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Identifying critical vegetation types for biodiversity conservation in the Americas

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ABSTRACT

The Americas contain highly biodiverse yet vulnerable ecosystems, with many threatened species inadequately protected. Finer-scale, localized habitat assessments are crucial for effective conservation planning, but continental-scale high-resolution vegetation maps remain limited. This study addresses this gap by identifying critical vegetation types across the Americas using the standardized framework of the International Vegetation Classification (IVC) system at the macrogroup level, representing the finest vegetation classification available across the region, as well as the highest-resolution Area of Habitat (AOH) maps currently available for birds and mammals. By combining these high-resolution IVC macrogroup maps with detailed AOH maps, we highlight at-risk vegetation types based on 1) threatened and macrogroup-associated species (species that have at least 50% of their AOH in one macrogroup), 2) current protection levels, and 3) projected threats from land use changes, and 4) develop a conservation value index (CVI) that accounts for all these factors. The results highlighted the remarkable diversity of high conservation value macrogroups across the Americas, emphasizing their significance in regions such as the Andes, montane Mesoamerica, the Caribbean, Brazil's Cerrado, and the Atlantic Forest. Among the highest-scoring macrogroups, the Northern Andean Montane & Upper Montane Humid Forest emerged as critically important, harboring a high number of threatened and macrogroup-associated species. Other macrogroups of immediate conservation concern include the Brazilian Atlantic Montane Humid Forest, Pacific Mesoamerican Seasonal Dry Forest, Caribbean Lowland Humid Forest, and Central Midwest Oak Forest, Woodland and Savanna. However, the study revealed that nearly three-quarters of the over 300 macrogroups in the Americas fall below the global target of 30% protection. Notably, a fifth of all species were macrogroup-associated species, including over 40% of threatened species. Our findings emphasize the need for targeted conservation strategies that consider finer-scale habitat classifications and paired with high-

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quality species distribution data to guide conservation strategies for biodiversity across the Americas.

1. Introduction

The Americas contain eight of the top 25 biodiversity hotspots, including the Tropical Andes, Mesoamerica, the Caribbean, and the Atlantic Forest recognized as the "hottest hotspots" in the world (Myers et al., 2000; Somveille et al., 2013). These regions harbor not only the largest number of the world's plant and animal species but are also home to the greatest number of endemic species (Myers et al., 2000; Brooks et al., 2006; Mittermeier et al., 2011). However, despite the existence of protected areas throughout the region, threatened species of birds and mammals, for example, are still inadequately protected (González-Maya et al., 2015; Wan and Wang, 2023; Williams et al., 2022). In hotspots like the Tropical Andes, 72% of all species and 90% of threatened endemics are not adequately covered by protected areas (Bax and Francesconi, 2019). Within the United States, despite decades of protections, only 12% of land is currently protected, leaving 40% of animals, 34% of plants, and 40% of nationwide ecosystems, including grasslands, forests, and wetlands, at risk for extinction or range-wide collapse (Dietz et al., 2020; Jenkins et al., 2015; NatureServe, 2023). To address gaps in the current protected areas network and mitigate escalating pressures on this biologically diverse but vulnerable region, it is crucial to identify critical at-risk habitats, particularly those that host a high number of threatened species.

Traditional habitat assessments have predominantly relied on broad classifications like ecoregions or biomes, yet the multidimensional landscape of biodiversity conservation calls for more nuanced, local, and region-specific assessments (Ceaușu et al., 2015; Sayre et al., 2020). Although broader habitat classifications are valuable at global scales, they often fall short in capturing the intricate habitat needs of many species (Dietz et al., 2020; Jung et al., 2020). Consequently, they may provide a false sense of security regarding protection, leaving finer-scale habitats, such as specific vegetation communities, vulnerable within these broader assessments (Dietz et al., 2020; Keith et al., 2013). This deficiency in finer-scale assessments can leave threatened and rare species inadequately covered within protected areas (Brooks et al., 2004; Jenkins et al., 2015; Rodrigues et al., 2004; Williams et al., 2022; Zeng et al., 2023), emphasizing the need for more localized and detailed conservation strategies. Additionally, although general habitat maps appear sufficient for wide-ranging species, localized endemics and species with specific microhabitat needs depend on particular vegetation structures and floristics obscured in regional assessments. Neglecting these finer-scale habitat distinctions and vegetation communities can have adverse effects, particularly on rare, highly specialized, or microhabitat-dependent species, even when the broader habitat remains relatively intact (Dietz et al., 2020; Visconti et al., 2019). To protect vulnerable species and habitats, effective conservation strategies require detailed localized assessments and mapping of finer-scale habitats and vegetation communities.

While finer-scale and high-resolution regional habitat and vegetation maps are crucial for conservation planning and decision-making, producing comprehensive and detailed continental-scale maps that capture localized habitat characteristics and variability remains challenging. Key issues include the large variations in landscape and environmental conditions over short distances, inconsistencies in land cover classifications between political jurisdictions, and constraints to data collection at finer spatiotemporal scales across continents (Comer et al., 2020). However, there are many efforts underway to improve the scale and resolution of habitat and vegetation maps through new mapping technologies and initiatives. Notably, in the Americas, the International Vegetation Classification (IVC) system offers a comprehensive framework for classifying ecosystems based on vegetation characteristics and ecological attributes (Comer et al., 2020). The IVC classification scheme comprises a hierarchy of eight levels, ranging from broad global groups delineating six major physiognomic and ecological types to 10,000 s finely detailed local floristic classification units (Faber-Langendoen et al., 2014). This structure facilitates a detailed assessment of terrestrial ecosystem distribution across various scales with high spatial and thematic resolution. The IVC has been extensively applied in ecosystem mapping across North and South America, as well as in Africa (Comer et al., 2022b; Marsh et al., 2022; Sayre et al., 2020, 2013). While habitats can be complex and species-specific, the IVC system can serve as a useful proxy for representing species habitats, considering the multidimensional nature of habitats, including factors such as vegetation structure, floristic composition, and environmental gradients (Comer et al., 2020). The IVC's standardized framework for classifying and comparing vegetation types within the Americas is crucial for ensuring that conservation actions are tailored to meet the unique needs of both habitats and species, ultimately enabling effective conservation efforts that consider unique species and habitat requirements across the region.

Although finer-scale vegetation maps reveal information about suitable habitat locations, species distribution maps are crucial for identifying species composition in different areas. However, range maps provided by authoritative organizations like the International Union for Conservation of Nature (IUCN) can often be imprecise, especially for rare and threatened species with limited data (Merow et al., 2017). These maps serve as vital data resources for comprehending species distributions, evaluating species richness, and identifying areas for conservation efforts (Kullberg et al., 2019; Mainali et al., 2020; Marsh et al., 2022; Rotenberry and Balasubramaniam, 2020). These maps are typically delineated to minimize errors of omission and therefore overestimate species' ranges, with the result that they often contain substantial areas that are not occupied by the species (Brooks et al., 2019; Lumbierres et al., 2022; Merow et al., 2017). While useful for assessing distribution and richness patterns, range maps can overestimate a species range and mask key details about habitat preferences, leading to ineffective targeting of critical habitats for threatened, rare, or habitat-associated species. To address these limitations, Area of Habitat (AOH) maps have been developed. AOH maps incorporate detailed data on habitat types, elevation ranges, and other environmental variables preferred by each species to exclude unsuitable areas within broad range boundaries. High-resolution AOH maps (100 m) have recently been produced for birds and mammals, enabling a more refined representation of potential species distributions (Lumbierres et al., 2022). By incorporating high-resolution

AOH maps alongside finer-scaled vegetation type data to better understand the intricate relationship between terrestrial bird and mammal species and their habitats, conservation efforts can be more effectively targeted to protect the vegetation types critical for threatened, rare, and vegetation-associated species that may depend on the habitat features obscured in broader classifications.

In this study, we employ finer-scale high-resolution vegetation and AOH species maps to identify critical vegetation types across the Americas. We focus on vegetation types that harbor threatened and vegetation-associated species, that are also under-protected and susceptible to future land use impacts. We utilize the fifth level of the IVC, known as macrogroups, which offers the highest thematic detail available for the whole region (Comer et al., 2020). This is coupled with the highest-resolution AOH maps currently available (Lumbierres et al., 2022). The specific objectives are to: 1) identify the vegetation types harboring the most threatened and macrogroup-associated species; 2) determine the percentage of each vegetation type that is currently protected; 3) assess the potential risk of future land-use impacts for each vegetation type; and 4) identify critical vegetation types using a conservation value index (CVI) that accounts for all these factors.

2. Methods

2.1. Datasets

2.1.1. Vegetation types

This study utilized maps depicting the standardized International Vegetation Classification (IVC) system to conduct a detailed analysis of vegetation patterns across the Americas. The IVC is a standardized approach for describing and categorizing terrestrial ecosystems based on vegetation and ecological criteria. It employs a hierarchical structure with multiple levels of detail, starting with global factors and progressively more localized and numerous units distinguished by floristics (Comer et al., 2022a; Faber-Langendoen et al., 2014). This study focused on the macrogroup level, the fifth of eight levels in the IVC hierarchy, which comprises 321 distinct natural vegetation types and represents the finest level mapped across the temperate and tropical Americas. The macrogroups exhibited significant variation in size, ranging from the smallest measuring 0.35 km^2 (Eastern North American Cool Temperate Seep) to the largest spanning an extensive area of 832,136.07 km^2 (Central Amazon Humid Forest). The continental vegetation map was generated at a spatial resolution of 90 × 90 m, representing the recent distribution of vegetation circa 2010 (Comer et al., 2020). To maintain consistency and enable accurate comparisons, all subsequent maps discussed in the following sections were resampled to align with this resolution.

2.1.2. Species distribution

We utilized a comprehensive Area of Habitat (AOH) dataset obtained from Lumbierres et al. (2022) to analyze the habitat patterns of terrestrial birds and mammals in the Americas. These AOH maps, with the highest resolution currently available of 100 × 100 m, represent the most extensive global coverage to date. For our study, 6204 species were identified whose ranges were within the Americas, encompassing 1868 mammal species and 4336 bird species. Among the bird species, 3661 were classified as non-migratory and 675 were migratory species. The migratory birds had separate AOH maps for their resident, breeding, and non-breeding areas, which were later merged to create a unified map for each species. The focus on mammals and birds stems from their extensive global distribution range maps compiled for the International Union for Conservation of Nature (IUCN) Red List assessments.

2.1.3. Protected areas

To assess the protection status of IVC macrogroups within the Americas, we utilized polygon data obtained from the World Database of Protected Areas (WDPA) (UNEP-WCMC and IUCN, 2023). The WDPA is a comprehensive global database that encompasses both marine and terrestrial protected areas and other effective area-based conservation measures (OECMs). The dataset consists of 273,263 polygons covering 244 countries and territories. It comprises six different protection classifications, ranging from Strict Nature Reserve to Managed Resource Protected Area. For this study, we included all terrestrial protected areas and OECMS across all six protection classes.

2.1.4. Projected land-use

We used finer-scale models to project future areas under anthropogenic land use obtained from Chen et al. (2020). This dataset offers high spatial resolution (0.05° × 0.05°) and covers a comprehensive range of Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP) scenarios with uncertainties from forcing climates. It is spatially consistent with the commonly used but lower resolution of the LUH2 (Land-Use Harmonization version 2), and useful for global Earth system modeling, analyzing land use impacts, socioeconomics, and associated uncertainties.

While various scenarios could have provided insights, we selected the SSP3-RCP4.5 scenario due to its balanced perspective, crucial for meaningful and unbiased insights within our study's scope. This scenario depicts a moderate trajectory where greenhouse gas emissions peak in 2040 and radiative forcing stabilizes at 4.5 W/m2 by 2100, allowing useful yet realistic results without an overly optimistic or pessimistic lens. Its balanced nature, coupled with consideration of interconnected socioeconomic, environmental, and regional dimensions, ensured the best opportunity to evaluate land use impacts within the confines of the study objectives.

These global land-use maps delineated 32 distinct land types. Among these types, we merged types 15–31, which encompass anthropogenic land uses such as crops, bioenergy, and urban habitats. The derived value indicates the proportion of each anthropogenic land type within the grid cell. We then aggregated these values to depict the projected percentage of each grid cell that is projected to be under anthropogenic land use in 2030. For the purpose of this study, we selected 2030 to align with global conservation targets, specifically the Convention on Biological Diversity (CBD) Aichi Biodiversity Target 11, which calls for at least 30% protection of representative terrestrial areas globally by 2030 (Belote et al., 2021; Convention on Biological Diversity, 2022).

2.2. *Data processing workflow*

The methodology employed in this study, as depicted in Fig. 1, consisted of several key steps. First, we conducted an overlay analysis of IVC macrogroup and Area of Habitat (AOH) data to determine the number of bird and mammal species per macrogroup (Fig. 1a). This allowed us to establish the species composition within each macrogroup. For migratory birds, we did the overlay analysis for each of the three separate AOHs. To keep the methodology consistent, we summed the results for each migratory bird species for our analysis. Next, we filtered the species based on their threatened status to identify the number of threatened species in each macrogroup (Fig. 1b). We define threatened species based on the classifications from the International Union for Conservation of Nature (IUCN) Red List, specifically encompassing all species categorized as Critically Endangered, Endangered, and Vulnerable.

To identify species that are highly associated with specific macrogroups in the Americas, we defined "macrogroup-associated species'' as those having 50% or more of their AOH in the Americas within a single macrogroup (Fig. 1c). This threshold strikes a balance between inclusivity and specificity, capturing species with a strong affiliation while accounting for some distribution variability. To determine the percentage of the range for each macrogroup currently protected, we performed an overlay analysis by superimposing the macrogroup data and protected areas (Fig. 1d). This allowed us to assess the total protection rate across the extent of each macrogroup. Finally, we integrated future land use data with the macrogroups and calculated the average probability of land use within the range of each macrogroup (Fig. 1e). By doing so, we could identify areas that were likely to undergo conversion to non-natural land types by the year 2030. This comprehensive workflow allowed us to analyze the distribution patterns of species, assess their threatened status, evaluate macrogroup-association, determine the extent of protected areas, and projected future land use within each macrogroup. These steps were then used to create a conservation value index (Fig. 1f) described in the next section.

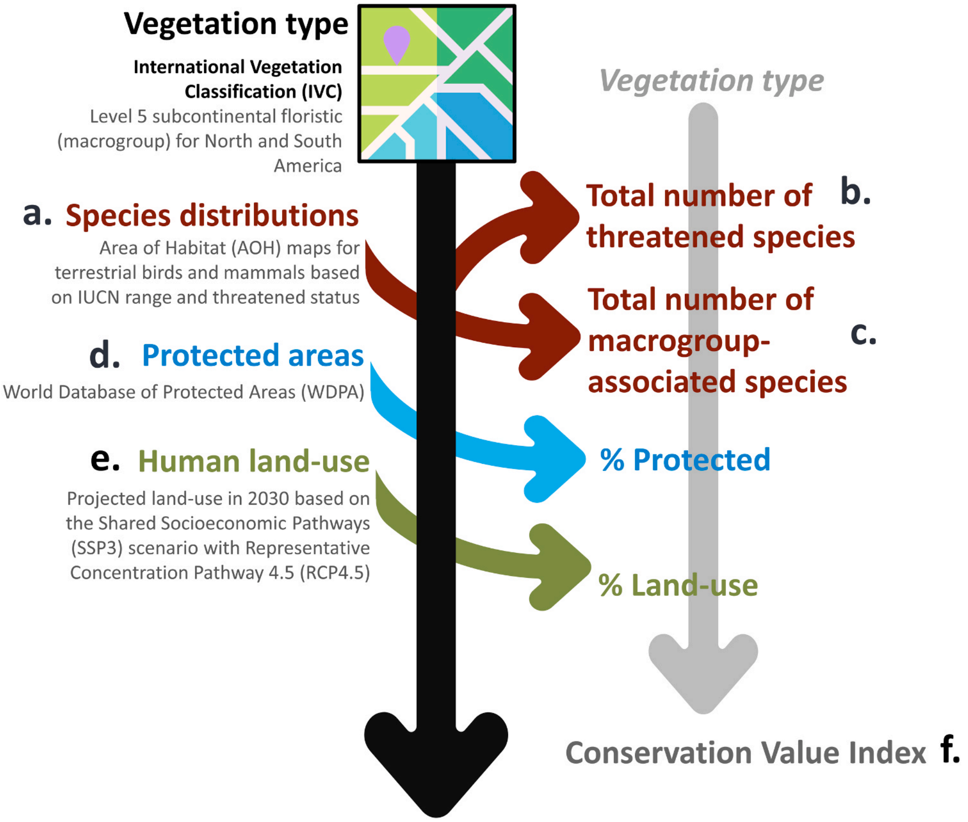

Fig. 1. Methodology workflow for analyzing species distribution, threatened status, macrogroup-association, protected areas, and future land use within macrogroups. The steps include (a) overlay analysis of macrogroup and Area of Habitat (AOH) data, (b) filtering species by threatened status, (c) identifying macrogroup-associated species (species whose at least half of their range is within one macrogroup), (d) assessing the extent of protected areas, (e) integrating future anthropogenic land use, and (f) creating a conservation value index (CVI).

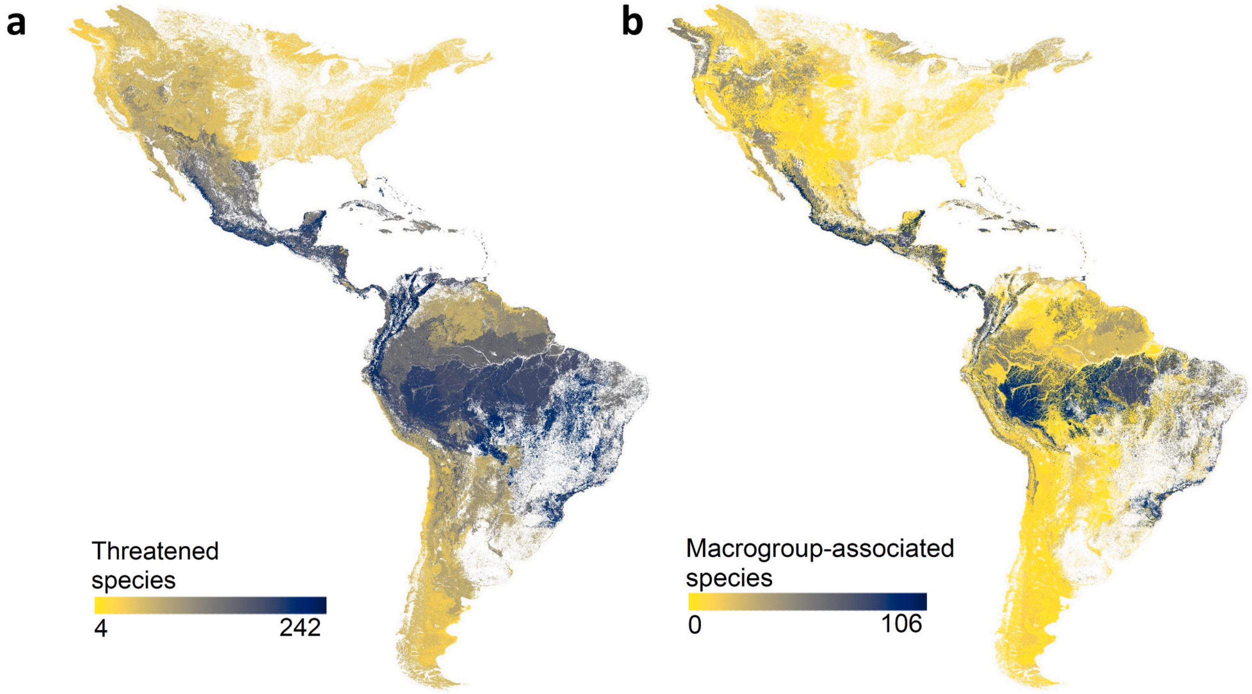

Fig. 2. Distribution of (a) threatened species and (b) macrogroup-associated species within natural macrogroups in the Americas based on the International Vegetation Classification (IVC). The colors on the map represent the total number of species whose area of habitat (AOH) range falls within each macrogroup, ranging from yellow (indicating the lowest number of species) to blue (representing the highest number of species). White areas represent non-natural or freshwater macrogroup types.

2.3. Conservation value index

The last step was to create a conservation value index (CVI) (Fig. 1f), combining information that takes all previous factors into account. The CVI was calculated using the following formula:

$$CVI = (0{\cdot}25 * (T / T\_max)) + (0{\cdot}25 * (MA/ MA\_max)) + (0{\cdot}25 * (1 - Pr / Pr\_max)) + (0{\cdot}25 * (LUC / LUC\_max))$$

Where:

- T represents the number of threatened species within the macrogroup.
- T_max represents the maximum number of threatened species among all macrogroups.
- MA represents the number of macrogroup-associated species within the macrogroup.
- MA_max represents the maximum number of macrogroup-associated species among all macrogroups.
- Pr represents the percentage of the IVC macrogroup within protected areas.
- Pr_max represents the maximum percentage of IVC macrogroup within protected areas across all macrogroups.
- LUC represents the average land use across the macrogroup
- LUC_max represents the maximum land use across all macrogroups.

The Conservation Value Index (CVI) is a composite metric developed for this study to assess vegetation types for conservation efforts. It integrates four key factors, each weighted equally: 1) the presence of threatened species, 2) macrogroup-associated species, 3) the current level of macrogroup protection, and 4) projected human land use. By integrating these relevant criteria in a balanced manner, the CVI provides a targeted, yet adaptable tool aligned with the specific research objectives of this study. Despite its ad-hoc design, the CVI's adaptable structure makes it a versatile tool, capable of adjusting to different conservation goals and applicable in a variety of contexts.

3. Results

3.1. Species distribution

In the Americas, the Western Atlantic & Caribbean Mangrove exhibited the highest species richness, with 2587 species, followed by the Northern Andean Montane & Upper Montane Humid Forest with 2577 species, and the Neotropical Floating & Submerged Freshwater Marsh with 2533 total species (Supplementary Table 1).

3.1.1. Threatened species

Within the Americas, a total of 822 threatened species were identified, which accounted for 13.25% of all species included in the study. This comprised 309 threatened mammal species (16.54%) and 513 threatened bird species (11.83%) (Supplementary Table 1). Among the threatened bird species, 453 were non-migratory and 60 were migratory, with a higher percentage of threatened non-migratory birds (12.27%) compared to migratory birds (8.89%). The highest concentration of threatened species was observed in macrogroups spanning the Tropical Andes, Brazil's Cerrado and Atlantic Forest, Central America, the eastern Yucatan to the Pacific Coast of Mexico, and the southwestern United States (Fig. 2a). The Northern Andean Xeromorphic Scrub & Woodland contained the largest number of threatened species, totaling 242 species. Other important macrogroups were the Northern Andean Seasonal Dry Forest with 241 species and the Northern Andean Montane & Upper Montane Humid Forest macrogroup with 234 species (Supplementary Table 1).

When comparing threatened mammals and birds, there were distinct differences in their distribution. Macrogroups in Central America and the Pacific Coast of Mexico hosted relatively more threatened mammal species compared to threatened bird species (Fig. 2). In particular, the Western Atlantic & Caribbean Mangrove stands out as the macrogroup with the highest number of threatened mammal species, totaling 86 species, and the Northern Andean Xeromorphic Scrub & Woodland harboring the most threatened bird species, with 171 (Supplementary Table 1). Notably, there are significant spatial differences in the richness of threatened non-migratory and migratory birds. The Andes region and the Amazonian rainforest exhibited higher counts of threatened non-migratory birds, while western North America boasted a greater diversity of threatened migratory birds (Supplementary Table 1). When considering only non-migratory birds, the Northern Andean Seasonal Dry Forest contained the highest number (166) of threatened species. For migratory birds, the Interior Warm & Cool Desert Riparian Forest served as the primary macrogroup type with 20 species (Supplementary Table 1).

3.1.2. Macrogroup-associated species

Our analysis revealed a total of 1203 macrogroup-associated species, representing 19.39% of the species in the Americas. Among these macrogroup-associated species, there were 448 mammal species, accounting for 23.98% of all mammal species, and 755 bird species, representing 17.41% of all bird species. Surprisingly, a total of 333 species (40.51% of all threatened species) were both threatened and classified as macrogroup-associated species. Among the threatened species, 124 mammal species (40.13%) and 209 bird species (40.74%) were found to be macrogroup-associated species. Out of the macrogroup-associated bird species, 193 were non-migratory (42.61%) and 16 were migratory (26.67%).

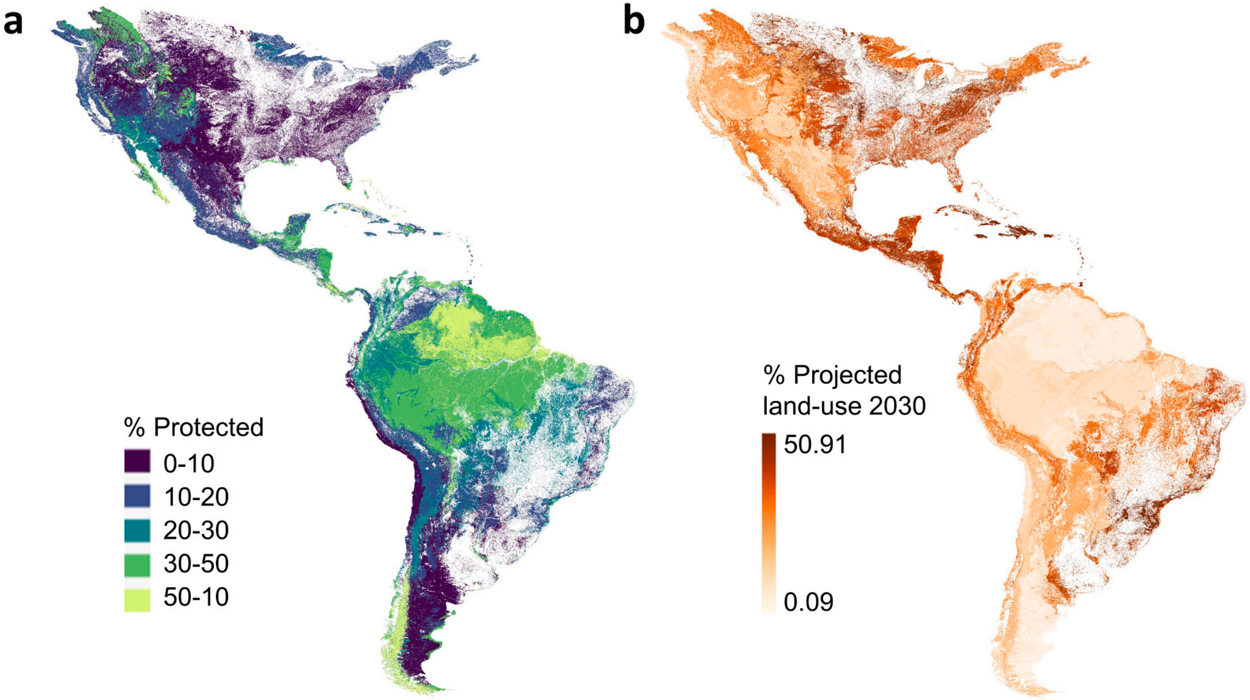

Fig. 3. Map of the Americas depicting the percentage of (a) macrogroups that are protected across their entire range based on data from the World Database of Protected Areas. The color scheme ranges from dark purple, representing macrogroups with less than 10% protection, to light -green, indicating macrogroups with over half of their range protected. White areas correspond to non-natural or freshwater habitats; and (b) estimated human land-use in 2030 under the SSP3 RCP4.5 scenario (Chen et al., 2020). The color scheme ranges from light orange, representing areas with the least anticipated land-use, to dark orange, indicating regions with the highest projected land-use across the region. White areas correspond to non-natural or freshwater habitats.

Interestingly, non-migratory birds exhibited a higher number of macrogroup-associated species, compared to migratory birds, which accounted for 43 species. The percentage of macrogroup-associated non-migratory bird species was 19.45%, compared to just 6.37% for migratory birds overall. However, when analyzing migratory birds' three activity-specific AOHs separately, it revealed substantially higher macrogroup associations than their full ranges suggest, with 22.37% associated with macrogroups in at least one of their ranges. The greatest levels of macrogroup-association were in breeding areas (81 species), followed by non-breeding (57 species) and resident areas (40 species).

In terms of geographical distribution, the areas with the highest concentration of macrogroup-associated species were the Amazon, Brazilian Highlands, Northern Andes, Gulf Caribbean regions of Central America, the Eastern Yucatan, and the Pacific Coast of Mexico (Fig. 2b). Within these high-concentration regions, the Northern Andean Montane & Upper Montane Humid Forest contained the most macrogroup-associated species with 106 species, including the most macrogroup-associated mammals (34 species) and birds (72 species) (Supplementary Table 1). However, the birds found in this macrogroup were exclusively non-migratory (Supplementary Table 1). The highest counts of macrogroup-associated migratory birds were in Laurentian-Acadian Mesic Hardwood-Conifer Forest and Vancouverian Coastal Rainforest (Supplementary Table 1). Other macrogroups with a large number of species were the Pacific Mesoamerican Seasonal Dry Forest with 82 and the Southern Mesoamerican Montane Humid Forest with 76 total macrogroup-associated species (Supplementary Table 1). The Caribbean Lowland Humid Forest exhibited the most macrogroup-associated species per square kilometer (Supplementary Table 1).

3.2. Protected areas

Notable variations exist between different regions in terms of macrogroup protection. The Amazon, southern Chile, the center of Hispaniola, and southeast of Central America exhibit the highest levels of protection, whereas the western Andes, Patagonia, and various regions throughout the United States, are among the least protected areas (Fig. 3a). Among these macrogroups, the Tepuyan Bog stands out as the most protected, with 95.33% of its range under protection, while the Eastern North American Riverscour Vegetation is the least protected, with only 0.20% of its range protected (Supplementary Table 1). The macrogroup with the highest richness of threatened species, the Northern Andean Xeromorphic Scrub & Woodland, has only 20.9% of its range protected (Supplementary Table 1). Regarding macrogroup-associated species, only half of the top ten macrogroup are at least 30% protected (Supplementary Table 1). The Northern Andean Montane & Upper Montane Humid Forest, which contains the greatest number of

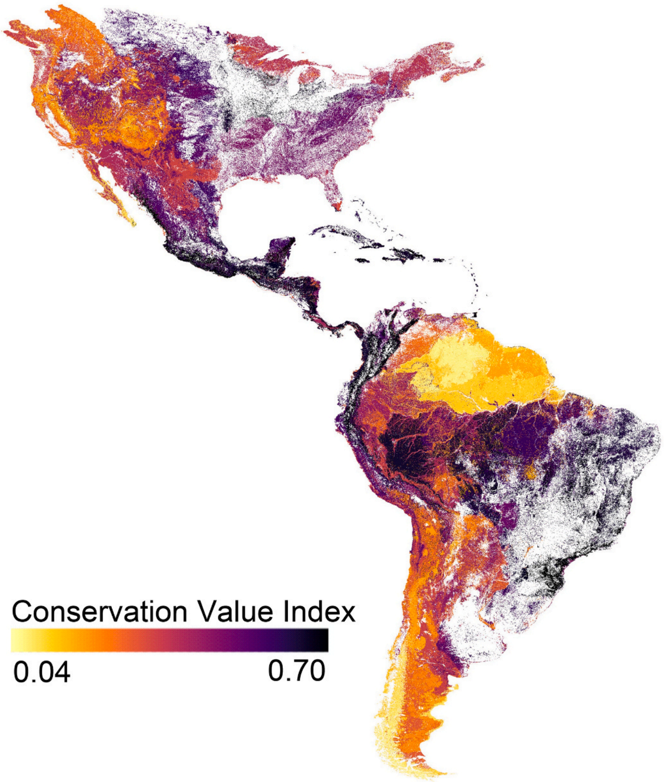

Fig. 4. Conservation Value Index (CVI) score for the Americas. The CVI combines multiple factors to determine a CVI score, including threatened species, macrogroup-associated species, macrogroup vegetation type protection percentage, and land use. Each factor is weighted equally to ensure balanced consideration.The CVI values are normalized, with 0 indicating the lowest conservation value and 1 representing the highest conservation value. The color scale ranges from light yellow (low) to dark purple (high).White areas correspond to non-natural or freshwater habitats.

macrogroup-associated species and threatened macrogroup-associated species, including the third highest concentration of macrogroup-associated per square kilometer, only has 35.6% of its range protected (Supplementary Table 1). For threatened macrogroup-associated species, only five out of the ten most significant macrogroups have sufficient protection (Supplementary Table 1).

3.3. Future land-use

The natural regions exhibiting the highest projected anthropogenic land-use for 2030 were primarily located in Central America, the Caribbean islands, southern Mexico, southeast South America, and the Midwest to the Southern United States (Fig. 3b). The average land-use across the Americas was 8.73%, which represented the percentage of natural macrogroups projected to be an anthropogenic land use type in 2030. Specifically, we found land-use estimations ranged from 0.09% (South American Pacific Desert Salt Flats) to 50.91% (Central Midwest Oak Forest, Woodland & Savanna) (Supplementary Table 1). Among the macrogroups in Northern America, the West-Central North American Boreal Forest & Woodland exhibited the lowest estimated land-use (0.22%), while the Central Midwest Oak Forest, Woodland & Savanna had the highest estimated land-use (50.91%) (Supplementary Table 1). In South America, land-use ranged from 0.09% in the South American Pacific Desert Salt Flats to 33.01% in the Brazilian Atlantic Montane Humid Forest (Supplementary Table 1).

3.4. Conservation value index

The areas with the highest CVI scores were primarily located in the Northern Tropical Andes, the Yucatan Peninsula, the Pacific and western coast of Mexico, the Caribbean, the Cerrado and eastern Brazil, and the Midwest to the Southern United States (Fig. 4). The average CVI score across the Americas was 0.29. The Northern Andean Montane & Upper Montane Humid Forest (Colombia, Ecuador, Peru, Venezuela) had the highest HPI at 0.70. Although over 35% of the area is protected and it faces low-level threats from land use, it contains the third greatest number of threatened species, and the most macrogroup-associated and threatened macrogroup-associated species (Table 1; Supplementary Table 1). The Brazilian Atlantic Montane Humid Forest (Argentina, Brazil) ranked as the second highest CVI score (0.66), harboring 140 threatened species with 17% protected, but approximately one-third of the region is threatened by land-use (Supplementary Table 1). The Pacific Mesoamerican Seasonal Dry Forest, spanning from Mexico to Panama (Mexico, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Belize Colombia), had the third highest CVI at 0.62

Table 1

The top ten macrogroup vegetation types from the International Vegetation Classification (IVC) based on the conservation value index (CVI) values. CVI values were calculated based on the total extent protected, future land-use, the total size of range, as well as the number of threatened species and macrogroup-associated species. The last column also provides information on the total number of threatened macrogroup-associated species. Darker shades of green represent factors contributing to a higher CVI, while darker shades of purple indicate factors associated with a lower CVI.

Conservation Value Indicator (CVI)	Macrogroup	% Protected	% Land-use	Threatened species	Macrogroup-associated species
0.7	Northern Andean Montane & Upper Montane Humid Forest	35.58	10.48	234	106
0.66	Brazilian Atlantic Montane Humid Forest	17.26	33.01	140	63
0.62	Pacific Mesoamerican Seasonal Dry Forest	15.87	12.84	154	82
0.57	Caribbean Lowland Humid Forest	17.68	32.45	66	57
0.51	Brazilian-Parana Montane Grassland, Savanna & Forb Meadow	13.71	21.91	176	2
0.5	Central Midwest Oak Forest, Woodland & Savanna	4.89	50.91	15	0
0.5	Northern Andean Lower Montane Humid Forest	23.37	8.36	216	21
0.5	Northern Andean Paramo	41.73	16.56	227	19
0.5	Brazilian Atlantic Humid Forest	25.81	19.16	134	34
0.49	Cerrado Savanna	22.19	8.29	178	32

(Table 1; Supplementary Table 1). It encompasses the second-highest number of macrogroup-associated species, half of which are threatened, and only 15.9% of the area is protected. However, it faces relatively little land use threats at 12.8% (Table 1; Supplementary Table 1). The Caribbean Lowland Humid Forest (Eastern Cuba, Jamaica, Dominican Republic, Haiti, Puerto Rico, Trinidad and Tobago, Lesser Antilles, British Virgin Islands, Guantanamo, Barbados, Guadeloupe) ranked as the fourth highest CVI score (0.51), hosting 176 threatened species, including 57 threatened macrogroup-associated species (Table 1; Supplementary Table 1). The Brazilian-Para Montane Grassland, Savanna & Forb Meadow had an HPI value of 0.51 (Table 1; Supplementary Table 1), with only 13% of the area protected and facing threats from land-use. Lastly, the Central Midwest Oak Forest, Woodland & Savanna (Midwest to southern Ontario, western New York) emerged as the highest CVI score for the United States, with an HPI value of 0.51 (Table 1; Supplementary Table 1). It faces significant threats from land use (50.9) and hosts 15 threatened species, of which 7 are threatened migratory birds, while only 4% of the area is protected (Table 1; Supplementary Table 1).

4. Discussion

This study identifies critical vegetation types for conservation attention across the Americas by assessing various factors, including the distribution of threatened and macrogroup-associated terrestrial bird and mammal species, current protection levels, and projected land use. To achieve this, we utilized a conservation value index (CVI) to pinpoint macrogroups with high biodiversity value that simultaneously face low protection and anthropogenic pressures. The results highlight the remarkable diversity of these high conservation value macrogroups across the Americas, encompassing multiple geographic areas and regions. Notably, the highest-scoring vegetation macrogroups are concentrated in key regions, including the Andes, montane Mesoamerica, the Caribbean, Brazil's Cerrado, and the Atlantic Forest, emphasizing the conservation significance of habitats in these areas and aligning with previous research highlighting them as biodiversity hotspots (Brooks et al., 2006; Myers et al., 2000; Wan and Wang, 2023). Among the highest-scoring macrogroups, the Northern Andean Montane & Upper Montane Humid Forest stands out as critically important in this study. Spanning Colombia, Ecuador, Peru, and Venezuela, this habitat has been previously noted for its exceptionally high biodiversity in plants, mammals, birds, and amphibians, often occupying narrow elevational ranges (Young and León, 2000). Our analysis found this macrogroup contains the third most threatened species and the highest number of macrogroup-associated species. Furthermore, it also not only harbors the most threatened macrogroup-associated species but the highest density of these species per square kilometer.

However, our findings underscore the pressing need for more comprehensive conservation strategies that encompass the full range of habitats across the Americas, particularly considering the global 30 × 30 initiative, striving to protect 30% of the Earth's land and oceans by 2030 (Belote et al., 2021; Convention on Biological Diversity, 2022). While the average macrogroup protection in the Americas reached 24.5%, nearing regional 30% targets, the substantial variability between vegetation types highlights that many macrogroups fall below these thresholds due to inadequate consideration of habitat diversity across ecosystems. Indeed, nearly three-quarters of the over 300 macrogroup types have less than 30% of their range currently protected, including 8 of the top 10 highest-scoring macrogroups falling below the targeted threshold. Among the highest-scoring macrogroups, specific critical habitats stand out. For example, the Brazilian Atlantic Montane Humid Forest in Argentina and Brazil hosts 140 threatened species, including 15 threatened macrogroup-associated species, with only 17% of the area currently protected while 33% is under future threat due to land use. Similarly, the Pacific Mesoamerican Seasonal Dry Forest in Central America, spanning from Mexico to Panama, hosts 154 threatened species and 52 macrogroup-associated species, with half currently threatened and only 15% protected. The Caribbean Lowland Humid Forest, found in Caribbean islands like Cuba, Jamaica, and Puerto Rico, contains 176 threatened species and 57 macrogroup-associated species, including 10 threatened macrogroup-associated species. However, only 17.7% of its remaining area is protected, and it faces a projected 32% land-use change across its range. Lastly, the Central Midwest Oak Forest, Woodland & Savanna in the United States, with a history of land conversion (Grundel and Pavlovic, 2007), remains highly threatened by future land use, with only 4% of the area currently protected. Despite having relatively few threatened species, they are vital for avian conservation due to their ecological distinctiveness as ecotones and their importance in providing habitats for disturbance-dependent bird species and migration stopover sites (Grundel and Pavlovic, 2007).

The hierarchical levels within the IVC play a pivotal role in discerning and assessing different vegetation types across scales. In our study, vegetation macrogroups are categorized within global vegetation classifications known as formations, two levels above macrogroups in the IVC hierarchy. The top five key formations included Tropical Montane Humid Forest, Tropical Montane Grassland and Shrubland, Tropical Dry Forest and Woodland, Tropical Lowland Humid Forest, and Cool Temperate Forest and Woodland. These broad habitat types have been highlighted in previous research as conservation priorities. For example, Tropical Dry Forests and Tropical Grassland, Savanna & Shrubland are considered threatened and classified as priority habitats due to diverse microhabitats, endemism, as well as their role in global terrestrial net primary productivity and carbon storage (Parr et al., 2014; Pinedo-Escatel et al., 2021; Salinas et al., 2021; Wan and Wang, 2023; Wilson and Peter, 1988). However, while these general classifications are useful starting points, this study goes further by identifying specific vegetation types within these broad categories that require particular attention. Focusing conservation efforts solely on broad habitat classifications may lead to prioritizing less critical areas while overlooking key finer-scale habitats and vegetation types in need of protection. This is particularly problematic for macrogroup-associated species, as the loss or disturbance of their specific vegetation types can lead to their extinction (Devictor et al., 2008). This highlights the importance of finer-scale vegetation analysis, as habitat loss and disturbance can lead to an increase in generalist species that mask declines in specialists (Matthews et al., 2014). This is critical in the Americas, where our analysis found that macrogroup-associated species, defined as those found primarily in a single macrogroup for over half their AOH range, accounted for 20% of all assessed species and over 40% of threatened species in the region. Although the currently restricted distributions of some species may reflect past habitat loss rather than inherent dependence on that singular habitat type, it remains imperative to protect their remaining habitat. By examining macrogroup-level or finer-level classification units and species distributions, we can better target habitats and species in critical need of conservation efforts before further losses occur.

While our conservation value index provides a continental snapshot to identify important vegetation types, it has limitations. For example, two macrogroups - Northern Andean Xeromorphic Scrub & Woodland and Northern Andean Seasonal Dry Forest - were not top priorities in our index, due to having no macrogroup-associated species and a low risk of land-use change, yet they harbor many threatened species and are considered conservation priorities in the Tropical Andes (Comer et al., 2022c). Similarly, despite having a high density of macrogroup-associated species, macrogroups like Southern Mesoamerican Montane Humid Forest ranked low as it was nearly three-quarters protected with a very low risk of land-use change. Although we integrated and weighted four factors based on their relevance to conservation goals, it is important to note that this approach was specific to the aims of this study. Ultimately, there is no definitive formula for systematically identifying the most important habitats for conservation. Careful consideration is required to select criteria and determine weights that best align with specific conservation goals. While a continental analysis offers an initial snapshot of priority vegetation, on-the-ground assessments investigating overlooked local priorities are essential, since ultimately, effective biodiversity conservation requires multilayered strategies operating at various scales. Nevertheless, this framework offers a good foundation that can be adapted based on differing conservation measures and local priorities.

Despite utilizing the best available data, it remains essential to acknowledge the inherent constraints of this research. While high thematic detail was employed for the Americas, even finer habitat categorizations and more precise range maps could enhance understanding of habitat dynamics and species interactions, especially at local and regional scales. Exploring vegetation classifications beyond the macrogroup level can also offer insights into the conservation needs of localized communities and rare species (Comer et al., 2022b). Additionally, while we focused on mammals and birds due to data availability, other taxa have distinct habitat requirements and ecological roles warranting consideration in future studies. However, as birds and mammals are useful indicators of habitat quality and ecosystem health (Cooke et al., 2019), they serve as valuable representative taxa for identifying important areas for conservation (Brooks et al., 2001; Larsen et al., 2012). Another constraint relates to the temporal aspect, as the circa 2010 ecosystem maps may limit accuracy in representing evolving distributions, particularly for localized planning. Furthermore, many other land-scenarios could have been used and focusing only on one scenario restricted the examination of diverse habitat changes. Additionally, our inclusion of all protected areas may inadvertently encompass regions with varying levels of protection, potentially resulting in the incorporation of areas that provide limited conservation value or inadequate safeguards for biodiversity. A more nuanced approach for different protection levels could provide additional insights. Lastly, we did not address the vulnerability of specific habitats to climate change, which also warrants an aspect warranting further investigation.

Several future directions could help address the existing limitations of habitat maps. Developing a consistent global finer-scale habitat classification system, building upon frameworks like the IVC, would enhance the ability to perform comprehensive assessments worldwide with ongoing mapping efforts. Regional systems, such as EUNIS in Europe (Chytrý et al., 2020), have demonstrated their utility and could be further leveraged when paired with detailed species range data at national or subnational levels. Such an approach would enhance the precision of habitat assessments, particularly in localized contexts. Additionally, improving the accuracy and effectiveness of habitat maps can be achieved by integrating feedback from field studies and monitoring programs. The integration of new data sources and the refinement of analytical approaches are crucial for improving the effectiveness of conservation efforts. Leveraging emerging technologies such as drones, LIDAR, satellite imagery, and machine learning algorithms, along with harnessing diverse data streams from citizen science initiatives and social media, can further enrich our understanding and yield more accurate habitat data (Amani et al., 2023; Chowdhury et al., 2023; Iglseder et al., 2023; Sumner et al., 2019). Moreover, downscaled threat assessments may uncover microhabitat refugia not apparent at broader scales. By complementing detailed habitat assessments with fine-filter approaches to refine threat analysis, we can better inform multi-scale conservation planning. Lastly, assessing the climate vulnerabilities of specific habitats is required for a multifaceted approach to understanding and protecting biodiversity and vegetation communities within constantly changing environments (Comer et al., 2019; Comer and Seddon, 2023).

5. Conclusion

This study addresses a critical gap in our understanding of biodiversity conservation by identifying critical vegetation types across the Americas, emphasizing the importance of finer-scale, or more localized assessments. The urgency of such efforts is highlighted by global initiatives that advocate for the conservation of at least 30% of lands and waters by 2030 (Belote et al., 2021; Convention on Biological Diversity, 2022). By combining high-resolution vegetation maps and detailed habitat data, this research provides a robust framework for pinpointing at-risk vegetation types and guiding targeted conservation actions. The systematic approach employed, centered on finer-scale habitat classifications and the specific needs of threatened and macrogroup-associated species, offers a powerful methodology for identifying critical habitats based on their conservation significance. As we navigate a world of increasing biodiversity loss and ecosystem degradation, the integration of large-scale habitat assessments with localized diversity patterns and emerging threats is essential for advancing proactive conservation strategies. This study serves as a framework for harnessing high-resolution distribution data within flexible prioritization frameworks to precisely identify critical habitats requiring immediate attention, ultimately enhancing the precision and effectiveness of conservation planning. This approach can help towards more effective conservation efforts aimed at safeguarding critical habitats, not only in the Americas but in other regions around the world.

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CRediT authorship contribution statement

Schulte Lea: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Quoss Luise:** Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Oceguera Conchas Emmanuel:** Writing – review & editing. **Pereira Henrique M.:** Conceptualization, Project administration, Resources, Writing – original draft, Writing – review & editing. **Comer Patrick J.:** Data curation, Investigation, Resources, Writing – review & editing. **Lumbierres Maria:** Data curation, Investigation, Resources, Writing – review & editing. **Valdez Jose:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The raster dataset produced in this study will be made publicly available on Dryad (https://doi.org/10.5061/dryad.44j0zpcn0) for open access. Additionally, the data will also be accessbile as a NetCDF data cube in the EBVcube format on the EBV data portal portal (https://doi.org/10.25829/ja2s47). This paper is available in Spanish at: https://doi.org/10.1590/SciELOPreprints.7272.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e02831.

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