Identifying hotspots and priority areas for xenarthran research and conservation

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Abstract

Aim: Limited funds for conservation and research require the development of prioritization schemes. Traditionally, biodiversity metrics were used to delineate priority areas; however, a growing realization emphasizes that logistic factors should be also considered. Here, we combine species richness, past collection efforts, degree of habitat loss and accessibility to define priority areas and spatially orient fieldwork in a cost-effective manner for xenarthrans.

Location: Neotropics.

Methods: We assessed spatial patterns of species richness in Xenarthra and identified diversity hotspots based on species distribution models. Spatial patterns and biases in the Xenarthra past collection efforts were analysed using a comprehensive database including 33,464 individual records for 34 species of Xenarthra. Finally, we produced priority area indices relating species richness and collection efforts with levels of habitat loss and accessibility (roads and rivers network) to highlight important but neglected areas.

Results: Collection efforts were concentrated to a small portion of the Neotropics (central-western Brazil, eastern Bolivia and north-western Argentina) and were biased towards access routes. Only 4% of the Neotropics can be considered well sampled. Major xenarthran diversity hotspots include the Amazonian lowlands of Bolivia and the dry Chaco of Paraguay and Argentina. Priority areas for research varied depending on the metric analysed. Amazon holds a high diversity that remains poorly explored. Central Argentina and eastern Brazil are priority areas for research and conservation given the low sampling efforts, high diversity and endemic species, high levels of habitat loss and a dense road network.

Main conclusions: Most areas of the Neotropics lack a proper assessment of the xenarthran assemblage, reflecting extensive knowledge shortfalls. Sites close to roads tend to be better sampled, but many areas with a dense road network are undersampled, being good candidates for low-cost studies. Xenarthra diversity hotspots facing the highest levels of habitat alteration are the least protected and are priority for both research and conservation. Simultaneous efforts of data collection and conservation actions across most of the xenarthran range should be stimulated.
INTRODUCTION

One of the main struggles in biodiversity conservation is the limited resource. As a consequence, scientists need to find ways to prioritize species and areas to devote their efforts (Brooks et al., 2006; Marchese, 2015). Species prioritization has been traditionally based on levels of extinction vulnerability, in which highly threatened taxa are given priority for research and conservation actions. Similarly, priority areas for research and conservation are often based on regions with elevated biodiversity, endemism and habitat loss (Brum et al., 2017; Galetti et al., 2009; Myers et al., 2000; Nori et al., 2018).

Nonetheless, there is a growing realization that research prioritization schemes should also consider logistic limitations (Schmitt, 2011), especially in developing nations where resources are scarce, but biodiversity and habitat loss are high. For example, the availability of access routes is an important parameter as field collections in remote and inaccessible regions have elevated costs associated. Defining priority areas for research and conservation management is thus of foremost importance given the limited funding, but socioeconomic and operational metrics should be incorporated to make it feasible (Brooks et al., 2006; Marchese, 2015).

The Neotropical realm harbours one of the highest biodiversity in the globe (Antonelli et al., 2018; Túnez et al., 2021) and includes eight of the 34 world's biodiversity hotspots (Mittermeier et al., 2011). This region spans from Mexico to southern South America and encompasses contrasting biomes, from the dense Amazon forest and seasonally dry forests to savannahs and the arid Atacama Desert. Among its typical fauna, xenarthrans (armadillos, anteaters and sloths) represent one of the four main branches of the placental mammalian radiation and are the only originated in South America (Gibb et al., 2016). Living xenarthrans occur across most of the Neotropics, with most species being either forest- or open-area dwellers, but some taxa exhibit a continental range and can be found in diverse habitats (Gardner, 2008). They are unique among mammals in exhibiting xantharthous vertebrae, dural ossification, absence of enamel on adult teeth and low metabolic rates (Vizcaíno & Loughry, 2008). Their evolutionary uniqueness reflected in odd morphology and physiology must place modern xenarthrans as a high priority for conservation (Aguir & Fonseca, 2008; Superina & Loughry, 2015; Superina et al., 2014). The ecosystem services provided by armadillos, sloths and anteaters (e.g. bioturbation, pest control, soil engineering, nutrient cycling) further highlight their importance in ecological systems throughout the Neotropics (Montgomery & Sunquist, 1975; Rodrigues et al., 2020).

Of the 38 Xenarthra species now recognized, only 12 are listed as Least Concern by IUCN Red List; the remaining are Near Threatened (four), Vulnerable (four), Critically Endangered (one), Data Deficient (five), or their extinction risk has not yet been reevaluated in light of recent taxonomic changes (12). Habitat loss caused by increasing agricultural activities, logging and urbanization is one of the main threats faced by xenarthrans. In addition, they are heavily hunted across their range for food resources as well as for pets, medicinal and religious purposes (Aguir & Fonseca, 2008; Fernandes-Ferreira, 2014; Superina & Abba, 2020). Successful conservation actions rely on well-founded knowledge of species’ life history to guide effective strategies. However, natural history information for most of the Xenarthra species is scarce and, when available, often limited to a few short-term studies or based on captive animals (Chiarello, 2008; McDonough & Loughry, 2008; Superina et al., 2014). Even for widespread taxa, available data are mostly derived from studies from few localities or a particular biome and may not reflect how the species respond under distinct environmental conditions (Diniz & Brito, 2012; Loughry & McDonough, 2013). Therefore, the effectiveness of actions for conserving xenarthrans may be hindered by extensive knowledge shortfalls. To help fill these gaps and guide scientific projects, previous studies have highlighted the most needed topics and defined priority species for research (Diniz & Brito, 2012; Loughry & McDonough, 2013; Superina et al., 2014). However, no attempt has been made to define priority areas and spatially orient fieldwork across the Neotropics in a cost-effective manner.

Here, we combine distinct parameters to identify priority areas for Xenarthra research and conservation. Specifically, we incorporate information on past collection efforts, species richness, availability of access routes and protected areas and levels of habitat alteration. Our first step was to analyse prior collection efforts and quantify sampling lacunas and associated biases using an extensive individual-occurrence database. Secondly, we estimate local Xenarthra diversity across the Neotropics by stacking species distribution models. Finally, we relate spatial patterns of collecting effort, species richness, habitat alteration and availability of protected areas and access routes to delineate priority areas for future studies. Our main objective is to reveal sites with elevated diversity and high deforestation levels that are poorly studied but around areas of easy access. In addition, using our Xenarthra richness map, we highlight hot- and coldspot zones that can guide conservation actions.

METHODS

2.1 | Species occurrence data

Collection records were retrieved from the Neotropical Xenarthrans data set that includes 42,528 records derived from studies based on camera trapping, roadkill surveys, active searches, live trapping, museums, among others (see Santos et al., 2019). This data set represents the most comprehensive assemblage of Xenarthra records.
to date, including studies developed in the whole Neotropical region, and it was thoroughly revised by experts. We complemented this data set with additional records from recent studies (Feijó & Anacleto, 2021; Feijó et al., 2019). Species classification for Cyclopes and Cabassous was updated following Miranda et al. (2018) and Feijó and Anacleto (2021) respectively.

After excluding records with uncertain species identification (classified as ‘sp.’) and with a high level (above 20 km) of imprecision in the geographic coordinates, the final data set comprises 33,464 individual records for 34 species of Xenarthra, ca. 85% of the records are within 1 km precision and ca. 80% were collected in the last 20 years. Four species were not included because of the restricted insular distribution (Bradypus pygmaeus) or because of few records available and unclear distribution limits (Cyclopes rufus, Cyclopes ida, Cyclopes xinguensis).

2.2 | Spatial collection effort

Using the filtered xenarthran data set, we quantified the density of records in the Neotropics at a 100-km grid resolution to characterize collection effort patterns. In addition, we used the Getis-Ord Gi* (Gi*) statistics (Getis & Ord, 1992) implemented in ArcGIS Pro software to identify collection hotspots; that is, grid cells that show a higher density of records relative to the mean than expected by chance. Details of Gi* statistics can be found elsewhere (Getis & Ord, 1992; Nelson & Boots, 2008; Ord & Getis, 1995; Sussman et al., 2019). In short, it represents a local measure of spatial autocorrelation that assesses the statistical significance of observed grid values against null models. Hotspots thus represent significant clusters of extreme high values relative to the global mean that have unlikely arisen by chance. Gi* was calculated using the eight shared-boundary grid cells as spatial neighbourhoods and we applied the false discovery rate correction to assess the statistical significance of observed hotspots while accounting for the spatial dependency in the data (Nelson & Boots, 2008).

2.3 | Collection effort biases

We explored potential factors associated with the spatial distribution of xenarthran records by testing whether the proximity of cities (population greater than 10,000 habitants), access routes (roads and navigable rivers) or protected areas (PAs) can explain the observed pattern. We first computed the Euclidean distance of each record to the nearest predictor (river, road, city and PA) and compared it with 100 null models via Mann-Whitney following Oliveira et al. (2016). The null models were defined by sampling 33,464 random points across the Xenarthra range in the Neotropics (the same number as in the observed data set) and calculating their Euclidean distance to the nearest predictor. Moreover, to assess differences in collection bias across distinct biomes, we further split the Neotropics into five ecoregions and performed the analyses separately. The five ecoregions are tropical grasslands/seasonally dry forests (representing the Chacoan dominion; Morrone, 2014), temperate grasslands, Amazon, Atlantic Forest and Central America. The data set of roads was based on Meijer et al. (2018) and includes paved and unpaved highways, primary, secondary, tertiary and local roads. Navigable rivers were based on HydroSHEDS database available at the Global Runoff Data Centre (GRDC, 2020). For PAs’ limits, we used the World Database on Protected Areas (UNEP-WCMC & IUCN, 2019), which includes national, subnational, private and indigenous protected areas. Cities’ populations and coordinates were retrieved from geonames.org.

Additionally, we quantified the degree of spatial aggregation of xenarthran records with those of the potential factors. As above, we calculated the density for each predictor at 100-km grid resolution (see Figure S1) and computed correlation coefficients while accounting for the spatial association between data sets using modified t-test function implemented in the SpatialPack R package (Vallejos et al., 2020).

2.4 | Xenarthran richness map

A critical component when defining priority areas is to consider species richness (Marchese, 2015). Here, we estimate the Xenarthra richness based on stacked species distribution probabilistic models (SDM). This approach provides a more reliable estimation of local diversity when compared to stacking species range polygons (e.g. from IUCN) (Hughes et al., 2021). Additional advantage of using species-specific suitability models, instead of binary (presence/absence) maps, is to reduce biased predictions of species richness (Calabrese et al., 2014) and to reveal distinct levels of habitat suitability related to environmental conditions across species range (Harvey et al., 2017).

For each of the 34 taxa, we compared a set of Maxent models using the ‘maxnet’ algorithm implemented in the ENMeval 2.0 R package (Kass et al., 2021). To reduce spatial correlation and sampling bias (Feeley & Silman, 2011), we excluded duplicated localities within 2.5° arc-min grid resolution, the same spatial resolution of the environmental layers used. This more coarse resolution was preferred given the variety of methods used to record species occurrence (Santos et al., 2019). Models vary in complexity and include regularization multipliers ranging from 1 to 5 with five combinations of feature classes (L, LQ, LQH and H; where L = linear, Q = quadratic, H = hinge). We select 13 less correlated (r < .8) climate predictors from the full set of 19 layers obtained from WorldClim at 2.5 arc-min spatial resolution (Fick & Hijmans, 2017). Isothermality, temperature annual range, mean temperature of warmest quarter and coldest quarter, precipitation of wettest and driest quarter were discarded because of their high collinearity with the other layers. We also included elevation and mean annual leaf area index (LAI) as environmental predictors given that most of the xenarthran distributions are constrained by mountain ranges and most species are either restricted to forest or open biomes. LAI monthly estimation was
retrieved for the year 2020 and used here as a proxy of vegetation type (Myneni & Knyazikhin, 2018; Rocha et al., 2015).

The performance of our models was tested by partitioning the localities into testing and training bins using the ‘checkerboard2’ method. Five thousand background points were randomly selected for model training from a buffer area that extended five decimal degrees from the most marginal records. The best model was selected based on spatial cross-validation metrics using the lowest average 10 percentile omission rate followed by the highest area under the curve (AUC) average. Models had overall low omission rates and high AUC (Table S1), indicating low overfit and high performance in discriminating occurrences from background points (Phillips et al., 2006). Individual SDM are provided in Figure S2 and available at Dryad Digital Repository (10.5061/dryad.2rbnzs7ph).

To produce the Xenarthra richness map, we used the logistic output of each species’ best model in which the probability of presence varies from 0 to 1 and allows direct comparison across models (Phillips & Dudík, 2008). Each logistic output was masked with a five-degree buffered convex hull based on species-specific occurrence points and constrained considering known geographic barriers to dispersal, such as the Andes and major rivers. The rationale for limiting the logistic output is to provide a better approximate estimation of the species’ occupied areas while avoiding potential but inaccessible regions (Peterson & Soberón, 2012). Additionally, to reduce overprediction in species-poor areas, grid cells with suitability values lower than the minimum training present threshold were removed. The 34 final SDM suitability outputs were then stacked to produce the Xenarthra richness map. Finally, based on the stacked output, we calculated the average Xenarthra richness at 100-km grid resolution to relate to the previous collection and predictor density maps. Areas outside of the known range of the group (e.g. Pacific coast of Chile) were removed. Xenarthra richness map shapefile is available at Dryad Digital Repository (10.5061/dryad.2rbnzs7ph).

2.5 | Hotspots delimitation

Based on the Xenarthra richness map, we applied two approaches to reveal the diversity hotspots. Areas holding an exceptional species diversity were identified and compared based on the top 10% quantile richest grid cells and the Gi* statistics (Ceballos & Ehrlich, 2006; Harvey et al., 2017). In addition to revealing the hotspot zones, the Gi* approach also identifies coldspots, that is, areas with significantly lower species diversity relative to the global mean. Despite low diversity, coldspots carry important conservation value given the presence of rare species (Le Roux et al., 2019) and were also considered here.

2.6 | Priority areas for Xenarthra research and conservation

To identify priority areas for future research on Xenarthra, we relate four metrics (species richness, availability of access routes (combining roads and river), degree of habitat alteration and presence of protected areas) with sampling effort. For habitat alteration, we used the recent data set of global human modification (Figure S1e; Theobald et al., 2020). This data set incorporated numerous human impacts on the environment (e.g. urbanization, crop and pasture lands, livestock grazing, logging, mining, roads) to estimate the current degree of habitat alteration across the globe (see Theobald et al., 2020). We consider priority areas those with high diversity, high levels of habitat alteration, closer to access routes or protected areas that have been poorly sampled. To avoid bias associated with distinct units, density grid values were normalized from 0 to 1. For each metric, we calculated an individual index dividing the normalized values by the log-transformed sampling effort, producing a 0–1 scale where values close to one indicate a higher density of each metric but lower sampling effort. Finally, we produced a unified index that incorporates information of all four metrics. The unified index was calculated as the ratio of the arithmetic mean of species richness, routes, habitat alteration and protected area normalized values with the log-transformed sampling effort.

Priority areas for conservation were detected by overlaying the map of Xenarthra diversity hotspots with that of human alteration and protected areas in order to highlight rich but unprotected lands that are facing high levels of habitat loss.

Spatial analyses were performed in the R software (R Development Core Team, 2021) using mainly sf (Pebesma, 2018) and raster (Hijmans, 2021) R packages. Maps were transformed to an equal-area projection (Mollweide) prior to analyses.

3 | RESULTS

3.1 | Collection effort spatial distribution and underlying drivers

The spatial distribution of Xenarthra records is concentrated to a small portion of the Neotropics and biased towards access routes. About half of the Neotropics have no records, and only ca. 6% of the entire region has more than 50 individual records at a 100-km grid resolution (Figure S3). Records are mainly distributed in central-southern Brazil, Uruguay, eastern Bolivia and north-western Argentina (Figure 1). The Amazon region, Central America, north-eastern Brazil and southern Argentina have the lowest sampling coverage. Our hotspot analysis further reveals that only 4% of the Neotropics can be considered well sampled. Collection hotspots are limited to central-western Brazil and north-western Argentina (Figure 1c). Together, they encompass 42% of all occurrence data.

The observed distribution of Xenarthra records was significantly different ($p < 2.2e-16$) from the null model in all scenarios. About 40% of all records are within 5 km from a road, 25% are within 10 km from a navigable river and 27% are within a protected area (Table S2). When analysing patterns per biomes, records within forested biomes (Amazon and Atlantic Forest) are more concentrated in protected areas than open biomes (Figure 2). In contrast, collection
effort in open habitats is largely concentrated near roads, where up to 75% of the records are within 10 km distance from a road in temperate grasslands. Nonetheless, we detected a weak correlation between the density of access routes and the density of records (cor: 0.05–0.09; Table S3).

3.2 | Xenarthra diversity hotspots

The Xenarthra species richness map reveals marked diversity in eastern Bolivia, western Paraguay and north-western Argentina (Figure 3a). Xenarthra diversity hotspots identified by the two methods show an overall congruence, but the quantile approach is more restrictive. The top 10% richest grid cells are located in eastern Bolivia and a small part of the adjacent Brazil region, western Paraguay and north-western Argentina. A secondary smaller hotspot zone includes French Guiana and adjacent northern Brazil (Figure 3b). Hotspots identified by Gi* statistics support previous areas and also include central and south-eastern Brazil and a small part of central Brazilian Amazon (Figure 3c). Furthermore, coldspots are located at the northern and southern extremes of the Neotropics, in the high Andes of Bolivia and Peru, and a small portion of north-eastern Brazil.

3.3 | Priority areas for research and conservation

Priority areas for research varied with the metric employed. Focusing only on species richness, we found a weak correlation ($r = .219; p = 1e-04$) between Xenarthra diversity and sampling density. The whole Amazon, Central America and central-north Argentina emerged as promising areas for future studies (Figure 4a). In addition, xenarthran assemblages within protected areas remain largely unstudied in the Amazon (Figure 4c). On the other hand, focusing on the availability of access routes, north-eastern Brazil and Argentina appeared as good candidates for relatively low-cost xenarthran research (Figure 4b). Accounting for habitat loss, central Argentina and the east coast of Mexico are highlighted as important areas for research and conservation given the elevated levels of habitat alteration (Figure 4d). Combining all four metrics to produce a unified index of target areas for future studies, only a few areas can be considered as a
low priority. Central Argentina, eastern Brazil and Central America appeared as top priority areas (>95% quantile).

From a conservation viewpoint, there is a high spatial overlap between diversity hotspots and areas with elevated human modification in central-eastern Brazil and north-western Argentina (Figure 5a). These overlapping zones exhibit the lowest coverage of protected areas (Figure 5b).

To assist project planning at a national level, we provided prioritization maps per country in the Figure S4 and in Dryad Digital Repository (10.5061/dryad.2rbnz5ph).

4 | DISCUSSION

Here, we explored spatial patterns and biases in the xenarthran collection at a continental scale. Assessing which regions have been undersampled is the first step to direct where future studies should be focused. It also allows us to appreciate how (in)accurate our current knowledge is. Additionally, we estimated the Xenarthra richness across the Neotropics based on species distribution models providing a baseline for future projects and revealing hotspot zones that should draw more conservation attention. The prioritization indices produced here combining diverse metrics inform areas requiring detailed assessment to fill the large existing knowledge shortfalls and, in many cases, highlight regions with conservation priorities.

4.1 | Spatial collection bias reflects species knowledge gaps

Our study reveals that collection effort in Xenarthra is extremely biased and concentrated on a small portion of the Neotropics. Only 4% of the entire region can be considered well sampled. This uneven spatial aggregation echoes knowledge shortfalls at the species level. For example, ecological aspects of the Amazonian endemics two-toed sloths (Choloepus hoffmanni and Choloepus didactylus) and greater long-nosed armadillos (Dasypus kappleri, Dasypus pastasae and Dasypus beniensis) are largely unknown (Chiarello, 2008; Superina et al., 2014). On the other hand, species whose distribution includes areas with high collection efforts tend to be better known. Recent studies on the giant armadillo and giant anteater populations from the central-western Brazil collection hotspot have greatly broadened our understanding of population dynamics, reproductive, movement and activity patterns.
of these species (Barragán-Ruíz et al., 2021; Desbiez et al., 2020; Giroux et al., 2021; Noonan et al., 2021). It is unclear nonetheless whether populations of these species from other regions show similar ecological behaviours. Notably, long-term studies provide rich and detailed information on species’ requirements. The scientific projects developed in the collection hotspots are thus important and should be continued to improve and refine our current knowledge.

A third category refers to taxa occurring in high sampled areas but with only limited natural history information available. As an example, the distribution of Dasypus mazzai and Calyptophractus retusus encompasses the north-western Argentina collection hotspot, but they are both classified as data deficient by the IUCN. To better illustrate this scenario, we calculated the difference between estimated and observed Xenarthra diversity across the most sampled grid cells (>40 records). We found a deficit of up to four species recorded across the Amazon and tropical open biomes (such as in north-western Argentina) suggesting that, even within the most sampled grid cells, records are likely biased towards the most common species and do not fully represent the local xenarthran assemblages (Figure 6). Alternatively, such deficit may suggest local extinctions, especially in highly sampled grid cells (>300 records). This seems particularly true across the Atlantic Forest, where high habitat modification has led to the local extirpation of many large-bodied species, including the giant anteater and the giant armadillo (Bogoni et al., 2018; Canale et al., 2012; Fontes et al., 2020). Therefore, in highly deforested regions, our estimated local Xenarthra richness may represent an optimistic prediction of the original fauna and may not reflect the anthropogenic defaunation.

Xenarthra distributional records are highly skewed towards access routes. This is not surprising given about a quarter of the records were derived from opportunistic encounters and road-killed animals (Santos et al., 2019) and similar biases are commonly recovered from diverse animal and plant occurrence databases (Hughes, Orr, Ma, et al., 2021; Kadmon et al., 2004; Oliveira et al., 2016). However, factors driving spatial bias varied among biomes. The influence of rivers on the collection effort is much higher in the Amazon than in other regions, whereas records in open habitats and the Atlantic Forest are highly concentrated near roads. Despite these biases, we still detected a very weak association between the availability of access routes and sampling effort, indicating that areas with a higher density of access routes or protected areas remain unsampled.

The scarcity of Xenarthra records across most of the Neotropics is likely multifactorial. Their solitary, fossorial (armadillos) or strictly arboreal (sloths and silky anteaters), and mostly nocturnal (except a few species) habits make in situ ecological studies quite challenging. In addition, they are not attracted by playback calls or baits and there are only a few Xenarthra-focused research groups across the

![Image of map](https://example.com/image.png)
Neotropical region (Superina & Abba, 2020). Not surprisingly, the field stations of two Brazilian research institutes focusing mainly on xenarthrans (the Tamanduá Institute—http://www.tamandua.org; and the Wildlife Conservation Institute—https://www.icawildlifeprotected.org.br) are located in the central-western Brazil collection hotspot.

4.2 | Xenarthra diversity hotspots

Xenarthrans are a tropical group with most of the living species being either restricted to forest or open-habitat and only seven of 38 taxa can occupy diverse habitat types (Gardner, 2008). This ecological segregation is reflected in the hotspot zones. Both the quantile
and Getis-Ord Gi* approaches recovered the Amazon lowlands of Bolivia as well as the dry Chaco of western Paraguay and northern Argentina as a major Xenarthra diversity hotspot. Other hotspot zones include central Amazon, the Brazilian south-eastern Atlantic Forest and savannahs of central-western Brazil. Worrisomely, a large part of these hotspots is within areas facing severe rates of deforestation in the last two decades (Theobald et al., 2020; Venter et al., 2016). Protected areas cover about 23% of the hotspot region, but they are concentrated in the less-deforested core area of the Brazilian Amazon (Figure 5b). Indeed, its eastern portion, which is heavily threatened by human activities, remains largely unprotected. For example, only 4% of the hotspot land in Argentina is under some protection (Figure 5).

It is noteworthy that hotspot delimitation has received wide attention in the literature with different methods available (Nelson & Boots, 2008; Sussman et al., 2019). The two approaches applied here yielded overall congruent maps. Additionally, our hotspot delimitation fits well the field-based information. For example, using the filtered xenarthran database, the maximum number of species recorded at a 100-km grid was 10 and are located within the areas listed as hotspots. Moreover, our results support recent studies (Calabrese et al., 2014; Hughes, Orr, Yang, et al., 2021) by showing that richness maps produced by stacking probabilistic species distribution models generate a more realistic estimation of diversity patterns compared to overlying species polygon maps (e.g. using IUCN maps or transforming the Maxent outputs into binary presence/absence maps). When using binary maps, we found unrealistic overestimations of local xenarthran diversity of up to 16 species (see Figure S5). Nonetheless, it should also be noted that limited and biased occurrence data may leave regions of the species' range underrepresented, which in turn affects the predictive accuracy of

Figure 5 (a) Distribution of Xenarthra diversity hotspot (yellow shadow) and areas facing an elevated (>70% quantile) level of human modification based on Theobald et al. (2020) in South America. Hotspot delimitation based on Gi* statistics. (b) Proportion of protected and unprotected land within Xenarthra diversity hotspot per country and biome for Brazil. Maps in equal-area projection at 100-km grid resolution.
distribution models (Wisz et al., 2008). Not surprisingly, the Amazon is both one of the least sampled regions and the biome showing the highest inaccuracy of estimated local diversity as illustrated in Figure 6. Future collection efforts to fill sampling gaps are thus critical to producing more accurate spatial diversity patterns.

Coldspots are often neglected in conservation prioritization schemes, but they may support an exclusive irreplaceable fauna (Marchese, 2015). For Xenarthra, the zones identified as coldspots harbour taxa with unique traits and physiological adaptations. For example, Zaedyus pichiy occurs in high latitudes of southern South America and is the only Xenarthra known to hibernate (Superina & Boily, 2007). In the coldspot of Peruvian highlands, the endemic long-nosed armadillo Dasypus pilosus exhibits an exquisite hairy carapace likely related to thermoregulation and unique skull features associated with vermivorous diet, adaptations to live in altitudes up to 3400 m (Feijó et al., 2018). The Brazilian three-banded armadillo Tolypeutes tricinctus lives in the north-eastern Brazil coldspot and is the only endemic armadillo to the country. Conserving these coldspots is the only way to preserve the full range of ecological behaviour displayed by modern Xenarthra.

4.3 Priority areas for research and conservation

The different priority regions identified using different factor combinations reflect the complexity associated when setting prioritization schemes. Each index informs specific aspects of assessment needs and is thus complementary in guiding research and funding allocation.

The Amazon represents an important region that hosts a high xenarthran diversity but remains largely understudied. About 46% of the whole Amazon lacks a single record. Opportunistically, it contains several protected areas where long-term studies can be developed (Figure 4c). A downside is that the core area of the Amazon lacks a dense road network, where access is mostly via rivers. On the other hand, north-eastern Brazil and central and south Argentina harbour endemic armadillos and are undersampled regions that can be easily accessed via roads. Given these areas are facing elevated levels of habitat alteration (Theobald et al., 2020) and are covered by only a few protected areas (Figure 5d), their populations are thus more vulnerable to extinction. This is especially concerning for species restricted or mainly distributed in these zones (e.g. Tolypeutes tricinctus, Dasypus mazzai, Cabassous chacoensis, Chlamyphorus truncatus and Zaedyus pichiy) where the limited knowledge together with high habitat loss places them as both high priorities for conservation and study.

The unified index combining all previous metrics reveals that a few areas in the Neotropics can be considered low priority for Xenarthra research (Figure 4e,f). The collection effort made over the last two centuries is still far from satisfactory and reflects the numerous knowledge shortfalls in the group. Even our current understanding of species diversity is underestimated. Only in the last decade, the taxonomic identity of four widely accepted species was revised leading to the recognition of nine additional xenarthran species (Feijó & Anacleto, 2021; Feijó & Cordeiro-Estrela, 2016; Feijó et al., 2018; Miranda et al., 2018). Furthermore, the highly biased and limited sampling effort not just translates into how inaccurate is our current knowledge but is a critical impediment for proper extinction risk assessment and development of efficient conservation actions (Robertson et al., 2010). It is reasonable to expect that conservation planning for species (or populations) inhabiting densely surveyed areas is more likely to yield better results given occurrence data alone can be used to infer habitat usage (e.g. Ferraz et al., 2021) and, with associated field data, can inform numerous ecological aspects (e.g. temporal activity, reproductive patterns, population dynamics). Therefore, collaborative efforts to fill the spatial sampling gaps will broaden our current knowledge of xenarthrans as well as have a strongly positive influence on conservation plans. Surely, logistic limitations can hinder Xenarthra-focused field research in remote areas; however, many poorly sampled areas holding a high diversity and endemic species are of easy access and closer to big cities, being good candidates for relatively low-cost studies.

Some of the priority areas for research identified here should also be viewed as priority areas for conservation. There is an alarming spatial overlap between Xenarthra diversity hotspots and areas facing intense human modification, especially in its eastern portion (Figure 5). Under this scenario, simultaneous efforts of data collection and conservation actions across most of the xenarthran distribution should be stimulated. As an example, initiatives combining
research and conservation were successfully applied in the Orinoco Llanos of Colombia (Superina et al., 2019) and can be replicated in other countries.

5 | CONCLUSION

In this study, we provided the first assessment of spatial distribution and bias on xenarhan collection effort at the continental scale. Mapping the available knowledge is the first step to recognizing shortfalls and allocating efforts and funding efficiently. Records gathered over the last century were disproportionately concentrated to a very small portion of the Neotropics. The large spatial lacunas reflect the limited information available on natural history for most species. Even the best-sampled areas fail to fully document the local xenarhan assemblage. By linking past collection efforts with metrics of species richness, habitat modification and accessibility, we identified priority areas that will spatially orient fieldwork to fill the extensive lacunas across the Neotropics in a cost-effective manner and help design efficient conservation actions. Moreover, we revealed that Xenartha diversity hotspot zones facing the highest levels of habitat alteration are the least protected and thus are a priority for both research and conservation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Occurrence data are available in the Neotropical Xenarhtz database at https://doi.org/10.1002/ecy.2663 and in Feijó et al., 2019 (https://doi.org/10.1007/s10530-019-02085-8) and Feijó & Anacleto, 2021 (https://doi.org/10.11646/ZOOTAXA.4974.1.2). Species distribution models and Xenertha richness map shapefiles are available at Dryad Digital Repository (https://doi.org/10.5061/dryad.2rhnz5n).

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Author contributions: AF and YQ conceived and designed the study; AF, DG, ZW, and LX organized data; AF performed analyses and led the writing of the manuscript. All authors revised the manuscript.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher’s website.

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