Ecological traits explain wild felid responses to human-modified landscapes in Brazil: an open-data approach for conservation

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Abstract

Understanding how wild felids respond to human-modified landscapes is critical for designing effective conservation strategies, yet comparative assessments across species remain scarce in tropical regions. Here, we assess the habitat selection and road sensitivity of nine wild felid species in Brazil using an integrative and scalable framework based entirely on open-access data. We compiled over 14,000 cleaned occurrence records and modelled habitat associations using generalized linear models across three spatial scales (5, 15, and 30 km). Species were grouped into three ecological categories: generalists, flexible specialists, and strict specialists, based on their ecological plasticity. Our results reveal marked interspecific variation in habitat preferences and responses to roads. While generalists like *Puma concolor* and *Herpailurus yagouaroundi* showed higher tolerance to anthropogenic environments, others like *Leopardus geoffroyi* exhibited more restricted patterns. Flexible specialists like *Panthera onca* and *Leopardus pardalis* avoided roads but used heterogeneous natural landscapes. Strict forest specialists (*L. wiedii*, *L. guttulus*, *L. tigrinus*) were highly dependent on forest cover and generally avoided open habitats. Notably, road effects were species-specific and not always aligned with ecological classification. Our findings emphasize that functional classification can aid in anticipating species vulnerabilities, but conservation actions must be tailored to species-level responses. This study highlights the potential of open biodiversity data to inform large-scale conservation planning for Neotropical carnivores, especially in data-poor regions.

Keywords: habitat selection, roads, *Leopardus*, *Herpailurus*, *Panthera*, *Puma*.

1. Introduction

Carnivore conservation faces multiple challenges driven by accelerated habitat loss due to urban and agricultural expansion and ecosystem alterations caused by global climate change (Ripple et al., 2014). Additionally, their historical conflict with human populations, combined with their low population densities and large area requirements, has led many species to remain in vulnerable or declining conservation status (Ripple et al., 2014; Carter & Linnell, 2016; Inskip & Zimmermann, 2009). Studying these species is particularly challenging due to their elusive behavior, slow life histories, and the need for long-term monitoring across large and often inaccessible areas, which generates high logistical and financial costs (Kays et al., 2015; Ripple et al., 2014; Tucker et al., 2018). As a result, ecological data for many carnivores remain scarce, hindering the development of effective conservation strategies. Although in some instances conservation efforts have succeeded in stabilizing some populations, such as the Eurasian lynx (*Lynx lynx*) in Europe (Chapron et al., 2014), a deep inequality persists in the distribution of ecological knowledge on carnivores and their ecosystems (Ripple et al., 2014; Torres-Romero & Giordano, 2022). These gaps, known as biodiversity shortfalls, reflect missing information on species identity, distribution, abundance, and ecological requirements, ultimately limiting our capacity to anticipate and mitigate the functional collapse of ecosystems (Hortal et al., 2015). Among carnivores, felids represent a diverse yet underrepresented group in ecological research, particularly in tropical regions (Tensen, 2018). Open-access information can provide a valuable starting point to understand species' ecological responses and inform future conservation efforts in such contexts, where field-based data are scarce or unevenly distributed.

Despite the growing literature on felid ecology and conservation, most studies have focused on emblematic large predators or local-scale analyses (Inskip & Zimmermann, 2009; Tensen, 2018). There is still an important gap regarding understanding how different felid species, with varying ecological requirements, respond to landscapes dominated by human activities, particularly in megadiverse regions such as Brazil (Tensen, 2018; Torres-Romero & Giordano, 2022). Furthermore, although it is recognized that the ability to adapt to anthropogenic environments varies among generalist and specialist species, few studies have empirically quantified how this variation influences habitat use and tolerance to human infrastructure, such as roads (Bateman & Fleming, 2012; Barbar et al., 2015; Liu et al., 2025). This lack of information hampers the ability to anticipate which species are more vulnerable to habitat loss and fragmentation and which may benefit from or coexist in modified landscapes, thus limiting the formulation of differentiated and compelling conservation actions. Understanding these divergent responses is critical to identifying higher-risk species and designing effective mitigation strategies in rapidly changing landscapes (Santini et al., 2019).

To address the widespread data deficiency affecting wild felids in Brazil, we implemented an integrative and scalable approach, based entirely on open-access data. By integrating occurrence records with annual high-resolution land cover data and spatially explicit habitat metrics, we developed a standardized analytical pipeline for modelling species-habitat relationships across nine felid species at three spatial scales throughout Brazil. This approach enables the investigation of habitat preferences, road sensitivity, and detection biases across multiple spatial scales, even for species with limited ecological information. By offering a cost-effective and replicable approach, it contributes to improving conservation planning in tropical, data-deficient contexts.

Specifically, our main objective is to assess whether interspecific differences in ecological strategies can predict distinct habitat use patterns and road infrastructure tolerance. To facilitate this analysis, we propose an exploratory functional classification based on general trends observed in the literature regarding habitat use and ecological plasticity for each species (Appendix A in Supplementary Data). We group the species into three categories: (i) generalists, characterized by high plasticity in habitat and resource use (e.g., *Puma concolor*, *Herpailurus yagouaroundi, Leopardus geoffroyi*); (ii) flexible specialists, which exhibit a preference for natural habitats but demonstrate some adaptive capacity in modified environments (e.g., *Leopardus pardalis*, *Panthera onca*, *Leopardus colocolo* (Colocola complex)); and (iii) strict specialists, dependent on specific habitats such as forests, with low tolerance to landscape modification (e.g., *Leopardus wiedii, Leopardus guttulus, Leopardus tigrinus*). This functional grouping aligns with recent findings that ecological traits such as home range size and behavioral flexibility help predict species' responses to anthropogenic pressures (Liu et al., 2025).

Based on this classification, we propose the following hypotheses: (H1) Generalist species will exhibit a more pronounced use of anthropogenic habitats (agriculture and pasture) and a greater tolerance to proximity to road infrastructure; (H2) Flexible specialist species will preferentially select natural habitats and demonstrate lower affinity for anthropogenic environments, including reduced tolerance to road proximity. Finally, (H3) Strict specialist species will exhibit a strong preference for forest cover and will avoid both natural non-forest areas and proximity to road infrastructure.

To our knowledge, this is the first study to propose and evaluate a functional classification of Brazil's felid species based on ecological traits and habitat plasticity. While we acknowledge that multiple factors beyond general ecological traits influence species responses, this framework offers a helpful structure for generating testable hypotheses, highlighting functional trends, and identifying species that deviate from expected patterns. Such deviations are, in themselves, informative for conservation planning.

2. Methods

2.1. Step 1: Data Collection and Preprocessing

We compiled occurrence records for wild felids in Brazil from multiple public databases and institutional sources (Appendix B, Table A, in Supplementary data). Data cleaning involved removing records with spatial errors (e.g., missing or erroneous coordinates), taxonomic inconsistencies, non-native species, missing temporal information, or observations derived from unverifiable methodologies (e.g., interviews or unverified tracks). Furthermore, we excluded all records collected before 2000 to ensure temporal consistency with the environmental layers.

Valid occurrence records were grouped by species and classified into seven temporal intervals: 2000–2004, 2005–2008, 2009–2012, 2013–2016, 2017–2019, 2020–2021, and 2022–2024. Each temporal group was associated with a central reference year for subsequent spatial modelling utilizing Mapbiomas datasets from 2001, 2005, 2009, 2013, 2017, 2021, and 2022, respectively (MapBiomas, 2024). This approach aimed to maximize each species' temporal precision and spatial representativeness (Figure 1). Given recent taxonomic revisions, we treated *L. colocolo*, *L. braccatus* and *L. munoai* as a single unit, the Colocola complex, following proposals supporting their lumping into a broader species concept (Nascimento et al., 2021).

Environmental layers were obtained from the MapBiomas project (MapBiomas, 2024; Souza et al., 2020) for each reference year, encompassing four key landscape cover categories: forest, natural non-forest formations (hereafter natural), pasture, and agriculture (Appendix B, Table B in Supplementary data). We generated binary (presence/absence) maps for each land cover category. Subsequently, we employed LSMetrics (Niebuhr, 2018) to calculate Euclidean distance rasters based on these binary layers, generating continuous surfaces representing each pixel's distance to the nearest habitat patch of each type. This approach enables us to assign negative distance values to pixels located inside habitat patches (indicating proximity to the edge) and positive values to those outside (indicating increasing distance from the patch). This dual representation allows for a nuanced interpretation of habitat edge use versus matrix avoidance, which may be ecologically relevant for cryptic or edge-adapted species. All layers were processed individually for each species and reference year, ensuring spatial alignment with the corresponding UTM zone of the occurrence data. All rasters were either resampled or maintained at a spatial resolution of 30 meters.

2.2. Step 2: Pseudo-Absence Points in multiple spatial scales

We generated random pseudo-absence points within circular buffers for each occurrence point by species from databases (Appendix B, Table C - Total sample size), and reference year map, employing a proportional sampling strategy: 100 points within 5 km buffers, 250 points within 15 km buffers, and 500 points within 30 km buffers (Figure 1). This proportional sampling strategy was adopted to balance the spatial extent of each buffer size with an adequate number of pseudo-absences, ensuring sufficient contrast between presences and available habitats. Larger buffers, encompassing greater landscape heterogeneity and a wider range of environmental conditions, necessitate a high number of pseudo-absence points to capture this variability adequately (Wisz et al., 2008). Additionally, maintaining a comparable sampling density across spatial scales enhances the robustness of habitat selection model inference by accounting for the accessible area hypothesis (Barve et al., 2011).

2.3. Step 3: Habitat Selection and Road Effects

For habitat selection models, we fitted 80 unique combinations of predictor variables in Generalized Linear Models (GLMs) for each species and random-point sampling scale (Supplementary Tables). To mitigate conceptual collinearity, binary and distance-based representations of the same land cover type were not included concurrently within any model formulation. Models were ranked using Akaike's Information Criterion (AIC), and the model with the lowest AIC value was selected as the best-performing model for each species and spatial scale (Figure 1). Although cross-validation was not conducted, our model selection relied on AIC-based ranking, a well-established approach for identifying parsimonious ecological models (Burnham & Anderson, 2002), particularly suitable for comparative inference across nested formulations. After model selection, we re-evaluated the multicollinearity among predictors included in the top-ranked model by assessing pairwise Spearman correlation coefficients (ρ), ensuring all correlations were below 0.7, and by calculating the Variance Inflation Factor (VIF), retaining only models with VIF values below 3 (Zuur et al., 2010). The goodness of fit of the selected models was evaluated using the DHARMa package (Hartig, 2022), which provides simulation-based diagnostics to test residual uniformity, overdispersion, and the presence of outliers in generalized regression models. Diagnostic tests indicated a good fit for the majority of models, except for *P. onca*; we adjusted the pseudoabsence ratio to 1:2 due to overdispersion. For *L. tigrinus*, one influential outlier (value >1) was removed to improve model performance (Appendix C).

We obtained road vector layers for Brazil from the National Department of Transport Infrastructure (DNIT, 2016) to evaluate the potential influence of roads on felid occurrence. We conducted two complementary analyses. First, we calculated a detectability index for each species by identifying occurrence records located within ≤10 meters of a road and estimating their proportion relative to the total number of records (Figure 1). This index was used to estimate the proportion of records near roads, which may reflect either increased detectability due to sampling bias (Kadmon et al., 2004), or true ecological tolerance to anthropogenic infrastructure (Tucker et al., 2018). Second, we evaluated the influence of roads on species occurrence using binomial Generalized Linear Models (GLMs), fitted separately for each species using presence and pseudo-absence data generated within 5 km buffers. Distance to the nearest road was included as a predictor variable. Model adequacy and assumption validation were conducted using simulation-based residual diagnostics implemented in the DHARMa package (Hartig, 2022). All modelling procedures were performed in R (R Core Team, 2024), utilizing the base stats package for GLM fitting and complementary packages for spatial data handling and diagnostics.

3. Results

We compiled 38,606 occurrence records of wild felids from Brazil, retrieved from 13 open-access data sources (Appendix B, Table A). Following a thorough data cleaning process, we retained 14,341 valid occurrences, representing nine species. The majority of records were located in forested habitats (e.g., *P. concolor* with 2,209 and *L. pardalis* with 2,526 occurrences), with average depths of entry ranging from 331.9 m (*L. guttulus*) to 993.2 m (*L. pardalis*). Conversely, pasture and agricultural areas consistently yielded the lowest number of occurrences, with species such as *L. geoffroyi* and the Colocola complex exhibiting non or very few records in these habitats. Although less represented than forests, natural non-forest areas were still relevant for species like *L. geoffroyi* (213 records) (Appendix B, Table C).

3.1. Habitat selection

To clarify our species-specific habitat selection patterns, we grouped the models according to the three proposed ecological categories: generalists, flexible specialists, and strict specialists (Appendix A). Across spatial scales, models using pseudo-absence points at the 5-km buffer consistently outperformed those at 15 km and 30 km and were thus selected for reporting the results.

- Generalist species

Among generalist species, *Puma concolor* and *Herpailurus yagouaroundi* exhibited contrasting patterns regarding native and anthropogenic habitats (Figure 2). *P. concolor* displayed a higher probability of occurrence in forested ($\beta = 0.67$, $p < 0.001$) and natural non-forest habitats ($\beta = 0.88$, $p < 0.001$), based on presence/absence variables. Furthermore, *P. concolor* showed a tendency to be located closer to pastures ($\beta = –0.09$, $p < 0.001$) and agricultural areas ($\beta = –0.40$,

$p < 0.001$), suggesting a degree of tolerance to human-modified environments. In contrast, *H. yagouaroundi*, modelled using distance-based variables, was more frequently observed farther from both forested (β = 0.29, $p < 0.001$) and natural non-forest areas (β = 0.21, $p < 0.001$), indicating avoidance in the inner depth of these native habitats. The species also exhibited strong avoidance of pasture presence (β = –1.00, $p < 0.001$) yet occurred closer to agricultural areas (β = –0.48, $p < 0.001$), suggesting some level of tolerance to agricultural landscapes. *Leopardus geoffroyi* showed an association nearest to the forest cover (β = -0.16, $p < 0.05$) but tended to occur at greater distances from pasture (β = 0.45, $p < 0.001$) and natural non-forest vegetation (β = 0.45, $p < 0.001$). *L. geoffroyi* avoided agricultural areas, as indicated by a negative association with agricultural presence (β = –1.5, $p < 0.001$). These findings suggest that, despite being grouped as generalists, these species exhibit distinct habitat preferences and varying degrees of tolerance or avoidance in relation to anthropogenic landscapes.

- Flexible Specialist species

Flexible specialists exhibited variable responses to natural non-forest areas and anthropogenic habitats (Figure 2). *Leopardus pardalis* displayed significant positive selection for forested (β = 0.50, $p < 0.001$) and natural non-forest areas (β = 0.52, $p < 0.001$) while avoiding pasture (β = –0.70, $p < 0.001$). The species also occurred closer to agricultural areas, as indicated by the negative association with agriculture distance (β = –0.16, $p < 0.001$), suggesting a degree of tolerance to modified landscapes. *Panthera onca* showed a tendency to be at greater distances from forests (β = 0.45, $p < 0.001$) and pastures (β = 0.42, $p < 0.001$), potentially reflecting the utilization of intermediate or edge habitats. In contrast, *P. onca* was more frequently observed near natural non-forest vegetation (β = –0.71, $p < 0.001$), and strongly avoided agricultural areas, with occurrences concentrated at greater distances from such landscapes (β = 0.73, $p < 0.001$). The Colocola complex showed a negative association with forested areas (β = –0.44, $p = 0.09$) and avoided pasture when present (β = –0.77, $p < 0.05$), while being more likely to occur farther from agricultural lands (β = 0.25, $p < 0.001$), indicating apparent avoidance of highly modified environments. Natural non-forest vegetation had no significant effect ($p = 0.16$). These flexible specialists exhibited a broad spectrum of habitat responses, ranging from a strong affinity for native environments to an apparent avoidance of anthropogenic landscapes. The Colocola complex showed the most restrictive habitat use pattern within this group.

- Strict Specialist species

Strict specialists demonstrated consistently strong associations with natural habitats and general avoidance of anthropogenic landscapes (Figure 2). *Leopardus wiedii* exhibited a strong positive association with forest (β = 0.86, $p < 0.001$) and a negative association with natural non-forest areas (β = –0.68, $p < 0.001$), indicating a clear preference for forest habitats and avoidance of natural non-forest formations. This species also occurred farther from pastures (β = 0.34, $p < 0.001$), suggesting avoidance of these modified areas, while showing a higher probability of occurrence closer to agricultural zones (β = –0.45, $p < 0.001$), which may reflect some tolerance to agriculture edges or nearby transitional zones. *Leopardus guttulus* was significantly more likely to occur closer to forests (β = –0.44, $p < 0.001$) and avoided pastures (β = –0.68, $p < 0.001$). They were also found closer to agricultural areas (β = –0.55, $p < 0.001$), indicating that areas where they persist are inserted in forest-agriculture mosaics. However, their strong preference for proximity to forests suggests a dependence on native cover. *Leopardus tigrinus* exhibited a positive association with forested areas (β = 0.42, $p < 0.01$) and a tendency to occur farther from pastures (β = 0.69, $p < 0.001$), indicating a preference for forested areas and a tendency to avoid natural non-forest and anthropogenic areas. They also occurred closer to agricultural areas (β = –1.18, $p < 0.001$), suggesting that, despite their overall selectivity, they persist in areas with some degree of proximity to human-altered environments. The association for this species was not statistically significant for natural non-forest areas (β = -0.41, $p = 0.08$). Strict specialists consistently favored forested environments while avoiding open habitats such as pasture and natural non-forest vegetation. Notably, all three species showed higher occurrence probabilities closer to agricultural areas, which may reflect a complex interplay between edge effects, tolerance thresholds, and spatial constraints within the remaining fragments of native habitat.

3.2. Road effects

We analyzed the effect of road proximity on the occurrence of nine wild felid species in Brazil using generalized linear models (GLMs), with distance to roads as a continuous predictor variable. The proportion of records within 10 meters of a road varied considerably among species. *L. geoffroyi* exhibited the highest proportion of detections near roads (35.8%), followed by Colocola complex (22.6%), *H. yagouaroundi* (7%), and *L. wiedii* (5.3%). In contrast, *L. guttulus* and *P. onca* displayed extremely low proportions near roads (0.001% and 0.5%, respectively), suggesting apparent avoidance of road infrastructure. The remaining species showed intermediate proportions, with values of 1% in *P. concolor*, 2.4% in *L. pardalis*, and 4% in *L. tigrinus*. GLMs revealed substantial interspecific differences in responses to distance from roads (Appendix C, Road Effects). *P onca* showed a strong and significant positive relationship between road distance and occurrence probability (β = 2.11e-06, $p < 0.001$), indicating apparent road avoidance. This trend was also evident in *L. wiedii* (β = 8.98e-06, $p < 0.001$) and *L. geoffroyi* (β = 2.48e-2, $p < 0.001$), the latter being a generalist species, which suggests unexpected sensitivity to road proximity despite its functional classification. Conversely, *P. concolor* (β = -3.35e-06, p < 0.001), *H. yagouaroundi* (β = -4.36e-06, p < 0.001), and *L. tigrinus* (β = -1.71×e-05, $p < 0.001$) were the only species that exhibited significant negative associations with distance to roads, indicating a higher likelihood of occurrence near roads. These results may reflect greater tolerance or even selective use of areas near road networks or suggest that those species could persist in habitats with higher road densities. The remaining species, *L. guttulus*, *L. pardalis*, and the Colocola complex, showed no significant associations ($\beta = 5.81\times10^{-6}$, $p = 0.25$; $\beta = 2.21\times10^{-7}$, $p = 0.35$; $\beta = 9.37\text{e-}07$, $p = 0.88$, respectively), suggesting neutral responses or more complex patterns not captured by the simple univariate model applied. These findings underscore the need for species-specific mitigation strategies in road planning and wildlife conservation (Figure 3).

We further explored the spatial distribution and identified specific road segments where the three species exhibited the highest number of detections within 10 meters of the roads. *L. geoffroyi* was recorded on 23 distinct roads, with a notable concentration of up to 30 detections along a single route near Estação Ecológica do Taim in Rio Grande do Sul. *L. pardalis* was detected along 33 different roads, with up to 12 occurrences each on two separate routes, one located in São Paulo State and the other in Mato Grosso do Sul. *H. yagouaroundi* exhibited the widest distribution near roads, recorded on 54 different routes, including four key roads in Rio Grande do Sul, where they were detected with a frequency of five to seven times per road (Figure 4). Other relevant observations were the frequent presence of *P. concolor* on 24 roads, one with seven frequencies close to 10 meters, on the road from Ilha Solteira to Rio Claro in São Paulo. *P. onca* was observed on five roads and at five frequencies on the road located in the Encontro das Aguas State Park, Mato Grosso. Complexo colocola, on 13 roads, two of them with five frequencies on roads near Miranda, Mato Grosso do Sul, and one road near Alegrete, Rio Grande do Sul. Finally, *L. wiedii* was observed on 34 roads, one with seven frequencies near Porto Alegre, Rio Grande do Sul (Codes proposed by DNIT in Appendix C - Supplementary Material).

Discussion

Our results indicated that the proposed functional classification and tested hypothesis, based on ecological literature and general ecological plasticity trends, had predictive value, although not entirely independent. Regarding hypothesis H1 (generalists tolerate anthropogenic environments and roads), we observed that species classified as generalists, such as *Puma concolor* and *Herpailurus yagouaroundi*, demonstrated greater tolerance to anthropogenic habitats, including agriculture, pasture, and proximity to roads. However, unexpectedly, *Leopardus geoffroyi*, also categorized as a generalist, showed avoidance patterns for modified areas and proximity to forests, suggesting a stricter preference for forests or an underestimated sensitivity potentially linked to its restricted distribution in Brazil. For hypothesis H2 (flexible specialists preferentially select natural habitats and less anthropogenic environments), species such as *Leopardus pardalis* and *Panthera onca*, as predicted, primarily selected natural habitats. While *P. onca* showed an apparent preference for natural non-forest vegetation and avoidance of forest, this could reflect the utilization of forest edge habitats or the influence of anthropogenic pressure on their current distribution. Species within the Colocola Complex exhibited a conservative response, apparently avoiding anthropogenic environments. Notably, all species in this category tended to avoid roads. These findings reveal that even within this group characterized by higher ecological plasticity in habitat use, distinct species-specific strategies exist, suggesting that habitat loss and fragmentation do not produce homogeneous responses and presence in habitat mosaics does not necessarily imply functional adaptation or long-term population persistence. Finally, strict specialists (*L. wiedii, L. guttulus*, and *L. tigrinus*) corroborated our hypothesis H3 (dependent on specific habitats with low tolerance to landscape modification) by exhibiting a clear preference for forest habitats and avoidance of open areas, including pasture and natural non-forest vegetation. However, these species' utilization of areas near agricultural land suggests a complex interplay between dependence on native habitat, edge effects, and limitations within the available landscape. Among these species, *L. tigrinus* showed a positive response to proximity to roads. Below, we discuss how each ecological group responded to habitat and infrastructure variables and the conservation implications of these patterns.

Although *P. concolor*, *H. yagouaroundi*, and *L. geoffroyi* were grouped as generalists based on ecological traits compiled from the IUCN and literature, our results, in line with previous literature, further demonstrate that generalist traits alone cannot predict consistent responses to anthropogenic landscapes. Despite the resilience of *P. concolor* to land-cover change and anthropogenic pressure, studies in Neotropical ecosystems underscore the importance of forested habitat patches for the species (Nanni et al., 2023; Azevedo et al., 2020; Coon et al., 2020; Angeliere et al. 2016). Furthermore, some studies also suggest the necessity of considering factors beyond land cover, emphasizing prey availability as critical for ensuring the long-term persistence of pumas within human-modified areas (Magioli and Ferraz, 2021; LaBarge et al., 2022; Azevedo et al., 2025). *H. yagouaroundi* appears more constrained, avoiding open areas and forest interiors and relying on dense vegetation near agricultural edges (Giordano, 2015), contrary to recent findings by Harmsen et al. (2024), who reported positive associations with non-tree vegetation and human land-use. These contrasting findings may reflect regional or scale-related differences in habitat use, but they also emphasize the species' potential vulnerability to landscape alterations. Supporting this, a global assessment of road impacts on carnivores identified *H. yagouaroundi*, *P. concolor*, and *P. onca* among the top 5% of species most exposed to road expansion, with 60%, 69%, and 38% of their respective distributions affected (Ceia-Hasse et al., 2017). *L. geoffroyi*, despite its generalist classification, avoided natural non-forest and human-modified habitats and had a negative association with road proximity. Studies have shown that *L. geoffroyi* concentrates its activity in riparian forest remnants and avoids human infrastructure despite being present at relatively high densities (Tirelli et al., 2019). This response may suggest finer-scale specialization or ecological constraints, potentially influenced by edge-of-range dynamics (Doherty et al., 2003). Alternatively, the pattern of our result could also reflect limitations in detection or data availability in certain habitat types rather than actual ecological intolerance (Tensen, 2018). Such findings underscore the limitations of functional classifications when not complemented by species-specific behavioral and distributional data.

The species classified as flexible specialists in our study, *Leopardus pardalis, Panthera onca*, and the Colocola complex, exhibited contrasting strategies in their interaction with human-modified landscapes. *L. pardalis* maintained strong associations with native vegetation but also showed some tolerance to agricultural zones, a pattern consistent with prior studies emphasizing its reliance on dense cover for concealment and prey capture while occasionally using edge habitats (Sergeyev et al., 2023; Wang et al., 2019). *P. onca*, although capable of wide-ranging movement and behavioral plasticity, showed consistent avoidance of roads in our study, suggesting high sensitivity to infrastructure across broad spatial scales. These results contrast with telemetry-based studies that have reported jaguars occasionally using roads or their edges, particularly at night or during territorial or reproductive movements (Alegre et al., 2023, 2024; Cerqueira et al., 2021; Morato et al., 2018). However, such use has been described as brief and associated with increased movement speed, suggesting that roads are tolerated but not selected (Alegre et al., 2024). Moreover, our data indicated a stronger selection by jaguars for natural non-forest areas, which may seem contradictory given their known preference for forests. This pattern is likely influenced by the spatial distribution of our records, which were heavily concentrated in regions such as the Pantanal and transitional zones, where jaguar populations are known to occupy a diversity of habitats, including open wetlands and savannas (Alvarenga et al., 2021) In contrast, the Amazon biome, which holds the largest and continuous habitats that harbour most stable jaguar populations globally (Alvarenga et al., 2025; Jedrzejewski et al., 2023), was underrepresented in our dataset. Moreover, jaguars are closer to extinction in the Atlantic Forest, a forest-dominated biome (Paviolo et al., 2016). This geographic bias may have skewed our findings towards more open biomes, underestimating forest associations observed in Amazonian populations. These observations underscore the importance of considering both habitat availability and sampling distribution when interpreting large-scale patterns of habitat selection. Lastly, the Colocola complex showed the most restrictive pattern within this group, avoiding forested and agricultural areas, suggesting a narrower niche than previously assumed. Their distribution is associated with naturally open-vegetation biomes such as the Pampa, Cerrado, and Pantanal (Lucherini et al., 2016). However, our findings advance the understanding of this wildcat species complex, whose habitat use remains one of the least documented among felids in Brazil. This behavior may reflect ecological specialization within specific complex lineages (Nascimento et al., 2021), calling for conservation actions that account for taxonomic uncertainty and local ecological requirements. These findings highlight the need to recognize cryptic diversity and localized specialization within this complex, moving beyond coarse taxonomic units in conservation planning.

The strict specialists in our study, *Leopardus wiedii, L. guttulus*, and *L. tigrinus*, consistently selected forested habitats and avoided open or modified environments, highlighting their strong reliance on forest. *L. wiedii* showed a clear preference for dense forest and avoidance of natural non-forest and pasture areas, aligning with its arboreal and cryptic behavior, likely contributing to its low detectability in camera trap surveys (Harmsen et al., 2021). *L. guttulus*, restricted to the Atlantic Forest, was strongly associated with high forest cover and showed limited use in non-forest areas. Although it may tolerate mosaics that include small-scale agriculture, its occurrence is tightly linked to the availability of continuous forest habitat (Sartor et al., 2024; de Oliveira et al., 2024). Habitat models and genetic analyses reveal that populations are fragmented and genetically isolated, particularly in southern Brazil, and may not remain viable without increased connectivity between forest patches (de Oliveira et al., 2024). *L. tigrinus,* while similarly forest-dependent, exhibits a slightly broader tolerance for more open biomes such as the Cerrado and Caatinga but remains constrained to structurally complex habitats with vegetation cover (Oliveira-Santos et al., 2012). Overall, these patterns reinforce the idea that strict forest specialists among Neotropical felids are highly vulnerable to habitat loss and fragmentation and that conservation efforts should focus on protecting remaining forest blocks and restoring ecological corridors to sustain long-term population viability.

Our findings underscore the ecological diversity and functional disparity among Neotropical cats when confronted with human-altered environments. While some species showed tolerance to modified landscapes, others exhibited marked avoidance, even within the same functional group, highlighting the limitations of assuming uniform responses across taxa. These patterns result from a complex interaction between species traits and human pressures' structure, intensity, and spatial configuration. For example, agricultural complexity, such as crop type, structure, size, and proximity to native areas, as well as chemical use, could influence cats' ability to traverse or utilize agricultural matrices (Fischer and Lindenmayer, 2007; Sanches et al., 2021). Our findings reinforce the idea that land-use impacts should not be considered in binary terms but rather as gradients of ecological pressure. While the functional classification proposed here did not fully predict individual species' responses, it was a valuable framework to highlight general trends, identify deviations from expected patterns, and guide comparative assessments. As such, it offers a complementary tool for anticipating potential vulnerabilities, prioritizing monitoring efforts, and informing conservation strategies in dynamic and heterogeneous landscapes. Therefore, landscape conservation must integrate structural complexity, spatial connectivity, and species-specific needs to maintain felid functional diversity.

Also, integrating open data from multiple platforms, as applied herein with 13 data sources, proves to be a robust and scalable alternative for assessing habitat selection and sensitivity in data-deficient tropical systems. In a country with continental dimensions such as Brazil, maintaining long-term, standardized field monitoring presents considerable challenges. Despite some limitations, access to continuous information from diverse sources enables a more comprehensive understanding of changes in species distribution and the effects of environmental transformations, facilitating the identification of priority areas and informed conservation actions. Furthermore, a more accurate analysis of habitat selection can significantly contribute to the future assessment of feline extinction risk, supporting effective management and conservation strategies. This analysis is particularly important for environmental agencies responsible for global, national, and regional species assessments.

However, we also recognize the limitations associated with working with open-access data. These datasets are often biased toward areas with greater accessibility, including protected zones, and may reflect uneven observer effort, detection probability, and temporal sampling (Tensen, 2018). Furthermore, given Brazil's continental dimensions, the sampling and availability of open data may be influenced by regional political and economic factors, such as the concentration of research funding in the southeast region compared to other areas (Oliveira et al., 2016). For instance, camera trap studies are frequently concentrated in specific areas, avoiding more anthropized areas to prevent theft or loss. Despite these limitations, the preliminary insights presented in this study offer a valuable starting point for refining future monitoring strategies, identifying ecological knowledge gaps, and enhancing the focus of research efforts on underrepresented felid species. Moreover, this approach provides a foundation for developing evidence-based conservation proposals and long-term ecological studies.

Implications for Felid Conservation

Our findings provide a framework for prioritizing conservation actions in Brazil's diverse wild cat community. We identified key vulnerabilities and adaptive potential by distinguishing species based on their ecological strategies and responses to human-modified landscapes. Generalist species such as *Puma concolor* and *Herpailurus yagouaroundi* can persist in modified habitats, provided remnants of native vegetation and structural heterogeneity are maintained (Azevedo et al., 2020; LaBarge et al., 2022). For these species, conservation planning should emphasize biodiversity-friendly land uses, including agroforestry, riparian corridors, and mixed-use matrices (Fischer & Lindenmayer, 2007). However, *Leopardus geoffroyi*, also categorized as a generalist, consistently avoided modified open habitats, including roads, suggesting fine-scale specialization or regional ecological constraints. As such, conservation measures for this species must go beyond the generalist label and prioritize protecting and restoring riparian and forest fragments (Tirelli et al., 2019), creating road-free buffer zones, and actively mitigating rural threats, including hunting, poisoning, and habitat degradation. These efforts are particularly critical in ecotonal regions and the northern edge of its distribution, where populations are more isolated and conservation attention remains limited.

Flexible specialists such as *Panthera onca*, *Leopardus pardalis*, and the Colocola complex demonstrate sensitivity to habitat and infrastructure disturbance. However, they were recorded in heterogeneous landscapes, suggesting that their persistence may be influenced by residual habitat continuity or proximity. Although explicit connectivity metrics were not assessed in this study, the observed occurrence patterns are consistent with the idea that specific landscape configurations can facilitate movement or occupancy. This reinforces the relevance of landscape planning tools, such as corridor design, road mitigation, and buffering of core habitats, to support ecological processes likely required by these species, including dispersal and gene flow (Hilty et al., 2020). In the case of the Colocola complex, where environmental and taxonomic uncertainties persist, flexible conservation units and regional monitoring are key to avoiding overlooking unique lineages (Crandall et al., 2000). Strict forest specialists, *L. guttulus, L. wiedii*, and *L. tigrinus*, remain the most vulnerable under current land-use trends. These species require large contiguous forest blocks, functional landscape connectivity, and strict native habitat protection to ensure long-term persistence. Their limited plasticity and fragmented ranges increase their susceptibility to local extinctions, even in landscapes with apparent habitat mosaics. Lastly, it is essential to consider the landscape scale, as habitat connectivity may be perceived differently depending on the species' body size.

Finally, our study highlights the heuristic value of using functional classifications to structure hypotheses and identify general patterns across species. While this framework proved helpful in guiding our analyses and discussion, our results also underscore that functional groupings do not fully determine species responses. Therefore, addressing conservation gaps will require species-specific assessments that consider local ecological and geographic contexts and improved data coverage in under-sampled regions such as the Pampas, the Caatinga, and the interior Amazon. Integrating open-access biodiversity data with information on landscape structure and function can enhance the effectiveness and equity of conservation planning. Although functionally informed strategies provide a valuable starting point, the long-term persistence of vulnerable felids, including strict forest specialists and potentially overlooked flexible species like the Colocola complex, depends on tailored, context-specific conservation actions.

Beyond species-specific recommendations, our findings offer a strategic tool for national-level conservation planning. They contribute directly to Brazil's National Action Plans for the Conservation of Small and Large Felids (PAN Pequenos Felinos and PAN Grandes Felinos; ICMBIO, 2024a, b), particularly by addressing key knowledge gaps related to habitat use, road sensitivity, and species-specific vulnerabilities. By integrating open-access data with spatially explicit modelling, this work supports core actions outlined in both PANs, including the identification of anthropogenic pressures, developing predictive habitat models, and improving conservation planning in under-sampled regions. Furthermore, these functionally informed, data-driven strategies align with global conservation priorities such as the IUCN Global Species Action Plan (IUCN, 2023), which highlights the importance of adaptive planning and integrative data use for threatened species management.

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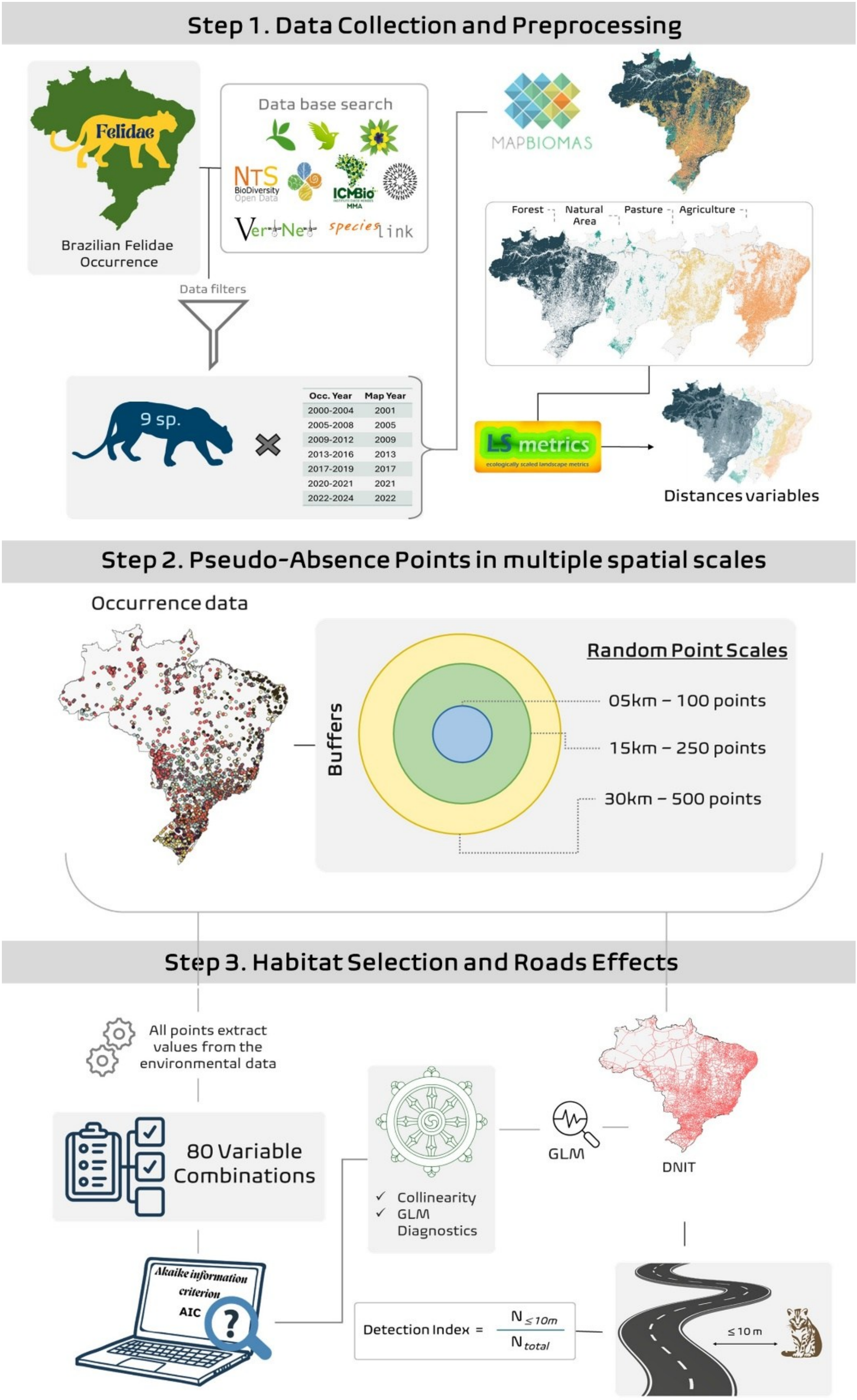

Figure 1. Workflow: Step 1: Collect data and preprocess environmental variables. Step 2: Prepare the dataset for the models according to species, year, and coordinates. Step 3: Use the dataset to run the habitat selection and road effect models.

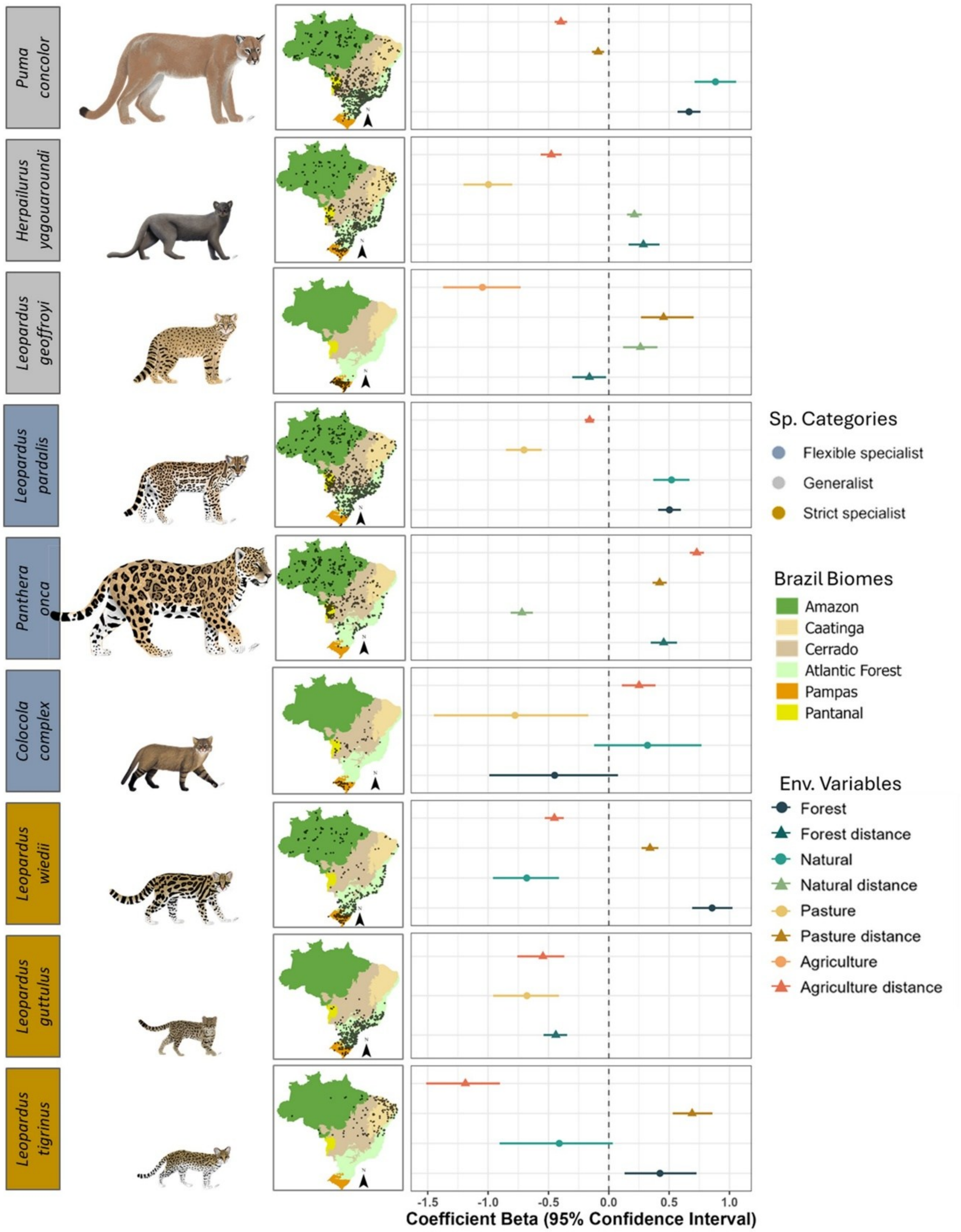

Figure 2. Species are organized into categories, along with their data distribution maps in the different Brazilian biomes. Beta coefficients estimated from the habitat selection model for the different species. Positive binary values indicate habitat selection, while negative ones indicate avoidance. The values correspond to the distances to landscape elements. Negative beta coefficients indicate selection of habitats close to said elements, while positive ones indicate selection of more distant sites. The graphs by coefficient are found in Supplementary Material, Appendix B, figure A. Illustrations of the cats by Ricardo Ribeiro da Silva.

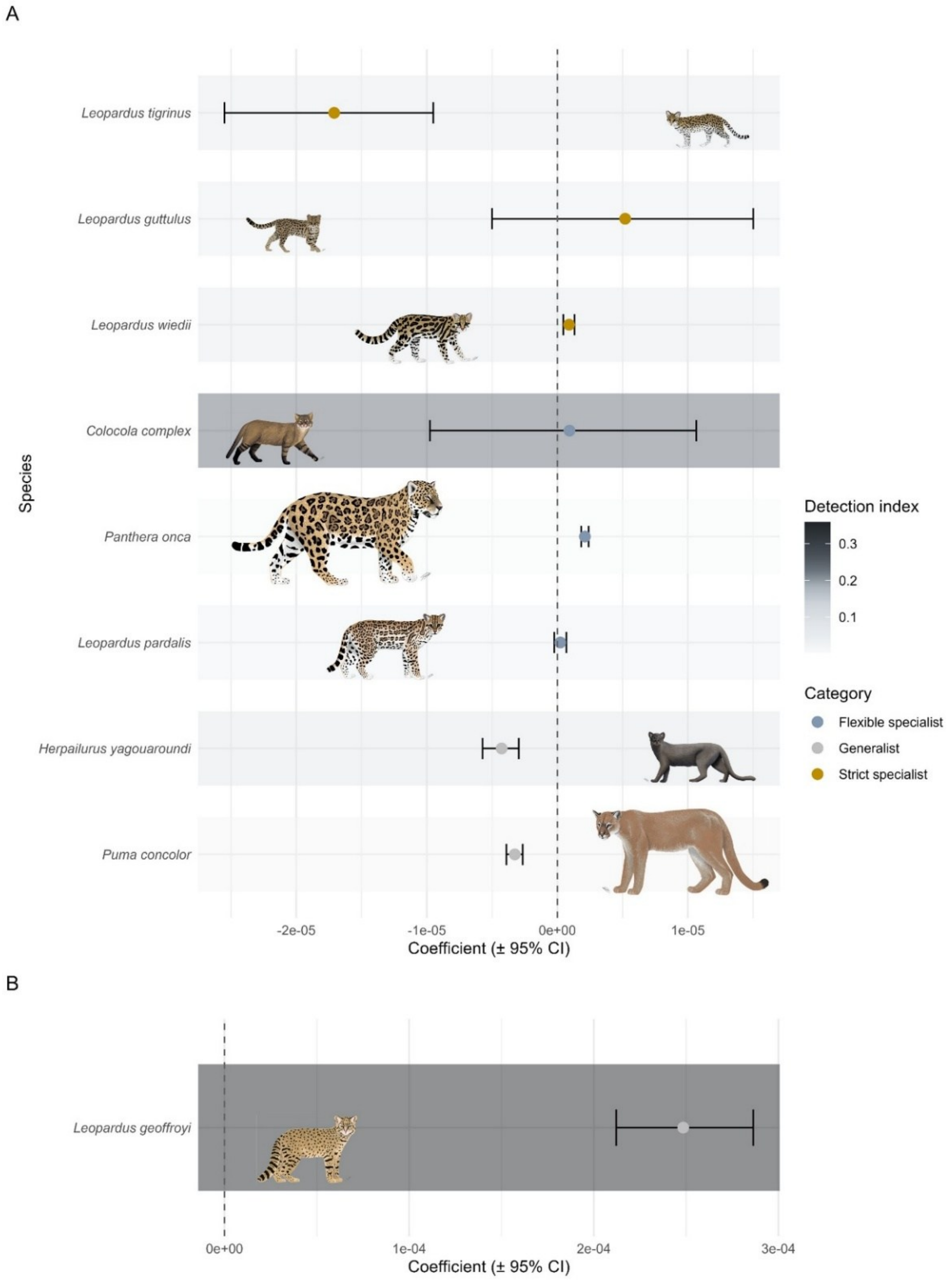

Figure 3. Beta coefficients are estimated from the road effects model for all species. Values correspond to distances to roads. Negative beta coefficients indicate proximity to roads, while positive beta coefficients indicate more distant selection. Species categories are shown in three different colors, and the species detection index according to our data is shown in gray gradients. For a better appreciation of the figure, A and B were created to highlight the limits of the coefficients, with B for Leopardus geoffroyi exhibiting greater detectability than the others. Illustrations of the cats by Ricardo Ribeiro da Silva.

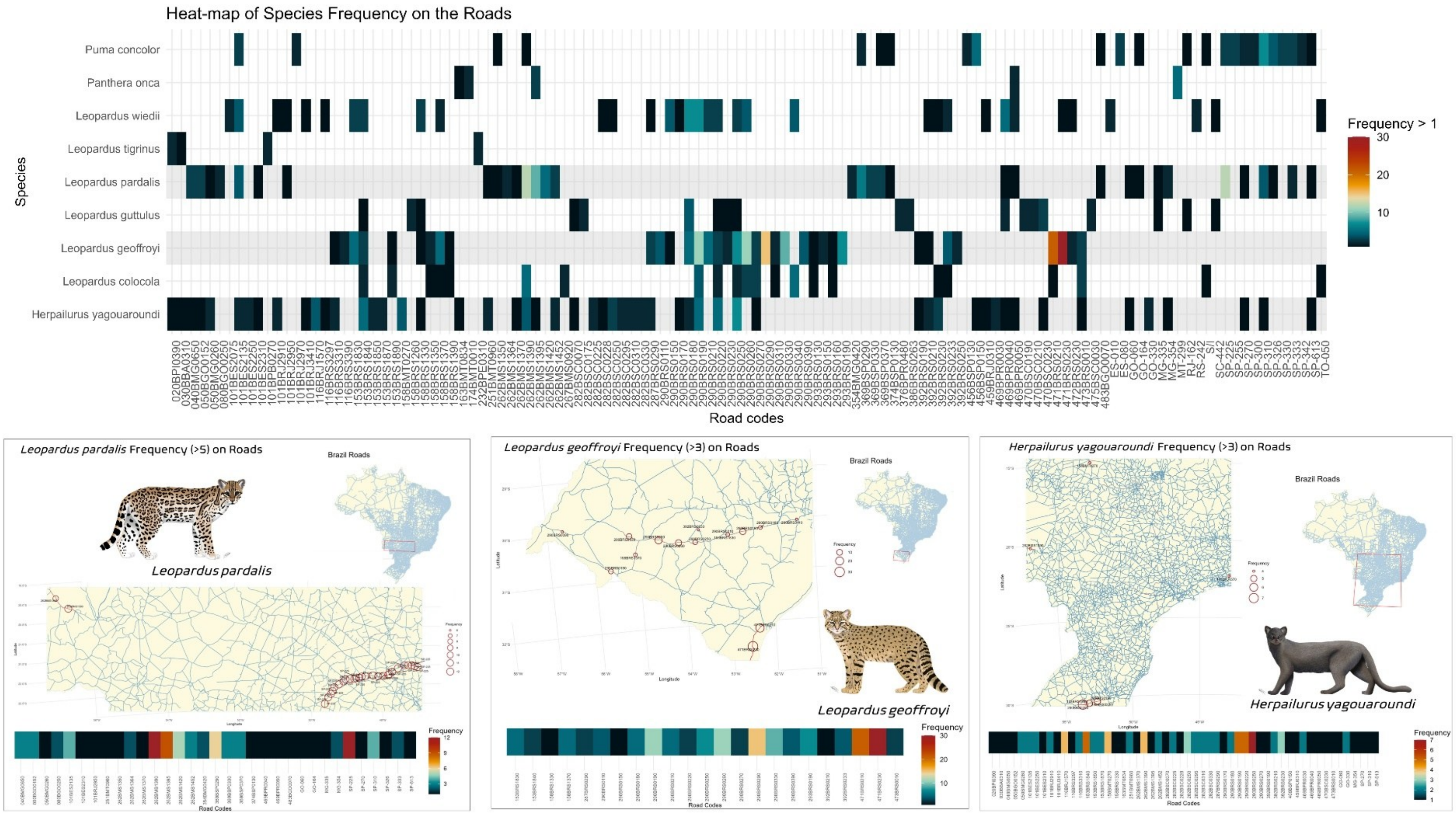

Figure 4. Heat map showing the frequency of recorded data by species along a specific road, identified by its codes. The gray lines in the background highlight the three species with the highest data frequencies on these roads (top). These three species have the highest frequencies on roads no wider than 10 meters. From left to right, they are: *Leopardus pardalis* (map representation with more than five recorded data frequencies), *Leopardus geoffroyi*, and *Herpailurus yagouaroundi* (both map representations with a data frequency of three times). Below each figure, the total data frequencies and corresponding codes for each species are shown (bottom). For viewing more details in the figures by species, see the supplementary material, Appendix C. Illustrations of the cats by Ricardo Ribeiro da Silva.