo, A.T.A., Alves, G.B., Cassaigne, I., Thompson, R., Sáenz-Bolaños, C., Cruz, J.C., Alfaro, L.D., Hagnauer, I., Xavier da Silva, M., Vogliotti, A., Moraes, M.F.D., Miyazaki, S.S., Araujo,

G.R., Cruz da Silva, L., Leuzinger, L., Carvalho, M.M., Rampim, L., Sartorello, L., Quigley, H., Tortato, F.R., Hoogesteijn, R., Crawshaw, P.G., Devlin, A.L., May Júnior, J.A., Powell, G.V.N., Tobler, M.W., Carrillo-Percastegui, S.E., Payán, E., Azevedo, F.C.C., Concone, H.V.B., Quiroga, V.A., Costa, S.A., Arrabal, J.P., Vanderhoeven, E., Di Blanco, Y.E., Lopes, A.M.C., Ribeiro, M.C., 2021. Environmental and anthropogenic factors synergistically affect space use of jaguars. Current Biology 31, 3457-3466.e4. https://doi.org/10.1016/j.cub.2021.06.029

Tobler, M.W., Carrillo-Percastegui, S.E., Zúñiga Hartley, A., Powell, G.V.N., 2013. High jaguar densities and large population sizes in the core habitat of the southwestern Amazon. Biol Conserv 159, 375–381. https://doi.org/10.1016/j.biocon.2012.12.012

Tobler, M.W., Garcia Anleu, R., Carrillo-Percastegui, S.E., Ponce Santizo, G., Polisar, J., Zuñiga Hartley, A., Goldstein, I., 2018. Do responsibly managed logging concessions adequately protect jaguars and other large and medium-sized mammals? Two case studies from Guatemala and Peru. Biol Conserv 220, 245–253. https://doi.org/10.1016/j.biocon.2018.02.015

Tobler, M.W., Powell, G.V.N., 2013. Estimating jaguar densities with camera traps: Problems with current designs and recommendations for future studies. Biol Conserv 159, 109–118. https://doi.org/10.1016/j.biocon.2012.12.009

Valsecchi, J., Monteiro, M.C.M., Alvarenga, G.C., Lemos, L.P., Ramalho, E.E., 2022. Community-based monitoring of wild felid hunting in Central Amazonia. Anim Conserv 1967, 1–10. https://doi.org/10.1111/acv.12811

Vancutsem, C., Achard, F., Pekel, J.-F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L.E.O.C., Nasi, R., 2021. Long-term (1990-2019) monitoring of forest cover changes in the humid tropics. Sci Adv.

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., Levy, M.A., Watson, J.E.M., 2016. Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nat Commun 7, 1–11. https://doi.org/10.1038/ncomms12558

Zanon, S., 2023. Deforestation in the Amazon: past, present and future. InfoAmazonia – RAISG.

Author Contributions

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. **Elildo 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 Esterci 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.

Supplementary Material

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 interfluve 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; IBAMA, 1998; 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 5,746,000 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 Xeruã 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 Güeppi-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.

Tables

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 (km²)	Captures	Individuals
Alto Turiaçu IL	02/2020-08/2020	-3.042000	-46.415700	Brazil	18	Yes	162	2,288	293	55	15
Arapaxi RESEX	04/2019-06/2019	-8.842683	-67.840581	Brazil	96	No	68	5,026	1,002	6	6
Cabo Orange NP	10/2019-01/2020	2.936570	-51.199910	Brazil	33	Yes	88	2,501	226	6	6
Cazumba-Iracema RESEX	05/2018-09/2018	-9.449309	-68.907706	Brazil	119	No	108	6,554	1,296	11	9
Chico Mendes RESEX	04/2019-08/2019	-10.288559	-68.173210	Brazil	23	Yes	122	2,473	164	13	6
Cuieiras REBIO	06/2018-10/2018	-2.574010	-60.304320	Brazil	40	No	110	3,587	34	3	2
Cuieiras REBIO	04/2019-06/2019	-2.574010	-60.304320	Brazil	40	No	73	2,646	34	3	3
Cuieiras REBIO	07/2019-09/2019	-2.574010	-60.304320	Brazil	40	No	68	2,426	34	9	6
Cuieiras REBIO	02/2020-05/2020	-2.574010	-60.304320	Brazil	40	No	104	3,850	34	8	2
Cuyabeno WR	12/2017-04/2018	-0.325916	-75.785472	Ecuador	29	Yes	126	3,309	87	8	7
Cuyabeno WR	07/2018-10/2018	-0.325916	-75.785472	Ecuador	43	Yes	145	4,199	147	15	12
Cuyabeno WR	01/2019-06/2019	-0.325916	-75.785472	Ecuador	25	Yes	98	1,676	95	9	6
Deni & Kanamari do Xeruã IL	07/2011-04/2012	-6.609180	-68.235440	Brazil	41	No	276	5,746	1,813	40	19
ESEC Maracá	02/2019-05/2019	3.395130	-61.542020	Brazil	28	Yes	83	1,802	164	39	13
ESEC Terra do Meio	06/2016-08/2016	-4.685691	-53.580800	Brazil	60	No	70	3,438	192	5	5
ESEC Terra do Meio	05/2017-08/2017	-4.685691	-53.580800	Brazil	53	No	91	4,022	174	8	8
Espinoza FC	10/2009-03/2010	-11.480000	-69.840000	Peru	38	Yes	140	3,460	335	82	29

Espinoza FC	06/2014-10/2014	-11.460000	-69.700000	Peru	89	Yes	121	8,780	864	481	43
FLONA Jamari	08/2016-11/2016	-9.346536	-62.966493	Brazil	41	No	90	1,610	156	2	2
FLONA Jamari	09/2017-12/2017	-9.346536	-62.966493	Brazil	105	No	111	4,803	662	4	4
FLONA Jamari	08/2018-12/2018	-9.346536	-62.966493	Brazil	109	No	128	4,111	580	8	7
FLONA Jamari	07/2019-12/2019	-9.346536	-62.966493	Brazil	94	No	135	3,857	526	6	5
Güeppi-Sekime NP	11/2017-02/2018	-0.370944	-75.214722	Peru	50	Yes	94	4,248	313	76	12
Güeppi-Sekime NP	02/2019-04/2019	-0.370944	-75.214722	Peru	44	Yes	70	2,863	140	58	9
Gurupi REBIO	02/2020-06/2020	-3.656000	-46.809000	Brazil	19	No	109	1,401	1,548	63	17
Jaú NP	09/2016-01/2017	-1.857490	-61.691670	Brazil	48	No	125	4,272	429	4	2
Jaú NP	12/2016-07/2017	-1.857490	-61.691670	Brazil	40	No	228	5,857	413	6	4
Juruena NP	06/2019-08/2019	-8.985254	-58.577000	Brazil	76	Yes	75	4,648	432	24	10
Los Amigos CC	09/2005-11/2005	-12.540000	-70.060000	Peru	24	Yes	63	1,478	63	14	10
Los Amigos CC	08/2006-10/2006	-12.540000	-70.060000	Peru	40	Yes	65	2,509	62	36	10
Los Amigos CC	09/2007-11/2007	-12.540000	-70.060000	Peru	40	Yes	69	2,510	62	48	11
Los Amigos CC	03/2010-12/2010	-12.430000	-70.210000	Peru	30	Yes	269	3,131	196	17	12
Médio Purus RESEX	07/2019-08/2019	-7.752370	-65.649433	Brazil	102	No	61	5,089	4,349	15	11
SDR Amanã	01/2013-04/2013	-2.474850	-64.620420	Brazil	49	Yes	83	1,866	131	11	8
SDR Amanã	12/2013-04/2014	-2.474850	-64.620420	Brazil	63	Yes	121	2,948	135	7	6
SDR Mamirauá	09/2013-12/2013	-3.045530	-64.861880	Brazil	54	Yes	87	2,225	216	22	15
SDR Mamirauá	09/2014-12/2014	-3.045530	-64.861880	Brazil	53	Yes	93	2,294	216	25	19
Tambopata NR & Bahuaja Sonene NP	04/2007-06/2007	-12.990000	-69.460000	Peru	43	Yes	68	2,663	58	12	7
Umancia IL	01/2018-04/2018	-0.314944	-74.375805	Colombia	50	No	68	3,030	144	26	6
Umancia IL	02/2019-06/2019	-0.314944	-74.375805	Colombia	48	No	113	4,352	146	8	5

Table A2. Model selection for sigma (σ) and a0. D: density; a0: 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	5,175.84	0
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean + sc_GPP2021_mean pmix~h2	5,178.39	2.55
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP pmix~h2	5,180.14	4.30
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_HumFP pmix~h2	5,182.23	6.39
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean pmix~h2	5,182.48	6.64
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_humModif pmix~h2	5,182.60	6.76
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_CTI pmix~h2	5,182.69	6.85
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_degradation2021 pmix~h2	5,182.81	6.97
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_HumFP pmix~h2	5,182.82	6.98
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 + sc_HumFP pmix~h2	5,184.92	9.08
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean + sc_degradation2021 pmix~h2	5,185.15	9.31
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_HumFP + sc_NDVI2021_mean + sc_CTI pmix~h2	5,185.16	9.32
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 + sc_HumFP + sc_NPP_mean pmix~h2	5,187.22	11.38
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_humModif + sc_NPP_mean pmix~h2	5,192.57	16.73
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 pmix~h2	5,191.40	15.56
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_humModif pmix~h2	5,192.24	16.40
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_humModif + sc_NPP_mean pmix~h2	5,194.34	18.50
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 pmix~h2	5,194.06	18.22
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 pmix~h2	5,194.06	18.22
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_humModif pmix~h2	5,194.85	19.01
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_humModif pmix~h2	5,194.91	19.07
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC3 + sc_NPP_mean pmix~h2	5,195.40	19.56
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_NPP_mean pmix~h2	5,195.54	19.70

D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 pmix~h2	5,196.73	20.89
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC1 + sc_PC2 + sc_PC3 + sc_humModif pmix~h2	5,197.52	21.68
D~session a0~h2 * Trail + Paired sigma~h2 + sc_humModif pmix~h2	5,202.10	26.26
D~session a0~h2 * Trail + Paired sigma~h2 + sc_HumFP pmix~h2	5,204.35	28.51
D~session a0~h2 * Trail + Paired sigma~h2 + sc_NDVI2021_mean pmix~h2	5,206.77	30.93
D~session a0~h2 * Trail + Paired sigma~h2 + sc_NPP_mean + sc_HumFP + sc_TreeCover_mean pmix~h2	5,209.44	33.60
D~session a0~h2 * Trail + Paired sigma~h2 + sc_BIO1_TempMean pmix~h2	5,211.92	36.08
D~session a0~h2 * Trail + Paired sigma~h2 + sc_CTI pmix~h2	5,215.43	39.59
D~session a0~h2 * Trail + Paired sigma~h2 + sc_BIO15_PercSeason pmix~h2	5,222.97	47.13
D~session a0~h2 * Trail + Paired sigma~h2 + sc_degradation2021 pmix~h2	5,223.68	47.84
D~session a0~h2 * Trail + Paired sigma~h2 + sc_GPP2021_mean pmix~h2	5,223.94	48.10
D~session a0~h2 * Trail + Paired sigma~h2 + sc_BIO12_PercTot pmix~h2	5,225.25	49.41
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC2 + sc_PC3 pmix~h2	5,230.31	54.47
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC2 + sc_PC3 + sc_NPP_mean pmix~h2	5,232.04	56.20
D~session a0~h2 * Trail + Paired sigma~h2 + sc_PC3 pmix~h2	5,230.78	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) (×100); BIO4: Temperature Seasonality (standard deviation ×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±211 (1483-2314)	3029±265 (2553-3593)
Arapaxi RESEX	2895±222 (2491-3365)	4733±327 (4134-5419)
Cabo Orange NP	1338±142 (1088-1646)	2188±178 (1865-2566)
Cazumbá-Iracema RESEX	2908±221 (2506-3374)	4754±307 (4189-5396)
Chico Mendes RESEX	3885±401 (3175-4753)	6351±586 (5302-7608)
Cuieiras REBIO 2018	3506±784 (2274-5407)	5732±1245 (3763-8730)
Cuieiras REBIO 2019a	3506±784 (2274-5407)	5732±1245 (3763-8730)
Cuieiras REBIO 2019b	3506±784 (2274-5407)	5732±1245 (3763-8730)
Cuieiras REBIO 2020	3506±784 (2274-5407)	5732±1245 (3763-8730)
Cuyabeno WR 2017-2018	1894±135 (1647-2179)	3096±179 (2764-3468)
Cuyabeno WR 2018	1736±127 (1504-2003)	2838±165 (2533-3179)
Cuyabeno WR 2019	1857±132 (1616-2135)	3037±173 (2716-3395)
Deni & Kanamari do Xeruã IL	1957±142 (1699-2255)	3200±180 (2866-3572)
ESEC Maracá-Jipioca	2098±171 (1788-2462)	3430±262 (2954-3983)
ESEC Terra do Meio 2016	1932±171 (1625-2297)	3159±238 (2726-3659)
ESEC Terra do Meio 2017	1932±171 (1626-2296)	3159±238 (2726-3659)
Espinoza FC 2009-2010	3017±223 (2611-3486)	4932±254 (4459-5455)
Espinoza FC 2014	3207±236 (2777-3703)	5243±272 (4737-5803)
FLONA Jamari 2016	3238±325 (2661-3939)	5293±539 (4338-6458)
FLONA Jamari 2017	3239±318 (2674-3925)	5296±525 (4363-6427)
FLONA Jamari 2018	3095±291 (2575-3720)	5060±476 (4210-6082)
FLONA Jamari 2019	3102±284 (2593-3711)	5071±461 (4244-6059)
Güeppi-Sekime NP 2017-2018	1658±125 (1431-1920)	2710±157 (2420-3035)
Güeppi-Sekime NP 2019	1578±127 (1348-1847)	2580±168 (2272-2930)
Gurupi REBIO	1768±158 (1485-2105)	2891±174 (2570-3252)
Jaú NP 2016-2017a	1580±153 (1308-1910)	2584±246 (2145-3112)
Jaú NP 2016-2017b	1582±153 (1309-1913)	2587±247 (2147-3117)
Juruena NP	2490±199 (2129-2911)	4070±288 (3543-4676)
Los Amigos 2005	2489±185 (2152-2878)	4068±268 (3576-4629)
Los Amigos 2006	2490±185 (2153-2881)	4071±269 (3577-4634)
Los Amigos 2007	2490±185 (2153-2881)	4071±269 (3577-4634)
Los Amigos CC 2010	2122±141 (1864-2416)	3469±139 (3208-3752)
Médio Purus RESEX	2335±213 (1954-2790)	3817±347 (3196-4559)
SDR Amanã 2013	1480±134 (1240-1766)	2419±196 (2064-2835)
SDR Amanã 2013-2014	1479±134 (1239-1765)	2418±196 (2064-2833)
SDR Mamirauá 2013	1988±256 (1546-2557)	3251±435 (2504-4220)
SDR Mamirauá 2014	1991±257 (1548-2561)	3255±436 (2506-4228)
Tambopata NR & Bahuaja Sonene NP	2733±209 (2352-3175)	4467±308 (3903-5113)
Umancia IL 2018	1967±147 (1700-2276)	3215±199 (2848-3630)
Umancia IL 2019	1972±148 (1704-2283)	3225±201 (2855-3642)

References Supplementary

Acre, 2010. Zoneamento Ecológico-Econômico do Estado do Acre, Fase II (Escala 1:250.000), Zoneamento Ecológico-Econômico do Acre Fase II. Rio Branco-AC, Brazil.

Almeida, J.L., Bezerra, J.F.R., Santos, J. de R.C. dos, Moraes, M.S. de, Lisboa, G.S., 2022. Revista Brasileira de Geografia Física. Revista Brasileira de Geografia Física 15, 1965–1877.

Bass, M.S., Finer, M., Jenkins, C.N., Kreft, H., Cisneros-Heredia, D.F., McCracken, S.F., Pitman, N.C.A., English, P.H., Swing, K., Villa, G., Di Fiore, A., Voigt, C.C., Kunz, T.H., 2010. Global conservation significance of Ecuador's Yasuní National Park. PLoS One 5. https://doi.org/10.1371/journal.pone.0008767

Brasil, 1976. RADAMBRASIL: Folha SC.19 Rio Branco: geologia, geomorfologia, pedologia, vegetação e uso potencial da terra. Rio de Janeiro, Brazil.

FVA; IBAMA, 1998. Plano de Manejo do Parque Nacional do Jaú, Manaus, Brazil.

Kerber, R. de L., Fagundes, S.T.S., Satilho, C. de O., Tronco, K.M. de Q., Vendruscolo, J., Sccoti, M.S.V., 2021. Flora arbórea na FLONA do Jamari, Rondônia. Research, Society and Development 10, e14410413915. https://doi.org/10.33448/rsd-v10i4.13915

MCT; IDSM, 2010. Plano de Gestão: Reserva de Desenvolvimento Sustentável Mamirauá - RDSM, Plano de Gestão. Reserva de Desenvolvimento Sustentável Mamirauá RDSM. Tefé-AM, Brazil.

MMA; IBAMA, 2005. Plano de Manejo da Floresta Nacional do Jamari — Rondônia. Brasília, Brazil.

MMA; ICMBio, 2015. Plano de Manejo Estação Ecológica de Maracá. Brasília, Brazil.

MMA; ICMBio, 2020. Plano de Manejo da Reserva Extrativista do Médio Purus/AM, Brazil.

MMA; ICMBio, 2017. Plano de Manejo da Estação Ecológica de Maracá-Jipioca. Brasília, Brazil.

MMA; ICMBio, 2011. Plano de Manejo do Parque Nacional do Juruena, Brasília, Brazil.

MMA; ICMBio, 2010. Plano de Manejo Participativo Reserva Extrativista Arapixi. Boca do Acre, AM, Brazil.

Oliveira, Tadeu Gomes de, 2011. Alerta vermelho à conservação da última fronteira da Amazônia Tocantina: avaliação do estado de conservação do Gurupi e da Amazônia maranhense, in: Martins, M.B.; Oliveira, T.G. (Eds.), Amazônia Maranhense: Diversidade e Conservação. Museu Paraense Emilio Goeldi, Belém, PA, pp. 283–295.

Oliveira, M., Baccaro, F., Braga-Neto, R., Magnusson, W., 2008. Reserva Ducke: A biodiversidade amazônica através de uma grade, INPA. Manaus, Brazil.

Pérez, M.S., 2015. Where the Xingu Bends and Will Soon Break. Am Sci 103, 395–403.

Pezzuti, J., Chaves, R.P., 2009. Ethnography and natural resources management by the Deni Indians, Amazonas, Brazil. Acta Amazon 39, 121–138. https://doi.org/10.1590/s0044-59672009000100013

Queiroz, H.L., 2005. A criação da Reserva Amanã: um importante estágio para a consolidação do embrião do Corredor da Amazônia Central, in: Ayres, J.M., Fonseca, G.A.B. da, Rylands, A.B., Queiroz, H.L., Pinto, L.P., Masterson, D., Cavalcanti, R.B. (Eds.), Os Corredores Ecológicos Das Florestas Tropicais Do Brasil. Sociedade Civil Mamirauá, Belém, PA, pp. 246–249.

SEMA; IDSM, 2019. Plano de Gestão da Reserva de Desenvolvimento Sustentável Amanã. Tefé-AM, Brazil.

Silva, C. da S., 2013. Áreas Protegidas Como Ferramenta De Contenção Do Desmatamento: Estudo De Caso Da Terra Do Meio. Instituto Nacional de Pesquisa da Amazônia, Manaus, Brazil.

Tobler, M.W., Carrillo-Percastegui, S.E., Zúñiga Hartley, A., Powell, G.V.N., 2013. High jaguar densities and large population sizes in the core habitat of the southwestern Amazon. Biol Conserv 159, 375–381. https://doi.org/10.1016/j.biocon.2012.12.012

Usma, J.S., Ortega, C., Valenzuela, S., Deza, J., Rivas, J., 2016. Diversidad biológica y cultural del Corredor Trinacional de áreas protegidas La Paya - Cuyabeno - Güeppí Sekime. Colombia - Ecuador - Perú. WWF Bogotá D.C., Colombia.


Emiliano E. Ramalho - Mamirauá Institute

Chapter 3

Range-wide assessment of habitat suitability for jaguars using multiscale species distribution modelling

Guilherme Costa Alvarenga; Caroline C. Sartor; Samuel A. Cushman; Alexandra Zimmermann; Ana Carolina Srbek-Araujo; Ana Cristina Mendes-Oliveira; Bart Harmsen; Carlos De Angelo; Carolina Franco Esteves; Claudia B. de Campos; Daiana Jeronimo Polli; Diego F. Passos Viana; Diogo Maia Gräbin; Emiliano Donadio; Emiliano E. Ramalho; Esteban Payán; Fernando C. C. Azevedo; Francisco Palomares; George V. N. Powell; Gerardo Ceballos; Grasiela Porfirio; Heliot Zarza; Ivonne Cassaigne; Juliano A. Bogoni; Leonardo Sena; Louise Maranhão; Marcos Roberto Monteiro de Brito; Mathias W. Tobler; Øystein Wiig; Rebecca J. Foster; Ricardo Sampaio; Rodrigo Nuñez; Ronaldo G. Morato; Valeria Boron; Wener Hugo Arruda Moreno; Yadvinder Malhi; David W. Macdonald; Żaneta Kaszta

Published at Scientific Reports
https://doi.org/10.1038/s41598-025-30512-5

Abstract

Jaguars (*Panthera onca*) are highly sensitive to persecution, habitat loss, and fragmentation, making the identification of suitable habitat critical for conservation planning. Using GPS telemetry data from 172 individuals across seven countries – the largest jaguar dataset to date – we developed multiscale Resource Selection Functions (RSFs) incorporating 15 environmental covariates to model habitat suitability across the species' historic range. Jaguars selected productive habitats near water and strongly avoided human-modified landscapes, including areas with high human population density and livestock presence. The resulting habitat suitability surface showed strong predictive performance (AUC = 0.88; Boyce Index = 0.91) and correlated with known density estimates and distribution models. Jaguar Conservation Units (JCUs) and Protected Areas (PAs) contained 68.7% and 53.9% of predicted suitable habitat, respectively, while occupying only a third of the range. Non-designated lands, though comprising just 4% of the range, held nearly 10% of total suitability. The Amazon and Mayan Forests were identified as core strongholds, while ecoregion-based modelling revealed additional areas of high suitability in the Pantanal, Gran Chaco, Cerrado, and coastal Mexico. While Brazil encompassed the largest extent of highly suitable habitat, countries such as Paraguay, Argentina, and the United States gained conservation relevance under the ecoregion-stratified scenario.

Key words

habitat suitability; indigenous lands; jaguar conservation units; multiscale modelling; *Panthera onca*; protected areas

Introduction

Large carnivores occupy the top of the food chain and consequently have naturally low population sizes, which makes them particularly susceptible to ecological perturbations [1]. For example, jaguars (*Panthera onca*) historically occurred from the southwestern United States (US) to central Argentina [2], but their range has been reduced by half over the last century mainly due to habitat loss and persecution [3]. Within their remaining range, the Amazonian biome, the wetlands of the Pantanal and the Mayan Forest still harbour large jaguar populations, while elsewhere they persist in smaller, isolated and generally highly threatened populations [4,5]. However, considerable variation exists in jaguars' habitat use and population densities even within these core areas, reflecting underlying differences in habitat quality and environmental pressures [6–8]. This study aims to refine our understanding of how jaguars respond to environmental and landscape changes by identifying critical habitat areas through the application of resource selection functions, remotely sensed predictors, and movement data spanning the species' historic range.

Resource selection functions (RSFs) have been widely used to quantify, predict and map interactions between species and their environments, and are well suited to defining important habitats (and habitat elements) for the species viability [9]. RSFs compare the used habitat (usually, the presences extracted from animal locations) with the available habitat to quantify the variation in the use of resources [10]. Ideally, "used" and "available" data should be temporally synchronized, ensuring that predictions are aligned with the actual choices made by the species/animal. In addition, species perceive and respond to the landscape features in different spatial scales, therefore defining the "scale of effect" in which each landscape feature has on the target species helps to avoid erroneous outcomes [11,12]. New methods, such as scale optimization approaches [13,14], enable precise tuning of the species-environmental relationship to scale within the context of RSF modelling. Nevertheless,

applying such techniques relies heavily on having adequate empirical data, which is often challenging to acquire for elusive species like jaguars.

The first maps delineating the core habitat areas for jaguars were developed solely based on expert knowledge, as empirical data were scarce. These maps identified 130 areas (Jaguar Conservation Units – JCUs) considered crucial for the long-term survival of the species although not necessarily formally protected [15]. Recently, as the emergence of new technologies has enabled the collection of large empirical data sets on jaguar occurrence and movement, researchers have been regionally evaluating JCUs [16–19]. Those studies have used various methods, and scales, and have focused on different geographical regions; nevertheless, some general patterns in the jaguar's response to the landscape have emerged. For instance, the importance of protected areas and Indigenous Lands ("PAs" for simplicity) for jaguar populations is notable throughout its geographical range, especially outside the Amazon biome, where all the remaining suitable habitats are fragmented [20–22]. Among landscape features and land cover types, primary and secondary forests, and water bodies, are consistently identified as the most important predictors of high habitat suitability and dispersal corridors for jaguars [23–25]. Conversely, jaguars generally avoid areas with high human densities and a high human footprint index, such as settlements, crop farms and roads [26–28]. In addition, it is well documented that male and female jaguars use their habitat differently. Compared to females, males have larger home ranges, use trails and secondary roads more intensively, and are less sensitive to human presence and activities [29–31] - although, recent studies have highlighted variation in these patterns [32,33]. Despite growing knowledge of jaguars' spatial requirements, empirically derived spatial data remain limited, posing a significant challenge across the species range.

To date, only two range-wide studies on jaguar distribution have been conducted, both of which relied on compiled occurrence data from multiple sources with varying levels of

accuracy and quality [34,35]. Additionally, neither study explored scale optimization, temporally matched observations to predictor variables, or accounted for sex differentiation. These methodological limitations, while understandable at the time, may have contributed to misleading or inaccurate predictions [36,37] and likely contributed to the incongruence of distribution predictions [34,35].

Here, we leverage the largest dataset on jaguar movement ever compiled, integrating a multi-scale approach, ensuring temporal alignment of datasets where available and sex-specific behavioural variation to model habitat suitability across the species' historical range. Using data from 172 GPS-collared jaguars, we aimed to produce the most up-to-date map of jaguar proportional probability of occurrence and assess its conservation implications. Specifically, we evaluate the effectiveness of JCUs and PAs in safeguarding critical jaguar habitats, analyse the distribution of suitable habitats across countries and, as a case study, estimate the proportion of these habitats within non-designated lands in Brazil. This effort represents a unique contribution to jaguar research and conservation, providing governments and stakeholders with essential information to guide conservation planning and policy.

Results

Resource Selection

After cleaning erroneous data and filtering locations that fell within the same pixel, 29,962 GPS-locations were retained for model development. Females contributed 12,302 locations, and males 17,660 (Table 1). Jaguars responded to the spatial covariates at varying scales with no clear preference for a specific scale (Table 2). From the retained covariates in the final models, only roughness was not significantly associated with jaguar habitat use. Our model indicated that jaguars were highly averse to anthropogenic features with human population density, livestock and human modification presenting the three strongest negative

effects on the species. Conversely, soil CEC, NDVI, and water surface had the strongest positive effect in the model, indicating jaguars are more likely to select productive habitats closer to water bodies (Table 2).

Table 1. Number (Nº) of jaguars (*Panthera onca*) and GPS-locations per biome.

Biome	Nº Locations (Individuals)		
	Females	**Males**	**Total**
Amazon	1350 (10)	3565 (16)	6145 (26)
Atlantic Forest	1686 (14)	2445 (10)	5164 (24)
Caatinga	958 (2)	2038 (4)	3746 (6)
Cerrado	411 (2)	1253 (4)	2079 (6)
Dry Chaco	354 (1)	2451 (6)	3505 (7)
Thornscrub of Sonora (Mexico)	445 (1)	511 (1)	1195 (2)
Humid Chaco	1626 (10)	572 (3)	2746 (13)
Llanos	22 (1)	64 (1)	108 (2)
Mangroves	78 (2)	257 (5)	418 (7)
Pantanal	3318 (31)	2867 (26)	7731 (57)
Tropical Forests of Central America	2054 (12)	1637 (10)	4616 (22)
Total	**12,302 (86)**	**17,660 (86)**	**29,962 (172)**

Table 2. Multi-scale Generalized Linear Mixed Model (GLMM) predicting jaguar (*Panthera onca*) habitat suitability across the species historic range.

Covariates	Scale (km)	β Coefficient	Std Error	Pr (>|z|)
Temperature Seasonality	16	-0.268	0.050	< 0.001
Surface Temperature	1	-0.232	0.010	< 0.001
Human Modification	4	-0.484	0.018	< 0.001
Human Population Density	8	-5.713	0.186	< 0.001
Livestock	8	-1.041	0.020	< 0.001
Compound Topographic Index	2	0.193	0.014	< 0.001
Elevation	0.5	-0.271	0.015	< 0.001
Roughness	4	-0.001	0.016	0.942
Topographic Position Index	32	-0.210	0.008	< 0.001
Cation Exchange Capacity	4	0.525	0.018	< 0.001
Water Surface	16	0.235	0.007	< 0.001
Forest Degradation	2	-0.042	0.010	< 0.001
Normalized Difference Vegetation Index	0.5	0.300	0.010	< 0.001
Defaunation Index	32	-0.241	0.015	< 0.001
Burned Areas	1	-0.061	0.007	< 0.001

Model prediction

Using the linear combination of variables in our optimized model, we predicted the habitat suitability surface for jaguars across their historical range (Fig. 1). Forested environments were the most suitable habitats for the species. The Amazon biome and the Mayan forests in southeast Mexico represented the two largest continuous areas of predicted suitable habitat. Additionally, the Gran Chaco from Paraguay and northern Argentina, the tropical forests across Central America, the wetlands of Pantanal on the borders between Brazil, Paraguay and Bolivia, and the remaining patches of Atlantic Forest were also predicted to have relatively high suitability. Large areas of intermediate suitability were found from northwest Mexico in Sonora through the west coast until the Sinaloa region, but also in the Oaxaca region in southern Mexico, as well as in the Cerrado and part of the Caatinga biome. Interestingly, the predictions identified as intermediate suitability some peripheral regions where jaguar no longer present – or may have never occurred – such as Baja California (Mexico), the gulf coastal plains in southern Texas (US) and central and southern Argentina in the extreme south of the species potential historical distribution (Fig. 1).

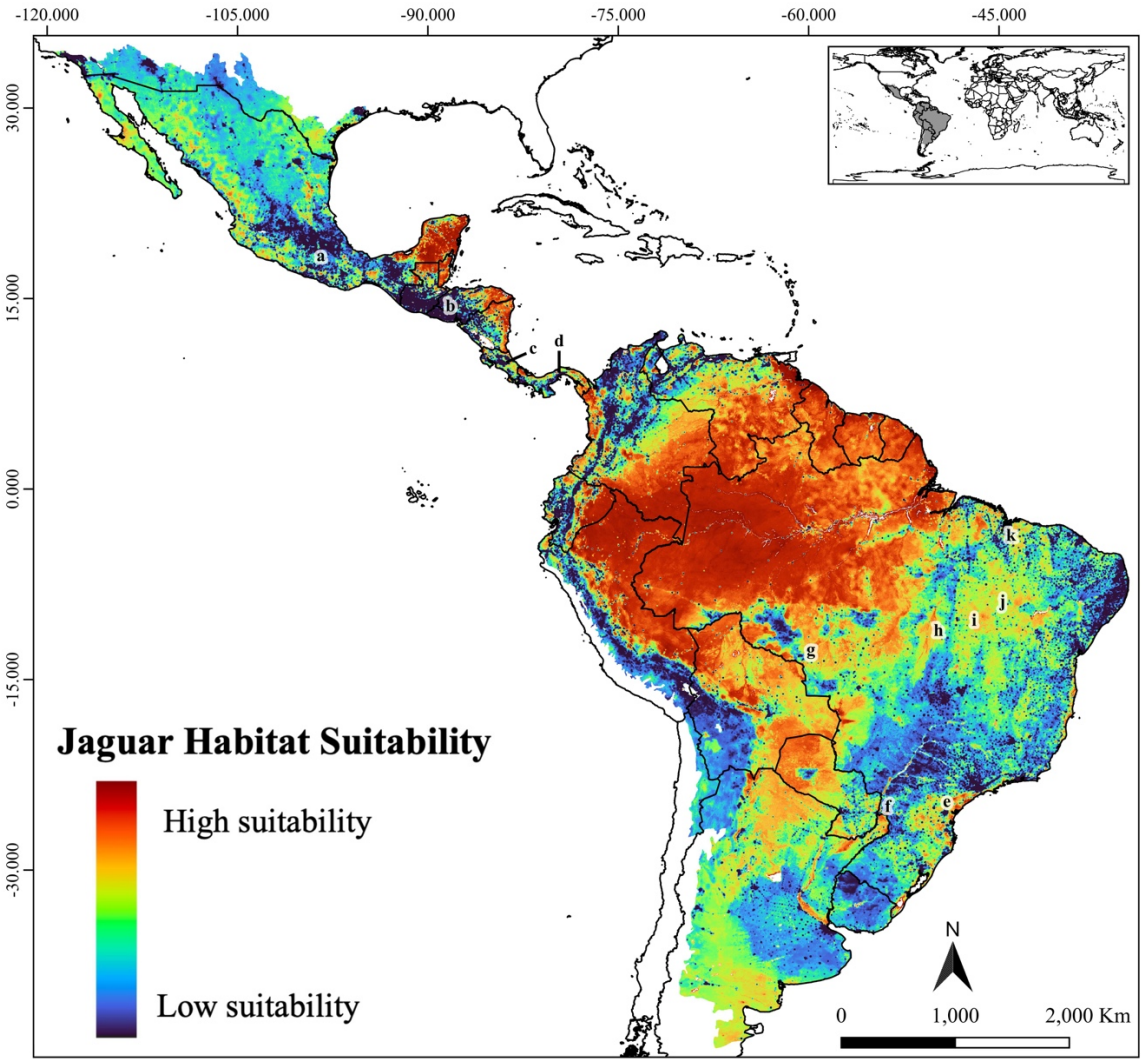


Figure 1. Predicted habitat suitability for jaguars (*Panthera onca*) across the species historical range. Letters mark specific regions of interest discussed in detail in the Discussion section. Figure created using QGIS v3.36.0 (https://qgis.org).

The two validation tests indicated our suitability surface was highly predictive: Boyce Index ($f = 0.91$; Fig. S1) and AUC = 0.88 (sensitivity = 0.93, specificity = 0.77). Additionally, the jaguar density estimates were positively related to our suitability surface ($\beta = 4.42$, SE = 1.20, $t = 3.7$, $p < 0.0001$, 95% CI = [2.03, 6.82], $R^2 = 0.14$) (Supplementary Fig. S2), and the correlation test demonstrated our prediction map is highly correlated with the distribution model by Jędrzejewski et al. (2018)34 ($r = 0.72$).

Conservation implications

Considering the total summed habitat suitability across the jaguar's current range – where each pixel contributes to the total according to its suitability value – non-designated lands account for 9.83% of the total, despite occupying only 4.0% of the range. Most of these lands are located in the central-western Brazilian Amazon. In comparison, JCUs and PAs concentrate 68.7% and 53.9% of the predicted habitat suitability while covering just 33.0% and 29.3% of the range, respectively (Supplementary Table S3).

When focusing on highly suitable habitats (upper quartile – top 25%), patterns varied depending on the analytical scenario (Fig. 2). In the range-based scenario, "Tropical & Subtropical Moist Broadleaf Forests" had a drastic domain, comprising 96.3% of all highly suitable habitat. This dominance was also evident within JCUs and PAs (Fig. 3A and 4A): the five units with the largest extents of highly suitable habitat were all located in the Amazon – a "Moist Broadleaf Forest", together accounting for approximately 9.8 and 4.7 million km² in JCUs and PAs, respectively (see Appendix S1 and S2 for detailed values). These findings emphasize the significance of large, continuous wild areas for jaguar conservation.

In the ecoregion-based scenario, however, the picture became more geographically diverse (Fig. 2). Although "Moist Broadleaf Forests" still held the majority (58.9%), other ecoregions gained prominence: "Tropical & Subtropical Grasslands, Savannas & Shrublands" and "Tropical & Subtropical Dry Broadleaf Forests", for instance, accounted for 20.7% and 10.9% of the highly suitable habitat, respectively. This shift was mirrored in JCUs and PAs (Fig. 3B and 4B). JCUs in the Pantanal and Gran Chaco biomes ranked among the top five, and PAs of known conservation value in Mexico, the Cerrado, and Caatinga also featured prominently, each containing over 1,000 km² of highly suitable habitat.

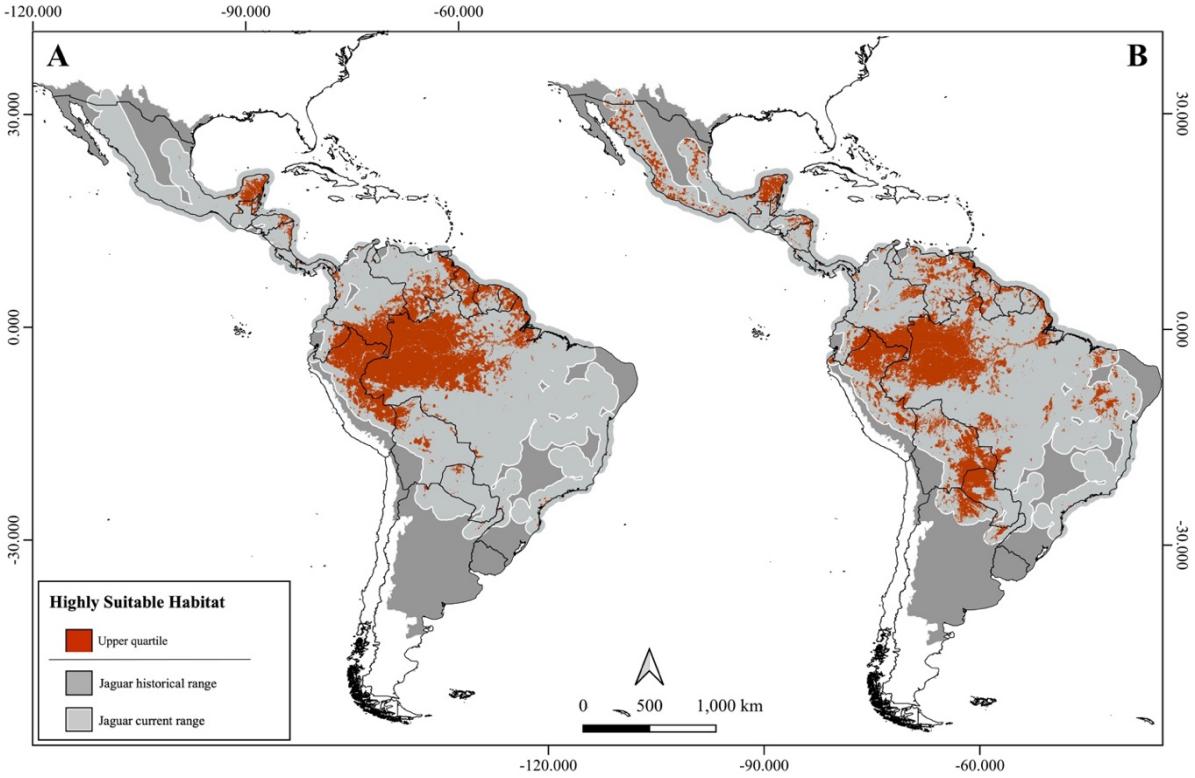


Figure 2. The jaguar highly suitable habitats considering the range-based (A) and ecoregion-based scenarios (B). Figure created using QGIS v3.36.0 (https://qgis.org).

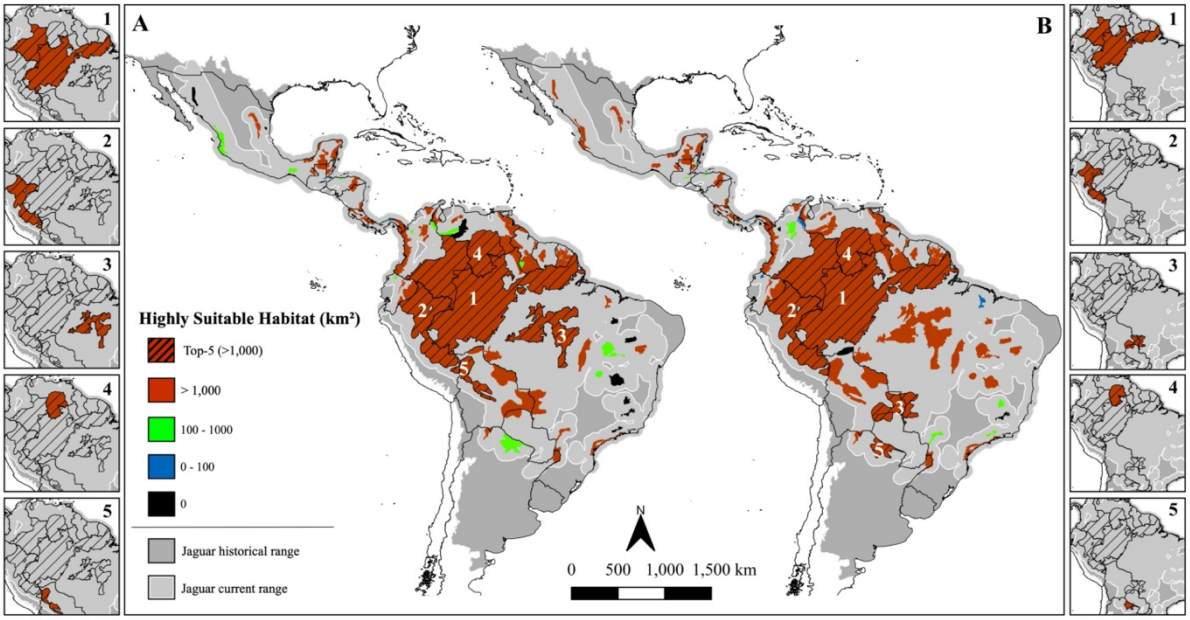


Figure 3. The Jaguar Conservation Units (JCUs) classified by the amount of highly suitable area for jaguars considering the range-based (A) and ecoregion-based scenarios

(B). The hashed pattern and side maps underline the five main JCUs in each scenario. Figure created using QGIS v3.36.0 (https://qgis.org).

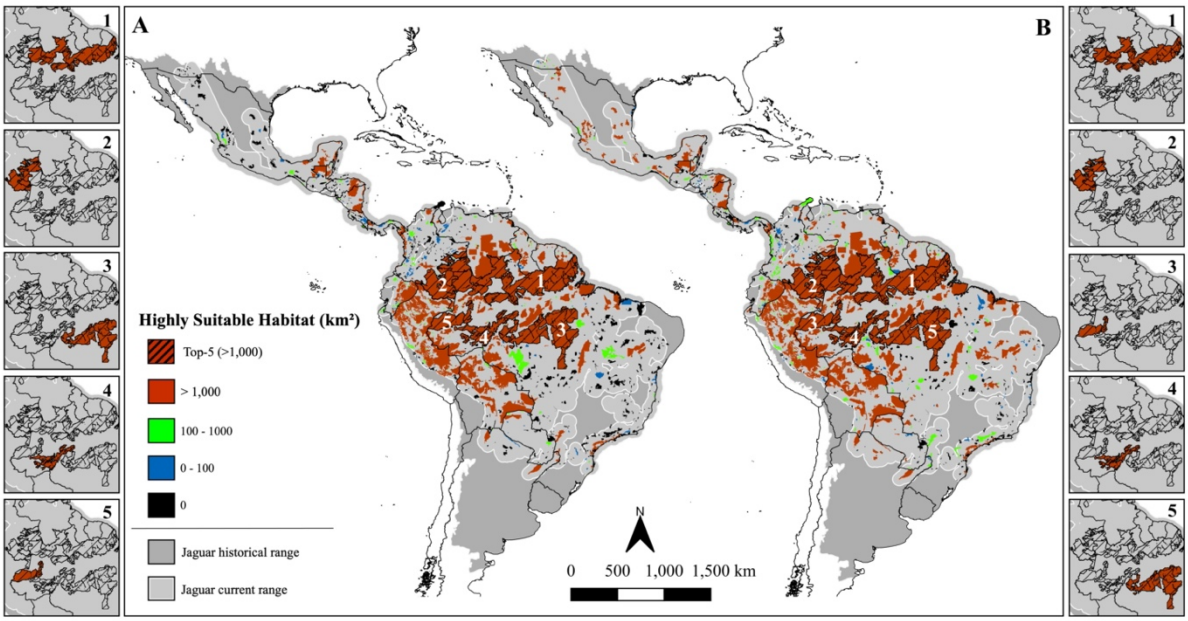


Figure 4. Protected Areas and Indigenous Lands (PAs) classified by the amount of highly suitable area for jaguars considering the range-based (A) and ecoregion-based scenarios (B). The hashed pattern and side maps underline the five main PAs in each scenario. Figure created using QGIS v3.36.0 (https://qgis.org).

When suitability was assessed as a proportion of each JCU or PA's area rather than absolute amount, similar trends emerged. In the range-based scenario, Amazonian units again stood out (Supplementary Fig. S3A and S4A), along with some in the Mayan Forest and Central America. In the ecoregion-based scenario, high-proportion areas were also identified in the Pantanal, Gran Chaco, Cerrado, Caatinga, and Mexico's coastal regions (Supplementary Fig. S3B and S4B), offering a more regionally balanced view.

At the national level, Brazil holds the largest share of the jaguar's current range – about 29.8 million km² or 50.7% – followed by Mexico (9.2%) and Colombia (7.5%) (Table

3). Brazil also contains the largest extent of highly suitable habitat under both scenarios: 7.9 million km² in the range-based analysis and 6.2 million km² in the ecoregion-based analysis. In several other countries, however, the difference between scenarios is more pronounced, highlighting the regional importance of habitats that may be overshadowed when the analysis is dominated by "Tropical and Subtropical Moist Broadleaf Forests" – primarily the Amazon. Regarding protection, an average of 54.3% of highly suitable habitats is under formal protection in the range-based scenario, and 43.4% in the ecoregion-based scenario.

Table 3. Country-wise assessment of the estimated amount of highly suitable habitat (top quartile of suitability) for jaguars (*Panthera onca*).

Country	Current range (Proportion)	Highly suitable area			
		Range-based [km²] (Percentage)	Proportion Protected (%)	Ecoregion-based [km²] (Percentage)	Proportion Protected (%)
Argentina	1,741,486 (2.97)	29,095 (1.7)	76.2	502,426 (28.9)	17.8
Belize	93,528 (0.16)	46,584 (49.8)	43.9	31,600 (33.8)	39.5
Bolivia	3,684,688 (6.27)	392,521 (10.7)	59.9	1,389,385 (37.7)	55.0
Brazil	29,792,722 (50.7)	7,849,538 (26.3)	62.1	6,232,107 (20.9)	54.0
Colombia	4,409,554 (7.51)	1,156,196 (26.2)	81.8	868,661 (19.7)	72.2
Costa Rica	209,228 (0.36)	7,048 (3.4)	78.2	8,043 (3.8)	53.3
Ecuador	821,461 (1.40)	271,792 (33.1)	87.1	258,322 (31.4)	86.3
French Guiana	336,117 (0.57)	191,019 (56.8)	41.7	48,008 (14.3)	33.7
Guatemala	449,440 (0.77)	48,764 (10.8)	99.0	26,295 (5.9)	90.4
Guyana	851,206 (1.45)	447,481 (52.6)	18.3	241,653 (28.4)	27.4
Honduras	444,194 (0.76)	59,430 (13.4)	75.4	94,116 (21.2)	44.0
Mexico	5,412,138 (9.21)	402,622 (7.4)	34.0	1,303,492 (24.1)	18.9
Nicaragua	527,923 (0.90)	82,327 (15.6)	53.8	77,836 (14.7)	32.2
Panama	295,251 (0.50)	22,867 (7.7)	60.7	8,002 (2.7)	63.4
Paraguay	1,680,725 (2.86)	62,217 (3.7)	38.4	711,125 (42.3)	11.4
Peru	3,491,372 (5.94)	2,297,798 (65.8)	55.8	1,716,467 (49.2)	56.9
Suriname	587,823 (1.00)	243,411 (41.4)	17.5	93,836 (16)	19.1
United States	334,762 (0.57)	0 (0)	0	42,637 (12.7)	18.6
Venezuela	3,572,203 (6.08)	970,291 (27.2)	47.8	923,865 (25.9)	29.9

"Current range" refers to the area (km²) of the jaguar's current range within each country, while "Proportion" is the percentage this range represents relative to the total area of the current range. "Highly suitable area" corresponds to the area (km²) classified as highly suitable habitat (top quartile of suitability) per country. "Range-based" refers to the suitable habitat identified when the entire current range was analysed as a single unit, whereas "Ecoregion-based" reflects the suitable habitat identified when each ecoregion was analysed separately. "Percentage" indicates the share of suitable habitat relative to the total current range area within each country. "Proportion Protected" shows the percentage of this suitable habitat that overlaps with protected areas, for both the Range- and Ecoregion-based approaches.

Discussion

The jaguar-habitat interactions found in our model demonstrated a trend of avoidance of anthropogenic features whilst favouring features associated with vegetation productivity and proximity to water. Such a pattern has been reported for the species at different geographic scales [30,34,38,39]. Jaguars are proficient swimmers and can even catch fish or caimans in the water [40]. In addition, they often use riverbanks for movement and hunting [41,42], explaining their strong selection for water in our model. Similarly, productive habitats tend to have higher carrying capacity, benefiting species diversity and ultimately, carnivores [43]. Conversely, anthropogenic variables, such as human modification, human population density, livestock, defaunation, burned areas, and forest degradation, are mostly related to highly transformed regions and their surroundings, hence the avoidance found. For instance, while livestock can attract jaguars at a local scale by providing an accessible source of food [44], suggesting a positive selection, the negative association found in our model likely reflects landscape-scale processes. Specifically, it captures the widespread conversion of natural habitats into pastures for extensive cattle grazing, rather than a direct avoidance of livestock itself. Jaguars were also negatively affected by topographic relief, higher surface temperature and higher seasonality in temperature. The general tendency to avoid seasonal climates indicates a decline in habitat suitability as distance from the equator increases, agreeing with a range-wide prediction of population density[34]. Meanwhile, jaguar avoidance of warmer surface temperatures is likely due to physiological constraints, as big cats have a limited

capacity for thermoregulation [45]. Regarding topography, our model indicated that jaguars prefer low altitudes and valleys. This corroborates previous studies and the common understanding that high mountain ranges, such as the Andes, are probably barriers for the species [3,46]. Nevertheless, jaguars are known for their behavioural plasticity in adapting to varying conditions [38]. For instance, local studies in the Caatinga biome reported preference towards higher elevation [47,48], while others in three different biomes of Mexico reported aversion to high altitudes, with jaguars using areas characterised by moderate slopes [17,49,50]. This variation highlights the complexities and limitations associated with predicting habitat use across the species' distribution. Therefore, we reiterate that the patterns described here represent general trends, and local contexts should always be considered.

Jaguar responses to landscape features depended largely on the scale of effect, with interactions occurring at different spatial scales for each covariate. This scale-dependency in species-habitat relationships has long been known to science [51–53], and widely described in carnivore habitat selection [51–53]. Our results corroborate this general pattern, although no clear selection for coarse scales was found as described in previous studies with the two large felids of the continent [16,54].

The validation tests, along with the comparisons to previous estimates indicated that our model successfully predicted jaguar habitat suitability. For instance, the strong correlation between our predicted suitability surface and independent density estimates suggests that areas classified as highly suitable are indeed likely to support larger jaguar populations. This reinforces the model's value for conservation planning across the species' range. Building on this, we explored two complementary scenarios for categorizing habitat suitability – one based on the entire range and another stratified by ecoregion – to better understand both large-scale and region-specific conservation priorities. The range-based scenario highlighted the dominance of the Amazon, followed by the Mayan Forest, as hosting

large expanses of highly suitable habitat. These two regions have previously been identified as key strongholds for jaguar conservation [4,34], and our findings reinforce their importance. In contrast, the ecoregion-based approach, revealed additional high-value areas elsewhere, such as the Pantanal, Gran Chaco, Caatinga, and parts of Mesoamerica, underscoring the importance of regional context when setting conservation priorities. This divergence likely stems from the disproportionate extent of continuous natural habitat in the "Moist Broadleaf Forests" ecoregion – particularly the Amazon – which increases its relevance in the range-based scenario. Although the "Moist Broadleaf Forests" still contain a significant portion (59%) of highly suitable habitat in the ecoregion-based scenario, this approach also highlights other critical regions for the species, offering more a balanced insight for conservation planning.

These regional differences in habitat suitability become particularly evident when examining conditions across specific biomes and subregions under the ecoregion-based scenario. Along Mexico's coasts, for instance, our model identifies several patches of highly suitable habitat – many of them with over 1,000 km² under formal protection (Fig. 4B). Nevertheless, our predictions suggest these habitats are more isolated than previously proposed [4,34]. While the Pacific coast has been considered a continuous corridor for jaguars, our results indicate possible gaps, particularly between the Chiapas region and the mangroves around Nayarit (Fig. 1 – a). Meanwhile, Atlantic coastal habitats appear to be highly fragmented, further emphasizing the importance of protection and connectivity efforts in the region. A similar pattern emerges in Central America, where jaguar habitat is highly fragmented across six countries, despite an average of 54% of the region's highly suitable habitat being formally protected (Table 3). Consistent with previous estimates [55], our model indicates at least three areas of very low suitability that may be isolating jaguar populations – along the Guatemala-Honduras border, in central Costa Rica, and in central Panama (Fig. 1 –

b, c, d). Central America is key for maintaining jaguar population connectivity across their range. However, it faces alarming levels of forest loss and degradation [56], and early signs of genetic isolation have already been detected in local populations [57], underscoring the urgent need for continued monitoring and targeted conservation action.

In South America, the scenario is equally complex, with habitat suitability shaped by an intricate mosaic of biological and sociopolitical conditions. In the Darién Gap – at the edge between Central and South America – our model indicates favourable conditions for jaguars, consistent with previous predictions [58]. Nevertheless, the region is highly unstable due to the intense human migration and narcotrafficking activity [59,60]. The Llanos wetlands spanning Colombia and Venezuela revealed extensive areas of highly suitable habitat in our model, particularly across central regions bordering the Amazon rainforest – similarly to recent occupancy predictions for the biome [61]. Since European colonization, cattle ranching has dominated land use in the region, contributing to habitat loss and increased human–jaguar conflict. Today, only 14% of the jaguar's current range in the Llanos is formally protected [61]. Despite these pressures, several independent studies have reported relatively high jaguar densities across the biome [61–63], highlighting the Llanos' importance for the species and its potential as an ecological corridor linking southern and northern jaguar populations in South America. In the other major South American freshwater wetland, the Pantanal, a similar scenario unfolds with high jaguar population densities frequently reported despite the dominance of privately owned cattle ranches, occupying approximately 90% of the biome [64–66]. In recent years, however, the biome has faced increasing threats from wildfires, exacerbated by extreme droughts and expanding land conversion [67,68]. Several of these fires occurred in areas identified as highly suitable for jaguars – particularly in the northern and central portions of the biome – indicating a disproportional impacting to the species in the region [67]. Our models indicate that the highly suitable habitats of the Pantanal are directly

connected to those of the Gran Chaco along its western borders, spanning Brazil, Bolivia, Paraguay, and Argentina. This forms the second-largest expanse of continuous suitable habitat for jaguars after the Amazon (Fig. 2). Although protected areas are sparse across the Gran Chaco – covering only about 9% of the biome – nearly all of them encompass more than 1,000 km² of highly suitable habitat (Fig. 4). However, the region is undergoing rapid human encroachment, and much of its jaguar habitat is under significant pressure from habitat loss and overhunting [69]. This is particularly concerning given that jaguar populations in the Gran Chaco are generally small [70,71], further increasing their vulnerability.

Three other key biomes for jaguars also warrant attention: the Atlantic Forest, Caatinga and Cerrado. The Atlantic Forest is classified as a "Moist Broadleaf Forest" and therefore presents larger extents of highly suitable habitat under the range-based scenario (Fig. 2A). As previously predicted [21], the largest highly suitable areas are concentrated in the Serra do Mar region (Fig. 1 – e) and the Green Corridor of Misiones (Fig. 1 – f). While these patches offer hope for jaguar recovery, the biome's extreme fragmentation poses a major challenge. Signs of declining genetic diversity have already been detected in the region's jaguar populations [72], and our models indicate that only the two aforementioned regions contain PAs with more than 1,000 km² of highly suitable habitat (Fig. 4A). In the Caatinga, our model identified the central-western region as the main stronghold for jaguars, aligning with prior studies [48]. The jaguar population in this biome is considered Critically Endangered, and signs of reduced genetic diversity have also been reported in the region [73]. Previous studies suggest that the biome's main potential connection to other populations is likely through the Cerrado along its western edge [18,74]. Although our study did not explicitly assess connectivity, our suitability predictions point in the same direction with higher levels of suitability around *Serra das Confusões* National Park (NP) and a protected area complex (*APA Dunas e Veredas do Baixo-Médio São Francisco* and *Boqueirão da Onça* APA and

NP) – both encompassing areas with more than 1000 km² of highly suitable habitat (Fig. 5B). As for the Cerrado, our predictions identified five main areas of continuous highly suitable habitat in the west and central-northern regions (Fig. 1 – g, h, i, j, k), partially aligning with previous studies [18,75,76]. Four of these areas (Fig. 1 – h, i, j, k) lie within the MaToPiBa region (an acronym for the Brazilian states of Maranhão, Tocantins, Piauí and Bahia), which is under intense anthropogenic pressure as it represents the current frontier of agricultural expansion [77,78]. Despite these growing threats, the Cerrado still retains approximately half of its natural vegetation [79], underscoring its importance for jaguar conservation. Owing to its central position within the jaguar's range, the Cerrado also functions as a crucial ecological corridor connecting multiple biomes – a role reflected in the spatial distribution of highly suitable areas identified by our models.

As the biome-level patterns illustrate, highly suitable jaguar habitats are distributed across a mosaic of land management types. To better understand the protection status of these areas, we examined their overlap with JCUs, PAs, and non-designated lands. JCUs, while identified by experts as areas of high conservation relevance, do not carry formal political designation and thus have limited practical effect for the species conservation [15]. Nonetheless, our model suggests that JCUs encompass a substantial share of priority areas, containing 76.7% and 62.2% of highly suitable habitats in the range-based and ecoregion-based scenarios, respectively. However, the assessment also reveals reduced suitability in smaller, isolated JCUs, underscoring the need for targeted monitoring and support for these areas. The same holds true for PAs, despite their evident effectiveness in securing suitable habitats for jaguars. Roughly half of all suitable habitats fall within PAs' boundaries regardless of how they were assessed – total summed suitability (54%) or highly suitable areas (range-based: 59% and ecoregion-based: 47%). A strong body of literature already shows the key role that protected areas and Indigenous Lands have in safeguarding natural habitats and biodiversity

[80,81] and our study reinforces that. Still, conservation efforts should also extend beyond formally designated areas, as significant portions of highly suitable habitat remain unprotected. One prominent example is the extensive area of non-designated public lands in Brazil, which – despite covering only 4% of the species' current range (about 63.5 million hectares) – contain nearly 10% of the predicted suitable habitat under both scenarios assessed. These lands also account for 50% of all deforestation in the Amazon [82] – something that could be greatly reduced by designating them for legal protection or sustainable use. Such actions would strengthen the PA network in the Amazon, ensuring protection of large continuous natural areas, benefiting not only jaguars but the entire ecosystem.

In the national level assessment, we calculated the area covered by highly suitable habitat for jaguars as well as how much of it is formally protected. Overall, countries encompassing the Amazon biome totalled the largest areas of suitable habitat. This pattern is particularly pronounced under the range-based scenario, with Brazil, Peru, Colombia, and Venezuela leading the list – each containing between 7.8 and 1.0 million km² of highly suitable habitat. As described before, though, under the ecoregion-based scenario this pattern becomes more geographically distributed. Peripheral countries at the edges of the jaguar's current range see a marked increase in the proportion of their territory identified as highly suitable. For instance, when considering the percentage of highly suitable habitat relative to each country's current range, Argentina, Paraguay, and the United States shift from having almost no suitable area in the range-based scenario to 29%, 42%, and 13%, respectively, in the ecoregion-based scenario. Considering formal protection of the highly suitable habitats, the average protection was relatively high regardless of the scenario considered – 54.3% in the range-based scenario and 43.4% ecoregion-based scenario. As jaguars require large areas of natural habitat to thrive, implementing new PAs is a strategy that tends to benefit a range of other species in the habitat - the "umbrella" effect [83]. In this sense, our results produce a

good overview and update of the species' main habitats, providing a good starting point for conservation planning at a national level.

Scope and limitations

Modelling exercises are simplifications of reality and, as such, are inherently imperfect. Our model aimed to identify suitable habitats across a vast and highly heterogeneous region – a challenging proposition even with a dataset as diverse as ours. Although we combined an impressive dataset of 172 monitored jaguars, our dataset was uneven, with areas such as the eastern and western Mexican coasts underrepresented. This uneven sampling prevented us to fully evaluate individual and regional variations across our study area (e.g., ecoregion-specific models subsequently integrated into a single ensemble prediction). To account for regional and individual variability, we included jaguar identity as a random effect, partially isolating such differences. Nonetheless, adding more individuals, particularly from underrepresented regions, would certainly benefit the model.

Our dataset had great variability in interval frequency of the GPS-locations; therefore, it was not possible to predict habitat use through more refined methods, such as step and path selection functions. Nevertheless, all validations showed our predictions were highly accurate. This indicates that our approach was capable of producing robust predictions, retaining the landscape features selected by the species and predicting spatial patterns of suitable habitat.

Finally, although our data were limited to areas where jaguars are currently found, we extrapolated predictions across the species' historic range (as considered in this study). We recognize that extrapolating into such areas carries uncertainty, particularly because validation is not feasible. Therefore, predictions in these regions should be interpreted with caution. In our view, though, the broader suitability surface provides value as an exploratory

exercise, potentially supporting field assessments and informing reintroduction and translocation initiatives – such as the ongoing efforts led by Rewilding Argentina in Iberá. Furthermore, generating a continuous suitability surface across the historic range benefits future analyses, including the development of resistance surfaces and connectivity modelling [10].

We hope our model serves as a valuable tool for governments and international agencies in developing effective conservation policies. Anthropogenic pressure, in various guises, is undeniably threatening the remaining jaguar habitat and our study highlights large, continuous protected areas as keystone elements in the network of high-quality jaguar habitat across its range. Considering the species vulnerability to landscape and climate change [84], we strongly advocate for the expansion of protected areas and Indigenous Lands, alongside the reinforcement of existing ones, to ensure the species' long-term adaptability. Equally important, guaranteeing connectivity across the range is paramount to maintain healthy jaguar populations. As a strong response to these threats, we call for the immediate allocation of currently non-designated lands for conservation and sustainable use, reinforcing global commitments to wildlife protection.

Methods

Study area & Jaguar telemetry data

The study area covers the entire jaguar historical range (19,000,000 km²), from southwest US to central Argentina [2] (Fig. 5). However, the precise boundaries of this historical range remain uncertain, leading to disagreements among experts regarding its true extent. These uncertainties are particularly notable at the edges, such as Baja California (Mexico) and the region near Península Valdés (Argentina), where historical jaguar presence is debated. For the purposes of this study, we consider the jaguar's historical range based on

the map previously produced[15], which represents the extent of knowledge about the species' status and distribution rather than a definitive record of past occurrence. This vast area exhibits great ecological heterogeneity, encompassing a diverse range of biological conditions reflected, for example, in the variety of habitats it harbours. It includes tropical rainforests, wetlands, dry forests, xeric forests, montane forests, temperate forests, savannahs, mangroves, and grasslands [15].

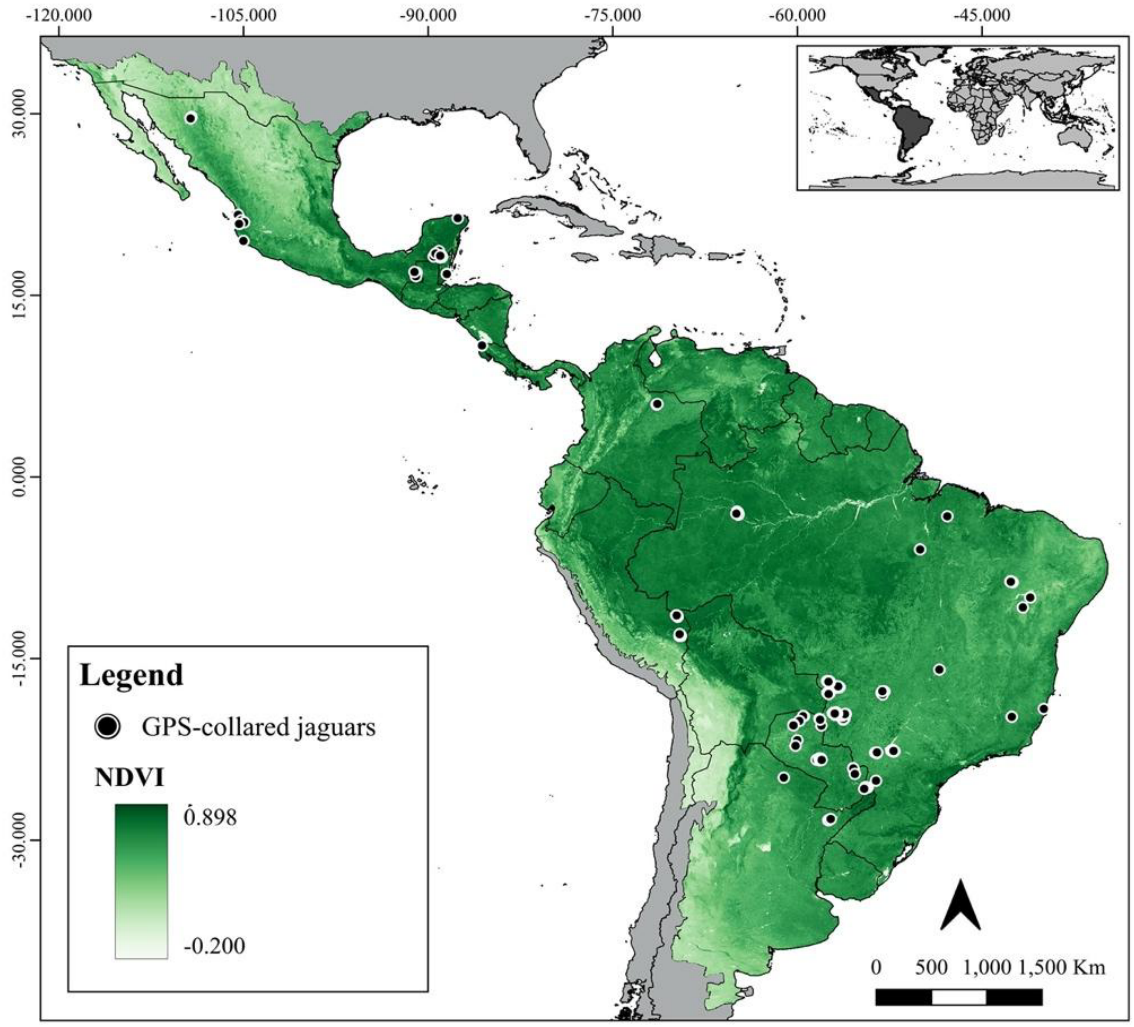


Figure 5. Reference sites of 172 GPS-collared jaguars (231,017 locations) monitored across the species range. The map depicts the mean normalized difference vegetation index (NDVI) in 2021 within the historical species range and the countries in grey. Figure created using QGIS v3.36.0 (https://qgis.org).

We used GPS collar-tracking data from 172 jaguars (86 females and 86 males) captured and monitored in eight different countries: Argentina, Belize, Brazil, Colombia, Costa Rica, Mexico, Paraguay, and Peru (Fig. 5 and Supplementary Table S1). This dataset combines data from 117 jaguars originally published in a data paper [85] and 55 additional individuals monitored under additional research projects led by co-authors of this study. All captures were conducted in accordance with the relevant institutional and governmental guidelines at the time, under permits obtained by the original project teams. No animals were captured specifically for this study. Jaguars were monitored across a wide range of ecological conditions, from arid regions of the xeric forests in the Northeast Brazil and the scrublands in the Northern Mexico, through tropical forests of the Atlantic Forest and the Mayan Forests, to the flooded habitats in the Paraguayan Chaco, Pantanal, and Amazonian floodplain forests. Since jaguars are capable of living in widely different ecological conditions, it is essential to represent habitat use across their range to produce accurate resource selection models [86].

Telemetry data processing

The 172 collared individuals (231,017 GPS locations) were monitored over different time periods across 25 years (from 1999 to 2023) with varying frequency intervals between the GPS-locations (Supplementary Table S1). To limit potential spatial bias, the locations of each individual were spatially rarefied, allowing only one location per 500 m pixel [87]. We applied a point selection function in which the 'used' habitat was sampled from the rarefied jaguar GPS-locations, and the 'available' habitat was sampled from randomly created background points. Background points did not overlap among themselves or with GPS-locations but were temporally and spatially delimited by the distribution of the GPS-locations of each jaguar.

Defining the size of the area available to create background points is crucial in resource selection functions as it directly affects model performance and covariate importance [88]. Essentially, background points should be a representation of the areas potentially available to an individual [89]. To define the available area for each individual, we used an estimate, in which home range size of mammalian species and their median dispersal distance is isometrically related by a multiple of seven [90]. We thus first averaged jaguar home range size for each biome, accounting for males and females separately [30]. Secondly, we extracted the square root of these home ranges and multiplied them by seven to calculate the potential dispersal distances per sex and biome (2nd order-selection [91]). These dispersal distances were used to create a buffer around GPS-locations of each jaguar, reflecting the available area for that individual. Within this buffer we randomly created 10 background points per each GPS-location, temporally matching them (e. g. for 100 GPS-locations from January 2020, 1,000 background points would be created with the assigned January 2020 date). Temporal matching was important to correctly reflect the relationships between GPS-locations and background points when extracting information from the covariates. Finally, the dataset was divided into training (80% of presences) and validating data (20% remaining).

Predictor variables

To model jaguar habitat suitability, we selected a set of anthropogenic, ecological, climatic and geomorphologic variables known to influence wild felids with large home ranges [21,92,93] (Table 4). The pervasive effects of human activities, such as habitat loss, fragmentation, direct persecution and depletion of prey populations are among the main threats to jaguars [3]. To account for these threats, we used the following variables: the global human disturbance index, human population density, night lights, roads, defaunation index, forest degradation, fire, and livestock density. For roads, we considered trunks, motorways,

primary and secondary classes, excluding small unpaved classes because they may have opposite effects on jaguars – unpaved roads could be used as travel routes, while paved ones tend to be avoided [27,94,95]. To calculate the defaunation index, we used the dataset and approach of a previous study [96] and pruned it to our study area. For the livestock density covariate, we combined the layers of cows (FAO [97]), goats (FAO [98]), and sheep (FAO [99]) as all three species tend to graze in open spaces and can be attacked by jaguars. Among ecological covariates, we tested: normalized difference vegetation index (NDVI), gross primary production (GPP), percentage of tree cover and canopy height. To describe climatic variability across the jaguar range, we selected land surface temperature, mean annual temperature, temperature seasonality, mean annual precipitation and precipitation seasonality. As our study area has significant variation in topography and soil composition, both known to influence jaguars and other large carnivores [93,100], we chose elevation, topographic position index (TPI), compound topographic index (CTI), roughness, soil organic carbon, cation exchange capacity (CEC), clay, sand, nitrogen, and water surface. CTI, or wetness index, identifies the potential for water accumulation and flow [101]. Roughness describes terrain ruggedness while TPI assesses the relative position of a focal point in comparison to its surroundings, identifying if the point is in a flat area, a ridge or valley for example [102,103]. As for soil composition, CEC represents soil capacity to hold/exchange ions, which directly affects soil fertility [104]. All predictors were incorporated in numeric form – 28 as continuous variables and one (night lights) as binary – and used as untransformed gradients in the model. Roads, the only predictor originally provided as a vector layer, was rasterised into a binary layer. All the layers were resampled to 500 m as a reasonable trade-off between the size of the area considered in this analysis and jaguar movement patterns. A summary of original format, units, and final data structure for each predictor is provided in Table 4.

Table 4. Data used to derive covariates tested in the jaguar habitat suitability model.

Category	Covariates	Resolution (m)	Year	Data type	Source
Anthropogenic	Global Human Modification	1000	2016	Continuous (0 to 1)	(Kennedy et al., 2019)
	Human Population Density	100	2002-2013[1]	Continuous (0 to 24,218)	(Sorichetta et al., 2015); www.worldpop.org
	Night Lights	1000	1992-2020	Continuous (0 to 63)	(Li et al., 2020)
	Roads	Shapefile	2022	Binary (0/1)	OSM, www.openstreetmap.org
	Defaunation Index	500	1993-2019[2]	Continuous (0 to 1)	(Bogoni et al., 2020)
	Forest Degradation	30	1999-2021	Continuous (0 to 1)	(Vancutsem et al., 2021); EC JRC
	Fire	500	2000-2022	Binary (0/1)	(Giglio et al., 2015)
	Livestock Density	1000	2005	Continuous (0 to 13,958)	(Gilbert et al., 2018a, 2018b, 2018c) FAO
Biological	Normalized Difference Vegetation Index (NDVI)	500	2000-2022	Continuous (-1 to +1)	(Didan, 2015); NASA EOSDIS Land Processes DAAC
	Gross Primary Production (GPP)	500	2000-2022	Continuous (0 to 0.3)	(Running et al., 2015); NASA EOSDIS Land Processes DAAC
	Percentage of Tree Cover	250	2000-2020	Continuous (0 to 1)	(DiMiceli et al., 2015); NASA EOSDIS Land Processes DAAC
	Canopy Height	30	2019	Continuous (0 to 36)	(Potapov et al., 2020); NASA GEDI
Climatic	Land Surface Temperature	1000	2000-2022[3]	Continuous (-0.4 to 48.9)	(Wan et al., 2021); NASA EOSDIS Land Processes DAAC
	Mean Annual Temperature	1000	1979-2013[4]	Continuous (-87 to 293)	(Brun et al., 2022); CHELSA-BIOCLIM+
	Temperature Seasonality			Continuous (147 to 8,283)	
	Mean Annual Precipitation			Continuous (12 to 11,089)	
	Precipitation Seasonality			Continuous (6 to 250)	
Geomorphological	Elevation	90	2000	Continuous (-71 to 6,292)	(Jarvis et al., 2008)
	Topographic Position Index (TPI)	90	2000	Continuous (-15 to 15.9)	(Amatulli et al., 2020)
	Compound Topographic Index (CTI)			Continuous (-4 to 10.2)	
	Roughness			Continuous (0 to 297)	
	Soil Organic Carbon	250	1960-2022[5]	Continuous (10 to 2,443)	(Hengl et al., 2017)

Cation Exchange Capacity (CEC)			Continuous (26 to 597)	
Clay			Continuous (34 to 707)	
Sand			Continuous (5.3 to 879.1)	
Nitrogen			Continuous (152 to 12,222)	
Water surface	30	1999-2020	Continuous (0 to 100)	(Pickens et al., 2020)

[1]It uses census from 2002 to 2013 to create one raster. [2]Authors combined mammal assemblage data covering this temporal range. [3]We calculated the seasonal mean for all years of the range, producing one layer for each season. [4]Mean of all years of the range. [5]It aggregates soil data from before 1960 until today.

Data analysis

Resource selection is inherently scale-dependent, and habitat use can be driven not only by local site characteristics but also by broader landscape context [12,105]. To account for this, we identified the best spatial scale for each tested covariate, following a multi-scale optimization approach (*sensu* [12,13]). For each covariate, we fitted a Gaussian kernel of varying width around presences and pseudo-absences, reflecting seven spatial scales: 0.5 km, 1 km, 2 km, 4 km, 8 km, 16 km, and 32 km. These scales were selected based on previous studies on jaguars [16] and clouded leopards [106]. Whenever possible, covariates, GPS-locations and background points were temporally matched or assigned to the closest date. Thus fire, forest degradation, night lights, and percentage of tree cover were annually matched, while GPP and NDVI were seasonally and annually matched, and surface temperature and water surface were seasonally averaged from data ranging from 2000-2020. All other variables were used according to the date/year available. Spatial analyses were done in R v3.5.1 [107], QGIS v3.36.0 [108], and Google Earth Engine [109].

Previous studies have shown that individual jaguars often behave differently, adapting according to the resources available in the landscape [30,110]. To account for this variability in individual behaviour, we applied conditional logistic regression (Generalized Linear Mixed Model - GLMM), accounting for jaguar ID as the random factor, to evaluate jaguars' habitat

use. For variable selection we adopted an approach identified by a comprehensive simulation [13] as the best workflow for variables and scale optimization. Firstly, we ran mixed-effect conditional logistic models at each scale, followed by model selection based on Akaike Information Criterion corrected for small sample size (AICc), retaining the scale for each variable with the lowest AICc [111]. Once the optimal scales were defined, we used the minimum redundancy-maximum relevance (mRMR) technique to find the most complementary and relevant set of covariates, applying Spearman's estimator to test covariates correlation [112].

As a good balance between model complexity and prediction performance, we selected the 15 most relevant covariates at their optimal scales. In the final step, the remaining covariates were standardized, and we applied a multiple mixed-effect conditional logistic regression model (random factor: jaguar ID). To produce the suitability surface, we used the most recent layers of the covariates selected in the final model at their optimal scale. Because RSFs fitted to use–availability data estimate relative selection strength rather than absolute probability of occurrence, predicted values represent proportional selection [113]. Accordingly, the final suitability surface is visualized using a continuous low-to-high gradient rather than an absolute probability scale. For mapping and model validation, the prediction raster was classified into ten equal-frequency (quantile-based) bins to ensure consistency with the Boyce Index assessment, with linear colour interpolation applied solely to smooth visual transitions between classes. The covariates "surface temperature", "water surface", and "NDVI" had their seasonal values averaged also using the most recent date possible. Models were conducted in R v3.5.1 [107], with packages *mRMRe* [112] and *lme4* [114], and predictions across the whole range were generated with the package *terra* [115].

Model validation and comparison

We evaluated our suitability surface using three different datasets and two approaches. In the first approach, we used the 20% of our dataset that was set aside for validation to assess how much the model differed from random expectations applying the Boyce index - a method widely used to evaluate models developed based on presence-only data [116]. This method divides the prediction layer into bins (classes) based on intervals of predicted values – in our case 10 equal-frequency bins representing 10 quantiles – and measures the frequency of predicted and expected values for each class [116]. The Boyce index varies between -1 and 1, with negative values indicating counter predictions, values close to zero a random model and values near 1 a highly accurate prediction [117]. In the second approach, we selected a completely independent dataset – jaguar occurrence records [118] – and calculated the area under the Receiver Operating Characteristic (ROC) curve (AUC), computed with the *pROC* package in R [119]. We also identified the optimal classification threshold based on the point closest to the top-left corner of the ROC space to calculate model sensitivity and specificity. The jaguar occurrence records (presence-absence) were derived from several sources, such as camera trapping, line transects and interviews, and were filtered to include only data from the most recent five-year period available (2013-2018) (N=2161).

Additionally, we compared our suitability surface with other predictions available in literature. Specifically, we compiled jaguar density estimates from literature by combining data from Jędrzejewski et al. (2018) [34] with additional studies published since then. To minimize potential bias from differing density estimation methods, we included only estimates derived from spatial explicit capture-recapture models (SECR) (Supplementary Table S2; N=80). For each location, we generated a buffer with an area of 100 km² – the scale used in jaguar density estimates – and extracted the average suitability within each buffer to serve as the predictor variable in a linear regression analysis. Finally, to assess the

consistency between different methodologies, we performed a Pearson correlation test between our suitability surface and the distribution model from Jędrzejewski et al. (2018) [34].

Conservation implications

To assess the conservation implications of our suitability surface, we evaluated the distribution of suitable habitats across non-designated lands (specific to Brazil), JCUs, PAs and countries. Non-designated lands are public areas that have not been officially assigned for specific uses, such as Indigenous Lands, protected areas, or agrarian reform settlements (Supplementary Fig. S5). In Brazil, these lands cover approximately 63.5 million hectares, primarily distributed across the Cerrado (savannahs) and Amazon biomes, and due to their unclear ownership, are highly vulnerable to illegal deforestation and land grabbing (*grilagem* in Portuguese) [82].

In the following analyses, we used the most up-to-date layers of non-designated lands [120], JCUs [121] and PAs (including Indigenous Lands) (Supplementary Fig. S5). The PAs layer from the World Database [122] was refined using a South American dataset [8] and country-level information with the support of experts. During this process, adjacent PAs within the same country were merged and assessed as one single protected block. While we acknowledge that different PA categories have varying levels of law enforcement, our primary goal was to distinguish protected (implemented with whatever stringency) from non-protected areas, which was both more feasible and informative than evaluating each category separately. To be included in our assessment, PAs (or PA blocks) had to meet three criteria: they had to be larger than 100 km², as jaguar are less likely to occur in smaller PAs [22]; located below 3,000 m in elevation, since no confirmed jaguar records exist above this threshold [123]; and intersect the jaguar's current range. As an estimate of current range, we combined the updated South America distribution [8] with the WCS jaguar distribution layer for the remaining area (from

Panama to South US [124]). Finally, assuming potential spatial uncertainties in the data and the species' high mobility (median dispersal distance: 111 km, calculated following Bowman et al., 2002 [90]), we applied a 100 km buffer around the estimated distribution. We considered this buffered area as the final jaguar's current range and used it to filter PAs for our assessment – except for El Salvador, where jaguars are currently extinct (Supplementary Fig. S5).

To explore our results, we used two complementary approaches: one treating the suitability surface as continuous data, and another based on categorized values. In the first, we calculated the summed total predicted habitat suitability across the species' current range and extracted the proportion of this total found within non-designated lands, JCUs, and PAs. In the second approach, we classified as highly suitable those areas falling within the upper quartile (top 25%) of the suitability surface. This classification was applied in two ways: first, across the entire current range (range-based scenario), and second, separately within each ecoregion (ecoregion-based scenario). In the range-based scenario, we quantified the amount of highly suitable habitat for the entire range as a unit, extracting then its amount within non-designated lands, JCUs, PAs, and countries. In the ecoregion-based scenario, we identified the highly suitability values within each ecoregion and then calculated how much of that highly suitable habitat fell within the same land categories. Because larger JCUs and PAs are more likely to contain more suitable habitat, we also calculated the proportion of highly suitable habitat relative to the area of each unit. Finally, to assess the importance of JCUs and PAs independently of size, we grouped them into five categories based on the percentage of highly suitable habitat they contain: 100–75%, 75–50%, 50–25%, 25–0%, and 0%.

Acknowledgements

GCA doctorate is supported by a grant to David Macdonald at WildCRU from the Robertson Foundation. We are extremely grateful to the Alianza WWF-Fundación, Telmex/Telcel, the Universidad Nacional Autónoma de México (project DGAPA, PAPIT IN208017), and Amigos de Calakmul A.C. for their financial support. We extend special thanks to the ejidos Caobas and Laguna Om, as well as the Calakmul Biosphere Reserve, for granting permission to conduct our research on their lands. The Instituto Homem Pantaneiro is grateful to ICMBio/CENAP, Panthera Brasil, and Onçafari for their valuable partnerships. The Mamirauá Institute thanks CNPq for the scholarships, and the communities of Mamirauá Sustainable Development Reserve for their essential field support - especially Lázaro Pinto dos Santos (Lazinho) and Railgler Gomes dos Santos (Raí), in memoriam. ACSA thanks the Espírito Santo Research and Innovation Support Foundation (FAPES) for funding the project (FAPES 510/2016), as well as for the Capixaba Researcher Fellowship (FAPES 404/2022). All figures were created by GCA using QGIS v3.36.0 (https://qgis.org). Editorial assistance was provided by ChatGPT (OpenAI) to improve clarity and language use.

Data Availability Statement

GPS telemetry data for 117 of the 172 jaguar individuals used in this study are publicly available via Morato et al. (2018) [82]. The remaining 55 individuals were provided by collaborators and remain under the stewardship of their respective research groups; these data are not publicly available due to ongoing research use and data-sharing agreements. However, access to these data may be granted upon reasonable request to the corresponding authors, pending approval from the original data providers. The resulting habitat suitability surface generated by this study will be made openly available on the Zenodo repository upon manuscript acceptance (currently accessible for peer review at:

https://zenodo.org/records/15824344?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjY3YTJjNzhjLTVmMzItNDFhZi04YmY1LTk0NTQzZmFkYjgyZSIsImRhdGEiOnt9LCJyYW5kb20iOiJiYTI3YTBjNDRhOGRkNjk3NWI1ZGI1OWEyMDRkYWU3NCJ9._5XjPvxWOw4azyxXv4Ww-eaoHm1FG54BexND5TEEsmBnBTahFRBpbdScnwD_8McXtH-eNHyVaqA6hoWbieufCQ).

References

1. Sunquist, M. E. & Sunquist, F. C. Ecological Constraints on Predation by Large Felids. Carnivore Behavior, Ecology, and Evolution 283–301 (1989).

2. Seymour, K. L. *Panthera onca*. Mammalian Species 340, 1–9 (1989).

3. Quigley, H. et al. *Pantera onca*. The IUCN Red List of Threatened Species 8235, 8 (2017).

4. Ceballos, G. et al. Beyond words: From jaguar population trends to conservation and public policy in Mexico. PLoS One 16, 1–22 (2021).

5. de la Torre, J. A., González-Maya, J. F., Zarza, H., Ceballos, G. & Medellín, R. A. The jaguar's spots are darker than they appear: assessing the global conservation status of the jaguar Panthera onca. Oryx 52, 300–315 (2018).

6. Alvarenga, G. C. et al. Jaguar (*Panthera onca*) density and population size across protected areas and indigenous lands in the Amazon biome, its largest stronghold. Biol Conserv 303, 111010 (2025).

7. Berzins, R. et al. Distribution and status of the jaguar in the Guiana shield. Cat News Special Issue 16, 1–22 (2023).

8. Jędrzejewski, W. et al. Estimating species distribution changes due to human impacts: the 2020's status of the jaguar in South America. CATnews Special Issue 16, 44–55 (2023).

9. Meyer, C. B. & Thuiller, W. Accuracy of resource selection functions across spatial scales. Divers Distrib 12, 288–297 (2006).

10. Zeller, K. A., McGarigal, K. & Whiteley, A. R. Estimating landscape resistance to movement: A review. Landsc Ecol 27, 777–797 (2012).

11. Mateo Sánchez, M. C., Cushman, S. A. & Saura, S. Scale dependence in habitat selection: the case of the endangered brown bear (*Ursus arctos*) in the Cantabrian Range

(NW Spain). International Journal of Geographical Information Science 28, 1531–1546 (2014).

12. McGarigal, K., Zeller, K. A. & Cushman, S. A. Multi-scale habitat selection modeling: introduction to the special issue. Landsc Ecol 31, 1157–1160 (2016).

13. Cushman, S. A. et al. Simulating multi-scale optimization and variable selection in species distribution modeling. Ecol Inform 83, 102832 (2024).

14. Macdonald, D. W. et al. Multi-scale habitat modelling identifies spatial conservation priorities for mainland clouded leopards (*Neofelis nebulosa*). Divers Distrib 00, 1–16 (2019).

15. Sanderson, E. W. et al. Planning to save a species: The jaguar as a model. Conservation Biology 16, 58–72 (2002).

16. Alvarenga, G. C. et al. Multi-scale path-level analysis of jaguar habitat use in the Pantanal ecosystem. Biol Conserv 253, (2021).

17. Balbuena-Serrano, Á. et al. Connectivity of priority areas for the conservation of large carnivores in northern Mexico. J Nat Conserv 65, (2022).

18. Ferraz, K. M. P. M. et al. Distribuição potencial e adequabilidade ambiental dos biomas brasileiros à ocorrência da onça-pintada. in Plano Nacional para Conservação da Onça-Pintada (eds. Paula, R. C. de, Desdiez, A. & Cavalcanti., S.) 125–206 (Instituto Chico Mendes de Conservação da Biodiversidade, ICMBio, Brasília, 2013).

19. Petracca, L. S. et al. Robust inference on large-scale species habitat use with interview data: The status of jaguars outside protected areas in Central America. Journal of Applied Ecology 55, 723–734 (2018).

20. Figel, J. J., Botero-Cañola, S., Lavariega, M. C. & Luna-Krauletz, M. D. Overlooked jaguar guardians: Indigenous territories and range-wide conservation of a cultural icon. Ambio https://doi.org/10.1007/s13280-022-01754-8 (2022).

21. Paviolo, A. et al. A biodiversity hotspot losing its top predator: The challenge of jaguar conservation in the Atlantic Forest of South America. Sci Rep 6, (2016).

22. Sollmann, R., Torres, N. M. & Silveira, L. Jaguar conservation in Brazil: the role of Protected Areas. CAT News 4, 15–20 (2008).

23. De Angelo, C., Paviolo, A., Wiegand, T., Kanagaraj, R. & Di Bitetti, M. S. Understanding species persistence for defining conservation actions: A management landscape for jaguars in the Atlantic Forest. Biol Conserv 159, 422–433 (2013).

24. Gese, E. M., Terletzky, P. A., Cavalcanti, S. M. C. & Neale, C. M. U. Influence of behavioral state, sex, and season on resource selection by jaguars (*Panthera onca*): Always on the prowl? Ecosphere 9, e02341 (2018).

25. Craighead, K., Yacelga, M., Wan, H. Y., Vogt, R. & Cushman, S. A. Scale-dependent seasonal habitat selection by jaguars (*Panthera onca*) and pumas (*Puma concolor*) in Panama. Landsc Ecol 37, 129–146 (2022).

26. Conde, D. A. et al. Sex matters: Modeling male and female habitat differences for jaguar conservation. Biol Conserv 143, 1980–1988 (2010).

27. Colchero, F. et al. Jaguars on the move: Modeling movement to mitigate fragmentation from road expansion in the Mayan Forest. Anim Conserv 14, 158–166 (2011).

28. Rodríguez-Soto, C., Monroy-Vilchis, O. & Zarco-González, M. M. Corridors for jaguar (*Panthera onca*) in Mexico: conservation strategies. J Nat Conserv 21, 438–443 (2013).

29. Harmsen, B. J. et al. Long term monitoring of jaguars in the Cockscomb Basin Wildlife Sanctuary, Belize; Implications for camera trap studies of carnivores. PLoS One 12, 1–19 (2017).

30. Thompson, J. J. et al. Environmental and anthropogenic factors synergistically affect space use of jaguars. Current Biology 31, 3457-3466.e4 (2021).

31. Srbek-Araujo, A. C. Do female jaguars (*Panthera onca* Linnaeus, 1758) deliberately avoid camera traps? Mammalian Biology 88, 26–30 (2018).

32. Cerqueira, R. C., de Rivera, O. R., Jaeger, J. A. G. & Grilo, C. Direct and indirect effects of roads on space use by jaguars in Brazil. Sci Rep 11, 1–9 (2021).

33. Alegre, V. B. et al. The effect of anthropogenic features on the habitat selection of a large carnivore is conditional on sex and circadian period, suggesting a landscape of coexistence. J Nat Conserv 73, 126412 (2023).

34. Jędrzejewski, W. et al. Estimating large carnivore populations at global scale based on spatial predictions of density and distribution - Application to the jaguar (*Panthera onca*). PLoS One 13, 1–25 (2018).

35. Tôrres, N. M. et al. Can species distribution modelling provide estimates of population densities? A case study with jaguars in the Neotropics. Divers Distrib 18, 615–627 (2012).

36. Wasserman, T. N., Cushman, S. A., Shirk, A. S., Landguth, E. L. & Littell, J. S. Simulating the effects of climate change on population connectivity of American marten (*Martes americana*) in the northern Rocky Mountains, USA. Landsc Ecol 27, 211–225 (2012).

37. Wan, H. Y. et al. Meta-replication reveals nonstationarity in multi-scale habitat selection of Mexican spotted owl. The Condor: Ornithological Applications 119, 641–658 (2017).

38. Morato, R. G. et al. Resource selection in an apex predator and variation in response to local landscape characteristics. Biol Conserv 228, 233–240 (2018).

39. Villalva, P., Palomares, F. & Zanin, M. Effect of uneven tolerance to human disturbance on dominance interactions of top predators. Conservation Biology 39, 1–10 (2024).

40. Eriksson, C. E. et al. Extensive aquatic subsidies lead to territorial breakdown and high density of an apex predator. Ecology e03543 (2021) doi:10.1002/ecy.3543.

41. Azevedo, F. C. C. & Verdade, L. M. Predator-prey interactions: Jaguar predation on caiman in a floodplain forest. J Zool 286, 200–207 (2012).

42. Schaller, G. B. & Crawshaw, P. G. Movement Patterns of Jaguar. Biotropica 12, 161–168 (1980).

43. Khamila, C. N. et al. There is a trade-off between forest productivity and animal biodiversity in Europe. Biodivers Conserv 32, 1879–1899 (2023).

44. Peña-Mondragón, J. L., Castillo, A., Hoogesteijn, A. & Martínez-Meyer, E. Livestock predation by jaguars *Panthera onca* in south-eastern Mexico: the role of local peoples' practices. Oryx 51, 254–262 (2016).

45. Stryker, J. A. Thermoregulatory Behaviour Assessment and Thermal Imaging of Large Felids. (The University of Guelph, 2016).

46. Rabinowitz, A. & Zeller, K. A. A range-wide model of landscape connectivity and conservation for the jaguar, *Panthera onca*. Biol Conserv 143, 939–945 (2010).

47. Astete, S. et al. Living in extreme environments: modeling habitat suitability for jaguars, pumas, and their prey in a semiarid habitat. J Mammal 98, 464–474 (2017).

48. Morato, R. G., Ferraz, K. M. P. M. D. B., De Paula, R. C. & Campos, C. B. De. Identification of priority conservation areas and potential corridors for Jaguars in the Caatinga Biome, Brazil. PLoS One 9, (2014).

49. de la Torre, J. A., Núñez, J. M. & Medellín, R. A. Habitat availability and connectivity for jaguars (*Panthera onca*) in the Southern Mayan Forest: Conservation priorities for a fragmented landscape. Biol Conserv 206, 270–282 (2017).

50. Ramirez-Reyes, C., Bateman, B. L. & Radeloff, V. C. Effects of habitat suitability and minimum patch size thresholds on the assessment of landscape connectivity for jaguars in the Sierra Gorda, Mexico. Biol Conserv 204, 296–305 (2016).

51. Penjor, U., Kaszta, Ż., Macdonald, D. W. & Cushman, S. A. Prioritizing areas for conservation outside the existing protected area network in Bhutan: the use of multi-species, multi-scale habitat suitability models. Landsc Ecol 36, 1281–1309 (2021).

52. Chiaverini, L. et al. Multi-scale, multivariate community models improve designation of biodiversity hotspots in the Sunda Islands. Anim Conserv 25, 660–679 (2022).

53. Macdonald, D. W. et al. Predicting biodiversity richness in rapidly changing landscapes: climate, low human pressure or protection as salvation? Biodivers Conserv 29, 4035–4057 (2020).

54. Zeller, K. A., Vickers, T. W., Ernest, H. B. & Boyce, W. M. Multi-level, multi-scale resource selection functions and resistance surfaces for conservation planning: Pumas as a case study. PLoS One 12, e0179570 (2017).

55. Calderón, A. P. et al. Occupancy models reveal potential of conservation prioritization for Central American jaguars. Anim Conserv 1–12 (2022). https://doi.org/10.1111/acv.12772.

56. Redo, D. J., Grau, H. R., Aide, T. M. & Clark, M. L. Asymmetric forest transition driven by the interaction of socioeconomic development and environmental heterogeneity in Central America. Proc Natl Acad Sci U S A 109, 8839–8844 (2012).

57. Wultsch, C. et al. Genetic diversity and population structure of Mesoamerican jaguars (*Panthera onca*): Implications for conservation and management. PLoS One 11, 1–25 (2016).

58. Meyer, N. F. V. et al. Effectiveness of Panama as an intercontinental land bridge for large mammals. Conservation Biology 0, 1–13 (2019).

59. Motlagh, J. A Terrifying Journey Through the World's Most Dangerous Jungle. Outside Online (2016).

60. Obinna, D. N. Camino de la Muerte: Crossing the Darién Gap and Migration in the Americas. Migr Dev 13, 7–24 (2024).

61. Jędrzejewski, W. et al. Jaguars (*Panthera onca*) in the Llanos of Colombia and Venezuela: Estimating Distribution and Population Size by Combining Different Modeling Approaches. in Neotropical Mammals (ed. Mandujano, S., Naranjo, E.J., Andrade Ponce, G. P.) (Springer, Cham, 2023). https://doi.org/10.1007/978-3-031-39566-6_9.

62. Hyde, M. et al. Tourism-supported working lands sustain a growing jaguar population in the Colombian Llanos. Sci Rep 13, 1–11 (2023).

63. Boron, V. et al. Jaguar Densities across Human-Dominated Landscapes in Colombia: The Contribution of Unprotected Areas to Long Term Conservation. PLoS One 11, e0153973 (2016).

64. Seidl, A. F., De Silva, J. D. S. V. & Moraes, A. S. Cattle ranching and deforestation in the Brazilian Pantanal. Ecological Economics 36, 413–425 (2001).

65. Soisalo, M. K. & Cavalcanti, S. M. C. Estimating the density of a jaguar population in the Brazilian Pantanal using camera-traps and capture-recapture sampling in combination with GPS radio-telemetry. Biol Conserv 129, 487–496 (2006).

66. Devlin, A. L. et al. Drivers of large carnivore density in non-hunted, multi-use landscapes. Conserv Sci Pract 5, 1–13 (2023).

67. de Barros, A. E. et al. Wildfires disproportionately affected jaguars in the Pantanal. Commun Biol 5, 1–12 (2022).

68. Santos, F. C., Chaves, F. M., Negri, R. G. & Massi, K. G. Fires in Pantanal: The link to Agriculture Conversions in Cerrado, and Hydrological Changes. Wetlands 44, 1–11 (2024).

69. Romero-Muñoz, A. et al. Habitat loss and overhunting synergistically drive the extirpation of jaguars from the Gran Chaco. Divers Distrib 25, 176–190 (2019).

70. Thompson, J. J. et al. Jaguar (*Panthera onca*) population density and landscape connectivity in a deforestation hotspot: The Paraguayan Dry Chaco as a case study. Perspect Ecol Conserv https://doi.org/10.1016/j.pecon.2022.09.001 (2022).

71. Quiroga, V. A., Boaglio, G. I., Noss, A. J. & Di Bitetti, M. S. Critical population status of the jaguar *Panthera onca* in the Argentine Chaco: camera-trap surveys suggest recent collapse and imminent regional extinction. Oryx 48, 141–148 (2014).

72. Haag, T. et al. The effect of habitat fragmentation on the genetic structure of a top predator: Loss of diversity and high differentiation among remnant populations of Atlantic Forest jaguars (*Panthera onca*). Mol Ecol 19, 4906–4921 (2010).

73. Roques, S. et al. Effects of habitat deterioration on the population genetics and conservation of the jaguar. Conservation Genetics 17, 125–139 (2016).

74. de Paula, R. C., Campos, C. B. & Oliveira, T. G. Red List assessment for the jaguar in the Caatinga Biome. Cat News Special Issue 7, 19–24 (2012).

75. Portugal, M. P., Morato, R. G., Ferraz, K. M. P. M. D. B., Rodrigues, F. H. G. & Jacobi, C. M. Priority areas for jaguar *Panthera onca* conservation in the Cerrado. Oryx 54, 854–865 (2019).

76. Moraes Jr., E. A. The status of the jaguar in the Cerrado. CATnews Special Issue 25–28 (2012).

77. Soterroni, A. C. et al. Expanding the soy moratorium to Brazil's Cerrado. Sci Adv 5, eaav7336 (2019).

78. Segura-Garcia, C. et al. The fire regimes of the Cerrado and their changes through time. Philosophical Transactions of the Royal Society B: Biological Sciences 380, (2025).

79. Pompeu, J., Assis, T. O. & Ometto, J. P. Landscape changes in the Cerrado: Challenges of land clearing, fragmentation and land tenure for biological conservation. Science of the Total Environment 906, (2024).

80. Pessôa, A. C. M. et al. Protected areas are effective on curbing fires in the Amazon. Ecological Economics 214, 107983 (2023).

81. Qin, Y. et al. Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. Nat Sustain 6, 295–305 (2023).

82. Moutinho, P. & Azevedo-Ramos, C. Untitled public forestlands threat Amazon conservation. Nat Commun 14, 1152 (2023).

83. Morán-López, R., Cortés Gañán, E., Uceda Tolosa, O. & Sánchez Guzmán, J. M. The umbrella effect of Natura 2000 annex species spreads over multiple taxonomic groups, conservation attributes and organizational levels. Anim Conserv 23, 407–419 (2020).

84. Zanin, M. et al. The differential genetic signatures related to climatic landscapes for jaguars and pumas on a continental scale. Integr Zool 16, 2–18 (2021).

85. Morato, R. G. et al. Jaguar movement database: a GPS-based movement dataset of an apex predator in the Neotropics. Ecology 99, 1691 (2018).

86. Rondinini, C. & Boitani, L. Mind the map: trips and pitfalls in making and reading maps of carnivore distribution. in Carnivore ecology and conservation: a handbook of techniques (eds. Boitani, L. & Powell, R. A.) 506 (Oxford University Press, New York, USA, 2012).

87. Crego, R. D., Stabach, J. A. & Connette, G. Implementation of species distribution models in Google Earth Engine. Divers Distrib 28, 904–916 (2022).

88. Zeller, K. A. et al. Sensitivity of landscape resistance estimates based on point selection functions to scale and behavioral state: Pumas as a case study. Landsc Ecol 29, 541–557 (2014).

89. Sillero, N. & Barbosa, A. M. Common mistakes in ecological niche models. International Journal of Geographical Information Science 35, 213–226 (2021).

90. Bowman, J., Jaeger, J. A. G. & Fahrig, L. Dispersal distance of mammals is proportional to home range size. Ecology 83, 2049–2055 (2002).

91. Johnson, D. H. The Comparison of Usage and Availability Measurements for Evaluating Resource Preference. Ecology 61, 65–71 (1980).

92. Rodríguez-Soto, C. et al. Predicting potential distribution of the jaguar (*Panthera onca*) in Mexico: Identification of priority areas for conservation. Divers Distrib 17, 350–361 (2011).

93. Searle, C. E. et al. Random forest modelling of multi-scale, multi-species habitat associations within KAZA transfrontier conservation area using spoor data. Journal of Applied Ecology 59, 2346–2359 (2022).

94. Ávila–Nájera, D. M., Chávez, C., Pérez–elizalde, S., Palacios–pérez, J. & Tigar, B. Coexistence of jaguars (*Panthera onca*) and pumas (*Puma concolor*) in a tropical forest in south–eastern mexico. Anim Biodivers Conserv 43, 55–66 (2020).

95. Schoen, J. M., DeFries, R. & Cushman, S. Open-source, environmentally dynamic machine learning models demonstrate behavior-dependent utilization of mixed-use landscapes by jaguars (*Panthera onca*). Biol Conserv 302, 110978 (2025).

96. Bogoni, J. A., Peres, C. A. & Ferraz, K. M. P. M. B. Extent, intensity and drivers of mammal defaunation: a continental-scale analysis across the Neotropics. Sci Rep 10, 1–16 (2020).

97. Gilbert, M. et al. Global cattle distribution in 2010 (5 minutes of arc). Harvard Dataverse, V3 https://doi.org/10.7910/DVN/GIVQ75 (2018).

98. Gilbert, M. et al. Global goats distribution in 2010 (5 minutes of arc). Harvard Dataverse, V3 https://doi.org/10.7910/DVN/OCPH42 (2018).

99. Gilbert, M. et al. Global sheep distribution in 2010 (5 minutes of arc). Harvard Dataverse, V3 https://doi.org/10.7910/DVN/BLWPZN (2018)

100. Montalvo, V. H., Sáenz-Bolaños, C., Carrillo, E. & Fuller, T. K. A review of environmental and anthropogenic variables used to model jaguar occurrence. Neotropical Biology and Conservation 18, 31–51 (2023).

101. Sørensen, R., Zinko, U. & Seibert, J. On the calculation of the topographic wetness index: evaluation of different methods based on field observations. Hydrol Earth Syst Sci 10, 101–112 (2006).

102. Jenness, J. Topographic Position Index (tpi_jen.avx) Extension for ArcView 3.x, v.1.-3a. Preprint at http://www.jennessent.com/arcview/tpi.htm (2006).

103. Amatulli, G., McInerney, D., Sethi, T., Strobl, P. & Domisch, S. Geomorpho90m, empirical evaluation and accuracy assessment of global high-resolution geomorphometric layers. Sci Data 7, 1–18 (2020).

104. Weill, R. R. & Brady, N. C. The Nature and Properties of Soils. (Pearson, New York, 2016).

105. Cushman, S. A., Elliot, N. B., Macdonald, D. W. & Loveridge, A. J. A multi-scale assessment of population connectivity in African lions (*Panthera leo*) in response to landscape change. Landsc Ecol 31, 1337–1353 (2016).

106. Macdonald, D. W. et al. Multi-scale habitat selection modeling identifies threats and conservation opportunities for the Sunda clouded leopard (*Neofelis diardi*). Biol Conserv 227, 92–103 (2018).

107. R Core Team. R: a language and environment for statistical computing. Preprint at (2018).

108. QGIS Development Team. QGIS Geographic Information System. Open Source Geospatial Foundation Project. http:// Preprint at http://www.qgis.org/en/site/ (2016).

109. Gorelick, N. et al. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sens Environ 202, 18–27 (2017).

110. Morato, R. G. et al. Space use and movement of a neotropical top predator: The endangered jaguar. PLoS One 11, 1–17 (2016).

111. Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A. & Smith, G. M. Mixed Effects Models and Extensions in Ecology with R. (Springer, New York, 2009). doi:10.1007/978-0-387-87458-6.

112. De Jay, N. et al. mRMRe: an R package for parallelized mRMR ensemble feature selection. Bioinformatics 29, 2365–2368 (2013).

113. Fletcher, R. & Fortin, M.-J. Spatial Ecology and Conservation Modeling. Spatial Ecology and Conservation Modeling (Springer Nature Switzerland, 2018). doi:10.1007/978-3-030-01989-1.

114. Bates, D., Maechler, M., Bolker, B. & Walker, S. Fitting Linear Mixed-Effects Models using lme4. J Stat Softw 67, 1–48 (2015).

115. Hijmans, R. terra: Spatial Data Analysis. Preprint at (2024).

116. Boyce, M. S., Vernier, P. R., Nielsen, S. E. & Schmiegelow, F. K. A. Evaluating resource selection functions. Ecol Modell 157, 281–300 (2002).

117. Hirzel, A. H., Le Lay, G., Helfer, V., Randin, C. & Guisan, A. Evaluating the ability of habitat suitability models to predict species presences. Ecol Modell 199, 142–152 (2006).

118. Nagy-Reis, M. et al. NEOTROPICAL CARNIVORES: a data set on carnivore distribution in the Neotropics. Ecology 101, 1–5 (2020).

119. Robin, X. et al. pROC: an open-source package for R and S+ to analyze and compare ROC curves. BMC Bioinformatics 12, 77 (2011).

120. MMAMC, M. do M. A. e M. C. Cadastro Nacional de Florestas Públicas (CNFP). (2022).

121. Nijhawan, S. Conservation units, priority areas and dispersal corridors for jaguars in Brazil. Cat News Special Issue 7, 43–47 (2012).

122. UNEP-WCMC & IUCN. Protected Planet: The World Database on Protected Areas (WDPA). Cambridge, UK: UNEP-WCMC and IUCN www.protectedplanet.net. (2022).

123. Griffith, D. M., Nivelo-Villavicencio, C., Rodas, F., Puglla, B. & Cisneros, R. New altitudinal records of *Panthera onca* (Carnivora: Felidae) in the Andean region of Ecuador. Mammalia 86, 190–195 (2021).

124. Zeller, K. Jaguars in the new millennium data set update: The state of the jaguar in 2006. Wildlife Conservation Society, Bronx, New York 1–77 (2007).

125. Kennedy, C. M., Oakleaf, J. R., Theobald, D. M., Baurch-Murdo, S. & Kiesecker., J. Managing the middle: A shift in conservation priorities based on the global human modification gradient. Glob Chang Biol 00, 1–16 (2019).

126. Sorichetta, A. et al. High-resolution gridded population datasets for Latin America and the Caribbean in 2010, 2015, and 2020. Sci Data 1–12 (2015) doi:10.1038/sdata.2015.45.

127. Li, X., Zhou, Y., Zhao, M. & Zhao, X. A harmonized global nighttime light dataset 1992–2018. Sci Data 7, 1–9 (2020).

128. Vancutsem, C. et al. Long-term (1990-2019) monitoring of forest cover changes in the humid tropics. Sci Adv 7 (2021).

129. Giglio, L., Justice, C., Boschetti, L. & Roy, D. MCD64A1 MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN Grid V006. NASA EOSDIS Land Processes DAAC https://doi.org/10.5067/MODIS/MCD64A1.006 (2015).

130. Didan, K. MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006. NASA EOSDIS Land Processes Distributed Active Archive Center https://doi.org/10.5067/MODIS/MOD13Q1.006 (2015).

131. Running, S., Mu, Q. & Zhao, M. MOD17A2H MODIS/Terra Gross Primary Productivity 8-Day L4 Global 500m SIN Grid V006. NASA EOSDIS Land Processes DAAC https://doi.org/10.5067/MODIS/MOD17A2H.006. (2015).

132. DiMiceli, C. et al. MOD44B MODIS/Terra Vegetation Continuous Fields Yearly L3 Global 250m SIN Grid V006. (2015) doi:10.5067/MODIS/MOD44B.006.

133. Potapov, P. et al. Mapping and monitoring global forest canopy height through integration of GEDI and Landsat data. Remote Sens Environ 112165 (2020) https://doi.org/10.1016/j.rse.2020.112165.

134. Wan, Z., Hook, S. & Hulley, G. MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V061. NASA EOSDIS Land Processes DAAC https://doi.org/10.5067/MODIS/MOD11A2.061. (2021).

135. Brun, P., Zimmermann, N. E., Hari, C., Pellissier, L. & Karger, D. CHELSA-BIOCLIM+ A novel set of global climate-related predictors at kilometre-resolution. EnviDat. https://doi.org/https://doi.org/10.16904/envidat.332 (2022).

136. Jarvis, A., Reuter, H. I., Nelson, A. & Guevara, E. Hole-filled SRTM for the globe Version 4. CGIAR-CSI SRTM 90m https://srtm.csi.cgiar.org. (2008).

137. Hengl, T. et al. SoilGrids250m: Global Gridded Soil Information Based on Machine Learning. PLoS ONE 12 (2017).

138. Pickens, A. H. et al. Mapping and sampling to characterize global inland water dynamics from 1999 to 2018 with full Landsat time-series. Remote Sens Environ 243, 111792 (2020).

Author Contributions

Guilherme Costa Alvarenga: Conceptualization, Investigation, Data curation, Methodology, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. **Caroline C. Sartor:** Methodology, Formal analysis, Writing – review & editing. **Samuel A. Cushman:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration. **Alexandra Zimmermann:** Writing – review & editing. **Ana Carolina Srbek-Araujo:** Investigation, Resources, Writing – review & editing. **Ana Cristina Mendes-Oliveira:** Investigation, Resources, Writing – review & editing. **Bart Harmsen:** Investigation, Resources, Writing – review & editing. **Carlos De Angelo:** Investigation, Resources, Writing – review & editing. **Carolina Franco Esteves:** Investigation, Resources, Writing – review & editing. **Claudia B. de Campos:** Investigation, Resources, Writing – review & editing. **Daiana Jeronimo Polli:** Investigation, Resources, Writing – review & editing. **Diego F. Passos Viana:** Investigation, Resources, Writing – review & editing. **Diogo Maia Gräbin:** Investigation, Resources, Writing – review & editing. **Emiliano Donadio:** Investigation, Resources, Writing – review & editing. **Emiliano E. Ramalho:** Investigation, Resources, Writing – review & editing. **Esteban Payán:** Investigation, Resources, Writing – review & editing. **Fernando C. C. Azevedo:** Investigation, Resources, Writing – review & editing. **Francisco Palomares:** Investigation, Resources, Writing – review & editing. **George V. N. Powell:** Investigation, Resources, Writing – review & editing. **Gerardo Ceballos:** Investigation, Resources, Writing – review & editing. **Grasiela Porfirio:** Investigation, Resources, Writing – review & editing. **Heliot Zarza:** Investigation, Resources, Writing – review & editing. **Ivonne Cassaigne:** Investigation, Resources, Writing – review & editing. **Juliano A. Bogoni:** Investigation, Resources, Writing – review & editing. **Leonardo Sena:** Investigation, Resources, Writing – review & editing. **Louise Maranhão:** Investigation, Resources, Writing – review & editing.

Marcos Roberto Monteiro de Brito: Investigation, Resources, Writing – review & editing. **Mathias W. Tobler:** Investigation, Resources, Writing – review & editing. **Øystein Wiig:** Investigation, Resources, Writing – review & editing. **Rebecca J. Foster:** Investigation, Resources, Writing – review & editing. **Ricardo Sampaio:** Investigation, Resources, Writing – review & editing. **Rodrigo Nuñez:** Investigation, Resources, Writing – review & editing. **Ronaldo G. Morato:** Investigation, Resources, Writing – review & editing. **Valeria Boron:** Investigation, Resources, Writing – review & editing. **Wener Hugo Arruda Moreno:** Investigation, Resources, Writing – review & editing. **Yadvinder Malhi:** Writing – review & editing. **David W. Macdonald:** Resources, Writing – review & editing, Funding acquisition. **Żaneta Kaszta:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration.

Supplementary Material

Tables

Table S1. Reference information of the 172 GPS-collared jaguars (*Panthera onca*) used in the study.

Jaguar ID	Sex	Nº Locations	Locations Filtered	Tracked Period	Latitude	Longitude	Country
1	F	288	132	06/2010-03/2011	-23.275652	-58.116174	Paraguay
2	F	150	107	07/2010-12/2011	-24.171145	-55.433106	Paraguay
3	M	148	106	06/2009-09/2009	-23.344435	-58.450313	Paraguay
4	F	500	179	07/2011-12/2011	-23.339263	-58.138876	Paraguay
5	F	280	57	07/2009-09/2009	-23.367736	-58.1908264	Paraguay
6	M	983	221	07/2009-12/2009	-23.232139	-58.2325172	Paraguay
7	M	621	207	07/2011-11/2011	-23.25648	-58.077142	Paraguay
8	M	540	196	07/2009-07/2010	-24.040429	-55.486192	Paraguay
9	F	1018	177	06/2014-12/2014	-23.326947	-58.041257	Paraguay
10	F	1668	463	06/2014-05/2015	-23.397239	-58.185852	Paraguay
11	F	913	180	07/2014-07/2015	-23.368049	-58.039784	Paraguay
12	F	2681	259	12/2014-04/2015	-16.9714833	-57.3899431	Brazil
13	M	5040	108	12/2014-08/2015	-16.9159483	-57.4977108	Brazil
14	M	192	64	04/2012-04/2012	-19.8744136	-56.4016528	Brazil
15	M	1323	292	10/2013-01/2014	-20.0301064	-56.3210047	Brazil
16	M	3462	581	04/2011-08/2012	-21.734897	-60.0206985	Paraguay
17	M	537	187	03/2014-07/2014	-17.808023	-53.183055	Brazil
18	M	2314	177	11/2014-04/2015	-16.9279125	-57.4243325	Brazil
19	F	741	111	10/2011-01/2012	-19.9582217	-56.3169619	Brazil
20	M	5590	739	09/2015-06/2016	-8.60977	-42.6801	Brazil
21	F	327	139	08/2011-06/2012	-24.067424	-55.466862	Paraguay
22	M	4709	171	09/2014-05/2015	-16.8864897	-57.4038397	Brazil
23	M	572	38	09/2014-09/2014	-16.8747392	-57.5129536	Brazil
24	M	153	75	12/2011-03/2012	-5.97859	-50.040107	Brazil
25	F	3219	188	10/2012-08/2015	-19.9448036	-56.2427367	Brazil
26	F	5924	294	11/2014-06/2016	10.8596451	-85.6343205	Costa Rica
27	F	560	86	09/2010-11/2013	-17.3260076	-56.7544166	Brazil
28	F	205	63	07/2010-10/2010	-17.828947	-57.40595	Brazil
29	F	67	30	07/2011-09/2011	-17.8398802	-57.3940782	Brazil
30	F	581	125	10/2011-11/2012	-17.3293188	-56.7126546	Brazil
31	F	103	36	10/2013-02/2014	-17.3367322	-56.7099957	Brazil
32	F	240	104	10/2012-04/2013	-17.3793419	-56.7819766	Brazil
33	F	133	68	10/2013-01/2014	-17.3285701	-56.7594096	Brazil

34	F	92	36	02/2003-07/2003	-22.63708499	-52.26445905	Brazil
35	F	17	15	08/2000-11/2001	-22.59397636	-52.25259646	Brazil
36	F	32	28	07/1999-07/2003	-22.5901957	-52.38519834	Brazil
37	F	211	90	07/2002-11/2002	-22.63878999	-52.12664972	Brazil
38	F	18	18	07/2002-08/2002	-22.53828697	-52.25666345	Brazil
39	F	326	187	02/2002-04/2005	-22.75705316	-53.68426924	Brazil
40	F	183	100	05/2004-12/2004	-22.80383586	-53.55541512	Brazil
41	F	4952	89	12/2014-08/2015	-16.8612211	-57.4243539	Brazil
42	M	7668	1039	02/2009-10/2009	-25.637647	-54.299678	Argentina
43	F	1512	556	01/2013-02/2013	29.74605	-109.23039	Mexico
44	F	104	65	01/2012-09/2013	16.835904	-91.042886	Mexico
45	F	39	14	08/2012-08/2012	16.889464	-90.955664	Mexico
46	F	443	250	08/2012-11/2013	16.898824	-91.083115	Mexico
47	M	636	329	01/2012-02/2013	16.579612	-90.999996	Mexico
48	M	72	53	08/2012-12/2012	16.938643	-91.120305	Mexico
49	M	979	280	01/2014-12/2015	21.3790875	-87.6018119	Mexico
50	M	1361	218	11/2014-01/2015	-8.6345197	-42.7049775	Brazil
51	M	727	238	06/2010-12/2010	-20.530443	-58.061521	Paraguay
52	F	615	40	11/2014-12/2014	-16.9132783	-57.4112914	Brazil
53	M	300	148	09/2010-10/2013	-17.265488	-56.8139292	Brazil
54	M	129	21	07/2010-08/2010	-17.8506281	-57.4067729	Brazil
55	M	141	65	06/2011-10/2011	-17.3527833	-56.5766747	Brazil
56	M	109	59	07/2011-10/2011	-17.8231802	-57.5760012	Brazil
57	M	28	8	07/2011-08/2011	-17.8351375	-57.4037579	Brazil
58	M	159	74	01/2003-06/2003	-22.67648014	-52.19555839	Brazil
59	M	434	223	10/2011-12/2013	-17.3239385	-56.7097386	Brazil
60	M	705	187	10/2012-10/2013	-17.3536055	-56.7575736	Brazil
61	M	109	61	06/2013-08/2013	-17.2932905	-56.7014317	Brazil
62	M	156	106	05/2003-10/2003	-22.62201182	-52.20074942	Brazil
63	M	797	408	03/2005-04/2006	-22.74154717	-53.54126196	Brazil
64	M	1694	639	10/2012-12/2012	29.61717	-109.31089	Mexico
65	F	1010	445	03/2014-10/2014	-17.871376	-53.103104	Brazil
66	F	53	38	02/2013-06/2013	-25.6485772	-54.4214814	Brazil
67	F	131	69	03/2014-06/2014	-17.706925	-52.936313	Brazil
68	M	1003	194	11/2011-12/2011	-20.0268575	-56.2552267	Brazil
69	F	3464	317	10/2013-05/2014	-19.9262692	-56.2414756	Brazil
70	M	1094	487	06/2002-06/2003	-22.195088	-60.160038	Paraguay
71	F	921	443	07/2003-07/2004	-19.753344	-59.480243	Paraguay
72	M	722	290	07/2003-07/2004	-19.747937	-59.551036	Paraguay
73	M	620	257	06/2004-09/2004	-20.142131	-59.851225	Paraguay
74	F	1300	185	08/2005-05/2006	-19.971896	-58.217231	Paraguay

75	F	1694	215	08/2005-08/2006	-20.039304	-58.165714	Paraguay
76	F	1610	616	06/2006-07/2007	-20.440784	-60.320772	Paraguay
77	M	1376	576	06/2006-05/2007	-20.51578	-60.33193	Paraguay
78	F	798	292	07/2008-07/2009	-24.522229	-55.34041	Paraguay
79	F	2300	201	04/2015-08/2015	-19.9936717	-56.2941214	Brazil
80	M	479	66	05/2010-07/2010	-25.60912108	-54.49638269	Argentina
81	M	10988	401	10/2013-05/2015	-16.97737	-57.3910972	Brazil
82	M	1335	576	05/2014-12/2015	-17.96005	-53.082933	Brazil
83	M	112	49	01/2012-03/2012	-25.08117226	-53.62542169	Brazil
84	F	4860	227	04/2013-01/2014	-19.95198	-56.3223003	Brazil
85	M	780	400	03/2014-02/2015	-17.690413	-53.107739	Brazil
86	F	1391	276	10/2013-01/2014	-19.9611475	-56.1977572	Brazil
87	F	413	32	05/2012-06/2012	-19.9725481	-56.2818497	Brazil
88	F	1296	116	10/2013-04/2014	-16.8718285	-57.5228518	Brazil
89	M	2432	402	09/2013-10/2015	-15.9061	-48.477581	Brazil
90	F	322	164	08/2012-04/2013	-25.7531786	-54.5845814	Argentina
91	M	88	33	01/2011-01/2012	-16.894062	-57.492675	Brazil
92	F	96	43	01/2011-01/2013	-16.917908	-57.487805	Brazil
93	F	784	144	12/2010-11/2011	-3.050582	-64.852288	Brazil
94	F	3837	244	11/2012-02/2014	-3.054921	-64.845133	Brazil
95	F	542	109	02/2013-07/2013	-2.933995	-64.834189	Brazil
96	M	230	125	01/2013-04/2013	-3.03768	-64.82531	Brazil
97	F	31	3	02/2013-02/2013	-3.037074	-64.843443	Brazil
98	M	61	26	01/2013-09/2013	-3.043342	-64.884696	Brazil
99	M	294	110	10/2013-11/2014	-2.944293	-64.940658	Brazil
100	M	1024	319	03/2014-08/2015	-3.090892	-64.813113	Brazil
101	M	404	207	08/2015-03/2016	-19.710234	-56.357117	Brazil
102	F	151	83	03/2016-05/2016	-19.603761	-56.211355	Brazil
103	F	20	12	06/2014-06/2014	-19.571285	-56.076128	Brazil
104	M	134	59	08/2015-06/2016	-19.578162	-56.151681	Brazil
105	F	2113	251	07/2008-10/2009	-19.51600071	-57.04450005	Brazil
106	M	227	131	09/2009-10/2011	-19.42884891	-56.91394335	Brazil
107	M	287	93	07/2008-12/2008	-19.53291063	-56.78271003	Brazil
108	M	481	197	07/2008-11/2008	-19.46945048	-56.86500405	Brazil
109	F	165	72	08/2008-10/2008	-19.56692044	-56.91692119	Brazil
110	M	166	93	02/2010-05/2010	-19.49668019	-57.12129559	Brazil
111	F	1758	188	07/2008-04/2011	-19.43423998	-56.86302315	Brazil
112	F	202	47	07/2008-10/2008	-19.63714532	-56.9650143	Brazil
113	F	709	128	08/2008-07/2009	-19.47401862	-56.94045639	Brazil
114	F	1645	191	06/2008-07/2009	-19.47993711	-57.08448275	Brazil
115	F	952	247	06/2008-03/2009	-19.53442239	-56.97638914	Brazil

116	M	3340	146	10/2015-04/2016	-16.8496492	-57.5967928	Brazil
117	F	2820	116	10/2015-02/2016	-16.9078125	-57.4846269	Brazil
118	F	451	175	01/2015-01/2016	-3.078417	-64.829936	Brazil
119	M	516	182	01/2015-07/2015	-2.852821	-64.908878	Brazil
120	F	843	137	03/2016-11/2016	-3.042296	-64.856324	Brazil
121	M	643	209	01/2016-10/2016	-3.108568	-64.817603	Brazil
122	M	835	275	02/2017-01/2018	-3.03765	-64.90765	Brazil
123	M	2622	269	03/2018-02/2019	-3.062562	-64.792863	Brazil
124	M	801	145	02/2020-05/2020	-3.021761	-64.964985	Brazil
125	M	4890	436	07/2019-07/2020	-19.14391	-39.99278	Brazil
126	F	4363	771	06/2019-02/2020	-10.76774	-41.69304	Brazil
127	F	1774	343	05/2013-05/2014	18.662806	-89.131262	Mexico
128	F	1221	653	07/2001-03/2009	18.232041	-88.898627	Mexico
129	F	166	125	03/2002-03/2003	18.31096889	-88.95445333	Mexico
130	M	526	72	05/2009-06/2009	18.383318	-89.300211	Mexico
131	M	1315	329	05/2009-07/2009	18.270961	-89.256905	Mexico
132	M	295	207	04/2005-11/2005	18.1338	-89.0362	Mexico
133	F	457	208	04/2005-05/2006	18.176021	-88.888454	Mexico
134	F	307	121	04/2001-01/2002	18.295253	-88.979485	Mexico
135	M	4831	871	01/2021-01/2023	-24.8283769	-61.1156142	Argentina
136	F	1290	190	05/2009-07/2009	18.324955	-89.397159	Mexico
137	M	364	253	06/2002-05/2003	18.215324	-89.558898	Mexico
138	M	1192	244	05/2009-09/2009	18.457128	-89.412146	Mexico
139	F	245	141	04/2008-03/2009	18.231913	-88.898713	Mexico
140	F	286	165	04/2005-08/2007	18.269887	-89.02367	Mexico
141	M	2851	557	10/2012-03/2013	-11.41943858	-69.84469181	Peru
142	M	1618	378	09/2009-12/2009	-11.43448933	-69.77944624	Peru
143	M	189	132	11/2012-02/2013	-11.5411808	-69.7436494	Peru
144	F	903	168	10/2012-12/2012	-11.4049256	-69.85074	Peru
145	F	3848	290	09/2007-02/2008	-13.12314509	-69.59072353	Peru
146	F	3054	321	08/2007-12/2007	-13.12049567	-69.46562018	Peru
147	M	4905	584	07/2012-05/2013	-11.42838766	-69.82209262	Peru
148	F	697	98	09/2007-12/2007	-13.05271558	-69.54118693	Peru
149	M	4199	686	07/2007-02/2008	-12.97864727	-69.58116607	Peru
150	M	2122	171	01/2022-06/2022	-17.925562	-57.476751	Brazil
151	M	13243	1274	08/2017-03/2019	-9.95224	-41.09542	Brazil
152	M	287	80	02/2018-05/2018	5.98766	-71.44483	Colombia
153	F	257	28	02/2018-05/2018	6.0383939	-71.3843953	Colombia
154	M	2555	384	11/2019-06/2020	-3.24246	-47.83422	Brazil
155	F	2361	278	09/2017-07/2018	-19.8004	-42.59652	Brazil
156	M	2174	461	11/2017-11/2018	-19.80304	-42.59469	Brazil

157	F	43	25	07/2021-08/2021	20.9937908	-105.2199662	Mexico
158	F	1257	73	11/2019-03/2020	21.6542017	-105.4480192	Mexico
159	M	296	70	12/2015-03/2016	20.929646	-105.297234	Mexico
160	M	309	41	04/2016-07/2016	21.1989024	-105.2000204	Mexico
161	M	88	41	07/2017-08/2017	21.0400516	-104.9517662	Mexico
162	M	94	37	05/2019-11/2019	20.9081558	-105.3694981	Mexico
163	M	189	131	06/2015-05/2016	19.5015409	-105.0139881	Mexico
164	F	2852	134	10/2021-01/2023	-28.267087	-57.338167	Argentina
165	M	2412	401	01/2022-01/2023	-28.329787	-57.437795	Argentina
166	F	1263	161	04/2021-11/2021	-28.343423	-57.509335	Argentina
167	F	676	99	10/2022-01/2023	-28.337012	-57.441685	Argentina
168	F	5183	450	01/2021-01/2023	-28.243248	-57.302054	Argentina
169	M	1248	318	06/2023-08/2023	-8.691146	-42.521022	Brazil
170	F	3057	426	09/2022-01/2023	-8.647565	-42.67408	Brazil
171	M	362	141	02/2015-02/2016	16.77688791	-88.4860169	Belize
172	M	597	139	02/2015-10/2015	16.7671903	-88.4881106	Belize
TOTAL	**-**	**231,017**	**37,453**	**-**	**-**	**-**	**-**

Table S2. Jaguar population density estimates (Spatially Explicit Capture-Recapture – SECR) used for model comparison.

ID	Date	Location	Latitude	Longitude	Density estimate	Average suitability	Study
1	2008-2011	Amazon, Brazil	-9.82316	-58.27086	3.03	0.075	[1]
2	2011	Amazon, Guyana	4.6024	-58.7774	1.72	0.298383	[2]
3	2013-2014	Amazon, French Guiana	5.2024	-52.8186	3.22	0.132664	[3]
4	2007-2009	Amazon, Ecuador	-1.676	-76.0065	5.44	0.445306	[4]
5	2007-2009	Amazon, Ecuador	-0.7043	-76.0044	1.49	0.555279	[4]
6	2007-2009	Amazon, Ecuador	-1.00503	-77.07275	0.89	0.443977	[4]
7	2007-2009	Amazon, Ecuador	-0.6754	-76.4429	0.29	0.178872	[4]
8	2003	Quendeque, Madidi, Amazon, Bolivia	-14.9998	-67.7931	0.27	0.260485	[5]
9	2004	Upper Madidi, Amazon, Bolivia	-13.6005	-68.7502	2.22	0.631798	[5]
10	2002-2008	Tuichi-Hondo, Madidi, Amazon, Bolivia	-14.6001	-67.6901	1.98	0.305409	[5]
11	2016-2017	PERD, Atlantic Forest	-19.729326	-42.554149	0.76	0.162563	[6]
12	2014-2015	Jaguar Northern Reserve, Sahuaripa, Sonora	29.46668152	-109.1670653	1.07	0.014422	[7]
13	2009	Nacori Chico village, Sonora	29.68862979	-108.9744721	1.54	0.003311	[8]
14	2014	San José de Los Pinos, Michoacán	18.17811663	-102.516495	0.75	0.11358	[9]
15	2015	Oaxaca	18.01953282	-96.53295899	1.16	0.012183	[10]

16	2019-2020	Nayarit, Mangroves	21.677971	-105.439576	2.35	0.009562	[11]
17	2016	Campeche	18.330556	-91.763889	1.93	0.666915	[12]
18	2013-2014	Cockscomb Basin Wildlife Sanctuary, Belize	16.89337146	-88.63772815	2.01	0.248315	[13]
19	2011-2014	Ranchs, Pantanal	-17.361279	-56.72257	4.08	0.088838	[14]
20	2011-2014	Near Serra do Amolar, Pantanal	-17.808839	-57.582707	3.59	0.349034	[14]
22	2014-2018	Taiamã Ecological Station, Pantanal	-16.898351	-57.489603	12.4	0.303388	[15]
23	2010	Emas National Park, Cerrado	-18.1127171	-52.91046398	0.17	0.118653	[16]
24	2016-2017	Santa Rosa, Guanacaste Conservation Area, Costa Rica	10.826708	-85.653633	7.6	0.583892	[17]
25	2016-2018	Site 1, Dry Chaco, Paraguay	-20.707466	-60.039135	1.26	0.217479	[18]
26	2016-2018	Site 2, Dry Chaco, Paraguay	-19.647921	-58.621898	1.6	0.132929	[18]
27	2016-2018	Site 3, Dry Chaco, Paraguay	-21.75072	-60.050121	0.58	0.209789	[18]
28	2016-2018	Site 4, Dry Chaco, Paraguay	-20.06512	-59.366222	0.44	0.183024	[18]
29	2013	Moist forest, Guatemala	17.240727	-89.19708	1.52	0.408925	[19]
30	2020	Alto Turiaçu IL, Amazon	-3.042	-46.4157	2.3	0.195899	[20]
31	2019	Arapaxi RESEX, Amazon	-8.842683	-67.840581	1.61	0.257086	[20]
32	2019	Cabo Orange NP, Amazon	2.93657	-51.19991	3.22	0.350902	[20]

33	2018	Cazumba-Iracema RESEX, Amazon	-9.449309	-68.907706	2	0.154032	[20]
34	2019	Chico Mendes RESEX, Amazon	-10.288559	-68.17321	2.92	0.075097	[20]
35	2018-2020	Cuieiras REBIO, Amazon	-2.57401	-60.30432	1.78	0.425174	[20]
36	2018-2019	Cuyabeno WR, Amazon	-0.325916	-75.785472	2.94	0.533674	[20]
37	2011-2012	Deni & Kanamari do Xeruã IL, Amazon	-6.60918	-68.23544	2.39	0.508857	[20]
38	2019	ESEC Maracá, Amazon	3.39513	-61.54202	2.58	0.289638	[20]
39	2016-2017	ESEC Terra do Meio, Amazon	-4.685691	-53.5808	3.57	0.285474	[20]
40	2009-2014	Espinoza FC, Amazon	-11.46	-69.7	3.39	0.285284	[20]
41	2016-2019	FLONA Jamari, Amazon	-9.346536	-62.966493	2.02	0.187772	[20]
42	2017-2019	Güeppi-Sekime NP, Amazon	-0.370944	-75.214722	2.73	0.466715	[20]
43	2020	Gurupi REBIO, Amazon	-3.656	-46.809	2.82	0.171871	[20]
44	2016-2017	Jaú NP, Amazon	-1.85749	-61.69167	1.08	0.395466	[20]
45	2019	Juruena NP, Amazon	-8.985254	-58.577	3.26	0.374892	[20]
46	2006-2010	Los Amigos CC, Amazon	-12.54	-70.06	4.37	0.382849	[20]
47	2019	Médio Purus RESEX, Amazon	-7.75237	-65.649433	3.23	0.375538	[20]
48	2013-2014	SDR Amanã, Amazon	-2.47485	-64.62042	5.17	0.597833	[20]
49	2013-2014	SDR Mamirauá, Amazon	-3.04553	-64.86188	8.94	0.643137	[20]

50	2007	Tambopata NR & Bahuaja Sonene NP, Amazon	-12.99	-69.46	1.82	0.414076	[20]
51	2018-2019	Umancia IL, Amazon	-0.314944	-74.375805	2.02	0.385838	[20]
52	2022	Site I, Magdalena River Colombia	6.033333	-71.4	3.8	0.03476	[21]
53	2014	Manu National Park, Amazon, Peru	-11.856921	-71.453699	2.5	0.528602	[22]
54	2009	Copo N.P., Argentina	-25.98	-61.9	0	0.102371	Quiroga et al., 2014, as cited in [23]
55	2006-2007	PN Iguazú, Iguazú-San Jorge, Argentina	-25.64	-54.33	1.2	0.299698	Paviolo et al., 2008; Paviolo et al., 2016, as cited in [23]
56	2008	Iguazú-Urugua-í, Green Corridor I and II, Argentina	-25.63	-54.21	0.89	0.263647	Paviolo et al., 2016, as cited in [23]
57	2008	Aborigen Region, Argentina	-24.76	-62.18	0	0.124446	Quiroga et al., 2014, as cited in [23]
58	2010	El Canton, Argentina	-23.36	-62.23	0	0.090012	Quiroga et al., 2014, as cited in [23]
59	2008-2013	Hill Bank, Belize	17.61	-88.79	4.24	0.476481	Kelly et al., 2014, as cited in [23]
60	2013	Gallon Jug, Belize	17.64	-89.11	1.8	0.334832	Kelly et al., 2014, as cited in [23]
61	2008-2013	La Milpa, Belize	17.73	-89.05	2.3	0.398255	Kelly et al., 2014, as cited in [23]
62	2004	Guanaco II, Kaa-Iya II, Bolivia, Bolivia	-20.07	-62.44	1.54	0.16912	Cuéllar et al., 2004; Noss et al., 2012, as cited in [23]

63	2002-2003	Cerro cortado II, Gran Chaco National Park, Bolivia	-19.54	-61.32	1.18	0.232521	Maffei et al., 2002; Maffei et al., 2003; Noss et al., 2012, as cited in [23]
64	2006-2007	Palmar-Ravelo II, Kaa-Iya, Bolivia	-19.42	-60.53	0.58	0.203844	Romero-Muñoz et al., 2006; Romero-Muñoz et al., 2007; Romero-Muñoz et al., 2008; Montaño and Noss, 2010; Noss et al., 2012, as cited in [23]
65	2003	Ravelo I, Gran Chaco National Park, Bolivia	-19.32	-60.61	0.59	0.172061	Cuéllar et al., 2003a; 2003b; Peña et al., 2004; Noss et al., 2012, as cited in [23]
66	2002-2004	Tucavaca I, Gran Chaco National Park, Bolivia	-18.52	-60.82	0.99	0.139787	Maffei et al., 2002; Maffei et al., 2004; Noss et al., 2012, as cited in [23]
67	2010-2011	Ilha do Cardoso, Brazil	-25.11	-47.94	0	0.153746	Paviolo et al., 2016, as cited in [23]
68	2012	Juréia-Itatins, Brazil	-24.38	-47.06	0	0.044525	Paviolo et al., 2016, as cited in [23]
69	2011	Intervales-Petar, Brazil	-24.22	-48.29	0.66	0.131818	Paviolo et al., 2016, as cited in [23]
70	2013	Santa Virginia, Brazil	-23.36	-45.2	0	0.059966	Paviolo et al., 2016, as cited in [23]
71	2008-2009	Ivinhema, Brazil	-23.08	-53.66	1.66	0.122123	Paviolo et al., 2016, as cited in [23]
72	2008-2009	Serra da Bocaina, Brazil	-22.96	-44.67	0	0.23185	Paviolo et al., 2016, as cited in [23]

73	2003	Moro do Diablo, Brazil	-22.61	-52.2	2.39	0.088483	Cullen Jr. 2006; Paviolo et al., 2016, as cited in [23]
74	2010-2011	Serra dos Órgãos I, II, III and IV., Brazil	-22.56	-43.13	0	0.000003	Paviolo et al., 2016, as cited in [23]
75	2005-2006	Vale NR I, II, III, IV and V, Brazil	-19.09	-39.91	2.42	0.157267	Paviolo et al., 2016, as cited in [23]
76	2007	Caatinga-Serra da Capivara, Brazil	-8.86	-42.61	1.45	0.037463	Silveira et al., 2010; Sollmann et al., 2013, as cited in [23]
77	2014	Magdalena river, Colombia	7.47	-73.8	3.04	0.016858	Boron et al., 2016, as cited in [23]
78	2009	Laguna del Tigre, Sur Corredor Biológico, Portion of Consecion AFISAP, Guatemala	17.3	-90.35	4.52	0.374862	Moreira et al., 2009; Tobler et al., 2013, as cited in [23]
79	2012-2013	Charabaru Conssesion, Guyana	4.89	-58.44	4.48	0.314056	Paemelaere et al., 2013, as cited in [23]
80	2008-2012	Reserva Ecológica El Eden, Mexico	21.35	-87.35	1.95	0.628039	Ávila-Nájera et al., 2015, as cited in [23]
81	2013-2014	Hato Piñero, Venezuela	8.9	-68.11	4.65	0.087615	Jędrzejewski et al., 2017, as cited in [23]

Table S3. Assessment of the estimated amount of suitable habitat for jaguars (*Panthera onca*) distributed across the species current range, non-designated lands, jaguar conservation units (JCUs) and protected areas (PAs). Total summed: the total summed habitat suitability (km²); Highly suitable area: corresponds to the area (km²) classified as highly suitable habitat (top quartile of suitability); Range-based: refers to the suitable habitat identified when the entire current range was analysed as a single unit; Ecoregion-based: reflects the suitable habitat identified when each ecoregion was analysed separately.

Region	Habitat Suitability		
	Total summed (%)	Highly suitable area	
		Range-based (%)	Ecoregion-based (%)
Current range	8,766,692.9 (100)	14,584,552 (100)	14,578,260 (100)
Non-Designated Lands	862,151.2 (9.8)	1,673,350 (11.5)	1,394,212 (9.7)
JCUs	6,023,761.1 (68.7)	11,190,394 (76.7)	9,063,221 (62.2)
PAs	4,721,829 (53.9)	8,603,742 (59.0)	6,868,576 (47.1)

Figures

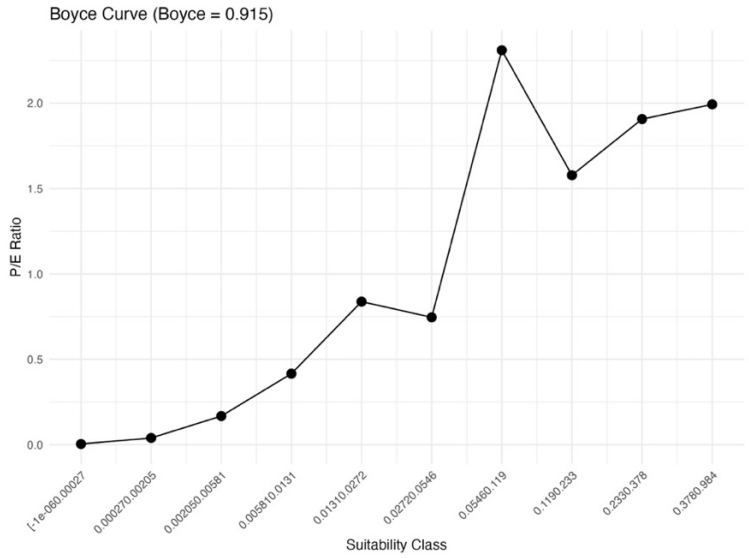


Figure S1. Boyce Index Evaluation Curve. The curve shows the Predicted-to-Expected (P/E) ratio across suitability classes of the model. Values above 1 indicate that presences occur more frequently than expected under random distribution, reflecting good model performance. The overall Boyce Index for the model is 0.91, indicating strong predictive power.

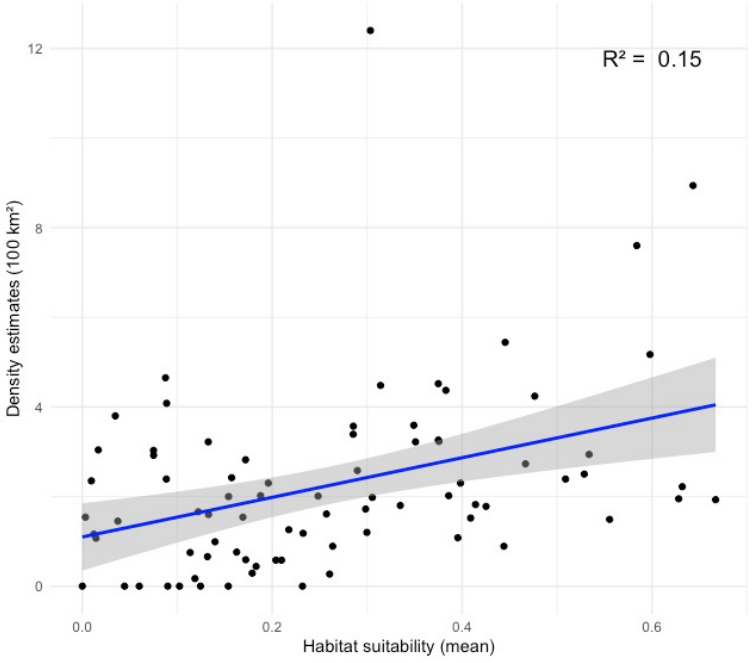


Figure S2. Linear regression showing a positive relationship between jaguar density estimates and the habitat suitability model.

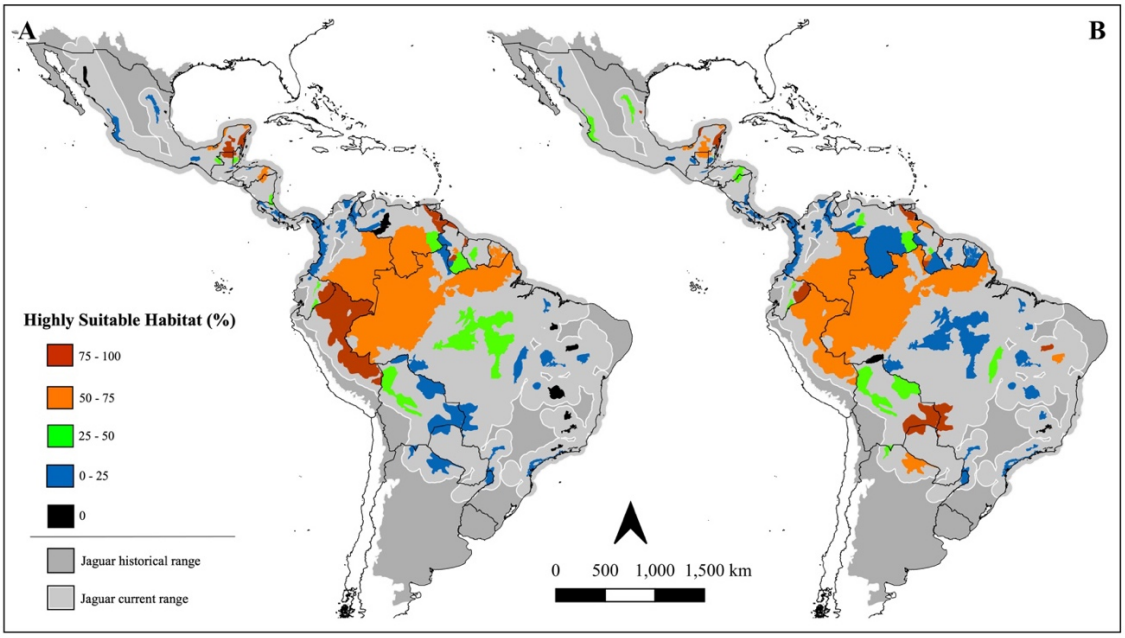


Figure S3. The Jaguar Conservation Units (JCUs) classified by the percentage of highly suitable areas relative to their respective areas considering the range-based (A) and ecoregion-based scenarios (B). Figure created using QGIS v3.36.0 (https://qgis.org).

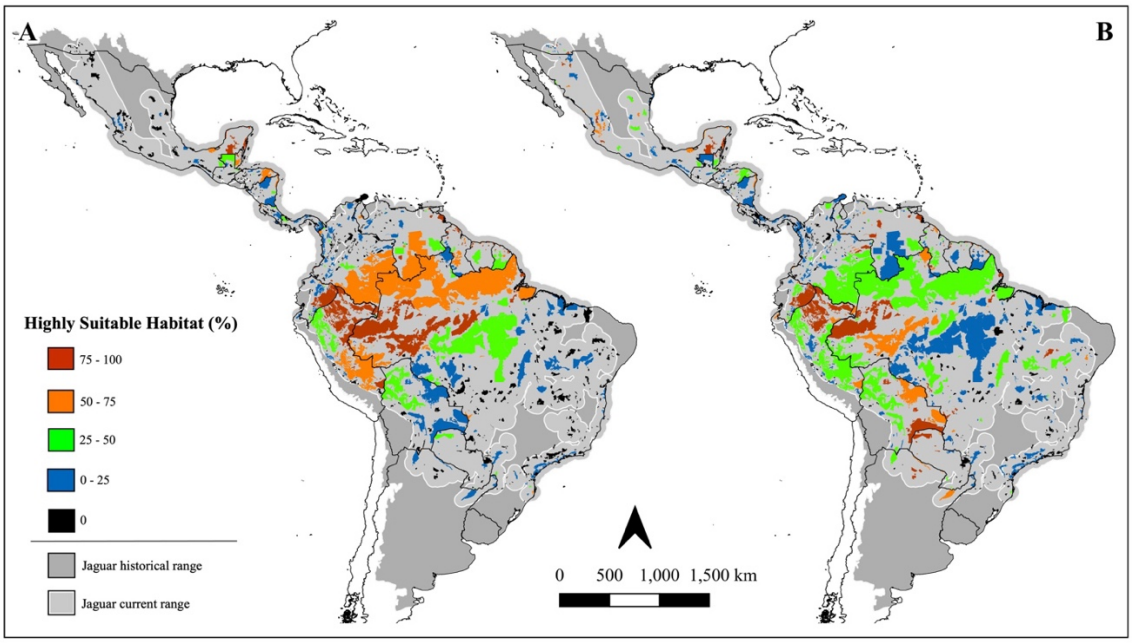


Figure S4. The Protected Areas and Indigenous Lands PAs classified by the percentage of highly suitable areas relative to their respective areas considering the range-based (A) and ecoregion-based scenarios (B). Figure created using QGIS v3.36.0 (https://qgis.org).

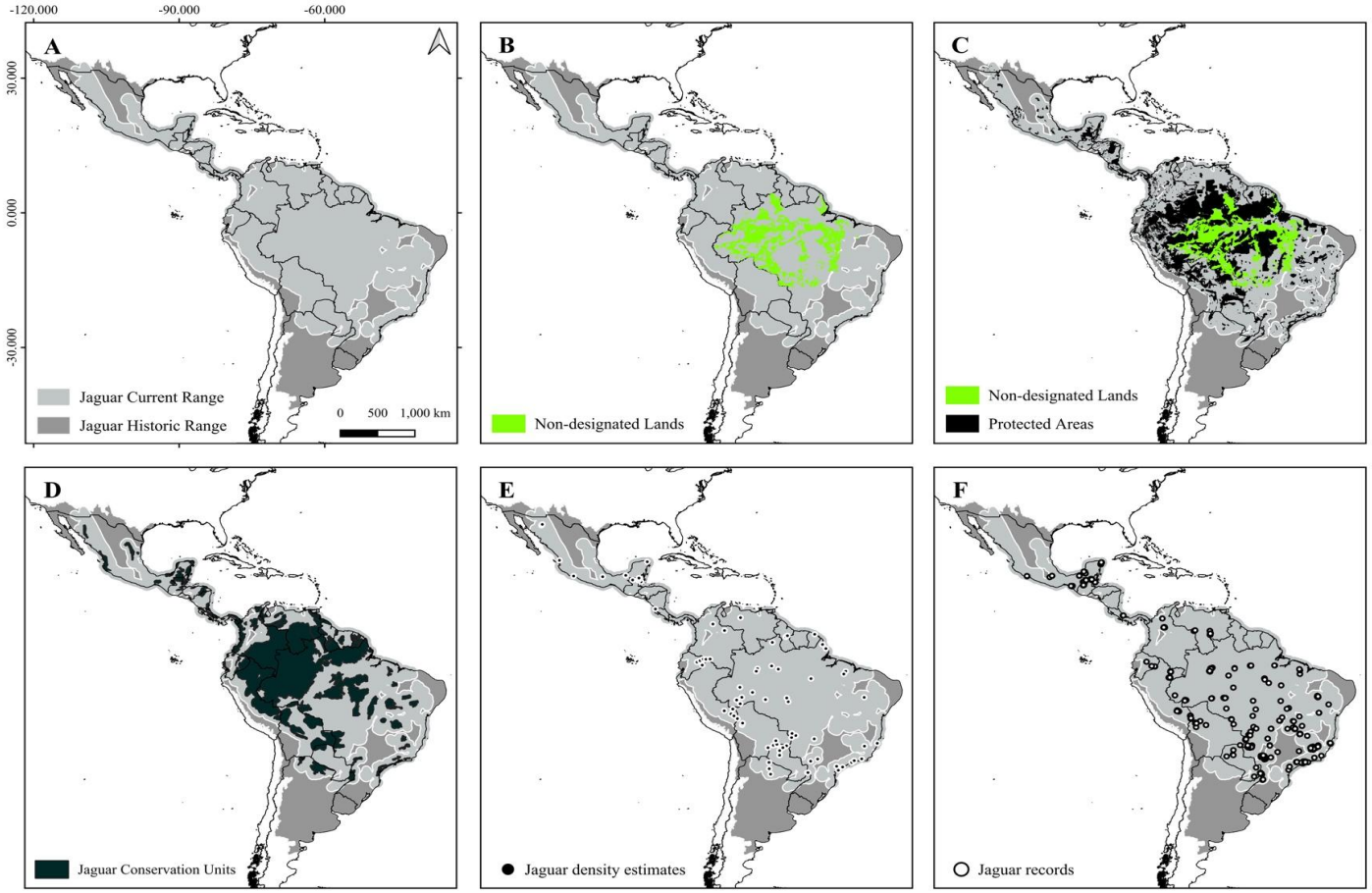


Figure S5. Reference maps depicting jaguar historic and current range (A), non-designated lands (B), protected areas (Indigenous Lands included – C), Jaguar Conservation Units (D), jaguar density estimates used in models' comparison (E), and jaguar records used for validation (F). Figure created using QGIS v3.36.0 (https://qgis.org).

References Supplementary

1. Trinca, C. T. Densidade populacional de felídeos e riqueza de mamíferos terrestres no sul da Amazônia. Universidade Federal da Paraíba (UFPB), 2014.

2. Roopsind, A., Caughlin, T. T., Sambhu, H., Fragoso, J. M. V. & Putz, F. E. Logging and indigenous hunting impacts on persistence of large Neotropical animals. Biotropica 49, 565–575 (2017).

3. Petit, M., Denis, T., Rux, O., Richard-Hansen, C. & Berzins, R. Estimating jaguar (*Panthera onca*) density in a preserved coastal area of French Guiana. Mammalia 82, 188–192 (2018).

4. Espinosa, S., Celis, G. & Branch, L. C. When roads appear jaguars decline: Increased access to an Amazonian wilderness area reduces potential for jaguar conservation. PLoS One 13, 1–18 (2018).

5. Ayala, G., Viscarra, M. E., Fonseca, C. & Wallace, R. B. Estimates of jaguar (*Panthera onca*) population density in the South American Greater Madidi- Tambopata Landscape. Revista de Ciencias Ambientales (Tropical Journal of Environmental Sciences) 56, 1–16 (2022).

6. de Azevedo, F. C. C., Pasa, J. B., Arrais, R. C., Massara, R. L. & Widmer, C. E. Density and habitat use of one of the last jaguar populations of the Brazilian Atlantic Forest: Is there still hope? Ecol Evol 12, 1–15 (2022).

7. Amador-Alcalá, S. A. et al. Abundance of the northernmost jaguar *Panthera onca* breeding population. Anim Biodivers Conserv 47, 49–61 (2024).

8. Greenspan, E., Anile, S. & Nielsen, C. K. Density of wild felids in Sonora, Mexico: a comparison of spatially explicit capture-recapture methods. Eur J Wildl Res 66, 1–13 (2020).

9. Charre-Medellín, J. F., Monterrubio-Rico, T. C., Acevedo, P., Guzmán-Díaz, E. O. & Jiménez, J. Jaguar (*Panthera onca*) density in the Sierra Madre del Sur; the last wilderness area in the central-western slope in Mexico. Stud Neotrop Fauna Environ 58, 47–60 (2023).

10. Lavariega, M. C. et al. Community-Based Monitoring of Jaguar (*Panthera onca*) in the Chinantla Region, Mexico. Trop Conserv Sci 13, (2020).

11. Luja, V. H., Guzmán-Báez, D. J., Nájera, O. & Vega-Frutis, R. Jaguars in the matrix: population, prey abundance and land-cover change in a fragmented landscape in western Mexico. Oryx 56, 546–554 (2022).

12. Hidalgo-Mihart, M. G. et al. Jaguar density in a mosaic of disturbed/preserved areas in southeastern Mexico. Mammalian Biology 98, 173–178 (2019).

13. Harmsen, B. J., Foster, R. J. & Quigley, H. Spatially explicit capture recapture density estimates: Robustness, accuracy and precision in a long-term study of jaguars (*Panthera onca*). PLoS One 15, 1–19 (2020).

14. Devlin, A. L. et al. Drivers of large carnivore density in non-hunted, multi-use landscapes. Conserv Sci Pract 5, 1–13 (2023).

15. Eriksson, C. E. et al. Extensive aquatic subsidies lead to territorial breakdown and high density of an apex predator. Ecology e03543 (2021) doi:10.1002/ecy.3543.

16. Finnegan, S. P. et al. Reserve size, dispersal and population viability in wide ranging carnivores: the case of jaguars in Emas National Park, Brazil. Anim Conserv 24, 3–14 (2021).

17. Montalvo, V. H., Sáenz-Bolaños, C., Cruz-Díaz, J. C., Carrillo, E. & Fuller, T. K. The Use of Camera Traps and Auxiliary Satellite Telemetry to Estimate Jaguar Population Density in Northwestern Costa Rica. Animals 12, 2544 (2022).

18. Thompson, J. J. et al. Jaguar (*Panthera onca*) population density and landscape connectivity in a deforestation hotspot: The Paraguayan Dry Chaco as a case study. Perspect Ecol Conserv (2022) doi:10.1016/j.pecon.2022.09.001.

19. Tobler, M. W. et al. Do responsibly managed logging concessions adequately protect jaguars and other large and medium-sized mammals? Two case studies from Guatemala and Peru. Biol Conserv 220, 245–253 (2018).

20. Alvarenga, G. C. et al. Jaguar (*Panthera onca*) density and population size across protected areas and indigenous lands in the Amazon biome, its largest stronghold. Biol Conserv 303, 111010 (2025).

21. Hyde, M. et al. Tourism-supported working lands sustain a growing jaguar population in the Colombian Llanos. Sci Rep 13, 1–11 (2023).

22. Maffei, L. et al. Assessment of jaguars *Panthera onca* (Mammalia: Carnivora: Felidae) and their prey in Manu National Park. Mammalogy Notes 7, 267 (2021).

23. Jędrzejewski, W. et al. Estimating large carnivore populations at global scale based on spatial predictions of density and distribution - Application to the jaguar (*Panthera onca*). PLoS One 13, 1–25 (2018).


Bruno Kelly - Mamirauá Institute

Chapter 4

Jaguar range-wide connectivity: Prioritizing core areas and corridors between protected areas and Indigenous Lands

Guilherme Costa Alvarenga; Caroline C. Sartor; Żaneta Kaszta; Ana Carolina Srbek-Araujo; Ana Cristina Mendes-Oliveira; Bart Harmsen; Carlos De Angelo; Carolina Franco Esteves; Claudia Bueno de Campos; Daiana Jeronimo Polli; Diego F. Passos Viana; Diogo Maia Gräbin; Emiliano Donadio; Emiliano E. Ramalho; Esteban Payán; Fernando C. C. Azevedo; Francisco Palomares; George V. N. Powell; Gerardo Ceballos; Grasiela Porfirio; Heliot Zarza; Ivonne Cassaigne; Juliano A. Bogoni; Leonardo Sena; Louise Maranhão; Marcos Roberto Monteiro de Brito; Mathias W. Tobler; Øystein Wiig; Rafael Antelo; Rebecca J. Foster; Ricardo Sampaio; Robin Naidoo; Rodrigo Nuñez; Ronaldo G. Morato; Sandra Petrone Mendoza; Valeria Boron; Wener Hugo Arruda Moreno; David W. Macdonald; Samuel A. Cushman

Under review at Global Change Biology

Abstract

Anthropogenic habitat transformation has led to population declines and increasing isolation of many species, particularly top predators, where small and fragmented populations often experience limited dispersal and reduced genetic diversity. Jaguars (*Panthera onca*), for example, have lost half of their historical range and most populations outside the Amazon biome are small, isolated, and highly threatened. Here, we assess jaguar population connectivity across the species' range by identifying and ranking core areas and dispersal corridors, including linkages among protected areas and Indigenous Lands (hereafter, PAs). We used two complementary connectivity approaches: cumulative resistant kernels and factorial Least-Cost Paths (fLCP). We identified 307 core areas for jaguar movement, covering ~7.75 million km² (55% of the current range), of which approximately half lies within PAs. The largest and highest-ranked core area spans ~6.5 million km² across four biomes (Amazon, Llanos, Chaco, and Pantanal). We identified 176 dispersal corridors connecting core areas, although connectivity was not continuous across the entire range. Northern populations (Mexico and Central America) showed several connectivity gaps, whereas South America displayed a large, highly interconnected network linking the Amazon, Llanos, Chaco, Pantanal, Cerrado, Caatinga, Iberá, and the Atlantic Forest's Green Corridor. In contrast, coastal Atlantic Forest patches appeared largely isolated. Using an alternative PA-based approach, we predicted 507 potential corridors connecting 905 PAs. This analysis revealed improved connectivity in Central America and a continuous corridor extending from the Darién Gap through the Amazon and southward to the coastal Atlantic Forest. Most top-ranked PAs were located in the Amazon, highlighting the importance of its extensive protected and Indigenous Land network. By identifying priority core areas and corridors, this study provides a spatial framework to guide jaguar conservation and emphasizes the need to integrate connectivity into large-scale conservation initiatives under accelerating landscape change.

Keywords

Panthera onca; Landscape connectivity; Resistance surface; Dispersal corridors; Least-cost path analysis

Introduction

The world has changed. Large portions of natural habitat have been transformed by anthropogenic actions (IPBES, 2019), leading to the reduction and fragmentation of wildlife populations and – in the worst scenarios – even the extinction of species (Ceballos et al., 2015). The distribution of these anthropogenic impacts is not homogeneous, nor is the way in which they affect different taxa (Bardales et al., 2024; Cardillo et al., 2005). Large apex carnivores require extensive areas of undisturbed habitat and healthy prey populations to thrive (Sunquist and Sunquist, 2002). Where apex carnivores still remain, small population sizes and geographical isolation frequently limit successful dispersal processes, causing loss of genetic diversity (e.g. Srbek-Araujo et al., 2018). Landscape connectivity models are useful tools for predicting individual (or species-level) movement across landscapes, identifying general patterns and informing conservation efforts (Taylor et al., 1993).

Jaguars (*Panthera onca*) have experienced significant range contraction over the last century (around 50%, Quigley et al., 2017). Although they still occupy an area of approximately 9 million km², most populations outside the Amazon are isolated and highly threatened (de la Torre et al., 2018), with reduced genetic diversity already reported in some of them (Haag et al., 2010; Lorenzana et al., 2020). Protected areas, including Indigenous Lands (PAs hereafter), have long been the cornerstone strategy for safeguarding ecological integrity and natural heritage (Rodríguez-Rodríguez and Martínez-Vega, 2022). Indeed, PAs safeguard large jaguar populations (Alvarenga et al., 2025; Bogoni et al., 2023) and extensive areas of suitable habitat (Alvarenga et al., 2026). However, a conservation strategy restricted solely to PAs is inadequate for large carnivores such as the jaguar as PAs are often too small and too isolated due to changes in the surrounding landscape (Laurance et al., 2012), which limits their efficacy in maintaining viable populations. Therefore, maintaining the extensiveness of both protected and unprotected jaguar populations are distributed across the

landscape, and maintaining as much connectivity as possible between these populations is paramount to reduce the risk of local extinctions.

Several studies have assessed landscape connectivity across the jaguar range using an array of techniques and types of biological data, from expert knowledge (Rabinowitz and Zeller, 2010) and interviews (Petracca et al., 2018a) to empirical observations of jaguar occurrence (telemetry – de la Torre et al., 2017, cameras-trap – Meyer et al., 2019, and databases compilation – Balbuena-Serrano et al., 2022). However, due to limited data availability, only one study covered the entire jaguar range and was based solely on expert knowledge (Rabinowitz and Zeller, 2010). Here, we present a broad-scale modelling approach based on empirical telemetry data (Alvarenga et al., 2026) to assess jaguar population connectivity across its range, updating the previously available model (Rabinowitz and Zeller, 2010). To support conservation prioritization, we model and rank priority areas for the species (hereafter, core areas) and the corridors that connect them. In parallel, we extend this framework to PAs, ranking both PAs and their potential corridors, thereby providing quantitative information relevant to governments and international agencies.

Methods

Resistance surface modelling

Landscape connectivity models can be developed from different approaches (Unnithan Kumar et al., 2022), with resistance surface-based methods being the most prominent (Zeller et al., 2012). Resistance surfaces represent the "physiological cost for a given species to move through a particular environment" (Zeller et al., 2012). Therefore, low resistance values represent landscape units (pixels) more easily traversed by a focal species, whereas high values represent less permeable landscape units. We based our resistance

surface modelling on a multi-scale habitat suitability model developed across the historical range of jaguars, using empirical data from 172 GPS-collared individuals (86 females and 86 males, Table S1) (Alvarenga et al., 2026). Due to inconsistencies in data among individuals (mainly the insufficient frequency of telemetry fixes), the authors were unable to apply a movement model per se (e.g., Path Selection Function) and instead used Point Selection Function (N = 231,017 GPS locations) (Alvarenga et al., 2026).

To transform the habitat suitability surface into resistance to movement, we applied a negative exponential transformation (Keeley et al., 2016). This approach assumes that animals may move through suboptimal areas during long-distance dispersal, a pattern previously reported for jaguars (Schoen et al., 2025), lions (Elliot et al., 2014), spotted hyenas (Beytell et al., 2024), and bears (Mateo-Sánchez et al., 2014). The negative exponential transformation produces a resistance surface in which landscape resistance increases nonlinearly and convexly as suitability decreases, instead of increasing at a constant rate in a negative linear function. We applied Keeley et al. (2016) transformation function, "R = 100–99*((1−exp(-c*h))/(1−exp(−c)))", where "R" is resistance, "h" is the suitability layer, and "c" determines the strength of the suitability-to-resistance transformation. A zero "c" value means a linear transformation, and as "c" increases, resistance values become an increasingly nonlinear negative exponential function of suitability. To select the correct "c" value that would produce a resistance surface representing jaguars' movement as realistically as possible, we visually inspected regions where jaguar movement is relatively well known, adjusting "c" values accordingly. After the adjustments, we opted to use c=16, the second steepest transformation curve from Keeley et al. (2016), resulting in a resistance layer ranging from 1 to 190 cost units.

The resistance layer described above was used to calculate dispersal thresholds (see Connectivity models for details). However, additional adjustments were required to account

for landscape features that are either underrepresented or not explicitly captured by the habitat suitability model, and to avoid routing corridors through areas that are ecologically implausible. Such expert-informed adjustments are widely used in large-scale connectivity modelling to ensure that dispersal pathways derived from suitability layers remain biologically realistic (e.g., McRae et al., 2008; Penjor et al., 2024; Zeller et al., 2012). For example, although jaguars may occasionally move close to urban areas (G1, 2019a), such events are sporadic and typically associated with high mortality risk (Bejarano Alegre et al., 2024). To minimize the likelihood of corridors being routed through urban centres, we applied a 4-km buffer around the centroids of villages, towns, and cities (OSM; www.openstreetmap.org), within which resistance values were increased by 1,000,000 cost units. The buffer width was defined as a practical compromise: while it may not entirely cover the extent of larger urban centres, it substantially reduces the chance of underrepresenting urban influence while avoiding excessive coverage of smaller villages. Similarly, considering that jaguar records are extremely rare above 2,500 m (Griffith et al., 2021), we applied a non-linear transformation that increasingly penalised values above this threshold with resistance values rising to the cubic order. At a lower intensity, we also increased the resistance of roads (OSM; www.openstreetmap.org) and water bodies (Lehner and Grill, 2013), acknowledging that jaguars are capable of crossing these features but that they can still impose movement costs (e.g., Hernández-Pérez et al., 2020). For roads, we considered the three largest paved classes, where traffic volume and vehicle speed are highest, increasing the risk of jaguar mortality due to collisions. Accordingly, we added 10 cost units to motorways and trunk roads, and 5 cost units to primary roads. For rivers, we used water flow order as a proxy for crossing difficulty. The two highest-order classes (orders 1 and 2), as well as lakes, were assigned an additional 10 cost units, while lower-order rivers (orders 3 and 4) were assigned an additional 5 cost units. Finally, given that jaguars often use

riparian forests for movement (Gese et al., 2018; Schoen et al., 2025), including in human-modified landscapes and in proximity to settlements (G1, 2019b), we adjusted resistance along major rivers using a land-cover map (Brown et al., 2022). This adjustment was necessary because the habitat suitability layer, while capturing broad environmental gradients, tended to overestimate resistance in riparian environments embedded within otherwise high-resistance matrices (e.g., near urban areas or agricultural mosaics). Land-cover data were extracted from the 2023 Dynamic World collection, with the most frequent classification across the year assigned to each pixel. Riparian areas were defined as an 8-km buffer on each river margin (orders 1-4), resulting in a 16 km-wide corridor – the scale shown to positively influence jaguar occurrence near water surfaces (Alvarenga et al., 2026). To capture decreasing resistance closer to riparian forests, we applied a linear decay based on river distance, reducing resistance by 50% in river-adjacent forest pixels and gradually returning to the baseline at the buffer's outer edge (8 km) (Final Resistance layer: Figure S1).

Dispersal source points

To assess jaguar habitat connectivity, we applied cumulative resistant kernels (Compton et al., 2007) and factorial Least-Cost Paths (fLCP) models (Cushman and Landguth, 2012). These models consider the rate of movement of organisms as a function of the species' distribution, abundance, and dispersal capacity. Therefore, to define the distribution and density of jaguars across their current range, we used the previously mentioned habitat suitability layer (Alvarenga et al., 2026) combined with a jaguar population estimate layer (Jędrzejewski et al., 2018). This combination served as a probability surface to distribute source points across the landscape, representing individual jaguars. First, we generated a uniform random raster with values ranging from 0 to 1, maintaining the same resolution as the habitat suitability layer (500 m). Then, we resampled

the jaguar population layer to 500 m and adjusted its pixel values to reflect potential jaguar density at a pixel level. We thus subtracted the stochastic map from the density raster, converting pixels with values greater than zero into points while excluding those where the expected density was excessively low. To ensure that no source points were placed in unsuitable areas, we filtered out points that fell within the five smallest quantiles of the jaguar habitat suitability layer. From the remaining points, we randomly selected 10,000 points to be used in the cumulative resistant kernels and 5,500 points for the fLCP. Both models focused on the linkages between landscapes that are biologically relevant for the species, regardless of their protection status. However, as PAs are more likely to maintain natural habitats in the long term, we also assessed connectivity linkages between them. For this, we created a centroid point for each PA to ensure that every PA had at least one source point on it. After that, we added more points within PAs from the previously generated pool, totalling 4,500 source points. While this selection included a random component, larger PAs with high habitat suitability and predicted jaguar density had a higher likelihood of being assigned more points.

We used the same PA and jaguar current range layers as Alvarenga et al. (2026). PAs were obtained from two databases (Jędrzejewski et al., 2023; UNEP-WCMC and IUCN, 2022), retaining only those PAs (or contiguous blocks of PAs) larger than 100 km² (Sollmann et al., 2008), located predominantly below 3,000 m in elevation on average (Griffith et al., 2021), and intersecting the species' current range (N = 905 PAs, Figure S2). The jaguar's current range was also defined by combining two datasets: the South American distribution (Jedrzejewski et al., 2023) and the Wildlife Conservation Society jaguar distribution layer covering areas from Panama to the southern United States (Zeller, 2007). To address spatial uncertainties and the species' high mobility, Alvarenga et al. (2026) applied a 100 km buffer

around the estimated range, which was then used as the final extent of the jaguar's current distribution (Figure S2).

Connectivity models

Due to computational constraints, we divided the study area into two regions (hereafter referred to as the northern and southern ranges), using the Panama Canal as a reference. This decision was partly based on Cushman et al. (2023), who predicted the canal to be an insurmountable barrier to large carnivores. We used UNIversal CORridor network simulator (UNICOR) (Landguth et al., 2012), applying two complementary methods: the cumulative resistant kernels (Compton et al., 2007) to define core areas of high-density movement and fLCP to model dispersal corridors between these core areas (Cushman and Landguth, 2012). UNICOR is a species connectivity identification tool that applies Dijkstra's shortest path algorithm to individual-based simulations (Landguth et al., 2012).

Cumulative resistant kernels provide one of the most biologically realistic measures of comprehensive landscape connectivity, as they incorporate species' distribution, abundance, and dispersal capacity into movement rates (Compton et al., 2007; Cushman et al., 2015; Unnithan Kumar and Cushman, 2022). Resistant kernels have been found to perform well in predicting patterns of organism movement (Cushman et al., 2014; Lumia et al., 2024) and genetic diversity (Atzeni et al., 2024; Macdonald et al., 2018). This method does not assume a priori destinations but calculates connectivity across the entire landscape by measuring the functional distance from a source point to every other cell in the considered landscape (Compton et al., 2007). The model applies a least-cost function to calculate the costs of moving from each source point to its neighbouring cells based on resistance surface values. The process continues with the costs accumulating with each movement along the pixel cells until a predefined cost-distance threshold from the source is reached (Cushman

and Landguth, 2012). This threshold constrains the dispersal distance used in the connectivity analysis and is described in detail below. Then, all least-cost kernels generated from all source points are summed to produce a cumulative resistant kernel surface whose values indicate the density of potential movement in every pixel (Compton et al., 2007; Cushman and Landguth, 2012). Because least-cost kernels tend to produce broadly circular patterns, reflecting movement expanding from a source point to all surrounding cells, we used this approach to identify core areas of intense movement. In contrast, fLCPs are better suited to identifying long, narrow linkages between core areas.

Considering the large heterogeneity found across our study area, we opted to take into account ecoregion differences when defining core areas and later during the ranking process (ranking full description in the following subsection). Ecoregions were derived from the classification of terrestrial biomes and ecoregions (Olson et al., 2001), but disjointed categories were treated separately, following the same approach of Antonelli et al. (2018) (Figure S3). Therefore, to define core areas from the cumulative resistant kernel surface, we (1) clipped the surface to the extent of the species' current range, (2) excluded zero values, then (3) used a threshold value of the 90th percentile of the cumulative kernel surface per ecoregion, (4) excluding any remaining individual area smaller than 100km². This was chosen to exclude areas of very low predicted rate of jaguar movement.

To model the long-distance dispersal corridors between the core jaguar habitats and PAs we used the fLCP approach. The fLCPs are an evolution of the regular Least-Cost Paths and have the advantage of being capable of calculating narrow landscape linkages (corridors) among many pairs of source-destination (Cushman and Landguth, 2012). Therefore, using the resistance layer as a basis, we calculated least-cost paths from each jaguar source point to every other source point within a predefined dispersal cost distance (dispersal thresholds detailed below). The final corridors surface is generated by summing all least cost paths; thus,

it represents the number of cost paths crossing each cell, which indicates the corridor strength (Cushman et al., 2013; Rudnick et al., 2012). Since this final summed up fLCP layer only represents narrow pixel-wide linkages, to make the corridors more biologically relevant we applied a smoothing moving window filter width of 9 km. Using both connectivity modelling methods allows us to map, quantify, and prioritize key areas and corridors that are most important for jaguar population connectivity (Cushman et al., 2018).

Our study area spans an extensive and heterogeneous region, resulting in significant variation in the resistance surface. This variability makes it challenging to establish a reliable dispersal threshold. Moreover, to the best of our knowledge, robust empirical estimates of jaguar dispersal distances are largely lacking in the scientific literature (see review in Gonzalez-Borrajo et al., 2017), with only sparse and disparate reports available, ranging from relatively short movements (~50 km: Morato et al., 2016), to exceptional long-distance dispersal events exceeding 1,600 km (Metrópoles, 2025). Therefore, to define the threshold for the resistant cumulative kernel, we tested various values and evaluated the outcomes in areas where jaguar movement is well-documented. Through this process, we identified an optimal threshold of 1,000,000 cost units, representing short-distance movements. For long-distance dispersal movements modelled through the fLCP corridors, we relied on the estimates from Bowman et al. (2002), which suggest that the median dispersal distance of mammalian species is isometrically related to their home range size by a factor of seven. First, we calculated the average jaguar home range size by sex and biome, selecting the largest home range observed (Thompson et al., 2021). Then, we determined the square root of this value and multiplied it by seven to estimate the median potential dispersal distance jaguars could achieve (352 km). Assuming an average resistance of 21.4 cost units across the resistance surface, the median dispersal distance translates to approximately 7,500,000 cost

units (dispersal distance × mean resistance). This value was used as the threshold for the fLCP analysis.

Identifying and ranking core areas, protected areas, and corridors

To identify the most important core areas, PAs, and their associated corridors, we ranked them using independent metrics, following the approach of previous studies (e.g., Cushman et al., 2018; Kaszta et al., 2020). Core areas and PAs were first ranked independently by (1) their size and (2) the sum of kernel density values within their extent. These two ranks were then averaged, so that core areas/PAs that were both large and contained high kernel sums received the highest scores. This process was repeated by ecoregion, calculating the rank position of every overlapping core area/PA for each ecoregion. Finally, we calculated a weighted average rank across all ecoregions for each core area/PA, dividing the sum of its ecoregion ranks by the number of ecoregions it overlapped. This approach assigned proportionally higher importance to core areas and PAs that intersect multiple ecoregions, as they contribute to connectivity across several distinct ecological contexts.

To calculate the metrics used to rank our two sets of corridors (between core areas and between PAs), we first used the narrow, pixel-wide linkages derived from the summed fLCP layers. Each corridor was independently ranked according to three criteria: (1) the total LCP values within its extent, (2) the number of core areas or PAs it connected (excluding corridors linking the same area), and (3) the mean kernel value of the connected core areas or PAs. These three rankings were averaged to produce an initial composite rank. Next, we applied the wide-version corridors (9 km), which merged nearby corridors into larger networks. For these merged networks, we recalculated rankings by averaging the positions of the component corridors, weighted by their size so that larger networks connecting more

areas contributed proportionally more to the rank. Finally, this combined ranking was reassessed at the ecoregion scale using the same approach as described for core areas and PAs.

Results

Core areas ranking

Based on the cumulative resistant kernel analysis, we identified 307 core areas for jaguar movement, representing regions of high predicted movement density: 70 in the northern range and 237 in the southern range (Fig. 1). Core areas cover approximately 7.75 million km², representing 55% of the jaguar's current range, with about half of this area under formal protection. The largest and highest-ranked core area spans 6.5 million km², encompassing four biomes – Llanos, Amazon, Chaco, and Pantanal – and 11 countries (Fig. 1E; Table 1). The Mayan Forest ranked second (Fig. 1B), followed in third place by three areas of equal rank: the Central American Moist Forest, the southern Amazon, and the Cerrado-Caatinga transition zone (Fig. 1C, F, G). The full ranking is provided in the Supplementary Material (Ranking_CoreAreas_Ecoregions.shp). The top-ranked core area alone accounts for 85.5% of the total predicted core area and 98.6% of cumulative kernel values. Considering the five highest-ranked areas together, these proportions increase to 91.4% of the total area and 99.9% of kernel values. Nonetheless, the ecoregion-stratified approach also highlighted smaller core areas of local importance, several of which appear among the ten highest-ranked (Fig. 1A-I; Table 1).

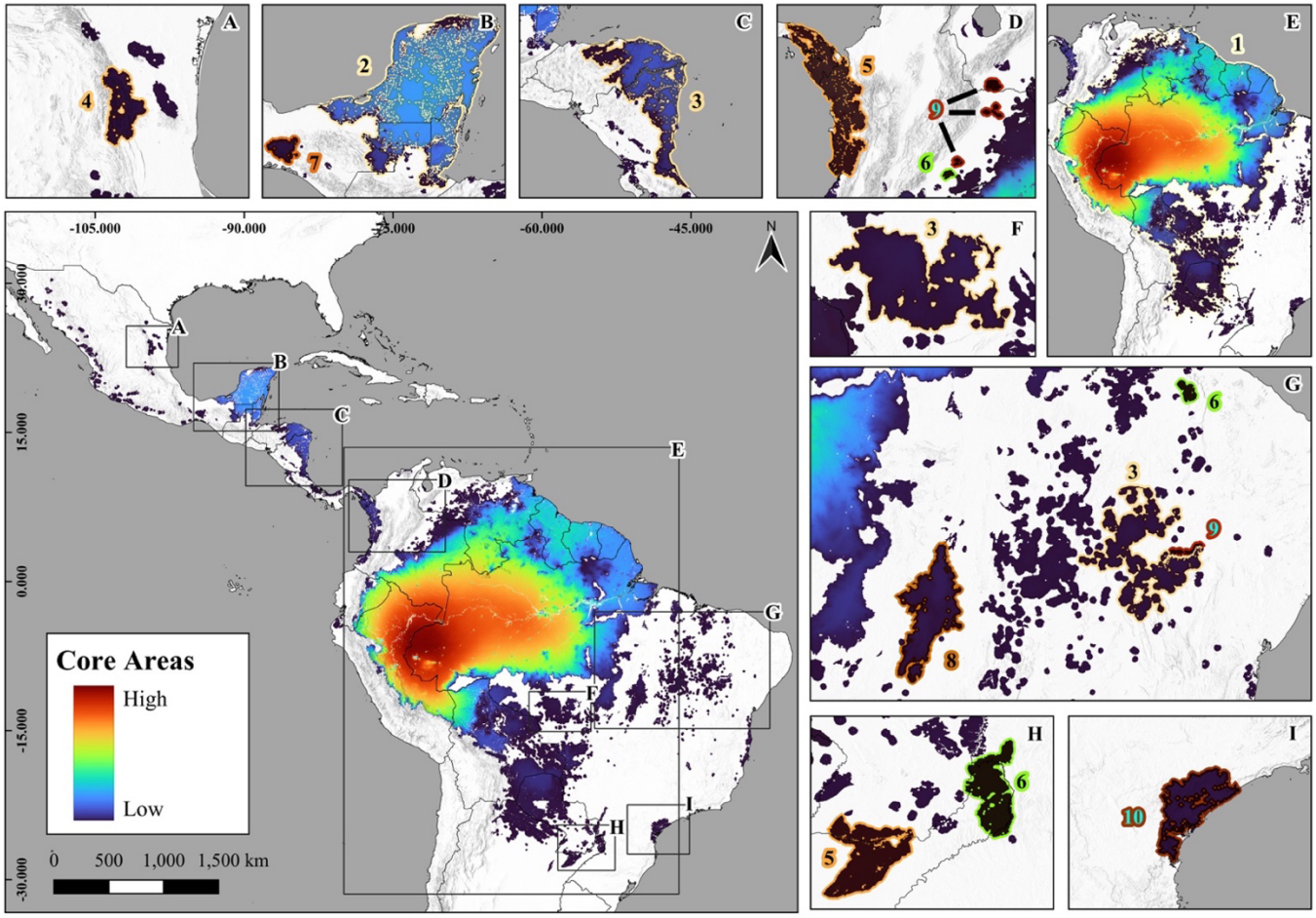


Figure 1. Ranking of core habitat areas for jaguars across the species current range. The strength of core areas is expressed as density of movement. The side maps highlight the ten highest-ranked core areas numbered by priority. In the side maps, buffer colours correspond to the respective rank positions.

Table 1. Ten highest-rank core habitat areas for jaguars across the species' current range, showing the countries encompassed by each core area, total area (km²), kernel sum, and final rank. Final rank positions (1–10) are also shown spatially in the side maps of Figure 1.

Countries	Area (km²)	Kernel Sum	Priority Rank
Argentina, Bolivia, Brazil, Colombia, Ecuador, Guyana, French Guyana, Paraguay, Peru, Suriname, Venezuela	6,540,315	2,514. 70	1

Belize, Guatemala, Mexico	171,255	26.49	2
Costa Rica, Honduras, Nicaragua	95,619	5.31	3
Brazil	78,215	0.10	3
Brazil	94,395	0.40	3
Mexico	9,134	0.03	4
Colombia, Panama	65,458	1.69	5
Argentina, Paraguay	21,013	0.02	5
Colombia	1,209	<0.01	6
Brazil	3,813	<0.01	6
Argentina, Brazil, Paraguay	15,954	0.01	6
Mexico	7,524	0.03	7
Brazil	62,606	0.27	8
Colombia, Venezuela	2,308	<0.00	9
Colombia	1,866	<0.00	9
Colombia	875	<0.00	9
Brazil	2,050	<0.00	9
Brazil	23,509	0.08	10

Corridor ranking

We identified 176 fLCP dispersal corridors connecting jaguar core habitat areas and ranked them by strength (Fig. 2). Of these, 45 corridors were located in the northern range and 131 in the southern range. However, our models did not indicate connectivity across the entire species' range. In the northern range, Mexico contains four interlinked groups of core areas, but these do not connect with each other or with the Mayan Forest to the south (Fig. 3A). A similar pattern emerges in Central America, where three major interconnected groups remain isolated: the Mayan Forest; a large cluster spanning Honduras to Panama; and the Darién Gap on the Panama-Colombia border. Notably, all three contain corridors ranked among the ten strongest (Fig. 3B, Table 2). In South America, our ranking highlights an important corridor (third highest overall) extending from the Venezuela-Colombia border toward the Darién Gap. However, this corridor does not connect to the Gap or to the largest southern core area, apparently blocked by the northern end of the Andes (Fig. 3B). The

highest-ranked core area – Llanos/Amazon/Chaco/Pantanal – shows multiple connections with smaller areas, suggesting links to the Cerrado and Caatinga biomes in northeastern Brazil, as well as to Iberá and the Green Corridor of the Atlantic Forest in Argentina and Brazil at the species' southern range limit (Fig. 4A-B). This represents the largest and most significant interlinked network of core areas, with several corridors among the ten highest-ranked (Fig. 4A-B). In contrast, all coastal Atlantic Forest patches appear isolated from this group and from each other, including the *Serra do Mar* core area in Brazil (Fig. 4B).

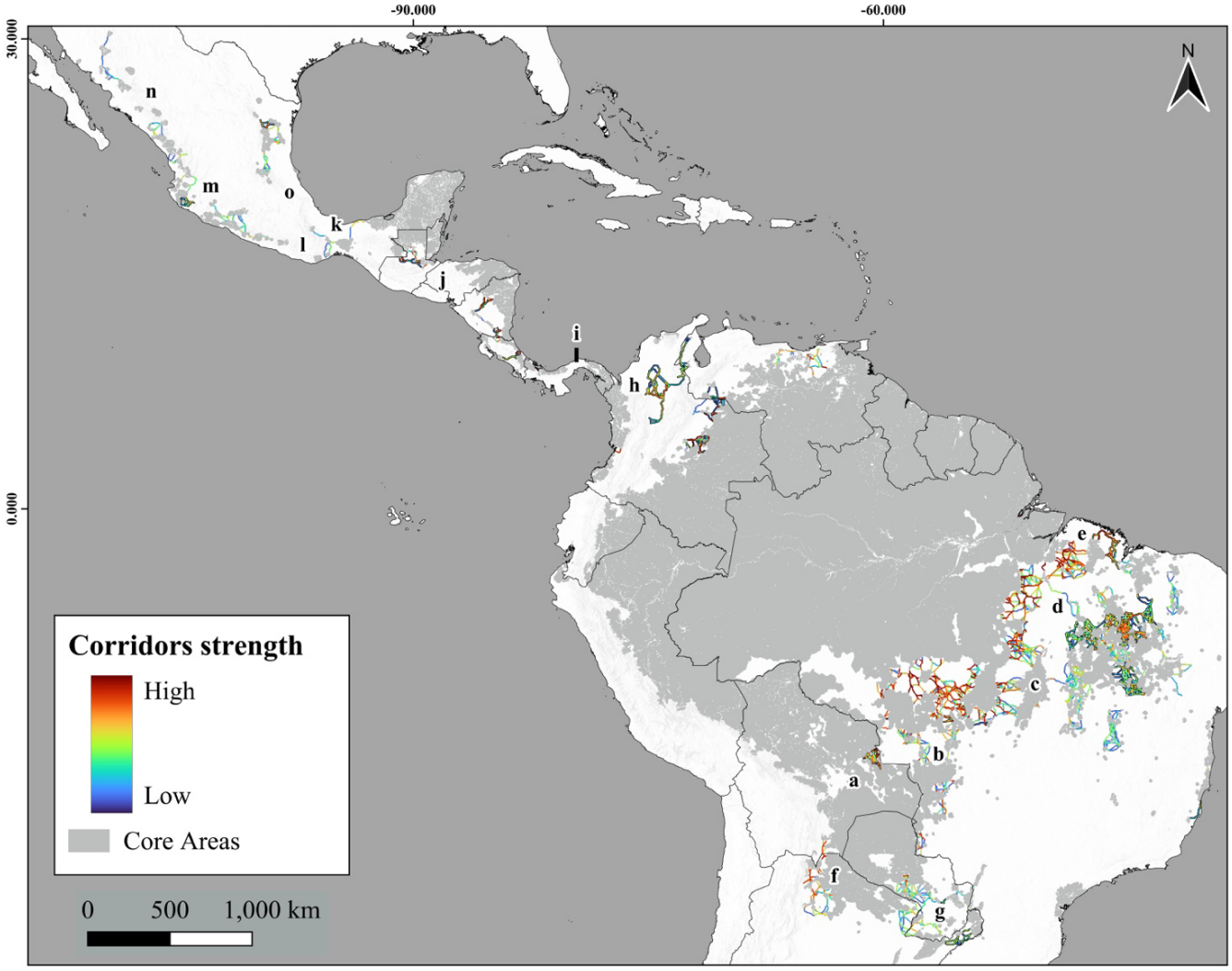


Figure 2. Corridors' strength between core habitat areas for jaguars across the species current range. Letters represent areas of interest described in detail in the Discussion section.

Table 2. Ten highest-rank corridors between jaguar core areas across the species' current range, showing the countries encompassed by each corridor, total area (km²), ids of narrow fLCP corridors, least-cost path sum of these corridors, kernel mean of the core areas linked, and final rank. Final rank positions (1–10) are also shown spatially in Figures 3-4.

ID	Area (km²)	Country	fLCP_IDs	LCP Sum	Kernel Mean	Priority Rank
13	28617	Brazil	93	73119	0.04	1
72	3920	Argentina	263	2275	0.01	1
133	1757	Costa Rica	56	26340	1.78	1
28	8590	Brazil	77, 83	40510	0.06	2
128	20311	Colombia, Venezuela	51	23072	0.00	3
125	5807	Colombia	68	668669	838.23	4
132	259	Panama	60	11448	0.02	4
153	1820	Mexico	5	2811	0.01	4
68	1064	Brazil	194	21535	0.01	5
122	5443	Colombia, Venezuela	63, 66, 67	100885	1047.79	5
142	2700	Guatemala	42	17802	8.83	5
137	2123	Nicaragua	45	10623	1.77	6
2	1525	Brazil	228	814	0.00	7
74	435	Argentina	262	350	0.01	7
84	1626	Brazil	188	19446	0.20	7
124	371	Venezuela	62	40	0.00	7
127	414	Colombia	69	249	838.23	7
136	220	Costa Rica	50	11520	2.66	7
14	16369	Brazil	141, 142	12070	0.04	8
91	457	Paraguay	255	165	0.00	9
108	143	Brazil	191	23952	1257.55	9
110	5995	Bolivia	216, 218	224757	419.12	9
123	828	Colombia	65	86603	1257.35	9
30	22126	Brazil	101, 103, 107, 111, 114	20599	0.03	10
131	74	Colombia	73	4656	0.05	10
134	1048	Nicaragua	48, 49	8434	0.67	10
167	2460	Mexico	18, 19, 20, 21	1841	0.00	10

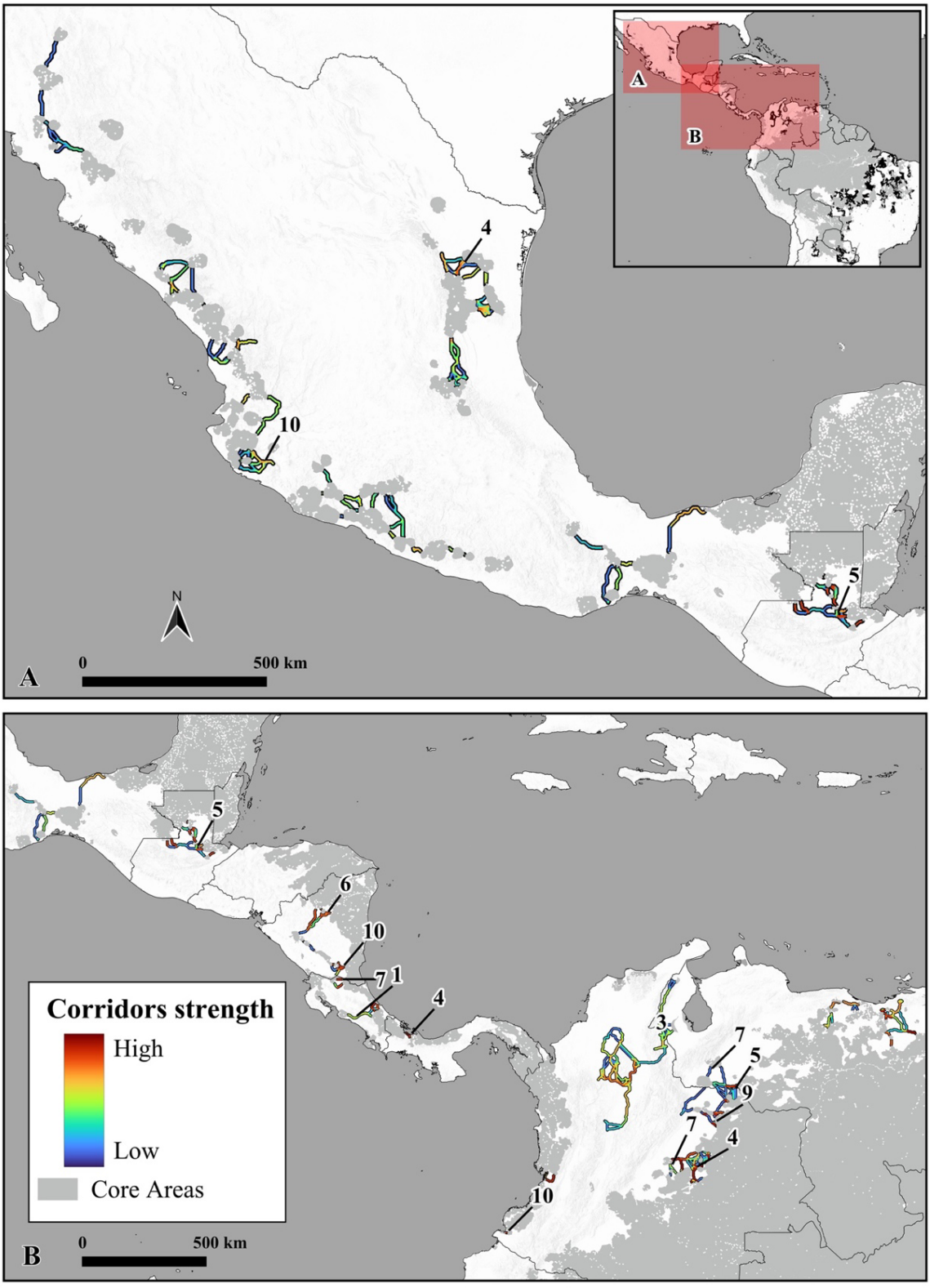


Figure 3. Ranking of the corridor's strength between jaguar core habitat areas across Mexico, Central America and northern South America (A-B). Numbers represent rank prioritization.

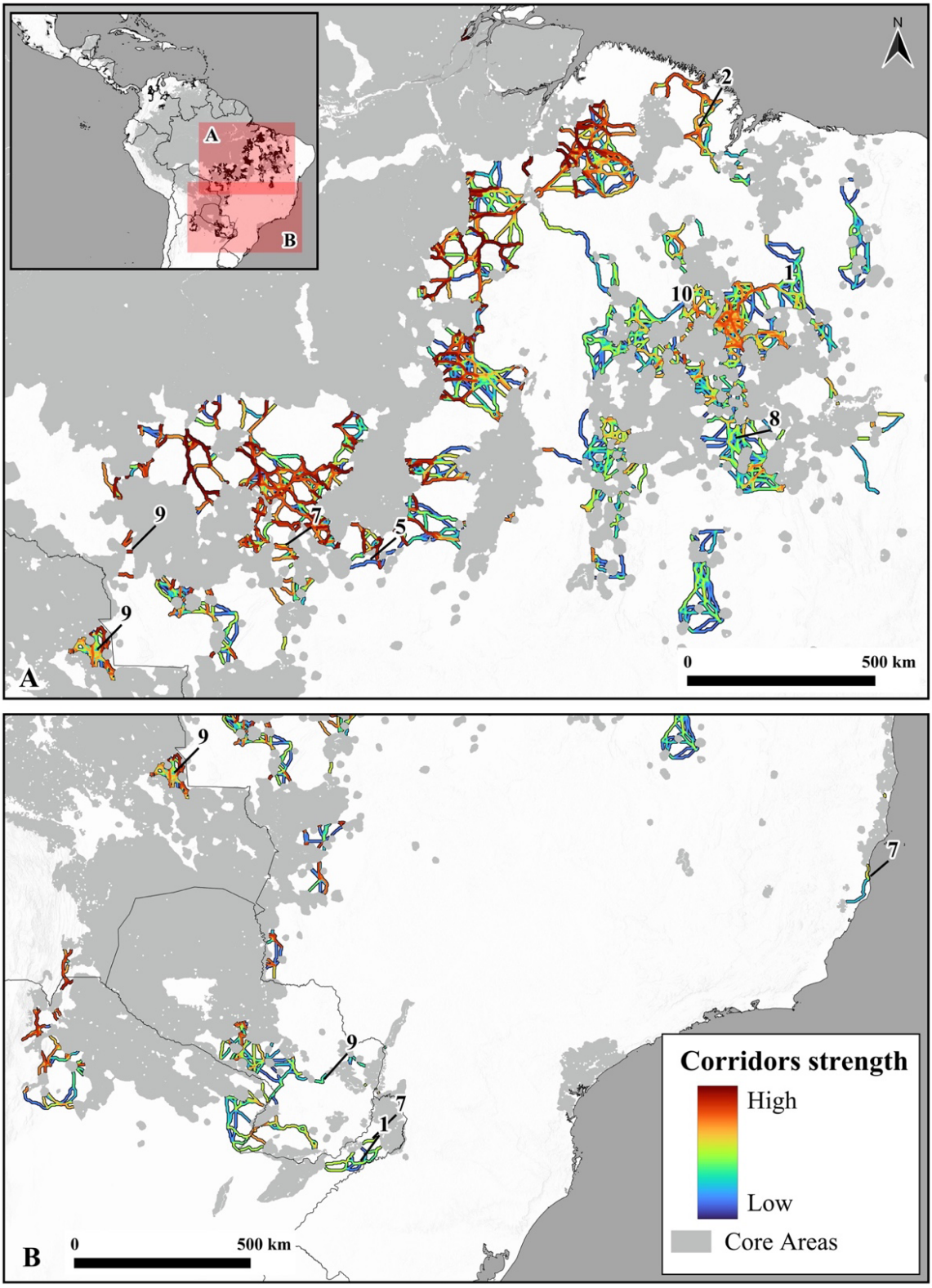


Figure 4. Ranking of the corridor's strength between jaguar core habitat areas in South America (A-B). Numbers represent rank prioritization.

Ranking protected areas and their corridors

In the alternative approach, we predicted potential jaguar corridors between PAs, ranking both the PAs and their associated corridors. In total, 507 fLCP corridors were identified among 905 PAs: 103 corridors in the northern range and 404 in the southern range (Fig. 5). In the northern range, Mexico showed a broadly similar pattern to the previous approach, with clusters of PAs interlinked in roughly the same locations as the clusters of connectivity identified among core areas and corridors – in both cases such clusters appeared isolated from the rest of the network (Fig. 6A). Moving south into Central America, however, predictions indicated improved connectivity compared with the previous approach, as corridors linked PAs from the Mayan Forest to Panama; several of these corridors ranked among the top ten. Nevertheless, the connection gap between this long corridor network and the Darién Gap persists (Fig. 6B). In South America, predictions were more positive, revealing a potential corridor from the Darién Gap through northern Colombia to the Venezuelan border, where it links to the Llanos and Amazon (Fig. 6B). This extensive PA-corridor network extends across the Amazon biome and southward to the Chaco, Pantanal, Iberá, the Green Corridor, and – surprisingly – the *Serra do Mar* in the Brazilian Atlantic Forest (Fig. 7A-B). Several of the highest-ranked corridors occur within this network (Table 3). Worryingly, the Cerrado and Caatinga biomes lost their connection to the wider network under this approach, and the northern Atlantic Forest patches remained isolated (Fig. 8A-B). Regarding PA ranking (highlighted PAs in Fig. 5), a strong concentration of high-ranked areas occurred in the Amazon biome, consistent with their extensive size and high-quality habitat. At the same time, the ecoregion-stratified strategy used in this study ensured that top-ranked PAs were also represented more broadly, spanning the Mayan Forest, Central America, the Chaco, and the Atlantic Forest (Table 4).

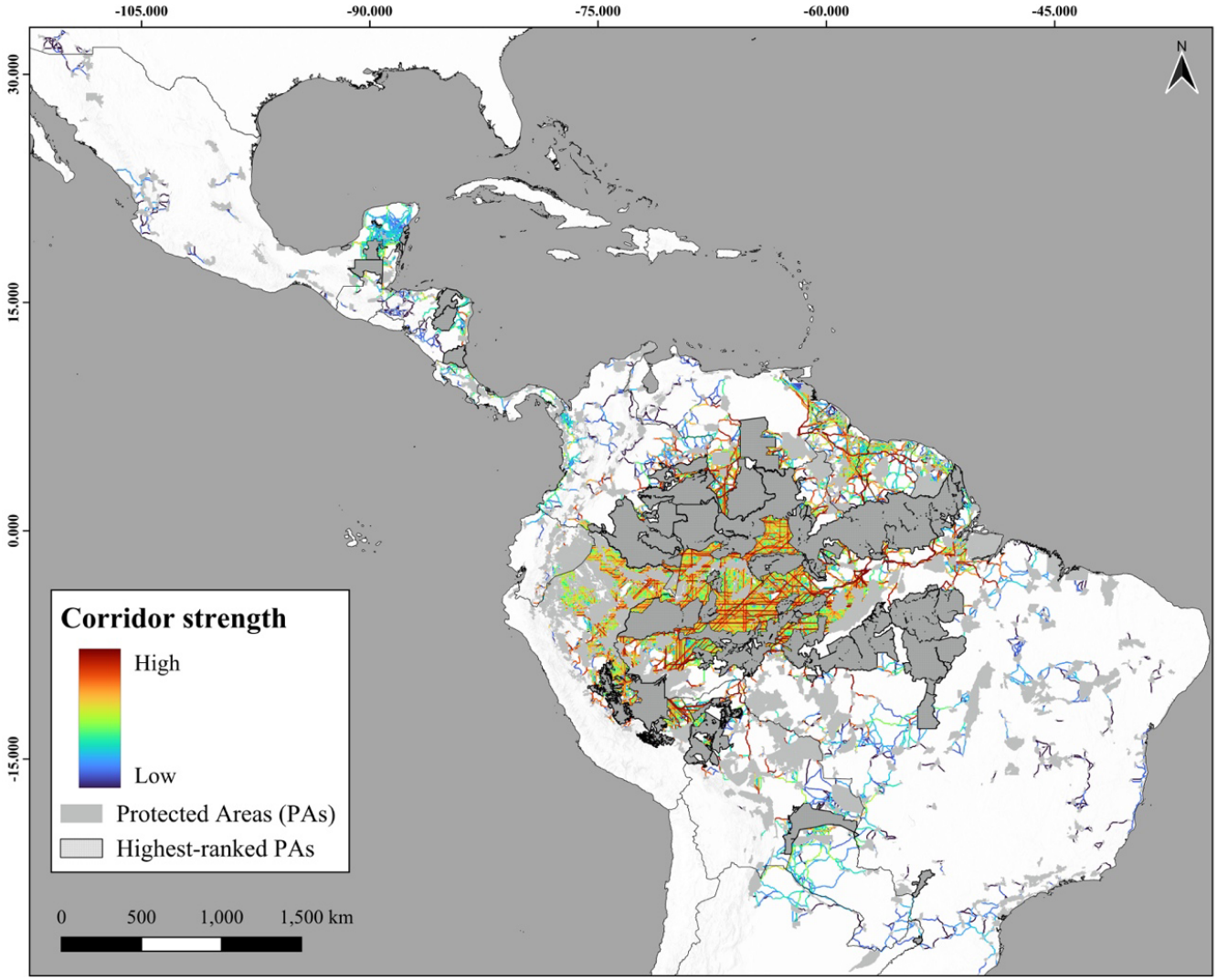


Figure 5. Jaguar corridor network among protected areas and Indigenous Lands (PAs) across the species current range. Highlighted PAs represent the 10 top-ranked ones.

Table 3. Ten highest-rank corridors between Protected Areas (PAs) across jaguar current range, showing the countries encompassed by each corridor, total area (km²), ids of narrow fLCP corridors, least-cost path sum of these corridors, kernel mean of the PAs linked, and final rank. Final rank positions (1–10) are also shown spatially in Figures 6-8.

ID	Area (km²)	Country	fLCPs_IDs	LCP Sum	Kernel Mean	Priority Rank
207	62,510.7	Brazil	617, 769, 772	96,452,202	165.44	1
124	424.5	Argentina	402	1,600	<0.01	2
247	7,290.4	Brazil	800	18,185,617	165.44	2

435	44,706.7	Mexico	141, 202, 207	913,443	2.41	2
450	3,058.2	Belize, Mexico	178	229,973	2.06	2
129	1,815.3	Argentina, Paraguay	424	2,177	<0.01	3
159	6,893.1	Brazil	495	9,488,060	159.76	3
208	14,005.0	Venezuela	619, 678	17,064,436	65.99	3
223	1,384.7	Bolivia	657	240,891	1.89	3
410	7,966.1	Nicaragua	70	990,641	0.44	3
447	1,501.0	Belize	172	194,146	1.37	3
31	351.4	Brazil	2243	576	0.01	4
82	1,023.1	Brazil	242	605	0.02	4
169	3,517.5	Brazil	521	4,709,562	159.76	4
194	300.8	Bolivia	585	182,595	0.60	4
424	336.1	Honduras	124	46,907	0.51	4
36	2,331.7	Brazil	2229	757	<0.01	5
177	14,740.8	Brazil, Guyana	537, 606	12,021,921	102.39	5
423	1,208.6	Honduras	123	15,755	0.76	5
458	815.9	Guatemala	206	78,410	1.56	5
21	156.6	Brazil	2240	256	0.02	6
130	655.1	Brazil, Paraguay	423	1,460	<0.01	6
276	6,096.3	Colombia	1036, 1128	4,750,364	84.75	6
412	350.8	Nicaragua	76	167,837	0.18	6
425	1,135.4	Honduras	125	80,275	<0.01	6
68	82,664.8	Brazil	232, 233, 260, 277	219,293,265	21.29	7
411	2,344.7	Honduras, Nicaragua	72, 73	43,661	0.48	7
147	3,705.2	Brazil	464	174,099	0.02	8
131	2,824.9	Brazil, Paraguay	429, 433	5,247	<0.01	9
154	417,269.7	Brazil	478, 562, 587, 653, 656, 670, 684, 687, 698, 752, 753, 754, 756, 757, 758	972,294,324	92.62	9
452	518.1	Belize	182	98,200	0.28	9
132	637.1	Paraguay	432	1,168	<0.01	10
244	91,927.0	Colombia, Venezuela	786, 810, 813, 819, 977, 984, 1033, 1271, 1301	84,293,863	11.35	10

Table 4. Ten highest-rank Protected Areas (PAs) across jaguar current range, showing the countries encompassed by each PA, total area (km²), kernel sum, and final rank.

ID	Country	Area (km²)	Kernel Sum	Priority Rank
133	Brazil	753553	317.13	1
545	Guatemala	22340	3.10	1

487	Colombia	321233	169.45	2
246	Brazil	495192	131.68	2
621	Mexico	14095	2.85	2
598	Honduras	19333	1.51	2
345	Brazil	10084	0.00	2
682	Nicaragua	19832	0.94	3
811	Peru	141428	80.67	4
52	Bolivia	64558	1.40	5
32	Bolivia	89894	21.06	6
60	Brazil	142890	131.38	7
211	Brazil	180574	123.26	7
2	Argentina	2259	0.00	7
839	Venezuela	84003	38.62	8
661	Mexico	6242	1.08	8
663	Mexico	1367	0.26	8
680	Nicaragua	17429	0.23	9
879	Venezuela	77540	24.09	10

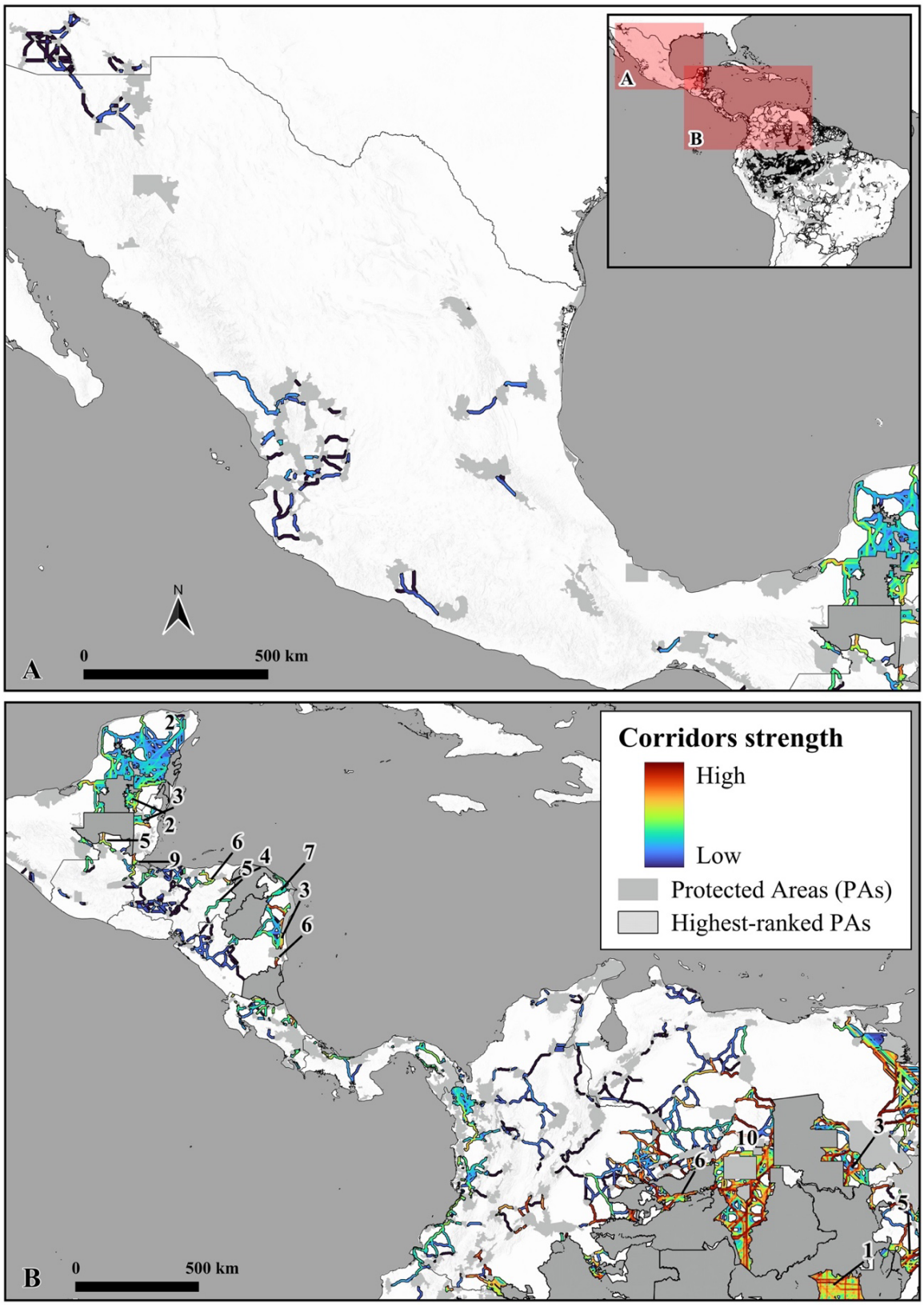


Figure 6. Ranking of the corridor's strength among protected areas and Indigenous Lands (PAs) across United States, Mexico, Central America and northern South America (A-B). Numbers represent rank prioritization.

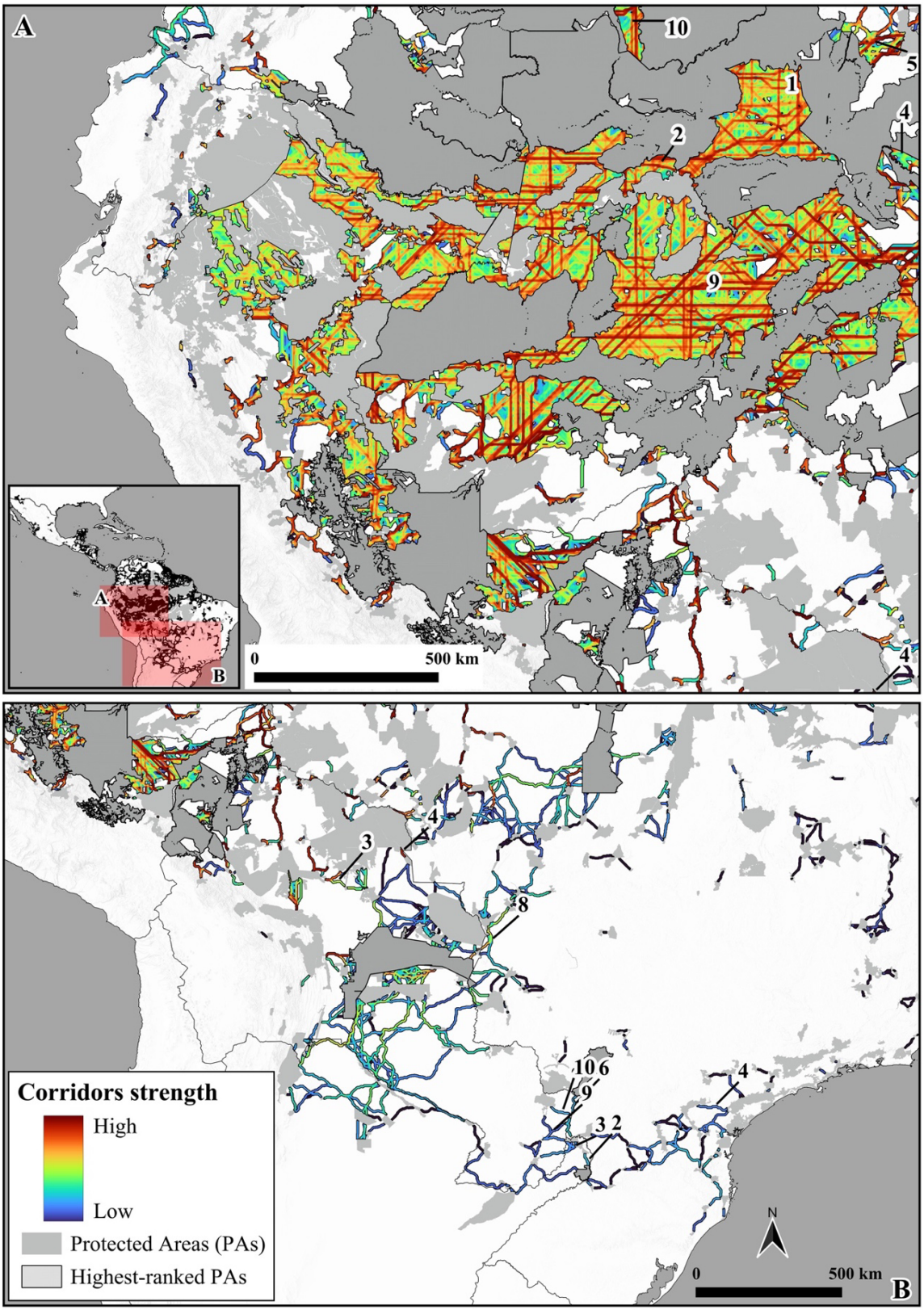


Figure 7. Ranking of the corridor's strength among protected areas and Indigenous Lands (PAs) across western and central-southern South America (A-B). Numbers represent rank prioritization.

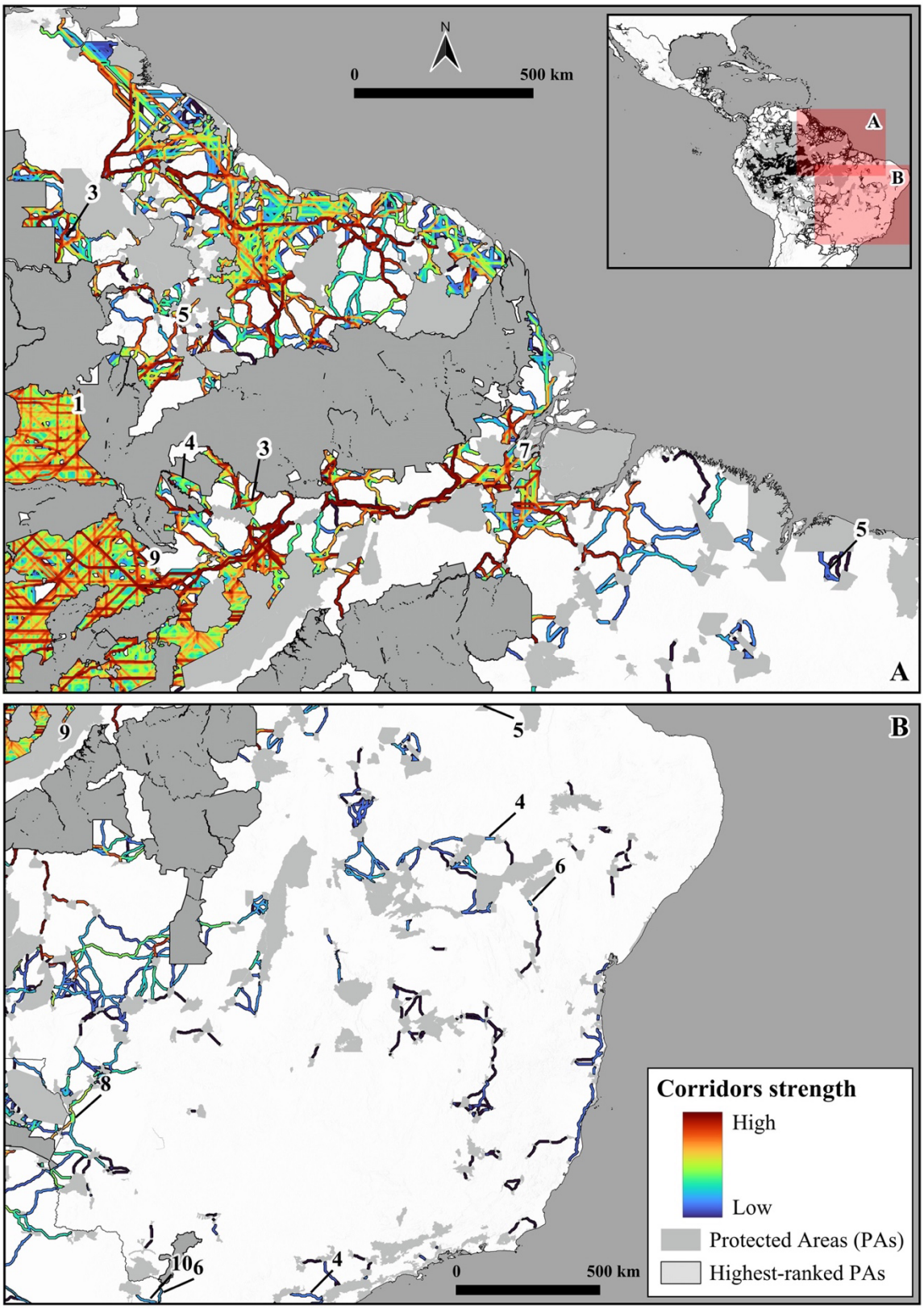


Figure 8. Ranking of the corridor's strength among protected areas and Indigenous Lands (PAs) across eastern and central South America (A-B). Numbers represent rank prioritization.

Discussion

We used a resistance surface produced empirically from the largest movement dataset ever compiled for jaguars and use state-of-the-art modelling techniques to identify potential jaguar corridors connecting core areas and PAs across the species' current range. This study updates and refines previous large-scale assessments, including the only wide-range analysis (Rabinowitz and Zeller, 2010) and more recent regional studies (e.g., Jedrzejewski et al., 2023). Overall, our model revealed a central core area within the jaguar's range, spanning portions of the Llanos, Amazon, Chaco, and Pantanal biomes (Fig. 1). This region supports high levels of movement and connectivity, representing a cornerstone for the species' long-term persistence. Several other important core areas were also identified by our models; however, most of them remain disconnected from the central core area of the species (Fig. 2-4). Regardless of the modelling approach used – whether linking core areas or PAs – major connectivity gaps persist across the jaguar's range. This indicates that, despite the substantial efforts that followed Rabinowitz and Zeller (2010) (e.g., the Jaguar Corridor Initiative, the Jaguar 2030 Roadmap), connectivity among all jaguar populations remains largely unachieved. Naturally, as the jaguar's range stretches across 19 countries, connecting all populations across landscapes with varying levels and types of anthropogenic land use is indeed a Herculean task. Still, the persistent connectivity gaps highlighted by our models reinforce previous concerns and underscore the need to revisit and strengthen strategies for reconnecting populations in the face of accelerating global change.

Core areas connectivity

The ranking of core areas highlights the jaguar's reliance on a limited number of extensive and interconnected strongholds, especially within the central portion of its range. The dominance of the Llanos-Amazon-Chaco-Pantanal complex in the ranking confirms this

region as the backbone of continental connectivity, consistent with previous work identifying it as the species' demographic core (Jedrzejewski et al., 2023). However, habitat quality is not homogeneous across this vast area (Alvarenga et al. 2026; this study), and the region of central Bolivia, where the northern (Llanos-Amazon) and southern (Chaco-Pantanal) sections converge (Fig. 2: a), warrants particular attention, as the connection there is eroding with deforestation and wildfires being the main drivers of habitat loss (Insight Crime and Iguarapé Institute, 2024). Moreover, genetic studies suggest limited connectivity between these two sections (Lorenzana et al., 2020; Roques et al., 2016). As acknowledged by the authors, though, limited sample size and its uneven geographic distribution may have influenced these patterns (Lorenzana et al., 2020; Roques et al., 2016). In both studies, samples were collected solely in southern Pantanal with none from the northern-southern transition zone in central Bolivia. Targeted actions are therefore needed to investigate the effectiveness of this link and, if confirmed, to maintain natural habitats that safeguard dispersal within the central core.

Our fLCP analysis also indicated other two potential alternative corridors between the northern and southern sections within Brazil, both starting in the northern edge of the Pantanal (Fig. 2: b; Fig. 4A). One corridor follows the Paraguay River, while the other extends eastward near *Chapada dos Guimarães* National Park. From these starting points, both corridors continue north through small clusters of core areas until reaching the southern limit of the Amazon main core. These corridors cross several major roads and the Arc of Deforestation, yet they still coincide with known jaguar populations along their extent (Moraes Jr., 2012). Moreover, as both routes lie entirely within Brazil, coordinated national efforts could facilitate their protection and restoration.

Along the eastern Amazon borders, our model also detected potential corridors linking the central core to two other regions: the Araguaia River plains and the clusters of core areas in the Cerrado-Caatinga interface (Fig. 2: c-e; Fig. 4B). The Araguaia River plains

are likely the most strategic corridor connecting the central jaguar populations of the Cerrado to the Amazon (Moraes Jr., 2012). These plains harbour key jaguar populations across nearly 20 PAs along their margins (Silveira, 2004). Their potential as a corridor has been suggested previously; however, the high level of anthropogenic disturbance in their central and northern portions could pose a major impediment to movement (Silveira et al., 2014). This intense disturbance may have disrupted the direct connection, leading our models to identify an alternative route between the Araguaia River plains and the Amazon core, formed by three independent networks of corridors that extend westward toward the Xingu complex (Fig. 2: c; Fig. 4B). All corridors in this region traverse large sections of the Arc of Deforestation, where only small forest fragments remain, with many of them lacking formal protection (MapBiomas Project, 2025).

The same pattern applies to the connections linking the Amazon to the Cerrado-Caatinga cluster (Fig. 2: c-e; Fig. 4B). Our model revealed a few potential links: one direct corridor following the Tocantins River (Fig. 2: d), and two others using intermediate stepping stones – one through the Araguaia River plains (Fig. 2: c) and another through isolated Amazonian fragments in the state of Maranhão, Brazil (Fig. 2: e). Similar routes have been identified in previous studies (Jedrzejewski et al., 2023; Silveira et al., 2014) but, as noted earlier, the landscape across this region is highly transformed, which could lead to limited dispersal movements and promote isolation, as genetic analyses suggest at least for the Caatinga population (Lazzari et al., 2025; Roques et al., 2016). In addition, recent estimates indicate that the Cerrado-Caatinga cluster continues to experience high rates of habitat loss, posing a serious threat to an already reduced population (Thompson et al., 2023). Considering that this cluster represents one of the last refuges for a singular jaguar population adapted to the karstic conditions of the region, we emphasize the need for urgent conservation action in the area.

The southern border of the central core extends across Chaco in central Paraguay and northern Argentina, and our model identified potential corridors linking the central core to other small core areas in its western and eastern edges (Fig. 2: f-g; Fig. 4B). To the west, the predicted corridors are relatively short, connecting the Chaco portion of the central core to the Yungas population along the eastern slopes of the Andes, as well as to a few small core areas in the southwest (Fig. 2: f), where permanent jaguar populations are unlikely to persist (Bustos et al., 2024). This Chaco-Yungas connection, although short, appears uncertain and likely weak, as jaguar records from the Argentine Chaco are scarce and the population faces a high risk of extinction (Bitetti et al., 2016; Quiroga et al., 2014). Density estimates in the Yungas region also indicate low jaguar numbers (Reppucci et al., 2024); nevertheless, it still supports the largest remaining population in Argentina (Bitetti et al., 2016) and there is evidence of ongoing connectivity with its western edge (Caruso et al., 2023).

The jaguar core areas identified by our model at the southern range closely align with recent predictions of the species' distribution (Thompson et al., 2023), but both models may be somewhat overoptimistic, particularly in the central Chaco region, where permanent occupation seems increasingly sparse (Bitetti et al., 2016; Romero-Muñoz et al., 2025). That said, the eastern corridors predicted by our model suggest potential links between the central Chaco and the Upper Paraná Atlantic Forest across Argentina, Paraguay, and Brazil (Fig. 2: g; Fig. 4B). These corridors follow two independent routes: one through central-southern Paraguay and another through Iberá in Argentina, both ultimately converging in the Green Corridor. While jaguar populations in Iberá and in the Green Corridor are recovering thanks to strong conservation efforts implemented by Fundación Rewilding Argentina (Donadio et al., 2022) and *Projeto Onças do Iguaçu*, their connections with the Chaco portion of the central core remain untested. According to our connectivity model among core areas, the Green Corridor represents the last remnant of Atlantic Forest still potentially connected to the

central core, suggesting that all other populations in the biome are now isolated – a worrisome pattern, as genetic drift and reduced diversity have already been reported for these populations (Lorenzana et al., 2020; Srbek-Araujo et al., 2018). Such isolation reflects the intense landscape conversion across the region, compounded by high human population density and a dense network of roads, all of which directly or indirectly contribute to jaguar mortality and displacement (Alegre et al., 2025; Cerqueira et al., 2021; Paviolo et al., 2016). For these regions, integrated management actions aimed at restoring genetic connectivity – through the management of individuals among isolated populations – remain the only plausible long-term conservation strategy for the species (Srbek-Araujo et al., 2018).

Moving north beyond the central core, across Colombia and throughout Central America, similar patterns of extensive habitat conversion associated with high human densities and road development once again disrupt connectivity across multiple regions (Fig. 2: h-j; Fig. 3A-B). Along the Venezuela-Colombia border, our models identified a narrow strip of corridors linking small core areas across the boundary and extending along the Magdalena River valley in north-central Colombia (Fig. 2: h). This is an important region, as it suggests potential connectivity between known jaguar populations in the valley and areas of high conservation priority, such as the *Serranía de San Lucas*, where a new PA has been proposed (Boron et al., 2016; Machado-Aguilera et al., 2024; Payán et al., 2016). However, our model also indicate that these populations are likely isolated by the rugged topography of the Andes, which appears to hinder connectivity with the central core to the south and the Darién Gap to the north.

From the Darién Gap on the Colombia-Panama border to the Mayan Forest in Guatemala-Belize-Mexico, three main core areas were identified, separated by two major connectivity gaps: one in central Panama and another between Guatemala and Honduras (Fig. 2: i-j; Fig. 3B). The distribution and extent of these areas closely align with previous findings

(Calderón et al., 2022), reinforcing their role as strongholds for the species in the region. Nevertheless, the Nicaraguan core area has experienced rapid agricultural expansion, even within protected areas, which appears to have reduced its suitability for jaguars (Petracca et al., 2014). In addition, these three core areas are highly susceptible to clandestine environmental degradation linked to narcotrafficking activities (Magliocca et al., 2024), which contribute to habitat fragmentation (Tellman et al., 2020) and the illegal trade of jaguar parts (Arias et al., 2020).

Regarding the two connectivity gaps, although Rabinowitz and Zeller (2010) predicted potential links in both areas, later assessments based on interviews (Petracca et al., 2018b) and genetic analyses (Calderón et al., 2024; Wultsch et al., 2016) indicate that the corridor between Guatemala and Honduras is particularly weak. These gaps in connectivity across Colombia and Central America are pivotal for jaguar conservation, as they will determine whether northern and southern populations remain part of a continuous metapopulation. Implementing corridors in this region, however, poses substantial challenges, given that they extend across several countries and are impacted by multiple human disturbances. Creative and context-specific conservation strategies will therefore be essential. The proposed protected area in *Serranía de San Lucas*, for instance, will be the first in Colombia to incorporate an Integrated Management District, promoting sustainable agriculture and mining within its buffer zone. If effectively regulated, this approach could represent a promising model for reconciling local development with the maintenance of natural habitats and may offer a transferable framework for other highly human-modified regions, such as Central America.

The pattern of fragmented connectivity continues northward from the Mayan Forest toward Mexico's Gulf and Pacific coasts, where several gaps separate clusters of core areas (Fig. 2: k-o; Fig. 3A). This contrasts with previous models suggesting continuous suitable

habitat and corridors extending along both coasts and converging at the Mayan Forest (Ceballos et al., 2021; Rodríguez-Soto et al., 2013). Such differences may stem from variations in the biological data and analytical approaches; for instance, contrary to the previous studies, our models imposed a dispersal threshold that limits how far corridors extend according to landscape resistance. Overall, the connectivity gaps we identified coincide with regions of high human footprint (González-Abraham et al., 2015), indicating these landscapes are too resistant for effective dispersal. According to our predictions, the only cluster of core areas still potentially connected to the Mayan Forest lies in the states of Oaxaca and Chiapas, through a corridor crossing the Isthmus of Tehuantepec (Fig. 2: k). This region supports important jaguar populations (Lavariega et al., 2020) and could act as a stepping stone linking northern populations from both coasts to those in the south. However, there is a considerable distance between this cluster and the next core areas along both coasts – approximately 160 km to the central Pacific (Fig. 2: l) and 400 km to the northern Atlantic (Fig. 2: o) – with the Atlantic side being particularly affected by anthropogenic pressures, which further reinforce the isolation predicted by our models (González-Abraham et al., 2015).

Along the Mexican Pacific coast, three clusters of core areas occur relatively close to one another, yet our model did not identify potential corridors among them (Fig. 2: l-n; Fig. 3A). The western edge of the country, particularly in the *Sierra Madre Occidental* and *Sierra Madre del Sur*, retains extensive tracts of natural habitat (González-Abraham et al., 2015) that could still support jaguar populations or at least function as dispersal routes linking nearby core areas. Nevertheless, previous studies have indicated moderate to low suitability (Alvarenga et al., 2026; Jędrzejewski et al., 2018) and low population densities for the species (Charre-Medellín et al., 2023), with the exception of the coastal mangroves of Nayarit (Luja et al., 2022) and Chamela-Cuixmala Biosphere Reserve (Núñez-Pérez, 2011). The lack

of genetic data further limits deeper conclusions, highlighting the need for future research on population structure in this region. Finally, our models did not identify core areas north of Mexico, and thus no corridors were predicted toward the United States when using the core area approach – although this gap was addressed under the protected area-based corridor analysis (Fig. 5).

Protected areas connectivity

Given the accelerating pace of global change affecting natural habitats, especially outside of PAs, we complemented our core area analysis with a protected area-based corridor model to assess potential links among existing PAs across the jaguar's range. This approach proved highly informative, revealing potential connections that the core area approach did not capture. For instance, our results identified the most likely dispersal corridors for the northernmost breeding jaguar population in Sonora, Mexico, extending toward protected areas in New Mexico and Arizona, US (Fig. 6A). Detecting these links is important, as dispersing males are occasionally recorded north of the Mexican border, and the region appears to retain suitable habitat for the species (Sanderson et al., 2022). A major obstacle to these movements, and to the potential establishment of a transboundary population, is the US-Mexico border wall, with ongoing construction occurring precisely in the area where our model predicts connectivity is more likely (Chambers et al., 2022). Moving southward, our protected area-based analysis revealed two major shifts in predicted connectivity. The Chiapas-Mayan Forest corridor disappeared, whereas, the Mayan Forest now appears connected across Central America, extending as far south as northern Panama (Fig. 6B). These changes likely reflect the distinct configuration of the PAs network, which does not fully overlap with the core areas. While this limits connectivity in southern Mexico, it enhances potential linkages such as those from the Mayan Forest to Honduras, where PAs

form a denser mosaic that appears to function as stepping stones connecting both sides. Such results highlight the importance of maintaining and strengthening this network to secure large-scale functional connectivity across the Mesoamerican Biological Corridor initiative.

In the southern range, another highly relevant and positive change is the emergence of corridors in two key regions. The first connecting the Darién Gap to PAs along the Colombia-Venezuela border, and from there to the Llanos-Amazon interface (Fig. 6B). If confirmed, this connection would represent a remarkable shift in the perspective of jaguar conservation, as it would not only bring significant genetic benefits but also renew hope for restoring connectivity between northern and southern populations. As in the previous model, this network of corridors extends across the Amazon Forest toward the Chaco, Pantanal, Iberá, and the Green Corridor but now adding one final, crucial link to the coastal Atlantic Forest of *Serra do Mar*, Brazil (Fig. 7A-B). Such a connection would be extremely valuable for jaguar conservation, and both cases warrant closer investigation to assess their potential effectiveness. On a less positive note, the previously predicted connectivity between the Amazon and the Cerrado-Caatinga interface was lost in the protected area–based analysis (Fig. 8A-B). As explained earlier, these differences stem from variations in the distribution and concentration of core areas versus PAs. Moreover, the protected area–based analysis assumes the presence of at least one source point (representing a dispersing individual) in each PA, which is unlikely to hold true in all cases. Overall, the differences between the two models highlight regions of greater uncertainty – areas that will likely require increased attention and targeted efforts to maintain or restore functional connectivity. We consider the core area approach to be more realistic than the protected area-based model, as it reflects the actual density and distribution of jaguar occurrence rather than assuming all PAs act as sources of dispersing individuals irrespective of surrounding habitat and population conditions. However, with increasing human pressure, PAs are more likely to persist into the

future than unprotected areas, albeit often as increasingly isolated habitat fragments. Thus, using the corridors mapped here to guide long-term conservation strategies, including the creation of new strategic located PAs, may represent a more pragmatic approach.

Management priorities and conservation implications

This study identified, mapped, and ranked the most important core areas, PAs, and dispersal corridors for jaguars, providing a framework to inform conservation priorities across the species' range. Given the pronounced ecological heterogeneity within the range, the ranking process accounted for ecoregional distribution. Accordingly, core areas, PAs, and corridors intersecting multiple ecoregions were assigned proportionally higher importance, as they contribute to maintaining connectivity across diverse ecological contexts. Therefore, stakeholders and decision-makers should consider top-ranked core areas and PAs as those most likely to offer stronger and more stable conditions for the species, while low-ranked features indicate areas of concern where jaguar populations may be more vulnerable and connectivity weaker. Similarly, the highest-ranked corridors generally represent broad, well-connected networks linking multiple strongholds across the landscape.

Among the top-ranked core areas, our model successfully identified the main regions known to support jaguar populations (Fig. 1), aligning with expert knowledge and empirical data (Jędrzejewski et al., 2023; Zeller, 2007). Notably, some populations fell just outside the ten highest-ranked areas – such as those along Mexico's western edge, the Costa Rica-Panama border, and northern Cerrado in Brazil – although they still appear within the top twenty (see Supplementary Material: Ranking_CoreAreas_Ecoregions.shp). As discussed previously, these regions harbour important jaguar populations and should not be overlooked in conservation planning. However, many of them experience intense anthropogenic

pressures with high rates of habitat conversion, which have reduced core area extent and likely contributed to their lower ranking (e. g., Soterroni et al., 2019).

Among the top-ranked PAs, most are located within the Amazon biome, reflecting the extensive network of protected areas and Indigenous Lands that has successfully kept much of the region in a near-pristine state (Pessôa et al., 2023). These Amazonian PAs are pivotal for jaguar conservation, supporting the largest and most stable populations while maintaining strong internal connectivity through several top-ranked corridors (Fig. 5). Outside the Amazon, a number of high-ranked PAs and corridors – particularly in the Mayan Forest, Central America (Honduras and Nicaragua), the Chaco, and the Atlantic Forest – also play critical roles in linking fragmented populations and sustaining regional connectivity. Their inclusion among the top ranks underscores their strategic importance for maintaining the species' functional range.

As expected, the top-ranked corridors tend to link the highest-ranked core areas, reflecting regions where jaguar populations are relatively more stable. It is important to note, however, that most jaguar populations outside the central core remain under considerable threat – a pattern that becomes increasingly severe toward the species' range margins (de la Torre et al., 2018). Consequently, high-ranked corridors in areas such as the Sierra de Tamaulipas (northeastern Mexico), the Iberá-Green Corridor (northeastern Argentina), and the coastal Atlantic Forest (Brazil) should be viewed as regionally significant linkages, emphasized here through our ecoregion-based prioritization approach. In these areas, the implementation of actions, such conservation translocations and reintroductions, to connect populations (and restore gene flow) is most urgent.

Scope and limitations

The population connectivity models developed in this study were based on a habitat suitability surface derived from telemetry data of 172 GPS-collared jaguars distributed across the species' current range. This dataset represents the most comprehensive compilation of jaguar movement information to date, covering individuals from a wide variety of ecosystems and environmental conditions (Alvarenga et al., 2026). As such, it provides a robust foundation for understanding large-scale connectivity patterns. However, as acknowledged by Alvarenga et al. (2026), the collared individuals were unevenly distributed across the species' range, and future models would certainly benefit from the inclusion of new data, particularly from underrepresented regions such as both Mexican coasts and parts of Central America. As with any modelling effort, our approach is constrained by the spatial and temporal extent of the available data, as well as by assumptions inherent to resistance-based connectivity models (Unnithan Kumar et al., 2022). These include potential biases in collaring locations and uneven sampling effort across regions, as well as simplifications related to jaguar dispersal behaviour and demographic dynamics. For instance, Alvarenga et al. (2026) used all available telemetry fixes – after appropriate processing – to produce the habitat suitability surface. Because jaguars often move through suboptimal habitats during dispersal (Schoen et al., 2025), we applied a negative exponential transformation to the suitability surface to better represent the non-linear costs of movement across such landscapes (Keeley et al., 2016). Nonetheless, we recommend that future connectivity models use telemetry data explicitly associated with dispersal behaviour to refine these estimates further. Finally, we manually adjusted the resistance cost of a few landscape features, including cities, roads, elevation, and riparian forests. Although resistance layers based solely on expert knowledge can be prone to error and should be avoided when biological data are available (Zeller et al., 2012), minor adjustments such as ours are widely used in the literature

(e.g., Brennan et al., 2022; Kaszta et al., 2024; Penjor et al., 2024) and, in our case, were strongly guided by known jaguar responses to these features (e.g., Alegre et al., 2025; Griffith et al., 2021; Morato et al., 2018). Finally, it is important to recognise that models are, by nature, simplifications of reality. The corridors identified here therefore represent potential linkages that require field validation and targeted conservation efforts to confirm their functionality and ensure they operate as intended rather than becoming ecological sinks.

Conclusions

The combination of cumulative resistant kernels and fLCP effectively identified critical areas for jaguar population connectivity across the species' current range. While fLCP corridors provide detailed insights into specific, direct linkages between PAs, cumulative kernels highlight broader core habitat regions for the species. These complementary approaches are especially valuable for diverse landscapes like those across the continent, where tailored conservation strategies are often required. For instance, pinpointing individual corridor lines within current large, continuous forest patches (e.g., the Mayan and Amazonian forests) may be unnecessary, as these areas likely function as effective corridors in their entirety – therefore called core areas. However, identifying the most probable dispersal pathways in already fragmented and suboptimal habitats of human-altered landscapes is crucial as these areas are likely to become increasingly fragmented in the future. Prioritising corridors is vital given the limited financial resources. As such, the results of these models should be utilized as complementary tools, leveraging their strengths to address varied ecological challenges.

Encouragingly, our models reveal an extensive central core area in South America that spans parts of 11 countries and encompasses the Llanos-Amazon-Pantanal-Chaco continuum. This region forms the backbone of continental connectivity for the species,

supporting the largest, most connected jaguar populations. Coordinated efforts are urgently needed to ensure it remains the demographic and genetic cornerstone of the species. Conversely, many core areas and corridors were identified in regions where connectivity is already severely threatened – such as the Mexican coasts, Central America, southern Paraguay, and south-southeast Brazil. These areas represent key opportunities for targeted restoration, refaunation, and the reinforcement of functional connectivity, particularly where predicted corridors intersect existing protected areas or Indigenous Lands.

At the national level, the prioritisation framework presented here can help guide resource allocation by identifying high-leverage actions, such as securing narrow linkages between major strongholds or maintaining transboundary corridors that connect populations across borders. Integrating these priorities into broader initiatives, such as the Mesoamerican Biological Corridor and national land-use planning, will be critical to ensure the long-term persistence of jaguars under accelerating habitat loss and landscape change.

Acknowledgements

We are extremely grateful to all field researchers and local guides who contributed to the capture and monitoring of the jaguars included in this study, as well as to the traditional and local communities who authorised and supported the underlying field research. GCA doctorate is supported by a grant to David Macdonald at WildCRU from the Robertson Foundation, as was ZK. SAC was supported by a grant to David Macdonald from the Dennis Curry Trust and by a NASA project (grant no. 80NSSC25K7244). ACS-A thanks the Espírito Santo Research and Innovation Support Foundation (FAPES) for funding the project (FAPES 510/2016), as well as for the Capixaba Researcher Fellowship (FAPES 404/2022). ACMO thanks the Biodiversity Research Consortium (BRC) for granting part of the data (Jaguar Project).

References

Alegre, V.B., Sepulvida, R., Oshima, J.E. de F., Azevedo, F.C., Kanda, C.Z., Morato, R.G., Ribeiro, M.C., 2025. Ecological traits explain wild felid responses to human-modified landscapes in Brazil: An open-data approach for conservation. Biol Conserv 311, 111461. https://doi.org/10.1016/j.biocon.2025.111461

Alvarenga, G.C., Sartor, C.C., Cushman, S.A., Zimmermann, A., Srbek-Araujo, A.C., Mendes-Oliveira, A.C., Harmsen, B., Angelo, C. De, Esteves, C.F., Campos, C.B. De, Polli, D.J., Viana, D.F.P., Gräbin, D.M., Donadio, E., Ramalho, E.E., Payán, E., Azevedo, F.C.C., Palomares, F., Powell, G.V.N., Ceballos, G., Porfirio, G., Zarza, H., Cassaigne, I., Bogoni, J.A., Sena, L., Maranhão, L., Brito, M.R.M. De, Tobler, M.W., Wiig, Ø., Foster, R.J., Sampaio, R., Nuñez, R., Morato, R.G., Boron, V., Moreno, W.H.A., Malhi, Y., Macdonald, D.W., Kaszta, Ż., 2026. Range-wide assessment of habitat suitability for jaguars using multiscale species distribution modelling. Sci Rep 16, 759. https://doi.org/10.1038/s41598-025-30512-5 2

Alvarenga, G.C., Tobler, M.W., Boron, V., de Carvalho, E.A.R., Morato, R.G., Endo, W., Mendonça, E.N., Sampaio, R., Durigan, C.C., Gonçalves, A.L.S., Ramalho, E.E., Pezzuti, J.C.B., de Paula, M.J., Antunes, A.P., Mena, J.L., Dupont, G., Spironello, W., Pacheco, J., La Rosa-Camino, F., Cabrera, J., Montanarin, A., da Costa, M.O., 2025. Jaguar (*Panthera onca*) density and population size across protected areas and indigenous lands in the Amazon biome, its largest stronghold. Biol Conserv 303, 111010. https://doi.org/10.1016/j.biocon.2025.111010

Antonelli, A., Zizka, A., Carvalho, F.A., Scharn, R., Bacon, C.D., Silvestro, D., Condamine, F.L., 2018. Amazonia is the primary source of Neotropical biodiversity. Proc Natl Acad Sci U S A 115, 6034–6039. https://doi.org/10.1073/pnas.1713819115

Arias, M., Hinsley, A., Milner-Gulland, E.J., 2020. Characteristics of, and uncertainties about, illegal jaguar trade in Belize and Guatemala. Biol Conserv 250, 108765. https://doi.org/10.1016/j.biocon.2020.108765

Atzeni, L., Cushman, S.A., Macdonald, D.W., 2024. Simulation modelling demonstrates differential performance of connectivity methods in their ability to predict genetic diversity in complex landscapes. Ecol Modell 498, 110886. https://doi.org/10.1016/j.ecolmodel.2024.110886

Balbuena-Serrano, Á., Zarco-González, M.M., Carreón-Arroyo, G., Carrera-Treviño, R., Amador-Alcalá, S., Monroy-Vilchis, O., 2022. Connectivity of priority areas for the conservation of large carnivores in northern Mexico. J Nat Conserv 65, 126116. https://doi.org/10.1016/j.jnc.2021.126116

Bardales, R., Boron, V., Passos Viana, D.F., Sousa, L.L., Dröge, E., Porfirio, G., Jaramillo, M., Payán, E., Sillero-Zubiri, C., Hyde, M., 2024. Neotropical mammal responses to megafires in the Brazilian Pantanal. Glob Chang Biol 30, 1–17. https://doi.org/10.1111/gcb.17278

Bejarano Alegre, V., Zukeran Kanda, C., Oshima, J.E. de F., Brandão Niebuhr, B., Morato, R.G., Thompson, J.J., Börger, L., Ribeiro, M.C., 2024. Jaguar at the Edge: movement patterns in human-altered landscapes. Perspect Ecol Conserv 22, 358–366. https://doi.org/10.1016/j.pecon.2024.10.002

Beytell, P., Hanssen, L., Aschenborn, O., Naidoo, R., 2024. Long-Distance, Transfrontier Carnivore Dispersals in Southern Africa. Ecol Evol 14, 1–7. https://doi.org/10.1002/ece3.70574

Bitetti, M.S., de Angelo, C., Quiroga, V., Altrichter, M., Paviolo, A., Cuyckens, G.A.E., Perovic, P.G., 2016. Estado de conservación del jaguar en Argentina, in: Medellín, R.A.,

Torre, J.A. de la, Zarza, H., Chávez, C., Ceballos, G. (Eds.), El Jaguar En El Siglo XXI. La Perspectiva Continental. pp. 447–478.

Bogoni, J.A., Boron, V., Peres, C.A., Coelho, M., Morato, R.G., Oliveira-da-Costa, M., 2023. Impending anthropogenic threats and protected area prioritization for jaguars in the Brazilian Amazon. Commun Biol 1–11. https://doi.org/10.1038/s42003-023-04490-1

Boron, V., Tzanopoulos, J., Gallo, J., Barragan, J., Jaimes-Rodriguez, L., Schaller, G., Payán, E., 2016. Jaguar Densities across Human-Dominated Landscapes in Colombia: The Contribution of Unprotected Areas to Long Term Conservation. PLoS One 11, e0153973. https://doi.org/10.1371/journal.pone.0153973

Bowman, J., Jaeger, J.A.G., Fahrig, L., 2002. Dispersal distance of mammals is proportional to home range size. Ecology 83, 2049–2055. https://doi.org/10.1890/0012-9658(2002)083[2049:DDOMIP]2.0.CO;2

Brennan, A., Naidoo, R., Greenstreet, L., Mehrabi, Z., Ramankutty, N., Kremen, C., 2022. Functional connectivity of the world's protected areas. Science (1979) 376, 1101–1104. https://doi.org/10.1126/science.abl8974

Brown, C.F., Brumby, S.P., Guzder-Williams, B., Birch, T., Hyde, S.B., Mazzariello, J., Czerwinski, W., Pasquarella, V.J., Haertel, R., Ilyushchenko, S., Schwehr, K., Weisse, M., Stolle, F., Hanson, C., Guinan, O., Moore, R., Tait, A.M., 2022. Dynamic World, Near real-time global 10 m land use land cover mapping. Sci Data 9, 251. https://doi.org/10.1038/s41597-022-01307-4

Bustos, S. De, Lizarraga, L., Caruso, F., Chanampa, M., Bracamonte, C., Bonduri, Y., Segovia, J., Reppucci, J., 2024. Plan estratégico para la conservación del yaguarete (*Panthera onca*) en las Yungas Argentinas.

Calderón, A.P., Louvrier, J., Planillo, A., Araya-Gamboa, D., Arroyo-Arce, S., Barrantes-Núñez, M., Carazo-Salazar, J., Corrales-Gutiérrez, D., Doncaster, C.P., Foster, R.,

García, M.J., Garcia-Anleu, R., Harmsen, B., Hernández-Potosme, S., Leonardo, R., Trigueros, D.M., McNab, R., Meyer, N., Moreno, R., Salom-Pérez, R., Sauma Rossi, A., Thomson, I., Thornton, D., Urbina, Y., Grimm, V., Kramer-Schadt, S., 2022. Occupancy models reveal potential of conservation prioritization for Central American jaguars. Anim Conserv 1–12. https://doi.org/10.1111/acv.12772

Cardillo, M., Mace, G.M., Jones, K.E., Bielby, J., Bininda-Emonds, O.R.P., Sechrest, W., Orme, C.D.L., Purvis, A., 2005. Evolution: Multiple causes of high extinction risk in large mammal species. Science (1979) 309, 1239–1241. https://doi.org/10.1126/science.1116030

Caruso, F., Perovic, P., De Angelo, C., Sillero-Zubiri, C., 2023. Recent jaguar records confirm the conservation value of the Baritú-Tariquía corridor between Argentina and Bolivia. Oryx 57, 670–672. https://doi.org/10.1017/S0030605322001211

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human-induced species losses: Entering the sixth mass extinction. Sci Adv 1, 9–13. https://doi.org/10.1126/sciadv.1400253

Ceballos, G., Zarza, H., González-Maya, J.F., de la Torre, J.A., Arias-Alzate, A., Alcerreca, C., Barcenas, H. V., Carreón-Arroyo, G., Chávez, C., Cruz, C., Medellín, D., García, A., Antonio-García, M., Lazcano-Barrero, M.A., Medellín, R.A., Moctezuma-Orozco, O., Ruiz, F., Rubio, Y., Luja, V.H., Torres-Romero, E.J., 2021. Beyond words: From jaguar population trends to conservation and public policy in Mexico. PLoS One 16, 1–22. https://doi.org/10.1371/journal.pone.0255555

Cerqueira, R.C., de Rivera, O.R., Jaeger, J.A.G., Grilo, C., 2021. Direct and indirect effects of roads on space use by jaguars in Brazil. Sci Rep 11, 1–9. https://doi.org/10.1038/s41598-021-01936-6

Chambers, S.N., Villarreal, M.L., Norman, L.M., Bravo, J.C., Traphagen, M.B., 2022. Spatial models of jaguar energy expenditure in response to border wall construction and remediation. Frontiers in Conservation Science 3, 1–9. https://doi.org/10.3389/fcosc.2022.1012010

Charre-Medellín, J.F., Monterrubio-Rico, T.C., Acevedo, P., Guzmán-Díaz, E.O., Jiménez, J., 2023. Jaguar (*Panthera onca*) density in the Sierra Madre del Sur; the last wilderness area in the central-western slope in Mexico. Stud Neotrop Fauna Environ 58, 47–60. https://doi.org/10.1080/01650521.2021.1895572

Compton, B.W., McGarigal, K., Cushman, S.A., Gamble, L.R., 2007. A resistant-kernel model of connectivity for amphibians that breed in vernal pools. Conservation Biology 21, 788–799. https://doi.org/10.1111/j.1523-1739.2007.00674.x

Cushman, S.A., Craighead, K.A., Yacelga, M., Kaszta, Z.M., Wan, H.Y., Macdonald, D.W., 2023. Seventy-two models of large mammal connectivity across Panama: insights into a critical biogeographic linkage zone. Front Ecol Evol 11, 1–17. https://doi.org/10.3389/fevo.2023.1250255

Cushman, S.A., Elliot, N.B., Macdonald, D.W., Loveridge, A.J., 2015. A multi-scale assessment of population connectivity in African lions (*Panthera leo*) in response to landscape change. Landsc Ecol 31, 1–17. https://doi.org/10.1007/s10980-015-0292-3

Cushman, S.A., Landguth, E.L., 2012. Multi-taxa population connectivity in the Northern Rocky Mountains. Ecol Modell 231, 101–112. https://doi.org/10.1016/j.ecolmodel.2012.02.011

Cushman, S.A., Landguth, E.L., Flather, C.H., 2013. Evaluating population connectivity for species of conservation concern in the American Great Plains. Biodivers Conserv 22, 2583–2605. https://doi.org/10.1007/s10531-013-0541-1

Cushman, S.A., Lewis, J.S., Landguth, E.L., 2014. Why did the bear cross the road? Comparing the performance of multiple resistance surfaces and connectivity modeling methods. Diversity (Basel) 6, 844–854. https://doi.org/10.3390/d6040844

de la Torre, J.A., González-Maya, J.F., Zarza, H., Ceballos, G., Medellín, R.A., 2018. The jaguar's spots are darker than they appear: assessing the global conservation status of the jaguar *Panthera onca*. Oryx 52, 300–315. https://doi.org/10.1017/S0030605316001046

de la Torre, J.A., Núñez, J.M., Medellín, R.A., 2017. Habitat availability and connectivity for jaguars (*Panthera onca*) in the Southern Mayan Forest: Conservation priorities for a fragmented landscape. Biol Conserv 206, 270–282. https://doi.org/10.1016/j.biocon.2016.11.034

Donadio, E., Zamboni, T., Martino., S. Di, 2022. Bringing jaguars and their prey base back to the Iberá wetlands, Argentina, in: Gaywood M., et al. (Ed.), Conservation Translocations. Cambridge University Press, Cambridge, UK, pp. 443–448.

Elliot, N., Cushman, S., Loveridge, A., Macdonald, D.W., 2014. Movements vary according to dispersal stage, group size and rainfall: the case of the African lion. Ecology 95, 2860–2869.

G1, 2019a. Onça-pintada é capturada no Jardim Botânico em Juiz de Fora [WWW Document]. May 13.

G1, 2019b. Onça é vista passeando em ilha no Centro de cidade em MT e Marinha orienta moradores a evitarem passar pela região [WWW Document]. Rede Globo. URL https://g1.globo.com/mt/mato-grosso/noticia/2019/11/04/onca-e-vista-passeando-em-ilha-no-centro-de-cidade-em-mt-e-marinha-orienta-moradores-a-evitarem-passar-pela-regiao.ghtml (accessed 12.29.25).

Gese, E.M., Terletzky, P.A., Cavalcanti, S.M.C., Neale, C.M.U., 2018. Influence of behavioral state, sex, and season on resource selection by jaguars (*Panthera onca*): Always on the prowl? Ecosphere 9, e02341. https://doi.org/10.1002/ecs2.2341

González-Abraham, C., Ezcurra, E., Garcillán, P.P., Ortega-Rubio, A., Kolb, M., Creel, J.E.B., 2015. The human footprint in mexico: Physical geography and historical legacies. PLoS One 10, 1–17. https://doi.org/10.1371/journal.pone.0121203

Gonzalez-Borrajo, N., López-Bao, J.V., Palomares, F., 2017. Spatial ecology of jaguars, pumas, and ocelots: a review of the state of knowledge. Mamm Rev 47, 62–75. https://doi.org/10.1111/mam.12081

Griffith, D.M., Nivelo-Villavicencio, C., Rodas, F., Puglla, B., Cisneros, R., 2021. New altitudinal records of *Panthera onca* (Carnivora: Felidae) in the Andean region of Ecuador. Mammalia 86, 190–195. https://doi.org/10.1515/mammalia-2021-0136

Haag, T., Santos, a. S., Sana, D. a., Morato, R.G., Cullen, L., Crawshaw, P.G., De Angelo, C., Di Bitetti, M.S., Salzano, F.M., Eizirik, E., 2010. The effect of habitat fragmentation on the genetic structure of a top predator: Loss of diversity and high differentiation among remnant populations of Atlantic Forest jaguars (*Panthera onca*). Mol Ecol 19, 4906–4921. https://doi.org/10.1111/j.1365-294X.2010.04856.x

Hernández-Pérez, E.L., Sosa, J.L., Friedeberg, D., Contreras-Moreno, F.M., Hidalgo-Mihart, M.G., 2020. Jaguars and roads in the Calakmul region: evidence of road crossing and collisions with vehicles. West N Am Nat 80, 556–562. https://doi.org/10.3398/064.080.0416

Insight Crime, Iguarapé Institute, 2024. Stolen Amazon: The roots of environmental crime in Bolivia.

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

IPBES secretariat, Bonn, Germany. https://doi.org/https://doi.org/10.5281/zenodo.3831673

Jędrzejewski, W., Morato, R.G.;, Negrões, N.;, Wallace, R.B.;, Paviolo, A.;, De Angelo, C.;, Thompson, J.J.;, Paemelaere, E., Hallett, M.T.;, Berzins, R.;, Tortato, F.;, Espinosa, S.;, Payán, E.;, Romero, A.P.;, Ouboter, P.E.;, Kadosoe, V.;, Quiroga, V.A.;, Tobler, M.;, Ferraz, K.M.P.M.;, Portugal, M.P.;, Viscarra, M.;, Crespo, G.M.A.;, Cruz, P.;, Ramalho, E.E.;, Maffei, L.;, Robinson, N.;, Breitenmoser, U.;, Breitenmoser, C.;, Polisar, J.;, Quigler, H.;, Hoogesteinjn, R.;, Guerra, N.;, Barboza, K.;, Cromwell, L.;, Gonzáles-Maya, J.F.;, Johnson, S.;, Velásquez, G., Vivas, I.;, Abarca, M., 2023. Estimating species distribution changes due to human impacts: the 2020's status of the jaguar in South America. CATnews Special Issue 16, 44–55.

Jedrzejewski, W., Morato, R.G., Wallace, R.B., Thompson, J.J., Paviolo, A., De Angelo, C., Negrões, N., Hoogesteijn, R., Tortato, F., Payan, E., Espinosa, S., Paemelaere, E.A.D., Hallet, M.T., Berzins, R., Romero, A.P., Ouboter, P.E., Kadosoe, V., Quiroga, V.A., Velasquez, G., Abarca, M., Tobler, M., Ferraz, K.M.P.M. de B., Portugal, M.P., Viscarra, M., Crespo, G.M.A., Cruz, P., Ramalho, E.E., Robinson, N., Quigley, H., Guerra, N., Barboza, K., Cromwell, L., González-Maya, J.F., Polisar, J., Breitenmoser, U., Breitenmoser, C., Johnson, S., 2023. Landscape connectivity analysis and proposition of the main corridor network for the jaguar in South America. CATnews Special Issue 56–61.

Jędrzejewski, W., Robinson, H.S., Abarca, M., Zeller, K.A., Velasquez, G., Paemelaere, E.A.D., Goldberg, J.F., Payan, E., Hoogesteijn, R., Boede, E.O., Schmidt, K., Lampo, M., Viloria, Á.L., Carreño, R., Robinson, N., Lukacs, P.M., Nowak, J.J., Salom-Pérez, R., Castañeda, F., Boron, V., Quigley, H., 2018. Estimating large carnivore populations at global scale based on spatial predictions of density and distribution - Application to

the jaguar (*Panthera onca*). PLoS One 13, 1–25. https://doi.org/10.1371/journal.pone.0194719

Kaszta, Ż., Cushman, S.A., Hearn, A., Sloan, S., Laurance, W.F., Haidir, I.A., Macdonald, D.W., 2024. Projected development in Borneo and Sumatra will greatly reduce connectivity for an apex carnivore. Science of the Total Environment 918, 170256. https://doi.org/10.1016/j.scitotenv.2024.170256

Keeley, A.T.H., Beier, P., Gagnon, J.W., 2016. Estimating landscape resistance from habitat suitability: effects of data source and nonlinearities. Landsc Ecol 31, 2151–2162. https://doi.org/10.1007/s10980-016-0387-5

Landguth, E.L., Hand, B.K., Glassy, J., Cushman, S.A., Sawaya, M.A., 2012. UNICOR: A species connectivity and corridor network simulator. Ecography 35, 9–14. https://doi.org/10.1111/j.1600-0587.2011.07149.x

Laurance, W.F., Carolina Useche, D., Rendeiro, J., Kalka, M., Bradshaw, C.J.A., Sloan, S.P., Laurance, S.G., Campbell, M., Abernethy, K., Alvarez, P., Arroyo-Rodriguez, V., Ashton, P., Benítez-Malvido, J., Blom, A., Bobo, K.S., Cannon, C.H., Cao, M., Carroll, R., Chapman, C., Coates, R., Cords, M., Danielsen, F., De Dijn, B., Dinerstein, E., Donnelly, M.A., Edwards, D., Edwards, F., Farwig, N., Fashing, P., Forget, P.M., Foster, M., Gale, G., Harris, D., Harrison, R., Hart, J., Karpanty, S., John Kress, W., Krishnaswamy, J., Logsdon, W., Lovett, J., Magnusson, W., Maisels, F., Marshall, A.R., McClearn, D., Mudappa, D., Nielsen, M.R., Pearson, R., Pitman, N., Van Der Ploeg, J., Plumptre, A., Poulsen, J., Quesada, M., Rainey, H., Robinson, D., Roetgers, C., Rovero, F., Scatena, F., Schulze, C., Sheil, D., Struhsaker, T., Terborgh, J., Thomas, D., Timm, R., Nicolas Urbina-Cardona, J., Vasudevan, K., Joseph Wright, S., Carlos Arias-G., J., Arroyo, L., Ashton, M., Auzel, P., Babaasa, D., Babweteera, F., Baker, P., Banki, O., Bass, M., Bila-Isia, I., Blake, S., Brockelman, W., Brokaw, N., Brühl, C.A.,

Bunyavejchewin, S., Chao, J.T., Chave, J., Chellam, R., Clark, C.J., Clavijo, J., Congdon, R., Corlett, R., Dattaraja, H.S., Dave, C., Davies, G., De Mello Beisiegel, B., De Nazaré Paes Da Silva, R., Di Fiore, A., Diesmos, A., Dirzo, R., Doran-Sheehy, D., Eaton, M., Emmons, L., Estrada, A., Ewango, C., Fedigan, L., Feer, F., Fruth, B., Giacalone Willis, J., Goodale, U., Goodman, S., Guix, J.C., Guthiga, P., Haber, W., Hamer, K., Herbinger, I., Hill, J., Huang, Z., Fang Sun, I., Ickes, K., Itoh, A., Ivanauskas, N., Jackes, B., Janovec, J., Janzen, D., Jiangming, M., Jin, C., Jones, T., Justiniano, H., Kalko, E., Kasangaki, A., Killeen, T., King, H.B., Klop, E., Knott, C., Koné, I., Kudavidanage, E., Lahoz Da Silva Ribeiro, J., Lattke, J., Laval, R., Lawton, R., Leal, M., Leighton, M., Lentino, M., Leonel, C., Lindsell, J., Ling-Ling, L., Eduard Linsenmair, K., Losos, E., Lugo, A., Lwanga, J., MacK, A.L., Martins, M., Scott McGraw, W., McNab, R., Montag, L., Myers Thompson, J., Nabe-Nielsen, J., Nakagawa, M., Nepal, S., Norconk, M., Novotny, V., O'Donnell, S., Opiang, M., Ouboter, P., Parker, K., Parthasarathy, N., Pisciotta, K., Prawiradilaga, D., Pringle, C., Rajathurai, S., Reichard, U., Reinartz, G., Renton, K., Reynolds, G., Reynolds, V., Riley, E., Rödel, M.O., Rothman, J., Round, P., Sakai, S., Sanaiotti, T., Savini, T., Schaab, G., Seidensticker, J., Siaka, A., Silman, M.R., Smith, T.B., De Almeida, S.S., Sodhi, N., Stanford, C., Stewart, K., Stokes, E., Stoner, K.E., Sukumar, R., Surbeck, M., Tobler, M., Tscharntke, T., Turkalo, A., Umapathy, G., Van Weerd, M., Vega Rivera, J., Venkataraman, M., Venn, L., Verea, C., Volkmer De Castilho, C., Waltert, M., Wang, B., Watts, D., Weber, W., West, P., Whitacre, D., Whitney, K., Wilkie, D., Williams, S., Wright, D.D., Wright, P., Xiankai, L., Yonzon, P., Zamzani, F., 2012. Averting biodiversity collapse in tropical forest protected areas. Nature 489, 290–293. https://doi.org/10.1038/nature11318

Lavariega, M.C., Ríos-Solís, J.A., Flores-Martínez, J.J., Galindo-Aguilar, R.E., Sánchez-Cordero, V., Juan-Albino, S., Soriano-Martínez, I., 2020. Community-Based Monitoring of Jaguar (*Panthera onca*) in the Chinantla Region, Mexico. Trop Conserv Sci 13. https://doi.org/10.1177/1940082920917825

Lazzari, G.Z., Figueiró, H.V., Sartor, C.C., Donadio, E., Di Martino, S., Draheim, H.M., Eizirik, E., 2025. Development of a SNP Panel for Geographic Assignment and Population Monitoring of Jaguars (*Panthera onca*). Ecol Evol 15. https://doi.org/10.1002/ece3.71465

Lehner, B., Grill, G., 2013. Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. Hydrol Process 27, 2171–2186. https://doi.org/10.1002/hyp.9740

Lorenzana, G., Heidtmann, L., Haag, T., Ramalho, E., Dias, G., Hrbek, T., Farias, I., Eizirik, E., 2020. Large-scale assessment of genetic diversity and population connectivity of Amazonian jaguars (*Panthera onca*) provides a baseline for their conservation and monitoring in fragmented landscapes. Biol Conserv 242, 108417. https://doi.org/10.1016/j.biocon.2020.108417

Luja, V.H., Guzmán-Báez, D.J., Nájera, O., Vega-Frutis, R., 2022. Jaguars in the matrix: population, prey abundance and land-cover change in a fragmented landscape in western Mexico. Oryx 56, 546–554. https://doi.org/10.1017/S0030605321001617

Lumia, G., Modica, G., Cushman, S., 2024. Using simulation modeling to demonstrate the performance of graph theory metrics and connectivity algorithms. J Environ Manage 352, 120073. https://doi.org/10.1016/j.jenvman.2024.120073

Macdonald, E.A., Cushman, S.A., Landguth, E.L., Hearn, A.J., Malhi, Y., Macdonald, D.W., 2018. Simulating impacts of rapid forest loss on population size, connectivity and

genetic diversity of Sunda clouded leopards (*Neofelis diardi*) in Borneo. PLoS One 13, e0196974. https://doi.org/10.1371/journal.pone.0196974

Machado-Aguilera, M.C., Lemus-Mejía, L., Pérez-Torres, J., Zárrate-Charry, D.A., Arias-Alzate, A., González-Maya, J.F., 2024. Preserving the spots: Jaguar (*Panthera onca*) distribution and priority conservation areas in Colombia. PLoS One 19, 1–19. https://doi.org/10.1371/journal.pone.0300375

Magliocca, N.R., Carter, N.H., Devine, J.A., Nielsen, E.A., Sesnie, S.E., 2024. Jaguar conservation is caught in the crossfire of America's "War on Drugs." Biol Conserv 296, 110687. https://doi.org/10.1016/j.biocon.2024.110687

MapBiomas Project, 2025. Collection 10 – Annual Land Use and Land Cover Maps of Brazil (1985–2024) [WWW Document]. URL https://plataforma.brasil.mapbiomas.org

Mateo-Sánchez, M.C., Cushman, S.A., Saura, S., 2014. Connecting endangered brown bear subpopulations in the Cantabrian Range (north-western Spain). Anim Conserv 17, 430–440. https://doi.org/10.1111/acv.12109

McRae, B.H., Dickson, B.G., Keitt, T.H., Shah, V.B., 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology 89, 2712–2724. https://doi.org/10.1890/07-1861.1

Metrópoles, 2025. Onça "viajante" andou 1,6 mil km por três estados em um mês. Entenda [WWW Document]. Metrópoles.com. URL https://www.metropoles.com/brasil/onca-viajante-andou-16-mil-km-por-tres-estados-em-um-mes-entenda (accessed 12.30.25).

Meyer, N.F.V., Moreno, R., Sutherland, C., de la Torre, J.A., Esser, H.J., Jordan, C.A., Olmos, M., Ortega, J., Reyna-Hurtado, R., Valdes, S., Jansen, P.A., 2019. Effectiveness of Panama as an intercontinental land bridge for large mammals. Conservation Biology 0, 1–13. https://doi.org/10.1111/cobi.13384

Moraes Jr., E.A., 2012. The status of the jaguar in the Cerrado. CATnews Special Issue 7, 25–28.

Morato, R.G., Connette, G.M., Stabach, J.A., De Paula, R.C., Ferraz, K.M.P.M., Kantek, D.L.Z., Miyazaki, S.S., Pereira, T.D.C., Silva, L.C., Paviolo, A., De Angelo, C., Di Bitetti, M.S., Cruz, P., Lima, F., Cullen, L., Sana, D.A., Ramalho, E.E., Carvalho, M.M., da Silva, M.X., Moraes, M.D.F., Vogliotti, A., May Jr., J.A., Haberfeld, M., Rampim, L., Sartorello, L., Araujo, G.R., Wittemyer, G., Ribeiro, M.C., Leimgruber, P., 2018. Resource selection in an apex predator and variation in response to local landscape characteristics. Biol Conserv 228, 233–240. https://doi.org/10.1016/j.biocon.2018.10.022

Morato, R.G., Stabach, J.A., Fleming, C.H., Calabrese, J.M., De Paula, R.C., Ferraz, K.M.P.M., Kantek, D.L.Z., Miyazaki, S.S., Pereira, T.D.C., Araujo, G.R., Paviolo, A., De Angelo, C., Di Bitetti, M.S., Cruz, P., Lima, F., Cullen, L., Sana, D.A., Ramalho, E.E., Carvalho, M.M., Soares, F.H.S., Zimbres, B., Silva, M.X., Moraes, M.D.F., Vogliotti, A., May, J.A., Haberfeld, M., Rampim, L., Sartorello, L., Ribeiro, M.C., Leimgruber, P., 2016. Space use and movement of a neotropical top predator: The endangered jaguar. PLoS One 11, 1–17. https://doi.org/10.1371/journal.pone.0168176

Núñez-Pérez, R., 2011. Estimating jaguar population density using camera-traps: A comparison with radio-telemetry estimates. J Zool 285, 39–45. https://doi.org/10.1111/j.1469-7998.2011.00812.x

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial ecoregions of the world: A new map of life on Earth.

Bioscience 51, 933–938. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2

Paviolo, A., De Angelo, C., Ferraz, K.M.P.M.B., Morato, R.G., Martinez Pardo, J., Srbek-Araujo, A.C., Beisiegel, B.D.M., Lima, F., Sana, D., Xavier Da Silva, M., Velázquez, M.C., Cullen, L., Crawshaw, P., Jorge, M.L.S.P., Galetti, P.M., Di Bitetti, M.S., De Paula, R.C., Eizirik, E., Aide, T.M., Cruz, P., Perilli, M.L.L., Souza, A.S.M.C., Quiroga, V., Nakano, E., Ramírez Pinto, F., Fernández, S., Costa, S., Moraes, E.A., Azevedo, F., 2016. A biodiversity hotspot losing its top predator: The challenge of jaguar conservation in the Atlantic Forest of South America. Sci Rep 6. https://doi.org/10.1038/srep37147

Payán, E., Soto, C., Ruiz-García, M., Nijhawan, S., González-Maya, J.F., Vásquez, C. V., Castaño-Uribe, C., 2016. Unidades de conservación, conectividad y calidad de hábitat de jaguar en Colombia, in: Medellín, R.A., De La Torre, A., Zarza, H., Chávez, C., Ceballos, G. (Eds.), El Jaguar En El Siglo XXI La Perspectiva Continental. Fondo de Cultura Económica, Universidad Nacional Autónoma de México, Mexico, pp. 240–274.

Penjor, U., Kaszta, Z.M., Macdonald, D.W., Cushman, S.A., 2024. Identifying umbrella and indicator species to support multispecies population connectivity in a Himalayan biodiversity hotspot. Frontiers in Conservation Science 5, 1–17. https://doi.org/10.3389/fcosc.2024.1306051

Pessôa, A.C.M., Morello, T.F.R.S., Silva-Junior, C.H.L., Doblas, J., Carvalho, N.S., Aragão, L.E.O.C., Anderson, L.O., 2023. Protected areas are effective on curbing fires in the Amazon. Ecological Economics 214, 107983. https://doi.org/10.1016/j.ecolecon.2023.107983

Petracca, L.S., Frair, J.L., Cohen, J.B., Calderón, A.P., Carazo-Salazar, J., Castañeda, F., Corrales-Gutiérrez, D., Foster, R.J., Harmsen, B., Hernández-Potosme, S., Herrera, L.,

Olmos, M., Pereira, S., Robinson, H.S., Robinson, N., Salom-Pérez, R., Urbina, Y., Zeller, K.A., Quigley, H., 2018a. Robust inference on large-scale species habitat use with interview data: The status of jaguars outside protected areas in Central America. Journal of Applied Ecology 55, 723–734. https://doi.org/10.1111/1365-2664.12972

Petracca, L.S., Frair, J.L., Cohen, J.B., Calderón, A.P., Carazo-Salazar, J., Castañeda, F., Corrales-Gutiérrez, D., Foster, R.J., Harmsen, B., Hernández-Potosme, S., Herrera, L., Olmos, M., Pereira, S., Robinson, H.S., Robinson, N., Salom-Pérez, R., Urbina, Y., Zeller, K.A., Quigley, H., 2018b. Robust inference on large-scale species habitat use with interview data: The status of jaguars outside protected areas in Central America. Journal of Applied Ecology 55, 723–734. https://doi.org/10.1111/1365-2664.12972

Petracca, L.S., Hernández-Potosme, S., Obando-Sampson, L., Salom-Pérez, R., Quigley, H., Robinson, H.S., 2014. Agricultural encroachment and lack of enforcement threaten connectivity of range-wide jaguar (*Panthera onca*) corridor. J Nat Conserv 22, 436–444. https://doi.org/10.1016/j.jnc.2014.04.002

Quigley, H., Foster, R.J., Petracca, L., Payan, E., Salom, R., Harmsen, B.J., 2017. *Panthera onca*, Jaguar (errata version published in 2018), The IUCN Red List of Threatened Species 2017.

Quiroga, V.A., Boaglio, G.I., Noss, A.J., Di Bitetti, M.S., 2014. Critical population status of the jaguar *Panthera onca* in the Argentine Chaco: camera-trap surveys suggest recent collapse and imminent regional extinction. Oryx 48, 141–148. https://doi.org/10.1017/S0030605312000944

Rabinowitz, A., Zeller, K. a., 2010. A range-wide model of landscape connectivity and conservation for the jaguar, *Panthera onca*. Biol Conserv 143, 939–945. https://doi.org/10.1016/j.biocon.2010.01.002

Reppucci, J.I., Perovic, P.G., An Erica Cuyckens, G., Caruso, F., de Bustos, S., Arrabal, J.P., Sillero-Zubirí, C., 2024. Jaguar density in the Argentine Yungas: Overcoming camera trap failure. J Nat Conserv 77. https://doi.org/10.1016/j.jnc.2023.126518

Rodríguez-Rodríguez, D., Martínez-Vega, J., 2022. Effectiveness of protected areas in conserving biodiversity. Switzerland. https://doi.org/10.1007/978-3-030-94297-7

Rodríguez-Soto, C., Monroy-Vilchis, O., Zarco-González, M.M., 2013. Corridors for jaguar (*Panthera onca*) in Mexico: conservation strategies. J Nat Conserv 21, 438–443. https://doi.org/10.1016/j.jnc.2013.07.002

Romero-Muñoz, A., Bleyhl, B., Benítez-López, A., Camino, M., Decarre, J., Nanni, A.S., Noss, A., Giordano, A.J., Quiroga, V.A., Torres, R., Thompson, J.J., Villalba, L., Nuñez Regueiro, M.M., De Angelo, C., Kuemmerle, T., 2025. Hunting and Habitat Destruction Drive Widespread Functional Declines of Top Predators in a Global Deforestation Hotspot. Divers Distrib 31, e70003. https://doi.org/10.1111/ddi.70003

Roques, S., Sollman, R., Jácomo, A., Tôrres, N., Silveira, L., Chávez, C., Keller, C., do Prado, D.M., Torres, P.C., dos Santos, C.J., da Luz, X.B.G., Magnusson, W.E., Godoy, J.A., Ceballos, G., Palomares, F., 2016. Effects of habitat deterioration on the population genetics and conservation of the jaguar. Conservation Genetics 17, 125–139. https://doi.org/10.1007/s10592-015-0766-5

Rudnick, D., Beier, P., Cushman, S., Dieffenbach, F., Epps, C.W., Gerber, L., Hartter, J., Jenness, J., Kintsch, J., Merenlender, A.M., Perkle, R.M., Preziosi, D.V., Ryan, S.J., Trombulak, S.C., 2012. The Role of Landscape Connectivity in Planning and Implementing Conservation and Restoration Priorities. Issues in Ecology, Ecological Society of America.

Sanderson, E.W., Fisher, K., Peters, R., Beckmann, J.P., Bird, B., Bradley, C.M., Bravo, J.C., Grigione, M.M., Hatten, J.R., Lopez González, C.A., Menke, K., Miller, J.R.B., Miller,

P.S., Mormorunni, C., Robinson, M.J., Thomas, R.E., Wilcox, S., 2022. A systematic review of potential habitat suitability for the jaguar *Panthera onca* in central Arizona and New Mexico, USA. Oryx 56, 116–127. https://doi.org/10.1017/S0030605320000459

Schoen, J.M., DeFries, R., Cushman, S., 2025. Open-source, environmentally dynamic machine learning models demonstrate behavior-dependent utilization of mixed-use landscapes by jaguars (*Panthera onca*). Biol Conserv 302, 110978. https://doi.org/10.1016/j.biocon.2025.110978

Silveira, L., 2004. Ecologia comparada e conservação da onça-pintada (*Panthera onca*) e onça-parda (*Puma concolor*), no Cerrado e Pantanal.

Silveira, L., Sollmann, R., Jácomo, A.T.A., Diniz Filho, J.A.F., Tôrres, N.M., 2014. The potential for large-scale wildlife corridors between protected areas in Brazil using the jaguar as a model species. Landsc Ecol 29, 1213–1223. https://doi.org/10.1007/s10980-014-0057-4

Sollmann, R., Torres, N.M., Silveira, L., 2008. Jaguar conservation in Brazil: the role of Protected Areas. CAT News 4, 15–20.

Soterroni, A.C., Ramos, F.M., Mosnier, A., Fargione, J., Andrade, P.R., Baumgarten, L., Pirker, J., Obersteiner, M., Kraxner, F., Câmara, G., Carvalho, A.X.Y., Polasky, S., 2019. Expanding the soy moratorium to Brazil's Cerrado. Sci Adv 5, eaav7336. https://doi.org/10.1126/sciadv.aav7336

Srbek-Araujo, A.C., Haag, T., Chiarello, A.G., Salzano, F.M., Eizirik, E., 2018. Worrisome isolation: Noninvasive genetic analyses shed light on the critical status of a remnant jaguar population. J Mammal 99, 397–407. https://doi.org/10.1093/jmammal/gyy007

Sunquist, M.E., Sunquist, F.C., 2002. Wild Cats of the World. University of Chicago Press, Chicago and London.

Taylor, P.D., Fahrig, L., Henein, K., Merriam, G., 1993. Connectivity is a vital element of landscape structure. Oikos 68, 571–573. https://doi.org/10.2307/3544927

Tellman, B., Sesnie, S.E., Magliocca, N.R., Nielsen, E.A., Devine, J.A., McSweeney, K., Jain, M., Wrathall, D.J., Dávila, A., Benessaiah, K., Aguilar-Gonzalez, B., 2020. Illicit Drivers of Land Use Change: Narcotrafficking and Forest Loss in Central America. Global Environmental Change 63, 102092. https://doi.org/10.1016/j.gloenvcha.2020.102092

Thompson, J.J., Morato, R.G., Niebuhr, B.B., Alegre, V.B., Oshima, J.E.F., de Barros, A.E., Paviolo, A., de la Torre, J.A., Lima, F., McBride, R.T., Cunha de Paula, R., Cullen, L., Silveira, L., Kantek, D.L.Z., Ramalho, E.E., Maranhão, L., Haberfeld, M., Sana, D.A., Medellin, R.A., Carrillo, E., Montalvo, V.H., Monroy-Vilchis, O., Cruz, P., Jacomo, A.T.A., Alves, G.B., Cassaigne, I., Thompson, R., Sáenz-Bolaños, C., Cruz, J.C., Alfaro, L.D., Hagnauer, I., Xavier da Silva, M., Vogliotti, A., Moraes, M.F.D., Miyazaki, S.S., Araujo, G.R., Cruz da Silva, L., Leuzinger, L., Carvalho, M.M., Rampim, L., Sartorello, L., Quigley, H., Tortato, F.R., Hoogesteijn, R., Crawshaw, P.G., Devlin, A.L., May Júnior, J.A., Powell, G.V.N., Tobler, M.W., Carrillo-Percastegui, S.E., Payán, E., Azevedo, F.C.C., Concone, H.V.B., Quiroga, V.A., Costa, S.A., Arrabal, J.P., Vanderhoeven, E., Di Blanco, Y.E., Lopes, A.M.C., Ribeiro, M.C., 2021. Environmental and anthropogenic factors synergistically affect space use of jaguars. Current Biology 31, 3457-3466.e4. https://doi.org/10.1016/j.cub.2021.06.029

Thompson, J.J., Paviolo, A.J., Morato, R.G., Jedrzejewski, W., Tortato, F.R., de Bustos, M.S., Reppucci, J.I., Perovic, P.G., Negroes, N., Romero Muñóz, A., Rumiz, D.I., Cruz, M.P., de Angelo, C.D., Quiroga, V.A., Barros, Y., Foster, V., Velilla, M., Srbek, A.C.;, De Campos, C.B., Breitenmoser, U., Breitenmoser, C., 2023. Jaguar status, distribution and conservation in south-eastern South America. CATnews Special Issue 35–43.

UNEP-WCMC, IUCN, 2022. Protected Planet: The World Database on Protected Areas (WDPA) [WWW Document]. Cambridge, UK: UNEP-WCMC and IUCN. URL www.protectedplanet.net. (accessed 1.9.22).

Unnithan Kumar, S., Cushman, S.A., 2022. Connectivity modelling in conservation science: a comparative evaluation. Sci Rep 12, 16680. https://doi.org/10.1038/s41598-022-20370-w

Unnithan Kumar, S., Turnbull, J., Hartman Davies, O., Hodgetts, T., Cushman, S.A., 2022. Moving beyond landscape resistance: considerations for the future of connectivity modelling and conservation science. Landsc Ecol 37, 2465–2480. https://doi.org/10.1007/s10980-022-01504-x

Wultsch, C., Caragiulo, A., Dias-Freedman, I., Quigley, H., Rabinowitz, S., Amato, G., 2016. Genetic diversity and population structure of Mesoamerican jaguars (*Panthera onca*): Implications for conservation and management. PLoS One 11, 1–25. https://doi.org/10.1371/journal.pone.0162377

Zeller, K., 2007. Jaguars in the new millennium data set update: The state of the jaguar in 2006. Wildlife Conservation Society, Bronx, New York 1–77.

Zeller, K.A., McGarigal, K., Whiteley, A.R., 2012. Estimating landscape resistance to movement: A review. Landsc Ecol 27, 777–797. https://doi.org/10.1007/s10980-012-9737-0

Author Contributions

Guilherme Costa Alvarenga: Conceptualization, Investigation, Data curation, Methodology, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. **Caroline C. Sartor:** Methodology, Formal analysis, Writing – review & editing. **Żaneta Kaszta:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Ana Carolina Srbek-Araujo:** Investigation, Resources, Writing – review & editing. **Ana Cristina Mendes-Oliveira:** Investigation, Resources, Writing – review & editing. **Bart Harmsen:** Investigation, Resources, Writing – review & editing. **Carlos De Angelo:** Investigation, Resources, Writing – review & editing. **Carolina Franco Esteves:** Investigation, Resources, Writing – review & editing. **Claudia B. de Campos:** Investigation, Resources, Writing – review & editing. **Daiana Jeronimo Polli:** Investigation, Resources, Writing – review & editing. **Diego F. Passos Viana:** Investigation, Resources, Writing – review & editing. **Diogo Maia Gräbin:** Investigation, Resources, Writing – review & editing. **Emiliano Donadio:** Investigation, Resources, Writing – review & editing. **Emiliano E. Ramalho:** Investigation, Resources, Writing – review & editing. **Esteban Payán:** Investigation, Resources, Writing – review & editing. **Fernando C. C. Azevedo:** Investigation, Resources, Writing – review & editing. **Francisco Palomares:** Investigation, Resources, Writing – review & editing. **George V. N. Powell:** Investigation, Resources, Writing – review & editing. **Gerardo Ceballos:** Investigation, Resources, Writing – review & editing. **Grasiela Porfirio:** Investigation, Resources, Writing – review & editing. **Heliot Zarza:** Investigation, Resources, Writing – review & editing. **Ivonne Cassaigne:** Investigation, Resources, Writing – review & editing. **Juliano A. Bogoni:** Investigation, Resources, Writing – review & editing. **Leonardo Sena:** Investigation, Resources, Writing – review & editing. **Louise Maranhão:** Investigation, Resources, Writing – review & editing. **Marcos Roberto Monteiro de Brito:** Investigation, Resources, Writing – review & editing.

Mathias W. Tobler: Investigation, Resources, Writing – review & editing. **Øystein Wiig:** Investigation, Resources, Writing – review & editing. **Rafael Antelo:** Investigation, Resources, Writing – review & editing. **Rebecca J. Foster:** Investigation, Resources, Writing – review & editing. **Ricardo Sampaio:** Investigation, Resources, Writing – review & editing. **Robin Naidoo:** Investigation, Resources, Writing – review & editing. **Rodrigo Nuñez:** Investigation, Resources, Writing – review & editing. **Ronaldo G. Morato:** Investigation, Resources, Writing – review & editing. **Sandra Petrone Mendoza:** Investigation, Resources, Writing – review & editing. **Valeria Boron:** Investigation, Resources, Writing – review & editing. **Wener Hugo Arruda Moreno:** Investigation, Resources, Writing – review & editing. **David W. Macdonald:** Resources, Writing – review & editing, Funding acquisition. **Samuel A. Cushman:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration.

Supplementary Material

Tables

Table S1. Reference information of the 172 GPS-collared jaguars used to predict the habitat suitability surface (Alvarenga et al., 2026), which underpinned the connectivity models.

Jaguar ID	Sex	Nº Locations	Nº Locations Filter	Tracked Period	Latitude	Longitude	Country
1	F	288	132	06/2010-03/2011	-23.275652	-58.116174	Paraguay
2	F	150	107	07/2010-12/2011	-24.171145	-55.433106	Paraguay
3	M	148	106	06/2009-09/2009	-23.344435	-58.450313	Paraguay
4	F	500	179	07/2011-12/2011	-23.339263	-58.138876	Paraguay
5	F	280	57	07/2009-09/2009	-23.367736	-58.1908264	Paraguay
6	M	983	221	07/2009-12/2009	-23.232139	-58.2325172	Paraguay
7	M	621	207	07/2011-11/2011	-23.25648	-58.077142	Paraguay
8	M	540	196	07/2009-07/2010	-24.040429	-55.486192	Paraguay
9	F	1018	177	06/2014-12/2014	-23.326947	-58.041257	Paraguay
10	F	1668	463	06/2014-05/2015	-23.397239	-58.185852	Paraguay
11	F	913	180	07/2014-07/2015	-23.368049	-58.039784	Paraguay
12	F	2681	261	12/2014-04/2015	-16.9714833	-57.3899431	Brazil
13	M	5040	109	12/2014-08/2015	-16.9159483	-57.4977108	Brazil
14	M	192	64	04/2012-04/2012	-19.8744136	-56.4016528	Brazil
15	M	1323	292	10/2013-01/2014	-20.0301064	-56.3210047	Brazil
16	M	3462	581	04/2011-08/2012	-21.734897	-60.0206985	Paraguay
17	M	537	187	03/2014-07/2014	-17.808023	-53.183055	Brazil
18	M	2314	180	11/2014-04/2015	-16.9279125	-57.4243325	Brazil
19	F	741	111	10/2011-01/2012	-19.9582217	-56.3169619	Brazil
20	M	5590	739	09/2015-06/2016	-8.60977	-42.6801	Brazil
21	F	327	139	08/2011-06/2012	-24.067424	-55.466862	Paraguay
22	M	4709	176	09/2014-05/2015	-16.8864897	-57.4038397	Brazil
23	M	572	38	09/2014-09/2014	-16.8747392	-57.5129536	Brazil
24	M	153	75	12/2011-03/2012	-5.97859	-50.040107	Brazil
25	F	3219	188	10/2012-08/2015	-19.9448036	-56.2427367	Brazil
26	F	5924	333	11/2014-06/2016	10.8596451	-85.6343205	Costa Rica
27	F	560	86	09/2010-11/2013	-17.3260076	-56.7544166	Brazil
28	F	205	65	07/2010-10/2010	-17.828947	-57.40595	Brazil
29	F	67	30	07/2011-09/2011	-17.8398802	-57.3940782	Brazil
30	F	581	125	10/2011-11/2012	-17.3293188	-56.7126546	Brazil
31	F	103	36	10/2013-02/2014	-17.3367322	-56.7099957	Brazil
32	F	240	104	10/2012-04/2013	-17.3793419	-56.7819766	Brazil
33	F	133	68	10/2013-01/2014	-17.3285701	-56.7594096	Brazil

34	F	92	39	02/2003-07/2003	-22.63708499	-52.26445905	Brazil
35	F	17	15	08/2000-11/2001	-22.59397636	-52.25259646	Brazil
36	F	32	28	07/1999-07/2003	-22.5901957	-52.38519834	Brazil
37	F	211	93	07/2002-11/2002	-22.63878999	-52.12664972	Brazil
38	F	18	18	07/2002-08/2002	-22.53828697	-52.25666345	Brazil
39	F	326	187	02/2002-04/2005	-22.75705316	-53.68426924	Brazil
40	F	183	100	05/2004-12/2004	-22.80383586	-53.55541512	Brazil
41	F	4952	90	12/2014-08/2015	-16.8612211	-57.4243539	Brazil
42	M	7668	1047	02/2009-10/2009	-25.637647	-54.299678	Argentina
43	F	1512	556	01/2013-02/2013	29.74605	-109.23039	Mexico
44	F	104	65	01/2012-09/2013	16.835904	-91.042886	Mexico
45	F	39	14	08/2012-08/2012	16.889464	-90.955664	Mexico
46	F	443	250	08/2012-11/2013	16.898824	-91.083115	Mexico
47	M	636	330	01/2012-02/2013	16.579612	-90.999996	Mexico
48	M	72	53	08/2012-12/2012	16.938643	-91.120305	Mexico
49	M	979	280	01/2014-12/2015	21.3790875	-87.6018119	Mexico
50	M	1361	218	11/2014-01/2015	-8.6345197	-42.7049775	Brazil
51	M	727	239	06/2010-12/2010	-20.530443	-58.061521	Paraguay
52	F	615	40	11/2014-12/2014	-16.9132783	-57.4112914	Brazil
53	M	300	148	09/2010-10/2013	-17.265488	-56.8139292	Brazil
54	M	129	22	07/2010-08/2010	-17.8506281	-57.4067729	Brazil
55	M	141	65	06/2011-10/2011	-17.3527833	-56.5766747	Brazil
56	M	109	59	07/2011-10/2011	-17.8231802	-57.5760012	Brazil
57	M	28	8	07/2011-08/2011	-17.8351375	-57.4037579	Brazil
58	M	159	79	01/2003-06/2003	-22.67648014	-52.19555839	Brazil
59	M	434	223	10/2011-12/2013	-17.3239385	-56.7097386	Brazil
60	M	705	187	10/2012-10/2013	-17.3536055	-56.7575736	Brazil
61	M	109	61	06/2013-08/2013	-17.2932905	-56.7014317	Brazil
62	M	156	113	05/2003-10/2003	-22.62201182	-52.20074942	Brazil
63	M	797	409	03/2005-04/2006	-22.74154717	-53.54126196	Brazil
64	M	1694	639	10/2012-12/2012	29.61717	-109.31089	Mexico
65	F	1010	445	03/2014-10/2014	-17.871376	-53.103104	Brazil
66	F	53	41	02/2013-06/2013	-25.6485772	-54.4214814	Brazil
67	F	131	69	03/2014-06/2014	-17.706925	-52.936313	Brazil
68	M	1003	194	11/2011-12/2011	-20.0268575	-56.2552267	Brazil
69	F	3464	317	10/2013-05/2014	-19.9262692	-56.2414756	Brazil
70	M	1094	487	06/2002-06/2003	-22.195088	-60.160038	Paraguay
71	F	921	443	07/2003-07/2004	-19.753344	-59.480243	Paraguay
72	M	722	290	07/2003-07/2004	-19.747937	-59.551036	Paraguay
73	M	620	257	06/2004-09/2004	-20.142131	-59.851225	Paraguay
74	F	1300	185	08/2005-05/2006	-19.971896	-58.217231	Paraguay
75	F	1694	215	08/2005-08/2006	-20.039304	-58.165714	Paraguay
76	F	1610	616	06/2006-07/2007	-20.440784	-60.320772	Paraguay

77	M	1376	576	06/2006-05/2007	-20.51578	-60.33193	Paraguay
78	F	798	292	07/2008-07/2009	-24.522229	-55.34041	Paraguay
79	F	2300	201	04/2015-08/2015	-19.9936717	-56.2941214	Brazil
80	M	479	70	05/2010-07/2010	-25.60912108	-54.49638269	Argentina
81	M	10988	407	10/2013-05/2015	-16.97737	-57.3910972	Brazil
82	M	1335	576	05/2014-12/2015	-17.96005	-53.082933	Brazil
83	M	112	49	01/2012-03/2012	-25.08117226	-53.62542169	Brazil
84	F	4860	227	04/2013-01/2014	-19.95198	-56.3223003	Brazil
85	M	780	400	03/2014-02/2015	-17.690413	-53.107739	Brazil
86	F	1391	276	10/2013-01/2014	-19.9611475	-56.1977572	Brazil
87	F	413	32	05/2012-06/2012	-19.9725481	-56.2818497	Brazil
88	F	1296	116	10/2013-04/2014	-16.8718285	-57.5228518	Brazil
89	M	2432	402	09/2013-10/2015	-15.9061	-48.477581	Brazil
90	F	322	164	08/2012-04/2013	-25.7531786	-54.5845814	Argentina
91	M	88	36	01/2011-01/2012	-16.894062	-57.492675	Brazil
92	F	96	43	01/2011-01/2013	-16.917908	-57.487805	Brazil
93	F	784	144	12/2010-11/2011	-3.050582	-64.852288	Brazil
94	F	3837	244	11/2012-02/2014	-3.054921	-64.845133	Brazil
95	F	542	109	02/2013-07/2013	-2.933995	-64.834189	Brazil
96	M	230	125	01/2013-04/2013	-3.03768	-64.82531	Brazil
97	F	31	3	02/2013-02/2013	-3.037074	-64.843443	Brazil
98	M	61	26	01/2013-09/2013	-3.043342	-64.884696	Brazil
99	M	294	110	10/2013-11/2014	-2.944293	-64.940658	Brazil
100	M	1024	319	03/2014-08/2015	-3.090892	-64.813113	Brazil
101	M	404	207	08/2015-03/2016	-19.710234	-56.357117	Brazil
102	F	151	83	03/2016-05/2016	-19.603761	-56.211355	Brazil
103	F	20	12	06/2014-06/2014	-19.571285	-56.076128	Brazil
104	M	134	59	08/2015-06/2016	-19.578162	-56.151681	Brazil
105	F	2113	251	07/2008-10/2009	-19.51600071	-57.04450005	Brazil
106	M	227	131	09/2009-10/2011	-19.42884891	-56.91394335	Brazil
107	M	287	93	07/2008-12/2008	-19.53291063	-56.78271003	Brazil
108	M	481	197	07/2008-11/2008	-19.46945048	-56.86500405	Brazil
109	F	165	72	08/2008-10/2008	-19.56692044	-56.91692119	Brazil
110	M	166	93	02/2010-05/2010	-19.49668019	-57.12129559	Brazil
111	F	1758	188	07/2008-04/2011	-19.43423998	-56.86302315	Brazil
112	F	202	47	07/2008-10/2008	-19.63714532	-56.9650143	Brazil
113	F	709	140	08/2008-07/2009	-19.47401862	-56.94045639	Brazil
114	F	1645	199	06/2008-07/2009	-19.47993711	-57.08448275	Brazil
115	F	952	247	06/2008-03/2009	-19.53442239	-56.97638914	Brazil
116	M	3340	146	10/2015-04/2016	-16.8496492	-57.5967928	Brazil
117	F	2820	116	10/2015-02/2016	-16.9078125	-57.4846269	Brazil
118	F	451	175	01/2015-01/2016	-3.078417	-64.829936	Brazil
119	M	516	183	01/2015-07/2015	-2.852821	-64.908878	Brazil

120	F	843	137	03/2016-11/2016	-3.042296	-64.856324	Brazil
121	M	643	211	01/2016-10/2016	-3.108568	-64.817603	Brazil
122	M	835	275	02/2017-01/2018	-3.03765	-64.90765	Brazil
123	M	2622	272	03/2018-02/2019	-3.062562	-64.792863	Brazil
124	M	801	146	02/2020-05/2020	-3.021761	-64.964985	Brazil
125	M	4890	436	07/2019-07/2020	-19.14391	-39.99278	Brazil
126	F	4363	771	06/2019-02/2020	-10.76774	-41.69304	Brazil
127	F	1774	343	05/2013-05/2014	18.662806	-89.131262	Mexico
128	F	1221	653	07/2001-03/2009	18.232041	-88.898627	Mexico
129	F	166	125	03/2002-03/2003	18.31096889	-88.95445333	Mexico
130	M	526	72	05/2009-06/2009	18.383318	-89.300211	Mexico
131	M	1315	329	05/2009-07/2009	18.270961	-89.256905	Mexico
132	M	295	207	04/2005-11/2005	18.1338	-89.0362	Mexico
133	F	457	208	04/2005-05/2006	18.176021	-88.888454	Mexico
134	F	307	121	04/2001-01/2002	18.295253	-88.979485	Mexico
135	M	4831	879	01/2021-01/2023	-24.8283769	-61.1156142	Argentina
136	F	1290	190	05/2009-07/2009	18.324955	-89.397159	Mexico
137	M	364	253	06/2002-05/2003	18.215324	-89.558898	Mexico
138	M	1192	244	05/2009-09/2009	18.457128	-89.412146	Mexico
139	F	245	141	04/2008-03/2009	18.231913	-88.898713	Mexico
140	F	286	165	04/2005-08/2007	18.269887	-89.02367	Mexico
141	M	2851	557	10/2012-03/2013	-11.41943858	-69.84469181	Peru
142	M	1618	378	09/2009-12/2009	-11.43448933	-69.77944624	Peru
143	M	189	132	11/2012-02/2013	-11.5411808	-69.7436494	Peru
144	F	903	168	10/2012-12/2012	-11.4049256	-69.85074	Peru
145	F	3848	293	09/2007-02/2008	-13.12314509	-69.59072353	Peru
146	F	3054	323	08/2007-12/2007	-13.12049567	-69.46562018	Peru
147	M	4905	584	07/2012-05/2013	-11.42838766	-69.82209262	Peru
148	F	697	98	09/2007-12/2007	-13.05271558	-69.54118693	Peru
149	M	4199	688	07/2007-02/2008	-12.97864727	-69.58116607	Peru
150	M	2122	172	01/2022-06/2022	-17.925562	-57.476751	Brazil
151	M	13243	1274	08/2017-03/2019	-9.95224	-41.09542	Brazil
152	M	287	80	02/2018-05/2018	5.98766	-71.44483	Colombia
153	F	257	28	02/2018-05/2018	6.0383939	-71.3843953	Colombia
154	M	2555	384	11/2019-06/2020	-3.24246	-47.83422	Brazil
155	F	2361	279	09/2017-07/2018	-19.8004	-42.59652	Brazil
156	M	2174	462	11/2017-11/2018	-19.80304	-42.59469	Brazil
157	F	43	25	07/2021-08/2021	20.9937908	-105.2199662	Mexico
158	F	1257	87	11/2019-03/2020	21.6542017	-105.4480192	Mexico
159	M	296	70	12/2015-03/2016	20.929646	-105.297234	Mexico
160	M	309	44	04/2016-07/2016	21.1989024	-105.2000204	Mexico
161	M	88	41	07/2017-08/2017	21.0400516	-104.9517662	Mexico
162	M	94	37	05/2019-11/2019	20.9081558	-105.3694981	Mexico

163	M	189	131	06/2015-05/2016	19.5015409	-105.0139881	Mexico
164	F	2852	134	10/2021-01/2023	-28.267087	-57.338167	Argentina
165	M	2412	402	01/2022-01/2023	-28.329787	-57.437795	Argentina
166	F	1263	161	04/2021-11/2021	-28.343423	-57.509335	Argentina
167	F	676	100	10/2022-01/2023	-28.337012	-57.441685	Argentina
168	F	5183	450	01/2021-01/2023	-28.243248	-57.302054	Argentina
169	M	1248	318	06/2023-08/2023	-8.691146	-42.521022	Brazil
170	F	3057	426	09/2022-01/2023	-8.647565	-42.67408	Brazil
171	M	362	203	02/2015-02/2016	16.77688791	-88.4860169	Belize
172	M	597	243	02/2015-10/2015	16.7671903	-88.4881106	Belize
TOTAL		231017	37782				

Figures

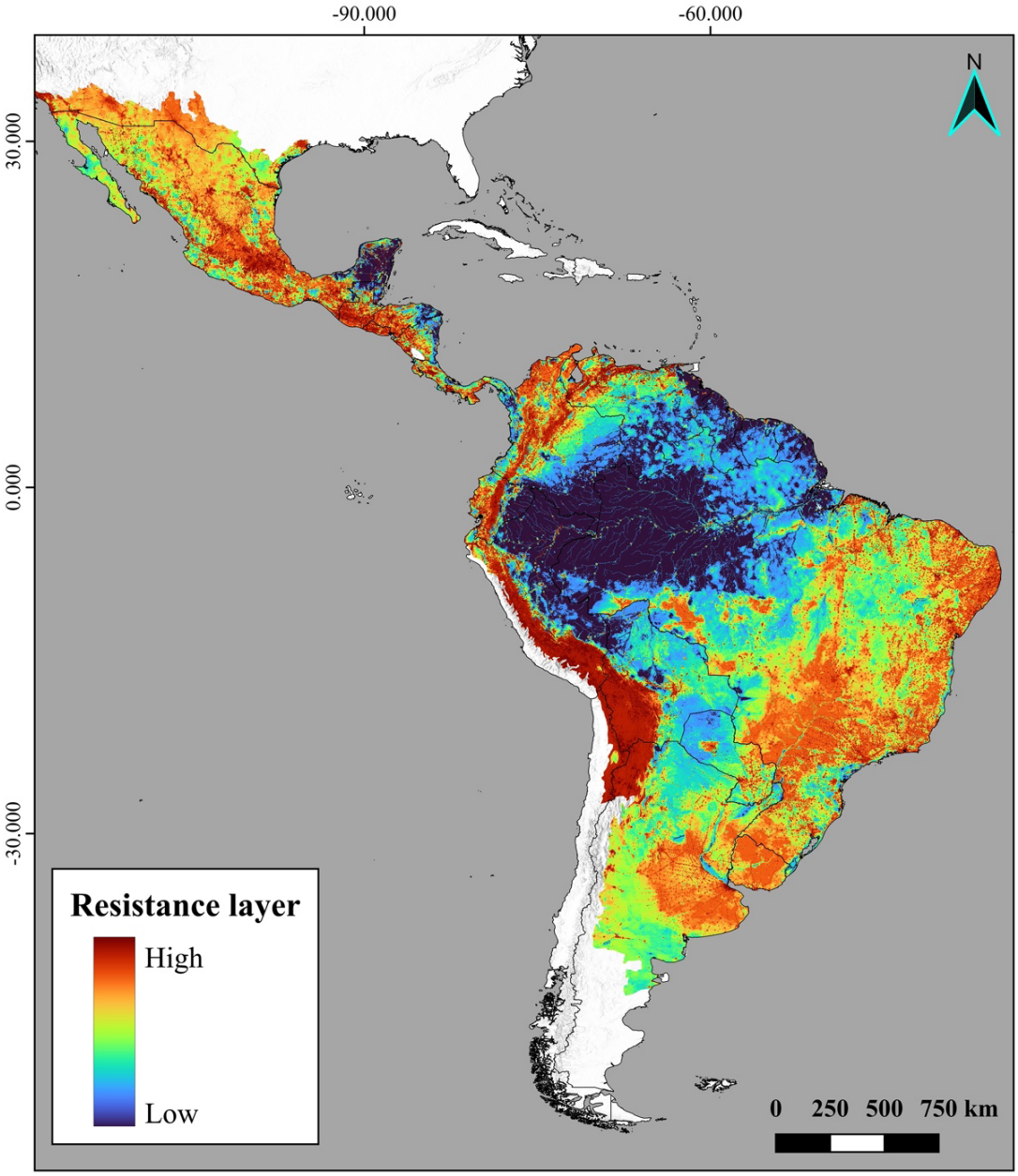


Figure S1. Resistance layer used in the jaguar (*Panthera onca*) population connectivity models.

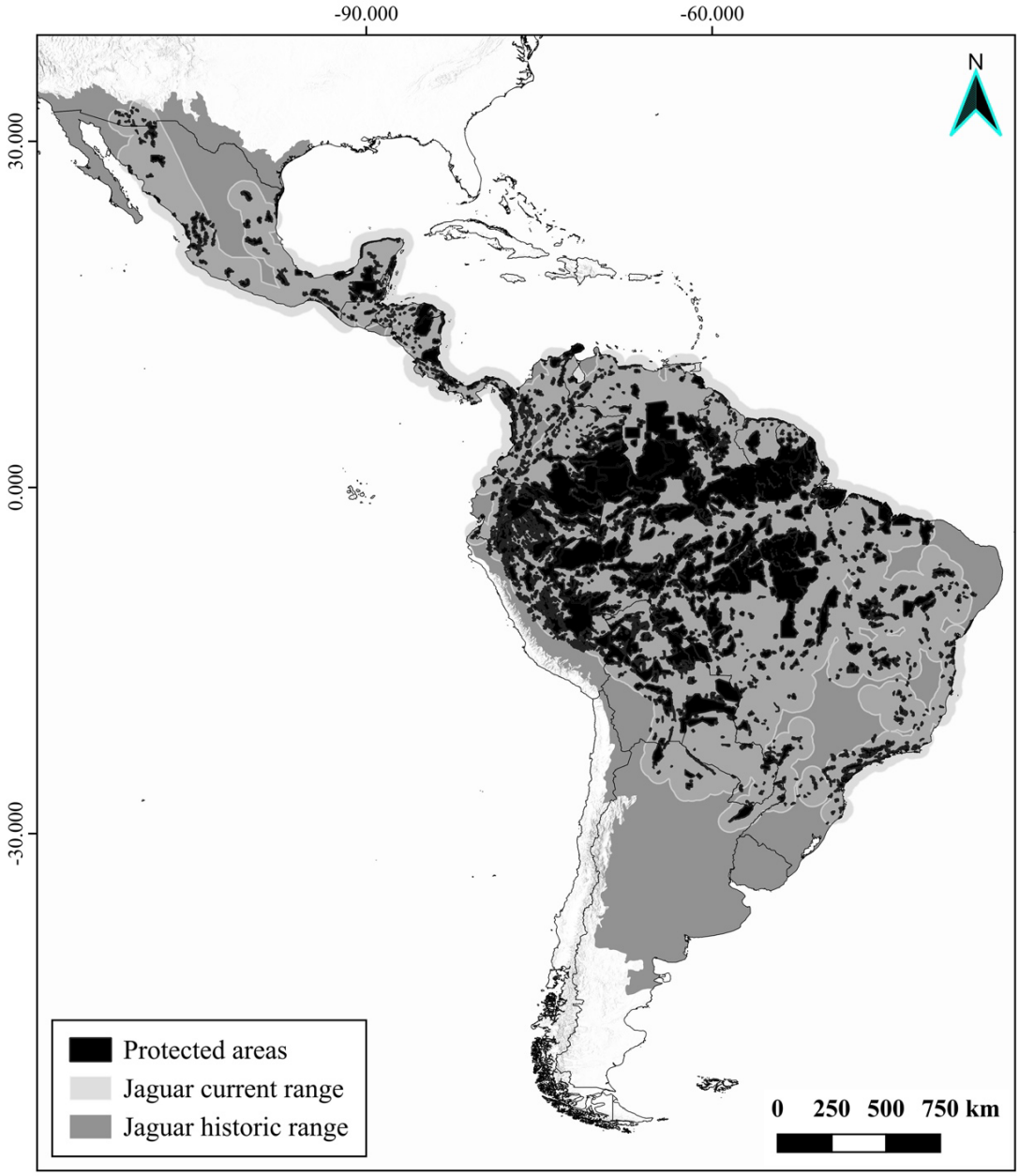


Figure S2. Protected areas, current and historic jaguar range considered in this study.

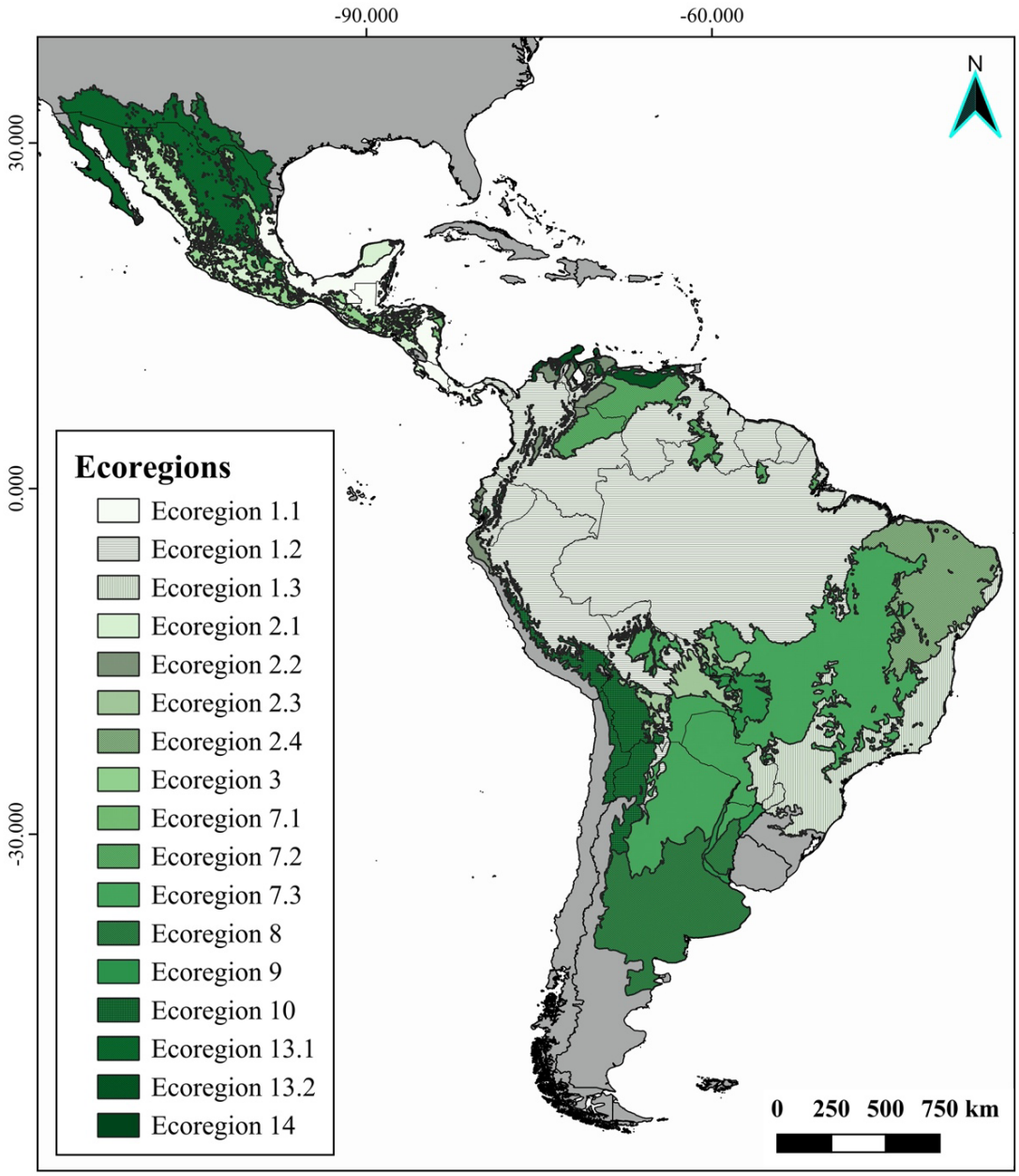


Figure S3. Ecoregions (derived from Olson et al., 2001) used in the ranking analysis of core areas, protected areas (PAs), and corridors. Ecoregions 1.1-1.3: Tropical & Subtropical Moist Broadleaf Forests; ecoregions 2.1-2.4: Tropical & Subtropical Dry Broadleaf Forests; ecoregions 3: Tropical & Subtropical Coniferous Forests; ecoregions 7.1-7.3: Tropical & Subtropical Grasslands, Savannas & Shrublands. ecoregions 8: Temperate Grasslands, Savannas & Shrublands; ecoregions 9: Flooded Grasslands & Savannas; ecoregions 10: Montane Grasslands & Shrublands; ecoregions 13.1, 13.2: Deserts & Xeric Shrublands; ecoregions 14: Mangroves.


Emiliano E. Ramalho - Mamirauá Institute

Chapter 5

Human-jaguar coexistence in the Pantanal-Amazon Corridor: attitudes and conservation implications

Guilherme Costa Alvarenga, Silvio Marchini, David W. Macdonald, Diogo Maia Gräbin, Fernanda da Paixão Alves, Fernando Tortato, Rodrigo Lima Massara, Ronaldo G. Morato, Samuel A. Cushman, Żaneta Kaszta, Alexandra Zimmermann, Darragh Hare

To be submitted to People and Nature

Abstract

Connectivity models simplify landscapes to estimate movement resistance, typically using anthropogenic predictors (e.g., population density, roads) but rarely integrating local perceptions that can determine corridor success. We conducted a quantitative social survey across ~10,000 km² of the Pantanal-Amazon Corridor (PAC; Brazil) to characterize human-jaguar interactions and tolerance toward both jaguars and conservation actions. We interviewed 117 respondents (91% men; mean age 48), including employees (37%), managers (25%), and landowners (38%). Education levels were generally low; religious affiliation was predominantly Catholic or Evangelical, and political orientation was mainly right-wing (47%), followed by no declared orientation (36%) and left-wing (13%). Reports of jaguar killings were infrequent, with ~40% having never heard of killings in their area and 50% reporting one killing per year or less. Neither distance to protected areas nor habitat suitability predicted the number or frequency of jaguar attacks on livestock (all $p > 0.05$). Overall tolerance was high toward both jaguars and conservation actions, although tolerance for conservation was significantly higher than tolerance for jaguars (Wilcoxon signed-rank: V = 1075, $p < 0.0001$; rank-biserial $W_c = 0.41$). Attitudes toward conservation were influenced by perceptions of extreme climatic events ($\chi^2 = 7.46$, $p = 0.024$), with respondents perceiving no increase in extreme events expressing lower conservation support than those perceiving increased frequency. Political orientation was the only significant predictor of tolerance toward jaguars ($\chi^2 = 6.73$, $p = 0.035$), with left-wing respondents showing higher tolerance than right-wing respondents or those with no declared orientation. This study provides the first on-the-ground social assessment of a newly proposed jaguar corridor. Results indicate that the PAC is functioning as an active corridor and that local attitudes toward jaguars and conservation are generally positive. Nonetheless, observed contradictions highlight ongoing challenges, underscoring the need for continued monitoring to ensure long-term jaguar persistence.

Keywords

Human-carnivore conflict; Landscape connectivity; *Panthera onca*; Social perceptions; Tolerance to carnivores

Introduction

The ongoing loss and fragmentation of natural habitats is the primary threat to biodiversity worldwide (Ceballos and Ehrlich, 2002). In response, researchers have developed connectivity models to identify ecological corridors capable of maintaining gene flow and facilitating movement between isolated habitat fragments. These corridors are typically modelled using environmental and anthropogenic variables such as land cover, road networks, and human population density (Titus and Jachowski, 2025). However, integrating social dimensions, such as people's acceptance of wildlife, remains challenging, particularly across large spatial scales. Yet, understanding human perceptions and attitudes is crucial, as these factors can shape landscape permeability and determine where conservation investments are most needed (Sage et al., 2022).

Jaguars (*Panthera onca*) are the largest felids in the Neotropics and the third largest in the world, after tigers and lions (Seymour, 1989). Across the Americas, jaguars hold cultural importance and are frequently regarded as symbols of strength, power, and spiritual authority (Figel et al., 2022; Pinto-Marroquin et al., 2022). On the other hand, as opportunistic predators, jaguars feed on a wide range of species – wild, domestic, and, although extremely rare, even humans (Campos Neto et al., 2011; Seymour, 1989). Admired and feared, jaguars are often persecuted for multiple reasons, such as retaliation (Jędrzejewski et al., 2017), subsistence/commercial hunting (Morcatty et al., 2020; Valsecchi et al., 2022), social norms and fear (Knox et al., 2019; Marchini and Macdonald, 2012). Conflict intensity varies considerably across regions, making it difficult to generalise behavioural patterns at broad spatial scales (Zimmermann et al., 2021). However, along ecological corridors – spatially narrow zones predicted to support dispersal – assessing local attitudes may provide valuable insights into their functionality and long-term viability (e.g., Petracca et al., 2014). Understanding local acceptance of environmental rules and the perceived difficulty of

protecting livestock is also relevant in these contexts, as both factors can shape tolerance for carnivores and willingness to adopt preventive practices.

Recent jaguar connectivity modelling identified core habitats across the species' current range and predicted potential corridors between them (Alvarenga et al., *in review*). The analysis revealed two major routes linking the Pantanal and Amazon biomes entirely within Brazil's territory, hereafter referred to as the Pantanal-Amazon Corridors (PAC). While additional cross-border routes exist, implementing national corridors may be more feasible due to shared governance and greater cultural homogeneity. The PAC region is dominated by agriculture and livestock production, with most land under private ownership and used primarily for commodity farming (IBGE, 2023a). Nonetheless, Brazilian environmental legislation requires private landholders to maintain "Legal Reserves" and "Areas of Permanent Protection" (APPs), which preserve significant natural habitat (Soterroni et al., 2018) and may support jaguar movement. These mandatory protected areas on private lands (APPs and Legal Reserves) are a source of social tension, and local perceptions of their adequacy or excess can influence compliance and conservation outcomes, an aspect increasingly recognised as central to corridor governance.

Despite this landscape structure with natural habitats protected on private lands, jaguar persecution remains common in the region. Traditional extensive cattle ranching increases vulnerability to carnivore attacks, reinforcing negative perceptions and retaliatory killing (Marchini and Macdonald, 2012; Zimmermann et al., 2005). Evidence also suggests that responses to jaguars are influenced not only by economic losses but by social cohesion (Marchini and Macdonald, 2012), in which shared identity and community norms among ranchers shape what is considered acceptable behaviour (Cialdini et al., 1990). In such contexts, killing jaguars may be perceived as typical or even expected behaviour (Knox et al., 2019; Marchini and Macdonald, 2012). Additional contextual factors, such as wildlife

hunting pressure, perceptions of climate-related environmental changes, and trust in environmental governance, may further shape attitudes toward carnivores but remain poorly understood within the PAC.

Beyond these documented drivers, political ideology may also play a role, although this relationship has not yet been examined for jaguars. Brazil has undergone increasing political polarisation in recent years, with right-wing movements frequently associated with anti-environmental discourse and close alignment with agribusiness interests (Mendes Motta and Hauber, 2023). While direct links between political identity and jaguar tolerance are not yet documented, comparable patterns have been reported for other large carnivores, such as wolves (von Essen and Allen, 2017), suggesting a similar mechanism may operate for jaguars. If hostility toward jaguars is widespread within the PAC, the predicted corridor could function as an ecological trap – also known as a "sink corridors" – a pathway that facilitates animal movement but exposes animals to elevated mortality risk, ultimately reducing dispersal success (Hess and Fischer, 2001). Understanding human aspects and interactions with jaguars is therefore essential for assessing the true conservation potential of the PAC and informing targeted interventions. This requires evaluating not only depredation patterns but also broader socio-environmental perceptions, including attitudes toward environmental laws, perceptions of climate-related risks, and social norms around practices such as hunting.

In this study, we report results from a questionnaire study examining perceptions among farm owners, managers, and employees along the PAC in Brazil. Specifically, we aimed to (1) identify where livestock depredation is most likely to occur along the corridor, and (2) quantify landowners' attitudes toward jaguars specifically and conservation more generally, examining the factors associated with variation in these attitudes. We hypothesised that reports of jaguar attacks would be more frequent in areas with higher predicted habitat suitability for the species (Alvarenga et al., 2026) and in closer proximity to protected areas

given their importance in maintaining jaguar populations (Alvarenga et al., 2025). Furthermore, we addressed our second objective by testing whether attitudes toward jaguars would be shaped by the interaction between political orientation and direct experience with human-jaguar conflict. Specifically, we expected that exposure to anti-environmental narratives commonly associated with far-right political discourse (Mendes Motta and Hauber, 2023) may translate into more hostile perceptions of jaguars, particularly among respondents with a history of livestock depredation (Ericsson and Heberlein, 2003). Finally, because conservation attitudes can also be shaped by perceptions of climatic changes, environmental regulations, and local use of wildlife, we anticipated that these broader socio-environmental factors would help explain variation in respondents' conservation attitudes. Therefore, we predicted generally positive attitudes toward conservation but more negative attitudes toward jaguars, especially among respondents who identify with right-wing political positions, depend economically on livestock, and report previous jaguar-related losses.

Methods

Study area

The research was conducted over an approximately 10,000 km² area, spanning multiple municipalities in Mato Grosso, Brazil: Nova Olímpia, Tangará da Serra, Salto do Céu, Rio Branco, Lambari d'Oeste, Mirassol d'Oeste, Curvelândia, Cáceres, Porto Estrela, and Barra do Bugres (Fig. 1). Population sizes in these municipalities range from 3,224 to 106,434 residents, with an average population density of 6.12 inhabitants/km² (IBGE, 2023b). The regional economy is largely driven by intensive agriculture – particularly soybean and sugarcane production – and livestock farming. Most of the land is privately owned and managed for commercial purposes with substantial areas of native vegetation

remaining within rural properties. These correspond to Legal Reserves and APPs, both of which are legally mandated conservation zones under the Brazilian Forest Code.

The study area represents a transition zone between three major biomes: the Pantanal, the Cerrado, and the Amazon Rainforest. Consequently, it supports a diverse mix of species typical of savanna and forest environments. Medium and large mammal species recorded in the region include the maned wolf (*Chrysocyon brachyurus*), giant anteater (*Myrmecophaga tridactyla*), marsh deer (*Blastocerus dichotomus*), capybara (*Hydrochoerus hydrochaeris*), white-lipped peccary (*Tayassu pecari*), collared peccary (*Dicotyles tajacu*), and tapir (*Tapirus terrestris*). Jaguars, pumas (*Puma concolor*), and ocelots (*Leopardus pardalis*) are the most frequently reported felids, based on local accounts. Additionally, the introduced wild boar (*Sus scrofa scrofa*) is widespread and considered a problem species due to its impact on crops and livestock (personal communication).

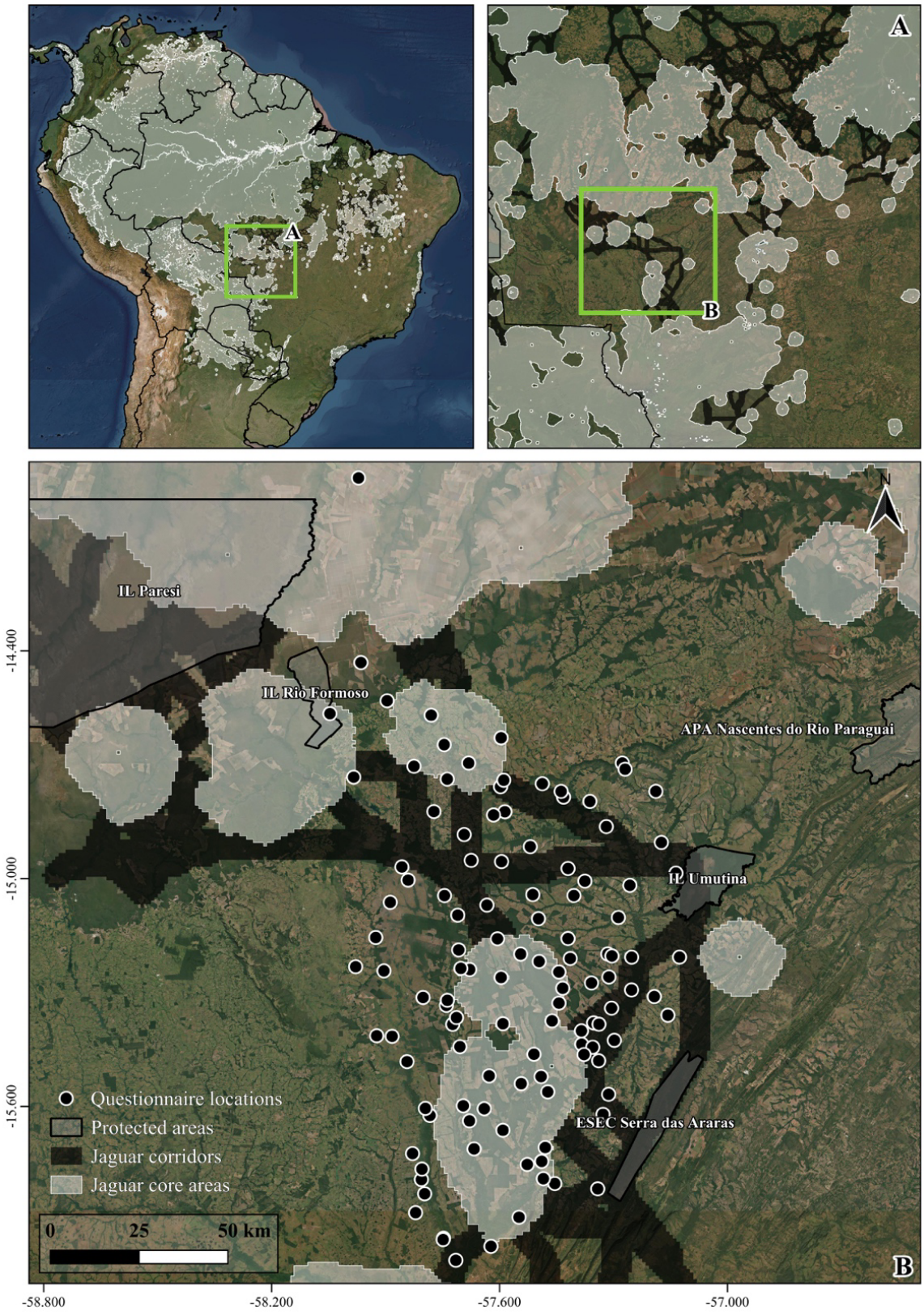


Figure 1. Study area in Brazil showing jaguar core areas and corridors predicted by Alvarenga et al. (*in review*), along with protected areas (including Indigenous Lands) and questionnaire locations.

Data collection

Data collection was conducted in 2024 using structured questionnaires. We surveyed 117 farms, completing one interview per property. We randomly selected 150 points on the landscape and invited representatives of nearby farms and residents in nearby settlements to participate in our survey. 117 people agreed to participate. When respondents were based in settlements not farms, we surveyed approximately three households per settlement. When farm owners did not reside on the property, interviews were carried out with the person responsible for management decisions (hereafter, manager) or, when appropriate, with a regular employee (hereafter, employee).

The questionnaire comprised three sections: (1) attitudes toward conservation and jaguars, (2) livestock husbandry practices, and (3) socio-demographic information. Section one included two thematic components. The first addressed general conservation topics, including perceptions of the importance of protected areas, natural habitats, wildlife protection, and climate change. The second focused specifically on jaguars and included questions regarding perceived abundance, acceptability of jaguar presence and protection, perceived risk or dangerousness, personal experience with livestock depredation, and the frequency with which respondents reported hearing about jaguars being killed in the region. The livestock husbandry section gathered information on farm size, livestock species, and management practices. The socio-demographic section included age, education level, political orientation, and religion (the full questionnaire is provided in the Supplementary Material).

Interviews were conducted by three Brazilian co-authors (GCA, DMG, and FPA) following standardised training to ensure consistent interviewer behaviour. Before beginning each interview, participants were informed about the aims of the study, the voluntary nature

of participation, and their right to decline any question or withdraw at any time. They were also informed that all responses would be anonymized, ensuring that no individual or property would be identified. Written informed consent was obtained from all respondents, and no incentives were provided. Ethical approval was granted by the Central University Research Ethics Committee (CUREC) at the University of Oxford (Protocol Number: R95304/RE001).

Analysis

Landscape analysis: Predictors of livestock depredation

To address our first research objective – understanding how landscape features influence livestock depredation by jaguars – we combined interview responses with geospatial data, specifically a jaguar habitat suitability raster and the location of protected areas (including Indigenous Lands). From the interviews, we used two response variables in separate models: (1) the self-reported frequency of livestock depredation by jaguars and (2) the number of livestock lost to jaguars over the previous five years. Depredation frequency was a categorical variable with four ordered levels: never, less than once per year, once per year, and once per month or more. The number of livestock losses was treated as a count variable. We detected one extreme value (300 animals in five years), which, while not impossible (Cavalcanti et al., 2010; Palmeira et al., 2008), was a clear outlier relative to the remaining distribution and was therefore excluded from modelling.

Habitat suitability and protected area data were obtained from Alvarenga et al. (2025); the protected area boundaries were derived from the World Database on Protected Areas (UNEP-WCMC and IUCN, 2022). The habitat suitability raster contained continuous values ranging from 0-1. To derive a landscape context for each respondent, we used reported farm size to create a buffer around the interview coordinate and extracted the mean suitability

value within that buffer. For respondents unable to provide farm size (N = 9), we used the mean farm size of the sample. For protected areas, we calculated the minimum Euclidean distance from each interview location to the nearest protected area boundary.

We modelled depredation frequency using ordinal logistic regression (polr), followed by Type II ANOVA to test predictor significance. The number of livestock losses was modelled using a negative binomial regression implemented in glmmTMB. Depredation events were generally infrequent across the study area, and model diagnostic checks confirmed the negative binomial distribution was appropriate (DHARMa tests: $p > 0.3$ for dispersion; $p > 0.8$ for zero-inflation and uniformity).

Index development and attitude modelling

"An attitude" is "the way in which a person views and evaluates something or someone" (Oxford U.P., 2025). To assess locals' attitudes toward nature and wildlife, we developed two composite measures: the Conservation Attitude Index (CAI) and the Jaguar Attitude Index (JAI). To construct the CAI, we combined four complementary variables reflecting respondents' perceptions of the importance of biodiversity and nature conservation: (1) the importance of protected areas, (2) the role of natural habitats in climate regulation, (3) concern about climate change, and (4) the importance of fauna protection. These variables included both ordinal and numeric data types; therefore, we summarised them using Factor Analysis of Mixed Data (FAMD). Scores from the first FAMD dimension – which captured the primary shared gradient of variation – were rescaled to a 0-1 range to produce the CAI, with higher values indicating stronger pro-conservation attitudes. The first dimension explained most of the variance among the four variables. Despite moderate correlations (r = 0.43-0.65), a sensitivity analysis excluding the most correlated variable produced a highly similar first-dimension score (r = 0.93), demonstrating robustness. Variable contributions to

the first dimension were examined and reported to support interpretation. Attitudes toward jaguars were summarised in the JAI using two measures: respondents' views on having jaguars in the region and their views on conserving jaguars locally. These items were moderately correlated (Spearman's $p = 0.35$; Cronbach's $\alpha = 0.53$), suggesting they capture related but distinct aspects of tolerance. We therefore averaged the two variables to generate the JAI with values ranging from -2 to +2, where negative values indicate antipathy, zero indicates neutrality and positive values indicate sympathy.

We first compared the CAI and JAI using a matched-pair rank-biserial correlation and a Wilcoxon signed-rank test, both appropriate for non-parametric paired data. For interpretability, JAI values were rescaled to match the 0-1 range of the CAI: values between 0-0.4 were interpreted as negative attitudes, values around 0.5 as neutral, and values ≥0.6 as positive. This standardisation enabled direct interpretation of both indexes on a common scale.

To assess which factors influenced respondents' conservation attitudes (CAI), we fitted a beta regression (betareg), appropriate for proportion-type response variables, followed by Type II ANOVA and post-hoc Tukey-Sidak comparisons. We initially selected nine predictors: opinion on APP size under the Forest Code, perceived effects of climate change on the farm, perceived occurrence of extreme climatic events, worker position, political orientation, religion, education level, age, and farm size. Religion was grouped into three categories (Catholic, Evangelical and none). Pairwise correlation tests indicated several collinearities ($|r| > 0.7$): opinion on APP size was correlated with worker position and political orientation (and opinion on APP size was therefore excluded); perceived climate-change effects were correlated with political orientation (and therefore climate-change effects was excluded); then education level and farm size were excluded due to their correlation with worker position and political orientation. The final model retained five predictors: perceived

occurrence of extreme climatic events, worker position, political orientation, religion, and age.

To explore the factors associated with attitudes toward jaguars, we modelled JAI using its original (unscaled) values. We initially considered twelve predictors: perception of jaguar abundance, perceived jaguar dangerousness, historic of livestock depredation by jaguars, perceived difficulty in preventing livestock predation, number of livestock losses to jaguars in the previous five years (outlier excluded: one report of 300 losses), worker position, political orientation, religion, education level, age, income, and farm size. During data cleaning, nearly 20% of respondents reported income categories tied to very specific professions with few respondents per category, preventing meaningful aggregation, and income was therefore removed. From the remaining variables, pairwise correlation tests identified several collinear relationships ($|r| > 0.7$): livestock losses were correlated with depredation occurrence and worker position (we retained the former and removed the latter two); age was correlated with education level (education removed); and farm size was correlated with political orientation (farm size removed). The final model therefore included seven predictors: perceived jaguar abundance, perceived dangerousness, perceived difficulty in preventing depredation, number of livestock losses in the last five years, political orientation, religion, and age. We fitted an ordinal logistic regression (polr), followed by a Type II ANOVA and post-hoc Tukey-Sidak comparisons.

Although not central to our primary research objectives, we conducted a set of exploratory comparisons to better understand variation in perceptions relevant to the local social context within the PAC landscape. During data exploration, we observed notable differences in how respondent groups (worker positions and political orientations) perceived APP size regulations. To examine these patterns formally, we tested associations between APP size perception and respondent characteristics using Pearson's χ^2 tests (applying Monte-

Carlo simulated p-values when expected cell counts were low), followed by pairwise comparisons of proportions with Holm correction to identify which specific groups differed. Nevertheless, these findings should be interpreted as exploratory and complementary to our hypothesis-driven analyses.

All analyses were conducted in R (R Core Team, 2018). Internal consistency was assessed using Cronbach's α from the *psych* package (Revelle, 2025). The Factor Analysis of Mixed Data (FAMD) was performed using *FactoMineR* (Lê et al., 2008). For the modelling procedures, negative binomial regression was implemented with *glmmTMB* (Brooks et al., 2017), beta regression with *betareg* (Cribari-Neto and Zeileis, 2010), ordinal logistic regression with *MASS* (Venables and Ripley, 2002), and Tukey post-hoc comparisons using *emmeans* (Lenth and Piaskowski, 2025). Diagnostic analyses were performed with *DHARMa* package (Hartig, 2025). Multicollinearity was evaluated using variance inflation factors (VIF) from the *car* package (Fox and Weisberg, 2019). Correlation analyses and diagnostics were carried out using functions from *lsr* (Navarro, 2015), *vcd* (Meyer et al., 2024), *nnet* (Venables and Ripley, 2002), and *FSA* (Ogle et al., 2025). Visualisations were produced using the *ggplot2* package (Wickham, 2016).

Results

We interviewed 117 respondents (91% men; mean age 48) spanning employees (37%), managers (25%), and owners (38%). Education generally skewed low, religious affiliation was predominantly Catholic (57%) or Evangelical (27%), and political orientation was mainly right-leaning (47%), followed by no declared orientation (36%) and left-leaning (13%). Property size varied substantially, ranging from smallholdings (0.7 ha) to large estates (32,000 ha; mean = 1,571.5 ha) (Table S1).

Jaguars were widely recognised as present in PAC, with three respondents reporting a total of eight direct sightings during the previous three months. In addition, 27 respondents reported finding jaguar footprints during the same period, considering only those who correctly identified the jaguar footprint image presented during the interview. Additionally, during fieldwork our team documented a confirmed jaguar roadkill within the study area, providing further direct evidence that the PAC is currently functioning as a movement route. The individual was a young female, estimated at 2-3 years old.

Reports of livestock depredation by jaguars were low: ~70% reported ≤1 event per year, and nearly 70% reported no livestock losses in the previous five years. Overall, 35 respondents (30%) reported livestock losses attributed to jaguars, totalling 236 animals over the past five years (or 536 animals if outlier is included). About 60% believed killing jaguars does not solve livestock depredation; nevertheless, jaguar killing for this purpose still occurs, albeit reportedly infrequently (~50% reported ≤1 per year) (Table S1).

Wildlife hunting was also undertaken in the region, though not universally accepted. Twenty-seven respondents (23%) stated that hunting is “acceptable” or “very acceptable.” Despite this low acceptance, 45 respondents (38%) reported hearing about hunting activities at least once per month or more, and another 39 reported (33%) hearing about hunting approximately once per year. The most frequently mentioned game species were paca (*Cuniculus paca*), wild boar, and peccaries (white-lipped and collared) (Table S1).

Neither distance to protected areas nor habitat suitability were significant predictors of the number of jaguar attacks on livestock (all $p > 0.14$, Fig. 2A-B, Table S2), indicating weak or absent relationships within the sampled range. Likewise, the frequency of depredation events was not explained by either variable (all $p > 0.20$; Fig. 2C-D; Table S2). These results suggest that livestock depredation is likely driven by additional local or socio-

ecological factors not captured in this study (e.g., livestock management, preventive measures, reporting behaviour, or local jaguar density).

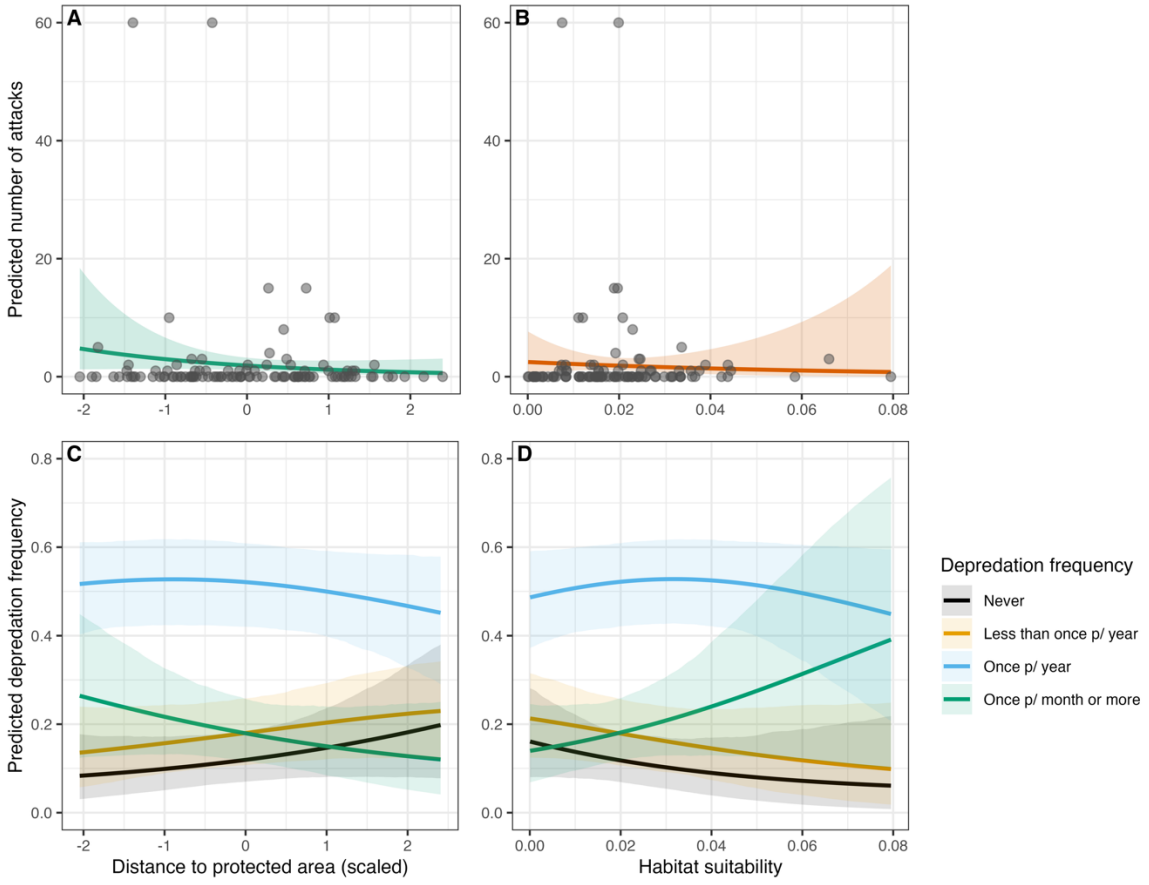


Figure 2. Predicted effects of distance to protected areas and habitat suitability on livestock depredation by jaguars. Panels A-B show predicted jaguar attacks, with grey points indicating observed values. Panels C-D show predicted probabilities for each depredation frequency category. Shaded bands represent 95% confidence intervals.

The first FAMD axis, which we used as a composite of the Conservation Attitude Index, was mainly driven by perception of natural habitat importance for climate (35.3%) and perceived importance of protected areas for the planet (34.5%), followed by concern about climate change (16.4%) and fauna protection importance (13.8%). Respondents were positive towards both, nature conservation and jaguars, but attitude was significantly more positive for

conservation than for jaguars (Wilcoxon signed-rank: V = 1025, $p < 0.0001$; rank-biserial W_c = 0.41, a medium-large effect; Fig. 3).

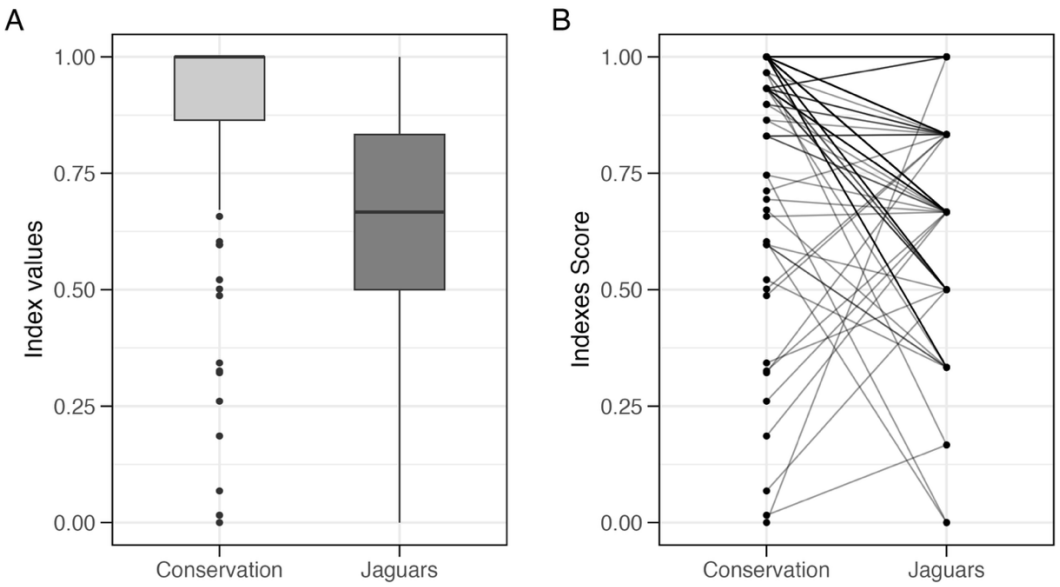


Figure 3. Comparison of conservation and jaguar attitude indices across respondents. Panel A presents boxplots summarising the distribution of scores for each index. Panel B shows paired observations, illustrating how individual scores differ between the two indices.

The only predictor that significantly affected conservation attitudes was the "perception of extreme climatic events occurrence" ($\chi^2 = 7.46$, $p = 0.024$; Table 1). Post-hoc comparisons showed that respondents who perceived no change in the frequency of extreme climatic events had significantly lower conservation attitude scores than those who perceived an increase (estimate = –0.235, SE = 0.097, $p = 0.041$; Fig. 4). No other pairwise differences among perception categories were statistically significant. All other variables (position, political leaning, religion, and age) did not significantly explain variation in conservation attitudes ($p > 0.05$; Table 1).

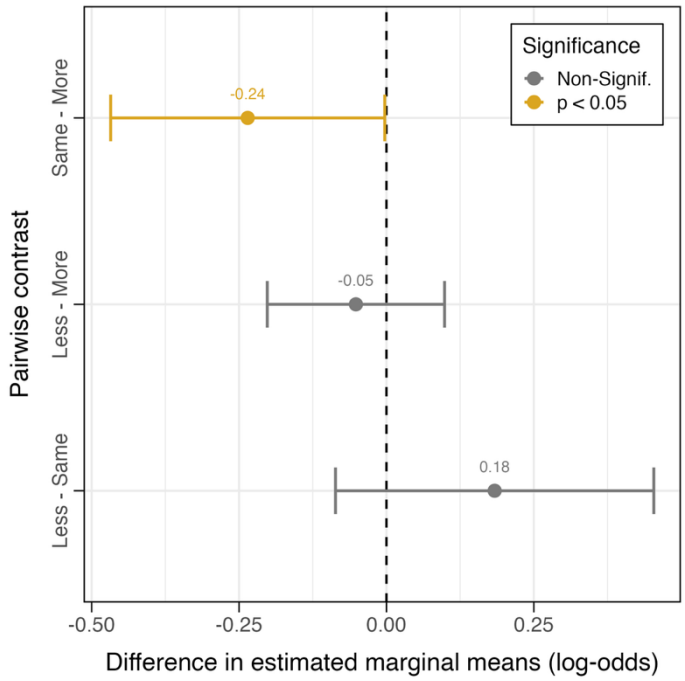


Figure 4. Pairwise contrasts among categories of perceived frequency of extreme climatic events based on estimated marginal means (log-odds). Error bars show 95% confidence intervals, and the dashed line represents no difference. Significant contrasts ($p < 0.05$) are highlighted in gold.

Perceptions of environmental legislation varied considerably. A minority (14.5%) stated that APPs were larger than necessary, while almost half (48.7%) considered APP size adequate and a third (33.3%) believed they were too small (Table S3). However, perceptions of APP size differed significantly among occupational groups ($\chi^2 = 12.85$, $p = 0.0105$). Owners were significantly more likely to report that APPs are "larger than they should be" compared to employees (pairwise proportion test with Holm correction, $p = 0.02$). No significant differences were found between owners and managers ($p = 0.66$) or between managers and employees ($p = 0.14$). Similarly, political orientation was significantly associated with perceptions of APP size ($\chi^2 = 20.86$, $p = 0.0003$). Pairwise comparisons revealed that right-leaning respondents were more likely to state that APPs are "larger than

they should be" compared to respondents with no political orientation (Holm-adjusted p = 0.008). No other pairwise differences were statistically significant.

Political orientation was the only significant predictor of attitudes toward jaguars (χ^2 = 6.73, p = 0.035; Table 1). Post-hoc comparisons indicated that respondents identifying as left-wing expressed significantly more positive attitudes toward jaguars than those reporting no political position (estimate = 1.62 log-odds, p = 0.044; Fig. 5). Left-wing respondents also tended to be more positive toward jaguars than right-wing respondents, although this contrast was only marginally significant (estimate = 1.55, p = 0.058; Fig. 5). No detectable difference was found between right-wing and politically neutral respondents. All remaining predictors were non-significant (p > 0.05; Table 1).

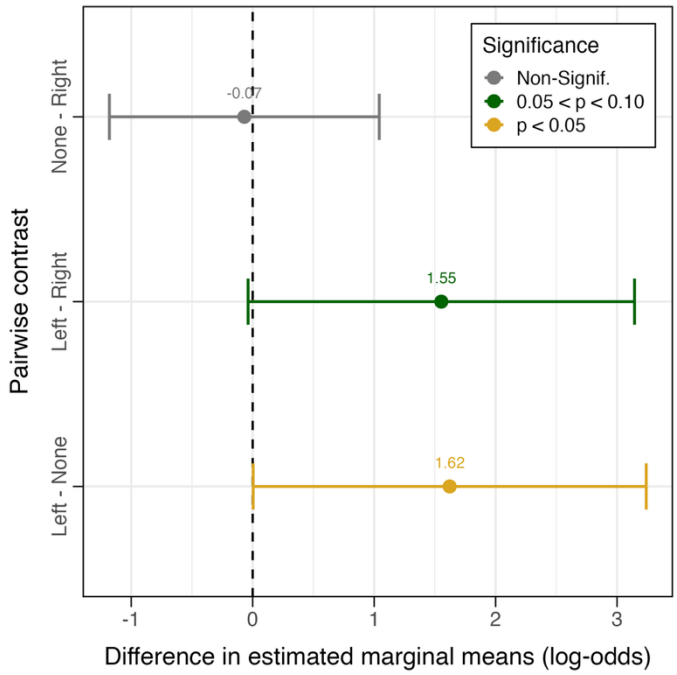


Figure 5. Pairwise contrasts among political orientation categories based on estimated marginal means (log-odds). Error bars show 95% confidence intervals, and the dashed line represents no difference. Significant contrasts (p < 0.05) are highlighted in gold.

Table 1. Summary of model results testing predictors of the Conservation Attitude Index (CAI) and Jaguar Attitude Index (JAI). Results are from Type II Wald χ^2 tests. Statistically significant effects ($p < 0.05$) are shown with an asterisk.

Response variable	Predictor	χ^2	df	p-value
Conservation Attitude Index (CAI)	Perception of extreme climatic events occurrence	7.46	2	0.024*
	Worker position	0.3	2	0.860
	Political orientation	0.27	2	0.873
	Religion	0.51	2	0.774
	Age	0.08	1	0.772
Jaguar Attitude Index (JAI)	Perception of jaguar abundance	3.94	2	0.140
	Jaguar dangerousness perception	5.02	5	0.413
	Perception of protecting livestock from jaguars	0.55	3	0.907
	Recent livestock attacks (5 yrs)	0.81	1	0.368
	Political orientation	6.73	2	0.035*
	Religion	0.38	2	0.827
	Age	0.02	1	0.895

* *p-value* < 0.05

Discussion

This study provides the first assessment of human attitudes across the Pantanal-Amazon Corridor (PAC), a region with strong potential to maintain functional connectivity between Brazil's two largest jaguar populations – the Pantanal and the Amazon (Quigley et al., 2017). Overall, respondents expressed favourable views toward both nature conservation

and jaguars, although support for general conservation issues was consistently stronger than support for the species itself. This is consistent with the finding of a similar study 20 years earlier in the northern Pantanal by Zimmermann et al. (2005). Attitudes toward jaguars were primarily shaped by political orientation: left-leaning respondents were more positive than others. In contrast, conservation attitudes were explained solely by respondents' perceptions of extreme climatic events, with those perceiving an increase in event frequency showing markedly stronger pro-conservation views. Understanding these social dynamics is essential for corridor planning, as they help identify where conservation strategies are more likely to succeed and where additional engagement may be required.

Our models did not detect any direct association between livestock depredation and the landscape variables tested, contradicting our expectation that farms surrounded by highly suitable jaguar habitat or located closer to protected areas would experience more attacks. Several non-exclusive explanations may account for this pattern, including limitations in sample size, potential scale mismatches between the study area and the habitat-suitability surface, low jaguar abundance in nearby protected areas, and local contextual factors not captured in our analysis, such as livestock husbandry practices at the time of the reported attacks. Additionally, reported depredation levels may be influenced by respondent memory or by the social sensitivity of reporting events involving jaguars, especially retaliatory killing, which could lead to under- or overestimation of true patterns. Below, we explore each of these possibilities in turn.

Depredation levels in the region appear to be generally low. Most interviewees reported no livestock losses to jaguars in the past five years (N = 62), and when asked about frequency of incidents among neighbours, 13 respondents said they had never heard of an attack, while 65 reported hearing about such events once a year or less. Consequently, both response variables – number of animals lost and attack frequency – showed limited variation,

which constrained our ability to detect meaningful patterns (Zuur et al., 2009). We will continue monitoring depredation in collaboration with local farmers and expand the sampling area to include additional properties across the corridor, as a larger dataset may help clarify the factors that drive depredation risk. It is important to mention, though, that the absence of detected relationships does not diminish the value of the information collected: even at low levels, confirmed incidents across the PAC indicate that jaguars are moving through the corridor – precisely the ecological function that corridors initiatives are intended to promote. At the same time, these attacks are understandably undesirable for farmers, and maintaining close engagement with them will be essential to ensure that they receive appropriate support to prevent or reduce losses.

The spatial covariates we tested – habitat suitability and proximity to protected areas – are both reasonable candidates for predicting livestock depredation. The habitat suitability surface was developed using an extensive and diverse dataset (N = 172 GPS-collared jaguars across eight countries), with validation metrics indicating high predictive performance (AUC = 0.88; Boyce Index = 0.91; Alvarenga et al. 2025a). As it is common practice in species distribution modelling, this surface integrates multiple key landscape features to identify areas most suitable for jaguars. However, this model was produced at a continental scale, covering the species' historical range (~19 million km²), which is orders of magnitude larger than our study area (~10,000 km²). Large-scale models are generally most effective at capturing broad spatial patterns, such as across biomes or countries, and this pronounced scale mismatch may limit their ability to predict highly localised ecological processes such as depredation (Fletcher and Fortin, 2018).

Regarding the protected areas, our survey grid is adjacent to only four units, and although jaguar presence is confirmed for at least two of them (ESEC Serra das Araras and IL Umutina; personal communication), no data exist on local abundance. If jaguar densities in

these areas are low and prey availability is sufficient, individuals may have little incentive to enter surrounding farms (Weckel et al., 2006; Zanin et al., 2015), reducing the likelihood of detectable spatial patterns in attacks. Future research should prioritise assessing jaguar density within these protected areas and, when possible, developing fine-resolution occupancy models tailored to local conditions, as such modes are better to capture the fine-scale dynamics that influence human-jaguar interactions in the PAC. In addition, incorporating farmer-reported attack locations and farm-level management variables would greatly strengthen future models, as depredation risk often emerges from fine-scale interactions between jaguar behaviour and livestock vulnerability, which are not captured in coarse-scale predictors.

Other local factors inherent to farm structure and livestock management are also likely to influence depredation risk. For instance, we were unable to record the exact location of each attack or how the landscape may have changed since the incident. Many farms periodically relocate their Legal Reserves, which alters both the amount and configuration of natural habitat available to jaguars. Additional structural features, such as the proximity of houses to the attack site or the presence and distribution of electric fences, could also provide valuable insights. However, gathering this level of detail would require a different, case-by-case interview approach, whereas our study aimed to capture broader patterns across the PAC. In addition, because we asked respondents to recall events from the past five years, collecting highly specific information would have introduced considerable recall bias, as such details are difficult to remember accurately. This limitation similarly applies to factors such as the presence of calves at the time of the attack or specific management practices at the period of the event. Nevertheless, we do not expect livestock management practices to play a major role in explaining the attacks' patterns given that the vast majority of respondents reported that cattle are currently left unattended in pastures day and night (N = 92), with no

guarding dogs (N = 102) or electric fences (N = 102), and we found no evidence of recent changes in these practices.

Partially supporting our second hypothesis, respondents expressed more positive attitudes toward general aspects of nature conservation than toward jaguars specifically. Nevertheless, contrary to our expectations, attitudes toward jaguars were also predominantly positive – a welcome and encouraging finding. Jaguars as other large felids are widely seen as charismatic species (Macdonald et al., 2015); however, this perception tends to find more advocates in large urban centres than in rural areas, where interactions are often problematic (Kellert et al., 1996). In our study area, jaguars were reported to be responsible for 536 livestock losses across 46 farms over the past five years, including the outlier and assuming incidents were correctly attributed. If evenly distributed, this would correspond to an average of at least two losses per farm per year. While such losses may be relatively negligible for large estates – which often account for this kind of prejudice (personal communication) – they can represent a substantial burden for smallholders with limited herds. Consistent with this, nearly half of respondents (44%) reported that protecting livestock from jaguar attacks was “hard” or “very hard,” and half (50%) ranked jaguars as the most or second most dangerous wild species to livestock. Despite these challenges, attitudes toward jaguars remained largely positive, suggesting that these perceptions may be linked to a sense of local pride or cultural value associated with the species – consistent with the findings from Pantanal in 2005 (Zimmermann et al., 2005). Similar patterns have been reported before for jaguars (Caruso and Jiménez Pérez, 2013; Porfirio et al., 2016) and other large carnivores (Ebrahimi Monfared et al., 2025). In our case, this pattern might be influenced by the strong economic value attributed to jaguar-based ecotourism in nearby regions (Tortato et al., 2017), even though such tourism activities do not occur directly within the study area. Overall, these findings indicate that positive attitudes toward jaguars can persist even in landscapes where

real economic costs exist, highlighting an important social foundation for promoting long-term human-jaguar coexistence.

When assessing JAI directly, we found that political orientation influenced respondents' scores, with left-leaning individuals expressing more positive attitudes toward jaguars than respondents reporting no political preference, and a similar but only marginally significant trend when compared to right-leaning individuals. These results provide only partial support for our third hypothesis. While left-leaning respondents tended to be more positive, we found no evidence of negative attitudes among right-leaning respondents, nor among those with a history of jaguar depredation. In addition, we were unable to test the effect of income dependency on livestock, which may represent an important unmeasured factor. Similar political patterns have been reported in the United States, where left-leaning respondents held more positive attitudes toward wildlife conservation (Czech and Borkhataria, 2001) and towards grey wolves (*Canis lupus*) specifically (van Eeden et al., 2021). Left-leaning individuals have been associated with stronger values related to solidarity and fairness, including toward non-human species, whereas right-leaning individuals tend to place greater emphasis on individualism and economic growth (Czech and Borkhataria, 2001), which may partially explain our findings. In our case, this tendency toward individualism among right-leaning respondents did not translate into hostility toward jaguars – an important aspect considering their numerical dominance in the region (TSE, 2022). Taken together, our findings suggest that political orientation may influence the social acceptance of jaguars and, consequently, the stability of the PAC as a functional dispersal route. In this context, increasing political polarization in Brazil and the growing visibility of anti-environmental discourse (Mendes Motta and Hauber, 2023) may represent emerging risks for long-term coexistence dynamics in the region and therefore warrant closer monitoring. Such political shifts may become particularly consequential in areas where

habitat suitability is already fragmented, as intolerance or reduced support for conservation could convert these zones into social bottlenecks that hinder jaguar movement.

This broader anti-environmental discourse is also concerning when considering attitudes toward nature conservation more generally. For instance, the CAI was primarily driven by perceptions of the occurrence of extreme climatic events, with respondents who did not perceive changes in the frequency of such events exhibiting lower conservation attitude scores than those who perceived an increase. Climate change is one of the principal targets of anti-environmental narratives globally (Jacques and Dunlap, 2025), and similar patterns have been documented in Brazil (Mendes Motta and Hauber, 2023). In the country, these narratives are often associated with processes that may undermine biodiversity conservation, including attempts to weaken environmental legislation – frequently justified as necessary for agricultural development and the expansion of agribusiness frontiers – which in turn are likely to lead to rising deforestation rates (Ferrante and Fearnside, 2019). Such legal and normative shifts could have profound implications for corridor functionality, given that its long-term effectiveness depends on the persistence of natural habitats maintained within Legal Reserves and APPs on private lands. Since these two types of protected areas form the structural backbone of the corridor, erosion of support for them could directly jeopardize its ecological continuity.

Currently, farmers in the study area demonstrated generally positive attitudes toward nature conservation; maintaining these attitudes will likely be critical for ensuring the long-term integrity of the corridor. The CAI was derived from the combination of four covariates and the two that most represent the index are perception of natural habitat importance for climate (35.3%) and protected area importance for the planet (34.5%). Positive attitudes towards these two topics are key for the maintenance of the landscape structure in the corridor. However, these patterns hide underlying tensions. Right-leaning respondents were

more likely to perceive APPs as exceeding appropriate size limits, as were farm owners. This apparent contradiction is commonly reported in conservation social science, where individuals often support conservation in principle but express resistance when measures directly affect private land use or economic activities (e.g., Ma et al., 2024). Negative perceptions of APPs may reflect broader political and institutional dynamics in the country. For example, a recent legislative initiative (Complementary Bill n° 18/2024), supported by agribusiness interests, sought to reduce the extent of native vegetation required on private properties in Mato Grosso (G1, 2025). Similarly, national debates around the "Marco Temporal" framework have aimed to constrain the recognition of Indigenous Lands, reflecting wider pressures on environmental governance (Lima et al., 2024). Together, these dynamics highlight the potential fragility of current pro-conservation attitudes and underscore the need for institutional stability to maintain functional connectivity in the corridor. From a management perspective, strengthening institutional trust and ensuring transparent governance may be as essential as ecological interventions for guaranteeing the long-term viability of the PAC.

Conclusion

This study provides the first on-the-ground assessment of one of the newly proposed jaguar corridors (Alvarenga et al., *in review*), shedding light on the key social and cultural factors that shape human–jaguar interactions across the PAC. Most importantly, we found strong evidence that the PAC is indeed functioning as an active corridor: jaguar presence was reported in multiple interviews, and our team witnessing an unfortunate event of a jaguar roadkill within the study area.

Local attitudes toward jaguars and conservation were generally positive, which is an encouraging finding. However, several contradictions point to ongoing challenges. Livestock

depredation and retaliatory killing do occur, and wildlife hunting remains widespread and socially accepted. This could reduce prey availability and indirectly increase conflict with jaguars. In addition, local dissatisfaction with APP boundaries and the broader political instability in Brazil are factors that may affect conservation outcomes. In addition, the jaguar roadkill recorded during fieldwork underscores an additional emerging threat: increasing mortality from expanding road networks. Such events highlight the need for mitigation measures (e.g., signage, wildlife crossings) to ensure that dispersing individuals can safely traverse the corridor.

Despite these concerns, the overall scenario remains favourable, and most landowners expressed willingness to collaborate with our research. This study forms part of a long-term initiative, and we aim to continue strengthening relationships with locals to ensure that the PAC remains a safe route for jaguars while also safeguarding farmers' livelihoods.

Acknowledgments

We are grateful to all residents of the PAC for their participation and support. GCA was supported by the Wildlife Conservation Network (WCN), Panthera, Berlin World Wild, and Lady Margaret Hall (LMH). ZK was supported by a grant to David Macdonald at WildCRU from the Robertson Foundation. SAC was supported by a grant to David Macdonald from the Dennis Curry Trust and by a NASA project (grant no. 80NSSC25K7244). FPA's master's scholarship is funded by the Brazilian Government Agency for the Coordination of Improvement of Higher Education Personnel (CAPES, Code: 88887.003877/2024-00).

References

Alvarenga, G.C., Sartor, C.C., Cushman, S.A., Zimmermann, A., Srbek-Araujo, A.C., Mendes-Oliveira, A.C., Harmsen, B., Angelo, C. De, Esteves, C.F., Campos, C.B. De, Polli, D.J., Viana, D.F.P., Gräbin, D.M., Donadio, E., Ramalho, E.E., Payán, E., Azevedo, F.C.C., Palomares, F., Powell, G.V.N., Ceballos, G., Porfirio, G., Zarza, H., Cassaigne, I., Bogoni, J.A., Sena, L., Maranhão, L., Brito, M.R.M. De, Tobler, M.W., Wiig, Ø., Foster, R.J., Sampaio, R., Nuñez, R., Morato, R.G., Boron, V., Moreno, W.H.A., Malhi, Y., Macdonald, D.W., Kaszta, Ż., 2026. Range-wide assessment of habitat suitability for jaguars using multiscale species distribution modelling. Sci Rep 16, 759. https://doi.org/10.1038/s41598-025-30512-5 2

Alvarenga, G.C., Tobler, M.W., Boron, V., de Carvalho, E.A.R., Morato, R.G., Endo, W., Mendonça, E.N., Sampaio, R., Durigan, C.C., Gonçalves, A.L.S., Ramalho, E.E., Pezzuti, J.C.B., de Paula, M.J., Antunes, A.P., Mena, J.L., Dupont, G., Spironello, W., Pacheco, J., La Rosa-Camino, F., Cabrera, J., Montanarin, A., da Costa, M.O., 2025. Jaguar (*Panthera onca*) density and population size across protected areas and indigenous lands in the Amazon biome, its largest stronghold. Biol Conserv 303, 111010. https://doi.org/10.1016/j.biocon.2025.111010

Alvarenga, G. C., Sartor, C.C., Kaszta, Ż., Srbek-Araujo, A.C., Mendes-Oliveira, A.C., Harmsen, B., Angelo, C. De, Esteves, C.F., Campos, C.B. De, Polli, D.J., Viana, D.F.P., Gräbin, D.M., Donadio, E., Ramalho, E.E., Payán, E., Azevedo, F.C.C., Palomares, F., Powell, G.V.N., Ceballos, G., Porfirio, G., Zarza, H., Cassaigne, I., Bogoni, J.A., Sena, L., Maranhão, L., Brito, M.R.M. De, Tobler, M.W., Wiig, Ø., Antelo, R., Foster, R.J., Sampaio, R., Naidoo, R., Nuñez, R., Morato, R.G., Mendoza, S. P., Boron, V., Moreno, W.H.A., Macdonald, D.W., Cushman, S.A., *in review*. Jaguar range-wide connectivity:

Prioritizing core areas and corridors between protected areas and Indigenous Lands. Global Change Biology.

Brooks, M., Kristensen, K., van Benthem, K., Magnusson, A., Berg, C., Nielsen, A., Skaug, H., Maechler, M., Bolker, B., 2017. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. R J 9, 378–400. https://doi.org/10.32614/RJ-2017-066

Campos Neto, M.F., Garrone Neto, D., Haddad, V., 2011. Attacks by jaguars (*Panthera onca*) on humans in central Brazil: Report of three cases, with observation of a death. Wilderness Environ Med 22, 130–135. https://doi.org/10.1016/j.wem.2011.01.007

Caruso, F., Jiménez Pérez, I., 2013. Tourism, local pride, and attitudes towards the reintroduction of a large predator, the jaguar *Panthera onca* in Corrientes, Argentina. Endanger Species Res 21, 263–272. https://doi.org/10.3354/esr00519

Cavalcanti, S.C., Marchini, S., Zimmermann, A., Gese, E.M., Macdonald, D.W., 2010. Jaguars, Livestock, and People in Brazil: Realities and Perceptions Behind the Conflict, in: Macdonald, D., Loveridge, A. (Eds.), The Biology and Conservation of Wild Felids. Oxford University Press, Oxford, United Kingdom, pp. 383–402.

Ceballos, G., Ehrlich, P.R., 2002. Mammal population losses and the extinction crisis. Science (1979) 296, 904–907. https://doi.org/10.1126/science.1069349

Cialdini, R.B., Reno, R.R., Kallgren, C.A., 1990. A Focus Theory of Normative Conduct: Recycling the Concept of Norms to Reduce Littering in Public Places. J Pers Soc Psychol 58, 1015–1026. https://doi.org/10.1037/0022-3514.58.6.1015

Cribari-Neto, F., Zeileis, A., 2010. Beta Regression in R. J Stat Softw 34, 1–24. https://doi.org/10.18637/jss.v034.i02

Czech, B., Borkhataria, R., 2001. The relationship of political party affiliation to wildlife conservation attitudes. Politics and the Life Sciences 20, 3–12.

Ebrahimi Monfared, Z., Mirkarimi, S.H., Kangarani, H.M., Soofi, M., 2025. Emotions and perceptions predict local communities' attitudes toward the conservation of large carnivores. Conserv Sci Pract e70176. https://doi.org/10.1111/csp2.70176

Ericsson, G., Heberlein, T.A., 2003. Attitudes of hunters, locals, and the general public in Sweden now that the wolves are back. Biol Conserv 111, 149–159. https://doi.org/10.1016/S0006-3207(02)00258-6

Ferrante, L., Fearnside, P.M., 2019. Brazil's new president and "ruralists" threaten Amazonia's environment, traditional peoples and the global climate. Environ Conserv 46, 261–263. https://doi.org/10.1017/S0376892919000213

Figel, J.J., Botero-Cañola, S., Lavariega, M.C., Luna-Krauletz, M.D., 2022. Overlooked jaguar guardians: Indigenous territories and range-wide conservation of a cultural icon. Ambio. https://doi.org/10.1007/s13280-022-01754-8

Fletcher, R., Fortin, M.-J., 2018. Spatial Ecology and Conservation Modeling, Spatial Ecology and Conservation Modeling. Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-01989-1

Fox, J., Weisberg, S., 2019. An R Companion to Applied Regression, Third edit. ed. Sage, Thousand Oaks CA.

G1, 2025. Governo de Mato Grosso veta projeto que previa reclassificação de áreas da Amazônia e Cerrado [WWW Document]. Globo. URL https://g1.globo.com/mt/mato-grosso/noticia/2025/01/21/governo-de-mt-veta-projeto-que-previa-reclassificacao-de-areas-da-amazonia-e-cerrado.ghtml (accessed 12.10.25).

Hartig, F., 2025. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models.

Hess, G.R., Fischer, R.A., 2001. Communicating clearly about conservation corridors. Landsc Urban Plan 55, 195–208. https://doi.org/10.1016/S0169-2046(01)00155-4

IBGE, 2023a. Produto Interno Bruto dos Municípios 2021, Contas Nacionais n. 96. Rio de Janeiro, Brazil.

IBGE, 2023b. Censo Brasileiro de 2022. Rio de Janeiro, Brazil.

Jacques, P.J., Dunlap, R.E., 2025. Foundations of climate change denial: Anti-environmentalism and anti-science. PLoS One 20, e0334544. https://doi.org/10.1371/journal.pone.0334544

Jędrzejewski, W., Carreño, R., Sánchez-Mercado, A., Schmidt, K., Abarca, M., Robinson, H.S., Boede, E.O., Hoogesteijn, R., Viloria, Á.L., Cerda, H., Velásquez, G., Zambrano-Martínez, S., 2017. Human-jaguar conflicts and the relative importance of retaliatory killing and hunting for jaguar (*Panthera onca*) populations in Venezuela. Biol Conserv 209, 524–532. https://doi.org/10.1016/j.biocon.2017.03.025

Kellert, S.R., Black, M., Rush, C.R., Bath, A.J., 1996. Human Culture and Large Carnivore Conservation in North America. Conservation Biology 10, 977–990. https://doi.org/10.1046/j.1523-1739.1996.10040977.x

Knox, J., Negrões, N., Marchini, S., Barboza, K., Guanacoma, G., Balhau, P., Tobler, M.W., Glikman, J.A., 2019. Jaguar Persecution Without "Cowflict": Insights From Protected Territories in the Bolivian Amazon. Front Ecol Evol 7. https://doi.org/10.3389/fevo.2019.00494

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: A Package for Multivariate Analysis. J Stat Softw 25, 1–18. https://doi.org/10.18637/jss.v025.i01

Lenth, R., Piaskowski, J., 2025. emmeans: Estimated Marginal Means, aka Least-Squares Means.

Lima, D.J., Silva, P., De Marco Júnior, P., 2024. Evaluating the ecological and climate contributions of indigenous lands under the Marco Temporal law in Brazil. Biol Conserv 297, 110739. https://doi.org/10.1016/j.biocon.2024.110739

Ma, L., Wu, J., Zhang, H., Lobora, A., Hou, Y., Wen, Y., 2024. Conflict Governance between Protected Areas and Surrounding Communities: Willingness and Behaviors of Communities—Empirical Evidence from Tanzania. Diversity (Basel) 16, 278. https://doi.org/10.3390/d16050278

Macdonald, E.A., Burnham, D., Hinks, A.E., Dickman, A.J., Malhi, Y., Macdonald, D.W., 2015. Conservation inequality and the charismatic cat: Felis felicis. Glob Ecol Conserv 3, 851–866. https://doi.org/10.1016/j.gecco.2015.04.006

Marchini, S., Macdonald, D.W., 2012. Predicting ranchers' intention to kill jaguars: Case studies in Amazonia and Pantanal. Biol Conserv 147, 213–221. https://doi.org/10.1016/j.biocon.2012.01.002

Mendes Motta, F., Hauber, G., 2023. Anti-environmentalism and proto-authoritarian populism in Brazil: Bolsonaro and the defence of global agri-business. Env Polit 32, 642–662. https://doi.org/10.1080/09644016.2022.2123993

Meyer, D., Zeileis, A., Hornik, K., Friendly, M., 2024. vcd: Visualizing Categorical Data.

Morcatty, T.Q., Bausch Macedo, J.C., Nekaris, K.A.I., Ni, Q., Durigan, C.C., Svensson, M.S., Nijman, V., 2020. Illegal trade in wild cats and its link to Chinese-led development in Central and South America. Conservation Biology 34, 1525–1535. https://doi.org/10.1111/cobi.13498

Navarro, D., 2015. Learning statistics with R: A tutorial for psychology students and other beginners (Version 0.6).

Ogle, D.H., Doll, J.C., Wheeler, A.P., Dinno, A., 2025. FSA: Simple Fisheries Stock Assessment Methods. https://doi.org/10.32614/CRAN.package.FSA

Oxford U.P., 2025. Attitude, n. [WWW Document]. Oxford English Dictionary. https://doi.org/10.1093/OED/3854324107

Palmeira, F.B.L., Crawshaw, P.G., Haddad, C.M., Ferraz, K.M.P.M.B., Verdade, L.M., 2008. Cattle depredation by puma (*Puma concolor*) and jaguar (*Panthera onca*) in central-western Brazil. Biol Conserv 141, 118–125. https://doi.org/10.1016/j.biocon.2007.09.015

Petracca, L.S., Ramírez-Bravo, O.E., Hernández-Santín, L., 2014. Occupancy estimation of jaguar *Panthera onca* to assess the value of east-central Mexico as a jaguar corridor. Oryx 48, 133–140. https://doi.org/10.1017/S0030605313000069

Pinto-Marroquin, M., Castaño-Uribe, C., Pérez-Torres, J., F. Aristizabal, J., Santos-Fita, D., Ramos Chaparro, A.B., Serio-Silva, J.C., 2022. Potential conflict as an opportunity for coexistence: cosmovision and attitudes of Arhuaco people towards jaguars. Ethnobiology and Conservation 11, 1–27. https://doi.org/10.15451/ec2022-11-11.21-1-27

Porfirio, G., Sarmento, P., Leal, S., Fonseca, C., 2016. How is the jaguar *Panthera onca* perceived by local communities along the Paraguai River in the Brazilian Pantanal? Oryx 50, 163–168. https://doi.org/10.1017/S0030605314000349

Quigley, H., Foster, R., Petracca, L., Payan, E., Salom, R., Harmsen, B., 2017. *Panthera onca* [WWW Document]. The IUCN Red List of Threatened Species 2017.

R Core Team, 2018. R: a language and environment for statistical computing.

Revelle, W., 2025. psych: Procedures for Psychological, Psychometric, and Personality Research.

Sage, A.H., Hillis, V., Graves, R.A., Burnham, M., Carter, N.H., 2022. Paths of coexistence: Spatially predicting acceptance of grizzly bears along key movement corridors. Biol Conserv 266, 109468. https://doi.org/10.1016/j.biocon.2022.109468

Seymour, K.L., 1989. *Panthera onca*. Mammalian Species 340, 1–9.

Soterroni, A.C., Mosnier, A., Carvalho, A.X.Y., Câmara, G., Obersteiner, M., Andrade, P.R., Souza, R.C., Brock, R., Pirker, J., Kraxner, F., Havlík, P., Kapos, V., Ermgassen,

E.K.H.J. zu, Valin, H., Ramos, F.M., 2018. Future environmental and agricultural impacts of Brazil's Forest Code. Environmental Research Letters 13, 074021.

Titus, K.L., Jachowski, D.S., 2025. Mapping human-carnivore coexistence: approaches to integrating anthropogenic influences on carnivore distribution and connectivity modelling. Anim Conserv 28, 185–196. https://doi.org/10.1111/acv.12966

Tortato, F.R., Izzo, T.J., Hoogesteijn, R., Peres, C.A., 2017. The numbers of the beast: Valuation of jaguar (*Panthera onca*) tourism and cattle depredation in the Brazilian Pantanal. Glob Ecol Conserv 11, 106–114. https://doi.org/10.1016/j.gecco.2017.05.003

TSE, T.S.E., 2022. Resultados – 2022 [Dataset] [WWW Document]. Portal de Dados Abertos TSE. URL https://dadosabertos.tse.jus.br/dataset/resultados-2022 (accessed 12.9.25).

UNEP-WCMC, IUCN, 2022. Protected Planet: The World Database on Protected Areas (WDPA) [WWW Document]. Cambridge, UK: UNEP-WCMC and IUCN. URL www.protectedplanet.net. (accessed 1.9.22).

Valsecchi, J., Monteiro, M.C.M., Alvarenga, G.C., Lemos, L.P., Ramalho, E.E., 2022. Community-based monitoring of wild felid hunting in Central Amazonia. Anim Conserv 1967, 1–10. https://doi.org/10.1111/acv.12811

van Eeden, L.M., S. Rabotyagov, S., Kather, M., Bogezi, C., Wirsing, A.J., Marzluff, J., 2021. Political affiliation predicts public attitudes toward gray wolf (*Canis lupus*) conservation and management. Conserv Sci Pract 3, e387. https://doi.org/10.1111/csp2.387

Venables, W., Ripley, B., 2002. Modern Applied Statistics with S, Fourth. ed. Springer, New York, USA.

von Essen, E., Allen, M., 2017. A reluctant right-wing social movement: On the 'good sense' of Swedish hunters. J Rural Stud 50, 139–147. https://doi.org/10.1016/j.jrurstud.2017.01.007

Weckel, M., Giuliano, W., Silver, S., 2006. Jaguar (*Panthera onca*) feeding ecology: Distribution of predator and prey through time and space. J Zool 270, 25–30. https://doi.org/10.1111/j.1469-7998.2006.00106.x

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Zanin, M., Sollmann, R., Tôrres, N.M., Furtado, M.M., Jácomo, A.T.A., Silveira, L., De Marco, P., 2015. Landscapes attributes and their consequences on jaguar *Panthera onca* and cattle depredation occurrence. Eur J Wildl Res 61, 529–537. https://doi.org/10.1007/s10344-015-0924-6

Zimmermann, A., Johnson, P., de Barros, A.E., Inskip, C., Amit, R., Soto, E.C., Lopez-Gonzalez, C.A., Sillero-Zubiri, C., de Paula, R., Marchini, S., Soto-Shoender, J., Perovic, P.G., Earle, S., Quiroga-Pacheco, C.J., Macdonald, D.W., 2021. Every case is different: Cautionary insights about generalisations in human-wildlife conflict from a range-wide study of people and jaguars. Biol Conserv 260, 109185. https://doi.org/10.1016/j.biocon.2021.109185

Zimmermann, A., Walpole, M.J., Leader-Williams, N., 2005. Cattle ranchers' attitudes to conflicts with jaguar Panthera onca in the Pantanal of Brazil. Oryx 39, 406–412.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer, New York. https://doi.org/10.1007/978-0-387-87458-6

Author Contributions

Guilherme Costa Alvarenga: Conceptualization, Investigation, Data curation, Methodology, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing, Project administration. **Silvio Marchini:** Conceptualization, Methodology, Writing – review & editing. **David W. Macdonald:** Writing – review & editing. **Diogo M. Gräbin:** Investigation, Writing – review & editing. **Fernanda da Paixão Alves:** Investigation, Writing – review & editing. **Fernando Tortato:** Resources, Writing – review & editing, Project administration. **Rodrigo Lima Massara:** Writing – review & editing. **Ronaldo G. Morato:** Resources, Writing – review & editing. **Samuel A. Cushman:** Writing – review & editing. **Żaneta Kaszta:** Writing – review & editing. **Alexandra Zimmermann:** Writing – review & editing. **Darragh Hare:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

Supplementary Material

Tables

Table S1. Summary of respondent characteristics, property attributes, and reported experiences and perceptions related to jaguars and wildlife use within the jaguar Pantanal-Amazon Corridor. Values are reported as percentages or counts unless otherwise indicated. Property size is reported in hectares (ha). Jaguar presence and depredation metrics are based on self-reported information from interviews, with footprint records considering only respondents who correctly identified the jaguar footprint image presented during the interview.

Sections	Category	Variable	Summary
Respondent characteristics	Demographics	Number of respondents	117
		Gender	91% men / 9% women
		Mean age (years)	48
	Socioeconomic role	Employees	37%
		Managers	25%
		Owners	38%
	Education	None	9%
		Primary - Elementary school	44%
		Secondary - High school	33%
		College or University	12%
	Religion	Catholic	57%
		Evangelical	27%
		Espirita	2%
	Political orientation	Right-leaning	47%
		No declared orientation	36%
		Left-leaning	13%
Property characteristics	Property size	Mean (ha)	1571.5
	Corral use at night	Never	79%
		Some few times	8%
	Pasture reinforcement	None	87%
		Electric fence	1%
	Guarding dogs	Never	87%
Jaguar presence and evidence	Sightings	Direct sighting	7%
	Tracks	Footprints (N = 67*)	40%
	Roadkill	Confirmed jaguar roadkill	1 (female, 2–3 yrs)

Livestock depredation	Depredation frequency	Never	12%
		≤1 event/year	68%
		1 event/month or more	18%
	Livestock losses (last 5 years)	No losses	67%
		Respondents reporting losses	30%
		Total animals lost	236
		Total including outlier	536
	Opinion of killing jaguar as a solution for attacks	Doesn't work	56%
		It works a little bit	30%
		Best solution	5%
	Jaguar killing for cattle protection	Never	39%
		≤1 event/year	50%
		1 event/month or more	4%
Wildlife hunting	Hunting attitudes	Inacceptable	63%
		Neutral	7%
		Acceptable	23%
	Hunting frequency	Never	13%
		≤1 event/year	44%
		1 event/month or more	33%
	Game species	Most cited	Paca, wild boar, peccaries

* Only 67 respondents correctly identified the jaguar footprint presented to them during the interview

Table S2. Results of regression models assessing the effects of distance to protected areas and jaguar habitat suitability on livestock depredation metrics. Values represent the number of respondents in each category. Perceptions of APP size refer to whether respondents considered APPs to be larger than necessary, adequate, or smaller than necessary.

Response Variable	Predictor	Model	Estimate	Std. Error	Test Type	Test Value	p-value
Depredation count (5 yrs)	Distance to Protected Area	Negative binomial	−0.454	0.312	Wald (z)	−1.46	0.146
Depredation count (5 yrs)	Jaguar habitat suitability	Negative binomial	−14.31	26.38	Wald (z)	−0.54	0.588
Depredation frequency (ordinal)	Distance to Protected Area	Ordinal regression	−0.225	0.19	Likelihood ratio test	$\chi^2 = 1.42$	0.234
Depredation frequency (ordinal)	Jaguar habitat suitability	Ordinal regression	17.49	13.67	Likelihood ratio test	$\chi^2 = 1.63$	0.202

p-values for the ordinal regression model are based on Type II likelihood ratio tests (car::Anova), as the polr model does not provide reliable coefficient-level significance testing.

Table S3. Respondent perceptions of APP size by worker position and political orientation. Values are counts of respondents.

Perception on APP size	Worker position			Political orientation		
	Employee	Manager	Owner	Left-leaning	Apolitical	Right-leaning
Larger	1	5	11	1	1	15
Adequate	21	16	20	3	23	28
Smaller	21	8	10	10	15	12

Questionnaire

SECTION 1 – Attitudes towards conservation and jaguars

Introduction: In this section we're going to ask you some questions about conservation in general. For instance, we will go through topics such as climate change, habitat protection, and wildlife hunting. During the process we will use the expression "in this area" and by that, we mean yours and the neighbouring farms.

The overall goal of this section is to understand how residents in the region feel toward conservation actions.

I. Attitude towards conservation

I.I. How important or unimportant are conservation units? *very important / important / neither important nor unimportant / unimportant / very unimportant / I don't know*

I.II. What do you think about the minimum size imposed by the government for Permanent Protected Areas (APPs in Portuguese)? *far too small / too small / about right / too large / far too large / I don't know*

I.III. How important or unimportant are the patches of natural habitat, such as Conservation Units and APPs, for a healthy climate? *very important / important / neither important nor unimportant / unimportant / very unimportant / I don't know*

I.IV. On a scale from 1-10, how worried or not should Brazilians be with climate change? Being 1 not worried at all and 10 being extremely worried: _____; *I don't know*

I.V. What effect does climate change has on your farm activities? *very negative / negative / neutral / positive / very positive / I don't know*

I.VI. When compared with your childhood, how often have extreme climate events, such as longer floods/droughts or fires, been happening? *much more often /more often / about the same / less often / much less often / I don't know*

I.VII. How important or unimportant is to protect native wildlife species? *very important / important / neither important nor unimportant / unimportant / very unimportant / I don't know*

I. VIII. How often do you hear of people hunting any wild animals in this area? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

I.IX. How acceptable or unacceptable is wildlife hunting? *very acceptable / acceptable / neither acceptable nor unacceptable / unacceptable / very unacceptable / I don't know*

I.X. In your opinion, what are the three most hunted species in the region?

1) _____; 2) _____; 3) _____.

Introduction: In this section we're going to ask you some questions about jaguar conservation specifically. During the process we will use the expression "in this area" and as for the previous section, we mean yours and the neighbouring farms.

The overall goal of this section is to understand the level of tolerance or intolerance towards jaguar in the region.

II. Attitudes towards jaguars

II.I. What do you think about the number of jaguars in this area at the moment? *far too many / too many / about right / too few / far too few / I don't know*

II.II. How acceptable or unacceptable is to have jaguars around this area? *very acceptable / acceptable / neither acceptable nor unacceptable / unacceptable / very unacceptable / I don't know*

II.III. How much do you support or oppose jaguars' protection in this area? *strongly support / support / neutral / oppose / strongly oppose / I don't know*

II.IV. Of these five species, which are most dangerous for domestic animals in this area? Rank from highest to lowest. *jaguars / pumas / wild boars / snakes / feral dogs / I don't know*

II.V. How often do you think jaguar attacks to domestic animals happen in this area? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

II.VI. How easy or difficult is to protect domestic animals from jaguars in this area? *very difficult / difficult / neutral / easy / very easy / I don't know*

II.VII. How effective or ineffective is jaguar killing at preventing attacks to domestic animals in this area? *very effective / effective / neutral / ineffective / very ineffective / I don't know*

II.VIII. What effect does jaguar killing have on their conservation in this area? *very negative / negative / neutral / positive / very positive / I don't know*

II.IX. How often do you hear of people killing jaguars in this area to protect people? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

II.X. How often do you hear of people killing jaguars in this area to protect livestock? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

II.XI. How often do you hear of people killing jaguars in this area for recreation/sport? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

II.XII. How often do you hear of people killing jaguars in this area for commercial purposes? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

II.XIII. How often do you hear of people killing jaguars in this area just because they encounter the jaguars? *never / less than once a year / about once a year / about once a month / about once a week / more than once a week / I don't know*

SECTION 2 – Husbandry Practices

Introduction: In this section we're going to ask you a few questions about your husbandry practices. Our goal is to try to understand how jaguar attacks are related or not with these practices in the region.

I. How many times your livestock (or domestic animals) have been attacked by jaguars in the past 5 years? _____

II. Do you currently have domestic animals? 1) Yes; 2) No

II.I. Which ones? *Cow / Horse / Goat / Pig / Dog / Other:* _____

III. During the night, how often do you keep the livestock in corrals? *never / some of the time / most of the time / always / I don't know*

IV. Do your corrals have any protection (reinforcement) against jaguars? *No / Yes / I don't know*

IV.I. Which ones? *reinforced fence / electric fence / night lights / guard dogs / other: _____*

V. Do your pastures have any protection (reinforcement) against jaguars? *No / Yes / I don't know*

V.I. Which ones? *reinforced fence / electric fence / night lights / guard dogs / other: _____*

VI. During the day, how often do you keep guard dogs with livestock? *never / some of the time / most of the time / always / I don't know*

VII. How far (approximately) is the farthest corral from the house? _____ *(meters)* / *I don't know*

VIII. Ranch size (approximately): Would you mind saying the approximate size of your ranch? _____ *(unit: _____) / I don't know / I'd rather not saying*

IX. Natural reserve/APP size (approximately): What about the approximate size of the APP? _____ *(unit: _____) / I don't know / I'd rather not saying*

SECTION 3 – Socio-demographic information

Introduction: At last, we'll collect some personal information. This information is important to characterise the profile of residents in the region. We would like to reiterate that your identity will remain protected and that none of your responses from any part of the

questionnaire will be able to be linked to you. As for the other sections, you can stop at any time, and you don't have to answer questions if you don't feel comfortable doing so.

I. Gender: *male / female*

II. Age: What is your age? *18-28 / 29-39 / 40-50 / above 50 / I'd rather not saying*

III. Education: What is the highest level of formal education you have completed? *None - no formal education / Primary - elementary education / Secondary - high school education / Higher - higher education (college or university) / I'd rather not saying*

IV. Religion: Do you belong to any particular religion? *Catholic / Evangelical / "Espirita" / None / Other: _____ / I'd rather not saying*

V. Political orientation: In general, which political agenda do you most identify yourself? *FHC-Bolsonaro / Lula-Dilma / None / Other: _____ / I'd rather not saying*

VI. Main source of income: Among these options, which one would say that is your main source of income? *Agriculture / Livestock ranching / Tourism / Commerce / Government program (e.g., bolsa família) / Other: _____ / I'd rather not saying*

Final Statement: We have come to the end of the survey! Thank you very much for taking time to answer these questions. If you have any questions or concerns, or would like more information, details of who to contact are in the flyer we gave you when we met.



Wezddy Del Toro - Mamirauá Institute

Chapter 6
General Discussion

Jaguars (*Panthera onca*) are wide-ranging apex predators whose persistence depends on the interplay between population dynamics, habitat availability, landscape connectivity, and human tolerance. This thesis integrates these dimensions to provide a comprehensive, large-scale assessment of jaguar ecology and conservation across the species' range. Through four interconnected chapters, it evaluates jaguar population density in Amazonian protected areas, identifies suitable habitat and assesses population connectivity at continental scales, and explores patterns of human–jaguar conflict and coexistence in one of the predicted corridors. By combining these analyses, the thesis offers a unified perspective on the ecological and social processes shaping jaguar populations in the Neotropics.

Below, I synthesise the main findings of the thesis around four interrelated themes: (i) ecological drivers of jaguar populations and habitat suitability, (ii) the role of protected areas and Indigenous Lands, (iii) landscape connectivity across suitable habitats, and (iv) the importance of on-the-ground assessments to contextualise and evaluate model-based predictions.

Habitat productivity was the most influential ecological driver for jaguars, consistently determining population densities in Amazonian (Chapter 2) and habitat suitability patterns across the species' continental range (Chapter 3). The convergence of results across independent datasets, analytical approaches and scales provides strong evidence of its importance, underscoring that bottom-up ecological processes are central to jaguar persistence. In this context, highly productive systems are likely to sustain greater prey availability, which in turn underpins the energetic requirements of large apex predators such as jaguars (Khamila et al., 2023). In the Amazonian system, for instance, this implies that habitats influenced by sediment-rich white-water rivers and geologically young soils, such as the *várzea* forests and the Andean-Amazon interface, are more suitable and capable of supporting higher jaguar densities. When looking beyond this biome, however, additional

covariates help explain jaguar habitat suitability, particularly proximity to water (positive effects) and the extent of human-modified landscapes (negative effects; Chapter 3).

The positive selection of water as one of the main predictors of jaguar habitat suitability at broad spatial scales is not surprising, as jaguars are exceptional swimmers and are often regarded as the most water-associated species among the genus Panthera (Nowell and Jackson, 1996; Sunquist and Sunquist, 2002). Jaguars are known to actively exploit aquatic environments by fishing (Eriksson et al., 2021) and even diving to hunt caimans (G1, 2025). In addition, riverbanks provide strategic locations for ambushing terrestrial prey, including capybaras (Astete et al., 2008). Riverine environments are also likely to function as natural movement corridors, facilitating individual dispersal across the landscape (Silveira et al., 2014). Nevertheless, not all jaguar populations exhibit the same degree of dependence on water (Morato et al., 2018). In drier habitats, where water is scarce, jaguars appear to adapt by selecting alternative landscape features, such as caves or rocky shelters (Astete et al., 2017). This behavioural flexibility highlights the importance of accounting for local ecological contexts when interpreting large-scale habitat suitability models and cautions against overly generalised predictions across environmentally distinct regions.

In contrast, covariates associated with human-modified landscapes showed a strong and consistent negative relationship with jaguar habitat use, ranging from increased home-range sizes (Chapter 2) to reduced habitat suitability at broader spatial scales (Chapter 3). Together, these results indicate that while jaguars may persist in anthropized regions, they are often forced to expand their home ranges, likely as a response to reduced prey availability and habitat quality (Thompson et al., 2021). As levels of human modification increase, however, landscapes may eventually become unsuitable for the species, leading to local extirpation and/or displacement (Menezes et al., 2021). This pattern is already evident in parts of the jaguar's historical range, including countries such as Uruguay and El Salvador,

where jaguars are now absent, and in several biomes where extensive habitat loss has occurred (Quigley et al., 2017). The Atlantic Forest represents one of the most emblematic examples: following the loss of approximately 24% of its original extent (MapBiomas Brasil, 2024), the remaining jaguar populations are confined to a small number of isolated protected areas, with limited demographic and genetic connectivity among them (Paviolo et al., 2016). These patterns highlight the critical role of protected areas and other low-disturbance landscapes in buffering jaguar populations against the negative effects of human land use.

Indeed, protected areas and Indigenous Lands (hereafter jointly referred to as PAs) once again emerge as central pillars for biodiversity conservation, with jaguars providing a compelling case study (Chapters 2 and 3). Estimates of jaguar population density indicate that Amazonian PAs can harbour large and viable populations (Chapter 2), while habitat suitability predictions show that PAs encompass more than half of all suitable jaguar habitat across the species' range, despite covering only around one third of it (Chapter 3). These figures are both encouraging and striking, though not entirely unexpected. The importance of PAs for jaguar conservation has been demonstrated previously (Sollmann et al., 2008), and more broadly for maintaining healthy populations of game species (Benítez-López et al., 2019), limiting deforestation (Qin et al., 2023), reducing mining pressure (Ribas and Galetti, 2025), and mitigating wildfires impacts (Pessôa et al., 2023). At the national scale, this thesis estimates that, on average, 40–50% of highly suitable jaguar habitat currently falls within PAs, depending on the methodological approach adopted (range-wide versus ecoregion-based assessments). This represents a relatively robust baseline for conservation. However, protection is far from homogeneous across the species' range. Several countries remain at the lower end of this spectrum, including Paraguay (11%), Argentina (17%), Mexico and the United States (18%), and Suriname (19%), under the ecoregion-based scenario, which better captures regional ecological contexts. These disparities highlight clear opportunities for

targeted public policies aimed at expanding and strengthening habitat protection for jaguars. A clear example is Brazil, where the designation of currently non-designated lands for conservation or sustainable use could increase the proportion of highly suitable jaguar habitat under protection by approximately 10%, illustrating the substantial conservation gains that could be achieved through strategic land-use planning.

Regarding land-use planning, this thesis identified, mapped, and ranked the most important core areas, PAs, and dispersal corridors for jaguars, providing a framework to inform conservation priorities across the species' range (Chapter 4). Given the high and increasing levels of anthropogenic habitat transformation worldwide, it is unlikely that traditional strategies focused solely on the creation of new protected areas will be sufficient to ensure long-term population connectivity. In this context, the development of models to predict potential movement corridors across human-modified landscapes represents a complementary approach (e.g., Brennan et al., 2022). Such corridors are typically smaller than protected areas and, if appropriately designed, can be implemented in collaboration with private landowners and other local stakeholders.

For jaguars, varying initiatives over the past 15 years have attempted to operationalise earlier corridor predictions, including the Jaguar Corridor Initiative and the Jaguar 2030 Roadmap (Salom-Pérez et al., 2010; WWF et al., 2019). Despite these efforts, population isolation persists, and reductions in genetic diversity are already evident in regions such as Central America and the Atlantic Forest (Srbek-Araujo et al., 2018; Wultsch et al., 2016). Against this backdrop, the connectivity predictions presented in this thesis provide an updated and integrative perspective. In particular, the identification of the Llanos-Amazon-Pantanal-Chaco continuum as a major core area is especially encouraging, as it suggests high levels of potential movement and functional connectivity across a vast landscape, reinforcing its role as a cornerstone for the long-term persistence of jaguar populations. Core areas such

as this, together with the dispersal corridors identified and prioritised here, represent clear targets for future conservation efforts. Beyond these well-connected regions, however, the analyses also reveal linkage gaps – areas where dispersal is unlikely to occur and where populations are therefore effectively isolated. Such areas warrant careful consideration, as alternative management strategies, including assisted dispersal, translocations, or rewilding initiatives, may be necessary to prevent local extinctions. Regardless of the region, however, the availability of these new corridor predictions highlights that a critical next step is on-the-ground validation, to assess local conditions (e.g. social dynamics) and thereby determine whether predicted corridors effectively support jaguar movement and dispersal under real-world conditions.

This thesis addressed that need in Chapter 5 through systematic questionnaire surveys across the Pantanal-Amazon Corridor (PAC). The strong evidence of jaguar presence in PAC supports the accuracy of the corridor model in this region and suggests that the Pantanal and Amazon biomes may still be connected within Brazil – although definitive confirmation will require more detailed investigations, such as telemetry tracking and genetic analyses. These findings are encouraging, as is the generally positive local attitude toward conservation and jaguars specifically. Nevertheless, challenges remain as livestock depredation and incidents of jaguar killing may affect the functionality of PAC, potentially limiting its effectiveness as a corridor. Continuous engagement in the region is therefore crucial, both to strengthen relationships with local farmers and to gain a more comprehensive understanding of the current situation, ultimately supporting initiatives that foster coexistence between humans and jaguars in PAC.

Implications for jaguar conservation

The outcomes of this thesis provide valuable starting points for conservation planning. First, the predicted corridors can serve as guidelines for national authorities and international agencies seeking to prioritize areas for protection and management. Second, these findings open opportunities for the creation of new study areas, supporting research groups interested in jaguar ecology, human-wildlife interactions, and landscape connectivity.

Importantly, this work highlights the need for on-the-ground evaluation of model predictions. Field validation through methods such as telemetry tracking, genetic analysis, and local surveys will be essential to assess whether predicted corridors truly support jaguar movement and dispersal. In PAC specifically, continued monitoring and engagement are recommended to better understand movement patterns, genetic flow, and potential human-wildlife conflicts, while fostering coexistence with local communities.

Finally, the methods and approaches applied in PAC have the potential to be adapted and expanded to other regions, enabling a broader assessment of connectivity across the jaguar's range and providing a framework for similar conservation initiatives elsewhere.

Conclusion

This thesis provides an integrative assessment of jaguar ecology, connectivity, and human-wildlife interactions across the species' range. By combining large-scale habitat and population analyses with on-the-ground evaluation in the Pantanal-Amazon Corridor, it demonstrates both the ecological and social dimensions shaping jaguar persistence. The findings offer actionable insights for conservation planning, highlight priority areas for connectivity, and emphasize the importance of field validation to ensure corridors function in practice. Looking forward, continued monitoring, engagement with local communities, and

the application of these approaches to other regions will be critical for maintaining viable jaguar populations and facilitating coexistence across human-dominated landscapes.

References

Astete, S., Marinho-Filho, J., Machado, R.B., Zimbres, B., Jácomo, A.T.A., Sollmann, R., Tôrres, N.M., Silveira, L., 2017. Living in extreme environments: modeling habitat suitability for jaguars, pumas, and their prey in a semiarid habitat. J Mammal 98, 464–474. https://doi.org/10.1093/jmammal/gyw184

Astete, S., Sollmann, R., Silveira, L., 2008. Comparative Ecology of Jaguars in Brazil. Cat News Special Issue 4 9–14.

Benítez-López, A., Santini, L., Schipper, A.M., Busana, M., Huijbregts, M.A.J., 2019. Intact but empty forests? Patterns of hunting induced mammal defaunation in the tropics. PLoS Biol 17, 1–18. https://doi.org/10.1371/journal.pbio.3000247

Brennan, A., Naidoo, R., Greenstreet, L., Mehrabi, Z., Ramankutty, N., Kremen, C., 2022. Functional connectivity of the world's protected areas. Science (1979) 376, 1101–1104. https://doi.org/10.1126/science.abl8974

Eriksson, C.E., Kantek, D.L.Z., Miyazaki, S.S., Morato, R.G., dos Santos-Filho, M., Ruprecht, J.S., Peres, C.A., Levi, T., 2021. Extensive aquatic subsidies lead to territorial breakdown and high density of an apex predator. Ecology e03543. https://doi.org/10.1002/ecy.3543

G1, 2025. Duelo embaixo d'água: onça ataca jacaré de surpresa durante caçada em rio no Pantanal de MT; veja vídeo [WWW Document]. Rede Globo. URL https://g1.globo.com/mt/mato-grosso/noticia/2025/06/18/duelo-embaixo-dagua-onca-ataca-jacare-de-surpresa-durante-cacada-em-rio-no-pantanal-de-mt-veja-video.ghtml (accessed 12.28.25).

Khamila, C.N., Groen, T.A., Toxopeus, A.G., Santini, L., Neumann, M., Van Swaay, C., Van Swaay, H., 2023. There is a trade-off between forest productivity and animal

biodiversity in Europe. Biodivers Conserv 32, 1879–1899. https://doi.org/10.1007/s10531-023-02582-2

MapBiomas Brasil, 2024. Projeto MapBiomas – Coleção 8.0 do Mapeamento [WWW Document]. Anual de Cobertura e Uso da Terra do Brasil.

Menezes, J.F.S., Tortato, F.R., Oliveira-Santos, L.G.R., Roque, F.O., Morato, R.G., 2021. Deforestation, fires, and lack of governance are displacing thousands of jaguars in Brazilian Amazon. Conserv Sci Pract 3, 1–10. https://doi.org/10.1111/csp2.477

Morato, R.G., Connette, G.M., Stabach, J.A., De Paula, R.C., Ferraz, K.M.P.M., Kantek, D.L.Z., Miyazaki, S.S., Pereira, T.D.C., Silva, L.C., Paviolo, A., De Angelo, C., Di Bitetti, M.S., Cruz, P., Lima, F., Cullen, L., Sana, D.A., Ramalho, E.E., Carvalho, M.M., da Silva, M.X., Moraes, M.D.F., Vogliotti, A., May Jr., J.A., Haberfeld, M., Rampim, L., Sartorello, L., Araujo, G.R., Wittemyer, G., Ribeiro, M.C., Leimgruber, P., 2018. Resource selection in an apex predator and variation in response to local landscape characteristics. Biol Conserv 228, 233–240. https://doi.org/10.1016/j.biocon.2018.10.022

Nowell, K., Jackson, P., 1996. Wild cats. Status Survey and Conservation Action Plan. IUCN, Gland, Switzerland. 110–113. https://doi.org/10.1023/A:1008907403806

Paviolo, A., De Angelo, C., Ferraz, K.M.P.M.B., Morato, R.G., Martinez Pardo, J., Srbek-Araujo, A.C., Beisiegel, B.D.M., Lima, F., Sana, D., Xavier Da Silva, M., Velázquez, M.C., Cullen, L., Crawshaw, P., Jorge, M.L.S.P., Galetti, P.M., Di Bitetti, M.S., De Paula, R.C., Eizirik, E., Aide, T.M., Cruz, P., Perilli, M.L.L., Souza, A.S.M.C., Quiroga, V., Nakano, E., Ramírez Pinto, F., Fernández, S., Costa, S., Moraes, E.A., Azevedo, F., 2016. A biodiversity hotspot losing its top predator: The challenge of jaguar conservation in the Atlantic Forest of South America. Sci Rep 6, 37147. https://doi.org/10.1038/srep37147

Pessôa, A.C.M., Morello, T.F.R.S., Silva-Junior, C.H.L., Doblas, J., Carvalho, N.S., Aragão, L.E.O.C., Anderson, L.O., 2023. Protected areas are effective on curbing fires in the

Amazon. Ecological Economics 214, 107983. https://doi.org/10.1016/j.ecolecon.2023.107983

Qin, Y., Xiao, X., Liu, F., de Sa e Silva, F., Shimabukuro, Y., Arai, E., Fearnside, P.M., 2023. Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. Nat Sustain 6, 295–305. https://doi.org/10.1038/s41893-022-01018-z

Quigley, H., Foster, R.J., Petracca, L., Payan, E., Salom, R., Harmsen, B.J., 2017. *Panthera onca*, Jaguar (errata version published in 2018), The IUCN Red List of Threatened Species 2017.

Ribas, L.G. dos S., Galetti, M., 2025. Indigenous Lands inhibit mining-induced deforestation in the Brazilian Amazon. Glob Ecol Conserv 59, e03540. https://doi.org/10.1016/j.gecco.2025.e03540

Salom-Pérez, R., Polisar, J., Quigley, H., Zeller, K., 2010. Iniciativa del Corredor del Jaguar: Un Corredor Biológico y un Compromiso a Largo Plazo para la Conservación. Mesoamericana 14 (3), 1–10.

Silveira, L., Sollmann, R., Jácomo, A.T.A., Diniz Filho, J.A.F., Tôrres, N.M., 2014. The potential for large-scale wildlife corridors between protected areas in Brazil using the jaguar as a model species. Landsc Ecol 29, 1213–1223. https://doi.org/10.1007/s10980-014-0057-4

Sollmann, R., Torres, N.M., Silveira, L., 2008. Jaguar conservation in Brazil: the role of Protected Areas. CAT News 4, 15–20.

Srbek-Araujo, A.C., Haag, T., Chiarello, A.G., Salzano, F.M., Eizirik, E., 2018. Worrisome isolation: Noninvasive genetic analyses shed light on the critical status of a remnant jaguar population. J Mammal 99, 397–407. https://doi.org/10.1093/jmammal/gyy007

Sunquist, M.E., Sunquist, F.C., 2002. Wild Cats of the World. University of Chicago Press, Chicago and London.

Thompson, J.J., Morato, R.G., Niebuhr, B.B., Alegre, V.B., Oshima, J.E.F., de Barros, A.E., Paviolo, A., de la Torre, J.A., Lima, F., McBride, R.T., Cunha de Paula, R., Cullen, L., Silveira, L., Kantek, D.L.Z., Ramalho, E.E., Maranhão, L., Haberfeld, M., Sana, D.A., Medellin, R.A., Carrillo, E., Montalvo, V.H., Monroy-Vilchis, O., Cruz, P., Jacomo, A.T.A., Alves, G.B., Cassaigne, I., Thompson, R., Sáenz-Bolaños, C., Cruz, J.C., Alfaro, L.D., Hagnauer, I., Xavier da Silva, M., Vogliotti, A., Moraes, M.F.D., Miyazaki, S.S., Araujo, G.R., Cruz da Silva, L., Leuzinger, L., Carvalho, M.M., Rampim, L., Sartorello, L., Quigley, H., Tortato, F.R., Hoogesteijn, R., Crawshaw, P.G., Devlin, A.L., May Júnior, J.A., Powell, G.V.N., Tobler, M.W., Carrillo-Percastegui, S.E., Payán, E., Azevedo, F.C.C., Concone, H.V.B., Quiroga, V.A., Costa, S.A., Arrabal, J.P., Vanderhoeven, E., Di Blanco, Y.E., Lopes, A.M.C., Ribeiro, M.C., 2021. Environmental and anthropogenic factors synergistically affect space use of jaguars. Current Biology 31, 3457-3466.e4. https://doi.org/10.1016/j.cub.2021.06.029

Wultsch, C., Caragiulo, A., Dias-Freedman, I., Quigley, H., Rabinowitz, S., Amato, G., 2016. Genetic diversity and population structure of Mesoamerican jaguars (*Panthera onca*): Implications for conservation and management. PLoS One 11, 1–25. https://doi.org/10.1371/journal.pone.0162377

WWF, WCS, Panthera, UNDP, 2019. Jaguar 2030: Conservation Roadmap for the Americas.



Emiliano E. Ramalho - Mamirauá Institute

Appendices

Other Publications (between 2021 and 2026)

AMAZONIA CAMTRAP: A dataset of mammal, bird, and reptile species recorded with camera traps in the Amazon forest

Antunes, A. C.; Montanarin, A.; Gräbin, D. M.; Monteiro, E. C. S.; Pinho, F. F.; **Alvarenga, G. C.**; et al. (2022)

Published in Ecology, v. 103 (9), p. e3738.

https://doi.org/10.1002/ecy.3738

Abstract

The Amazon forest has the highest biodiversity on Earth. However, information on Amazonian vertebrate diversity is still deficient and scattered across the published, peer-reviewed, and gray literature and in unpublished raw data. Camera traps are an effective non-invasive method of surveying vertebrates, applicable to different scales of time and space. In this study, we organized and standardized camera trap records from different Amazon regions to compile the most extensive data set of inventories of mammal, bird, and reptile species ever assembled for the area. The complete data set comprises 154,123 records of 317 species (185 birds, 119 mammals, and 13 reptiles) gathered from surveys from the Amazonian portion of eight countries (Brazil, Bolivia, Colombia, Ecuador, French Guiana, Peru, Suriname, and Venezuela). The most frequently recorded species per taxa were: mammals: *Cuniculus paca* (11,907 records); birds: *Pauxi tuberosa* (3713 records); and reptiles: *Tupinambis teguixin* (716 records). The information detailed in this data paper opens up opportunities for new ecological studies at different spatial and temporal scales, allowing for a more accurate evaluation of the effects of habitat loss, fragmentation, climate change, and other human-mediated defaunation processes in one of the most important and threatened tropical environments in the world. The

data set is not copyright restricted; please cite this data paper when using its data in publications and we also request that researchers and educators inform us of how they are using these data.

Hematology and Serum Chemistry of Free-Ranging Jaguars (*Panthera onca*) from a Floodplain Forest Site in Amazonia, Brazil.

Maranhão, L.; Ramalho, E. E.; **Alvarenga, G. C.**; Brito, M. R. M.; Brandão, P. E.; Miyagi, S. A. T.; Barone, G. T.; Conselheiro, J. A.; Galinari, G. C. F.; Lobato, Z. I. P.; Ferreira Neto, J. S. (2022).

Published in Journal of Wildlife Diseases, v. 58 (2), p. 425-430

https://doi.org/10.7589/JWD-D-21-00012

Abstract

We provide hematologic and biochemical information for 13 jaguars (*Panthera onca*) from the Amazon. Most showed increased lymphocytes, monocytes, eosinophils, aspartate aminotransferase, and alanine aminotransferase; all individuals showed lower mean red blood cell (RBC) counts compared to findings from other biomes. Males had a significantly higher RBC count and alkaline phosphatase than did females.

Community-based monitoring of wild felid hunting in Central Amazonia

Valsecchi, J.; Monteiro, M. C. M.; **Alvarenga, G. C.**; Lemos, L. P.; Ramalho, E. E. (2022).

Published in Animal Conservation, v. 26 (2),p. 189-198

https://doi.org/10.1111/acv.12811

Abstract

Hunting is a critical issue in wild felid conservation, contributing to the decline of these species worldwide. Here, we present 18 years of a community-based monitoring program, quantifying and characterizing wild felid hunting in two sustainable development reserves in Central Amazonia. We investigated how felid hunting was affected by the flood pulse and whether local human population size, habitat type, and total hunting events influenced felid hunting. We recorded 71 adult felids being killed, most of them in opportunistic events (88.7%), usually during hunting expeditions aimed at other game species. Four felid species were recorded in the hunts (*Panthera onca*, *Leopardus pardalis*, *Puma concolor*, and *Leopardus wiedii*) with jaguars accounting for almost half of all hunting events ($N = 35$). We found that more felid hunting events occurred during the flooded season, in more populated communities, and in *várzea*habitats. Most felids were hunted opportunistically, demonstrating the complexity of human-felid interactions. Stories of attacks on humans are widespread in the study area, which may strengthen an instinctive fear of felids, driving their persecution. The increase of hunting events during the flooded season seems to be related to a higher probability of encounters between humans and wild felids. High waters make fishing difficult, therefore, locals hunt more, entering deep into the forest through flooded habitats. Since jaguars have an arboreal lifestyle during the flooded season in *várzea* forests, they are easily spotted by locals and have

less of a chance to escape since they are slower and more exposed when swimming, which increases the probability of being killed. It is generally acknowledged that involving local stakeholders in conservation projects is essential for their success. In our case, collaboration among researchers and community members was fundamental to access hunting information. We show that community-based monitoring empowers the local communities and facilitates data collection on sensitive topics.

Divergent effects of lure on multi-species camera-trap detections and quality of photos

Barcelos, D. C.; **Alvarenga, G. C.**; Gräbin, D. M.; Baccaro, F. B.; Ramalho, E. E. (2023).

Published in Journal for Nature Conservation, v. 71, p. 126317

https://doi.org/10.1016/j.jnc.2022.126317

Abstract

The use of attractants to increase detection of target species, such as carnivores, in camera trap studies must be tested for its effectiveness and be carefully planned, as it can lead to misleading comparisons among species. We analyzed a five-year multi-species camera trap dataset of lured and control stations in a protected area in the Amazon rainforest. We aimed to identify the lure effect on a wider range of species and assess whether its use is an efficient strategy to increase the number and the quality of carnivore records. From the 14 vertebrate species analyzed, we found that the use of lures had a negligible effect on nine species, and did not improve the number of records or the detection probability of the carnivores. On the other hand, lured stations attracted omnivores and scavengers (common opossum, black-and-white tegu, and turkey vulture) while had the opposite effect on potential prey species (Black-capped capuchin and Northern Amazon squirrel). We detected a stronger effect of the lure when considering the number of records (relative abundance models) than the probability of detection (occupancy models). The lure increased the proportion of high-quality photos, suitable for individual recognition of jaguars, but only for the first weeks, when the lure was fresh. Therefore, we suggest that the sardine and egg-based lures should be refreshed every-two weeks to ensure greater effectiveness in the quality of photos for jaguar individualization. However, it is important to consider that lure renewing will imply a significant increase in field-related costs

and it's likely to bias other species studies. Thus, we advise that lures should only be used if researchers are certain that the focus is only to increase carnivore data at the expense of using non-target species. Camera traps survey design must be carefully planned *a priori* and the cost-benefit of lure use and refreshment should be weighed in the study context.

Anthropogenic factors do not affect male or female jaguar habitat use in an Amazonian Sustainable Reserve

Montanarin, A.; Ramalho, E. E.; Rocha, D. G.; Gräbin, D. M.; **Alvarenga, G. C.**; Pequeno, P. A. C. L.; Baccaro, F. B.; Magnusson, W. E. (2023).

Published in Perspectives in Ecology and Conservation, v. 21 (3), p. 224-230.

https://doi.org/10.1016/j.pecon.2023.06.004

Abstract

Conservation actions should account for species natural history and behavior related to differences between sexes. However, most studies have not taken into consideration non-independence of observations from the same individual. We used data from camera-trap surveys undertaken over six consecutive years to investigate habitat use by jaguar (*Panthera onca*) in *varzea* seasonally flooded forest. We used hierarchical modeling to assess sex differences in occurrence probability related to environmental factors, while accounting for individual and spatial autocorrelation. Specifically, we tested whether male and female jaguars responded differently to habitat type and anthropogenic influence. Our results do not support previous conclusions related to differences between sexes and indicate that, in the studied area, jaguars are habitat generalists, exploring all environments with similar probability during the low-water season. Human settlements also apparently have little effect on habitat use by jaguars in this area. The lack of avoidance of settlements might be due to the low levels of anthropogenic pressure in the area, which adds support to the effectiveness of sustainable-development reserves. The difference between our results and previous studies may be due to the fact that we took into account individual differences, or may be related to the unique

environmental characteristics of the *varzea* of Mamirauá Sustainable Development Reserve in Central Amazonia.

Mammal responses to global changes in human activity vary by trophic group and landscape

Burton, A. C.; Beirne, C.; Gaynor, K. M.; Sun, C.; Granados, A.; Allen, M. L.; Alston, J. M.; **Alvarenga, G. C.**; et al. (2024).

Published in Nature Ecology and Evolution, v. 8, p. 924-935.

https://doi.org/10.1038/s41559-024-02363-2

Abstract

Wildlife must adapt to human presence to survive in the Anthropocene, so it is critical to understand species responses to humans in different contexts. We used camera trapping as a lens to view mammal responses to changes in human activity during the COVID-19 pandemic. Across 163 species sampled in 102 projects around the world, changes in the amount and timing of animal activity varied widely. Under higher human activity, mammals were less active in undeveloped areas but unexpectedly more active in developed areas while exhibiting greater nocturnality. Carnivores were most sensitive, showing the strongest decreases in activity and greatest increases in nocturnality. Wildlife managers must consider how habituation and uneven sensitivity across species may cause fundamental differences in human–wildlife interactions along gradients of human influence.

Impact of seasonal flooding on Jaguar (*Panthera onca*) home range and movements

Brito, M. R. M.; **Alvarenga, G. C.**; Oliveira-Santos, L. G. R.; Maranhão, L.; Santos, L. P.; Santos, R. G.; Menezes, Jorge F. S.; Ramalho, E. E. (2025).

Published in Journal of Mammalogy, v. 106 (3), p. 612-621.

https://doi.org/10.1093/jmammal/gyae145

Abstract

Movement is an integral part of animal foraging and survival. Thus, conditions that hamper animal movement should cause significant shifts in their ecology, especially in traits directly related to movement such as home range, displacement, and site fidelity. Using jaguars (*Panthera onca*) as our model species, we measured the effect of reduced mobility in a unique natural experiment. The Amazonian varzeas of the Mamirauá Reserve have such a prevalent and intense flooding that jaguars in the region adopt a semiaquatic and arboreal lifestyle during the wet season. We hypothesized that Jaguar space use would change substantially between seasons with decreasing home ranges, core areas, and displacements during the high-water periods. Given previously documented sex-based differences in Jaguar space use and movement we also evaluated sex-based differences in movement parameters in our study system. We measured seasonal home ranges and core areas using autocorrelated kernel density estimation, with the 95% contour for home ranges and 50% for core areas. Displacement was calculated as the velocity of movement in meters per second in each given step comprised of locations every 6 h. Our results indicated that home range area remained constant between seasons, but displacement decreased during high-water periods as expected. We discuss the possibility that jaguars switch to an ambushing form of predation, which is made possible by

the large number of prey in the region. This ambushing tactic would allow jaguars to retain a large home range despite low mobility and larger movement costs.

Gender dynamics of tropical wildmeat systems: A systematic map of women's roles and influence

Willis J.; Nurbandi, W.; González-Nava, B.; Gomez, J.; Castera, F.; **Alvarenga, G. C.**; Flottes De Pouzols, A.; Lemaire, M.; Linden, J.F.; Madsen, E. K.; Coad, L.; Hinsley, A.; Milner-Gulland, E. J. (2025).

Published in People and Nature, v. 00, p. 1-16.

https://doi.org/10.1002/pan3.70133

Abstract

Wildmeat is a vital natural resource globally, which must be managed sustainably to avoid livelihood insecurity, species decline and biodiversity loss. Women have a pivotal role in harvesting, processing and distributing wildmeat, yet their contributions are often overlooked. Engaging women is essential for sustainable wildmeat management and equitable conservation, which requires an understanding of their roles and influence—an area that remains under-researched. To address this gap, we conducted a systematic map exploring gender dynamics in wildmeat systems. We searched six academic and grey literature directories using key terms in five languages and extracted data on women's presence and absence in wildmeat systems from relevant publications. Our analysis of 334 publications across 54 countries identified 935 records of women's presence and absence in 36 roles within tropical wildmeat systems. Women were most commonly consumers, traders and harvesters. Their presence and absence were strongly linked to their gender, such as domestic responsibilities assigned to women, or taboos against hunting and consuming wildmeat linked often with pregnancy and fertility. Women occupy vital roles in tropical wildmeat systems, from

household consumption to commercial trade, influencing food security, community cohesion and market demand. Their contributions could support sustainable management, balancing conservation with livelihoods, but their participation in governance is poorly documented, risking their exclusion from decision-making. More research is also needed on gendered power dynamics and intersecting factors like age and ethnicity. We provide robust evidence linking gender and wildmeat and call for more gender-sensitive interventions that recognise women's contributions, address their challenges and ensure their meaningful role in wildmeat governance. Women's active participation in decision-making is essential for inclusive, equitable policies and interventions that promote both conservation outcomes and sustainable resource use.


Emiliano E. Ramalho - Mamirauá Institute


UNIVERSITY·OF·OXFORD
DOMI NUS ILLV
MINA TIO MEA