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Closing the research-implementation gap: Integrating species and human footprint data into Argentina's forest planning

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ABSTRACT

Closing the research-implementation gap is key for advancing biodiversity conservation. One approach is to generate ecologically relevant spatial datasets that integrate easily with existing management plans. Our goal was to identify priority forest conservation areas in Argentina by combining species distributions, human footprint data, and existing forest zoning. We: (i) mapped potential habitat distributions of 70 plant and animal species associated with forests, and of recognized social and ecological importance, (ii) combined the species distributions with human footprint data to identify priority conservation areas, and (iii) evaluated the juxtaposition of our priority conservation areas with current forest management zones. We found that priority conservation areas (i.e., high number of species and low human footprint) are poorly protected by the current zoning scheme. While the Andean-Patagonian region had a substantial portion (57 %) of priority conservation areas in high protection zones, in four other forest regions we evaluated, only 16–37 % of priority areas had high protection levels. Of great concern are the Chaco and Espinal regions, where 36 % and 39 %, respectively, of priority conservation areas are in low protection zones, where conversion to other uses (row crops, livestock) is allowed. Our results provide new spatial information to managers and conservationists highlighting where current forest zoning performs well, and where it may warrant re-evaluation. Overall, our study highlights the value of integrating species distributions and human footprint maps into existing land use plans to guide conservation efforts in data-poor countries, and is an example of a strategy for closing the research-implementation gap.

1. Introduction

Despite the rich academic literature devoted to developing spatially explicit techniques for identifying priority areas for biodiversity conservation, assessments published in the peer-reviewed literature rarely translate into conservation action (Carter et al., 2020; Knight et al., 2008). In the face of alarming biodiversity loss (Cardinale et al., 2012), this "research-implementation gap" is a major problem, permeating not only the field of conservation planning but ecology and environmental management in general (Toomey et al., 2017; Turner et al., 2002; Walsh et al., 2015). Closing the research-implementation gap is hence crucial to advance biodiversity conservation and management planning (Nguyen et al., 2021; Whitehorn et al., 2019).

One way to close this research-implementation gap is to provide management-relevant information that can be easily integrated into existing conservation plans (Carter et al., 2019; Josse and Fernández, 2021; Sievert et al., 2020; Sunderland et al., 2009). Research that is not readily accessible, that cannot be easily translated into decision-relevant terms, or that is conducted at inappropriate scales, poses challenges to adoption or incorporation by managers (Ferreira and Klütsch, 2021;

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Knight et al., 2008; Sunderland et al., 2009). In addition, because on-the-ground conservation requires institutional support, assessments that do not build upon the ongoing work of local natural resource planning institutions, such as governmental agencies, NGOs, etc., have little likelihood being integrated into established practices (Carter et al., 2020; Guzman et al., 2020). Thus, developing conservation-relevant datasets that local resource managers are invested in, and which can be easily incorporated into existing management plans, improves the likelihood that conservation research will be used by managers, and can help bridge the research-implementation gap (Ferreira and Klütsch, 2021).

Detailed information on the distribution of species of conservation concern and of the remaining wild areas (i.e., where human influence is low) are crucial for advancing forest conservation and management (Maxwell et al., 2020; Meyer et al., 2015; Watson et al., 2018). Having this information in map form is valuable for guiding regional conservation planning and management actions (Martinuzzi et al., 2018). Previous efforts at identifying priority areas for conservation have typically focused on identifying areas based on either species distributions (Brum et al., 2017; Jenkins et al., 2015; Politi et al., 2020) or location of the wildest areas (Martinuzzi et al., 2021; Riggio et al., 2020; Watson et al., 2018), but rarely both, and studies incorporating either or both sets of information into ongoing, national conservation strategies are rare (Martinuzzi et al., 2018; Schmidt-Traub, 2021).

In developing countries, management-relevant information for supporting national biodiversity strategies is limited (Fajardo et al., 2014; Fernández et al., 2015), and the research-implementation gap is particularly large (Josse and Fernández, 2021; Stephenson et al., 2021). While information on biodiversity and human influence from global maps abound (Jenkins et al., 2013; Riggio et al., 2020), global maps typically lack spatial detail nor do they address country-specific management needs (Christie et al., 2020; Rodrigues, 2011; Rondinini et al., 2006). Thus, the challenge is to ensure that countries have meaningful and rigorous analyses on priority areas for biodiversity conservation based on existing data.

One way of doing so is to focus on small select sets of high-profile species that are representative of different ecoregions and that are widely recognized and valued by the citizens of a region because of their ecological role, conservation status, and/or cultural values, and for which there is available information to model their potential habitat distribution, referred here as "species of regional importance". We think that focusing on these high-profile species is a strategy that can promote conservation planning at regional scales because the focal species are readily recognized and evoke positive associations (e.g., pride, empathy, a sense of responsibility), as opposed to a strategy that addresses biodiversity broadly, which is more intangible because of the many poorly recognized and cryptic species included. Focusing on these high-profile species has two advantages; regional conservation planners with little or no biodiversity training are motivated by tangible target species, and many other species may be afforded adequate or partial protection (Drummond et al., 2010; McGowan et al., 2020; Politi et al., 2021). Further, by using human footprint maps, which depict the potential human influence on the landscape based on spatial data layers of human land use and infrastructure, the most ecologically intact (i.e., wildest) areas of each region can be identified (Kennedy et al., 2019; Venter et al., 2016). Nowadays, more and more developing countries have human footprint maps derived from locally-relevant information (González-Abraham et al., 2015; Guzmán-Colón et al., 2020; Inostroza et al., 2016; Martinuzzi et al., 2021), which provide a unique opportunity to integrate information about species distributions and human footprint to enhance conservation in these regions.

Argentina is an example of a developing country with a wide variety of forest ecosystems and wildlife species, but also with some of the highest rates of deforestation in the world (Martínez Pastur et al., 2020). To regulate deforestation and protect the ecological and cultural values of native forests, the Argentinian government in 2007 passed National Law 26,331/07 (Law on Minimum Environmental Protection Standards for Native Forests), which mandates that provinces create a zonation plan for their forest areas based on their conservation value, also known as the "Native Forest Law" (Marinaro et al., 2020; Volante et al., 2016). The Native Forest Law zonation plan identifies three land use categories: Category I (red) encompasses forests with high conservation values where land-use transformation is forbidden; Category II (yellow) includes forests with intermediate conservation values where sustainable activities are permitted, including logging and cattle grazing (i.e., silvopasture); and Category III (green) corresponds to forests with low conservation values where partial or total transformation, including deforestation for row-crop agriculture or artificial pastures, is allowed (Camba Sans et al., 2018). Provinces have to update their zoning plan every five years.

However, when the Native Forest Law was implemented, many provinces made decisions about which forest areas should be in which land use category based on different criteria, and based on inconsistent and/or incomplete biodiversity data. Subsequently, a few studies in Argentina integrated species distributions and human footprint data to guide conservation prioritizations, but they were restricted to small areas and used different methodologies (Martinuzzi et al., 2018; Politi et al., 2021; Rosas et al., 2021a, 2021b). Recently, Martinuzzi et al. (2021) mapped the human footprint for Argentina native forests in a consistent fashion, but consistent maps of the potential distribution of species of regional importance are lacking. Thus, crucial questions remain about both the location of forest areas where high numbers of species of regional importance and low potential human influence across Argentina are found, and how these areas are zoned under the Native Forest Law. Such information is critical to accomplish the goal of biodiversity persistence.

Our goal was to identify priority areas for forest conservation based on species distributions, human footprint, and existing forest conservation designation in Argentina. Our specific objectives were to: (i) map the potential distribution of species of regional importance across Argentina native forests; (ii) identify priority conservation areas corresponding to the areas with both the highest number of species of regional importance and lowest human influence within each forest region; and (iii) evaluate the protection status of those areas according to the current Native Forest Law land zonation.

2. Material and methods

2.1. Study area

We focused on five of the seven forest regions of Argentina, including Andean-Patagonian (known in Argentina as "Bosque Andino Patagónico"), Atlantic ("Selva Paranaense"), Chaco ("Parque Chaqueño"), Espinal, and Yungas, which together encompass 90 % of the forest area under the Native Forest Law (Fig. 1b). These regions contain distinct forest ecosystems, ranging from rainforests (Atlantic and Yungas) to subtropical dry forest (Chaco), sub-Antarctic temperate forest (Andean-Patagonian) and xerophytic forest (Espinal; Pastorino, 2021). We did not include the regions Monte nor Parana River Delta and Islands ("Delta e Islands del Río Parana") because of low data availability. We adopted the spatial delineation of forest regions that the Argentine government uses for forest monitoring and inventory purposes.

2.2. Data

2.2.1. Species of regional importance

We selected for each forest region between 13 and 23 species of regional importance, including birds, mammals, trees, and herbaceous plants that are associated with forests and are widely considered representative of the specific region, for a total of 80 species (Table S1). Some species (Jaguar [*Panthera onca*], Ocelot [*Leopardus pardalis*],

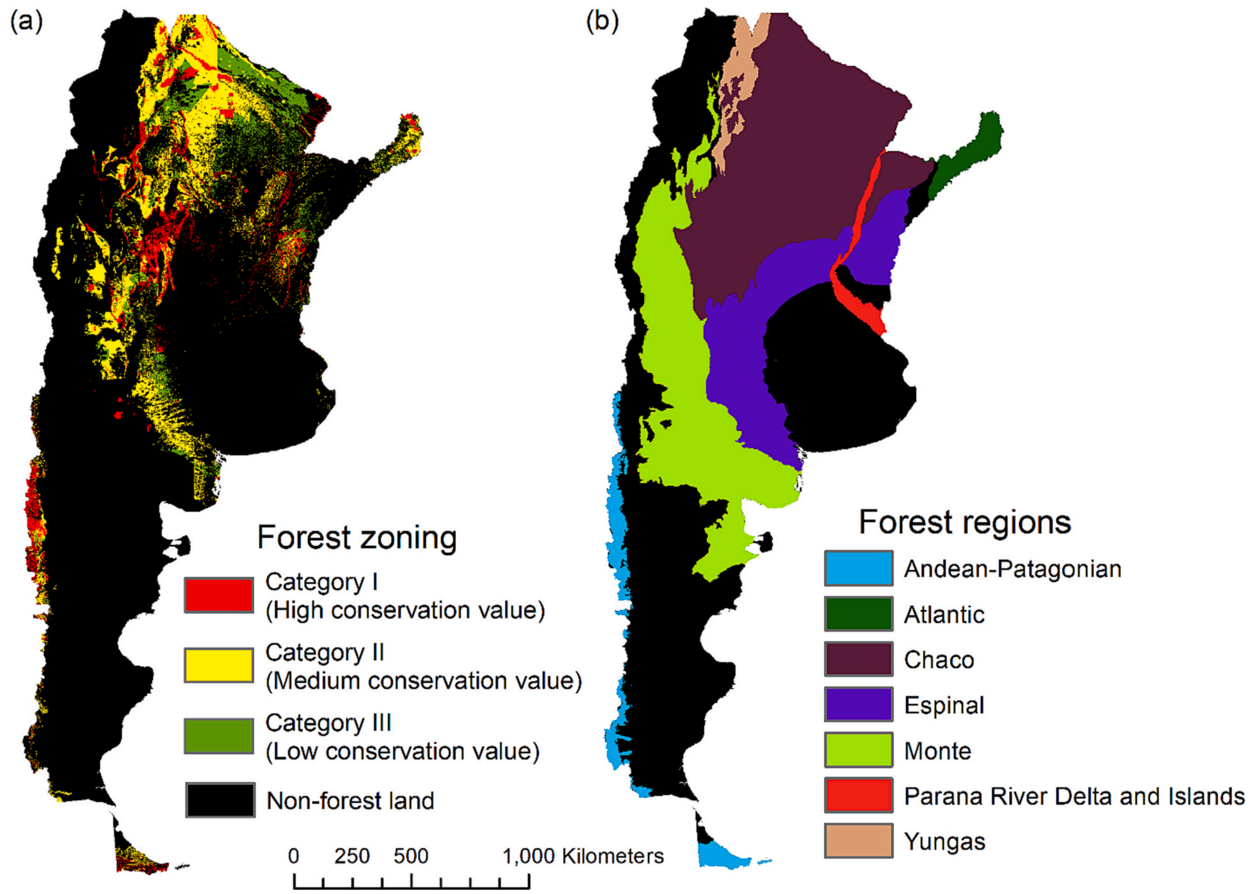

Fig. 1. Forest zoning according to Argentina's Native Forest Law (a), and forest regions (b). Regions include non-forested as well as forested area.

South American tapir [*Tapirus terrestris*], White-lipped peccary [*Tayassu pecari*]) were considered representative of more than one region, and our regional species lists reflect this. The species are widely recognized due to their ecological importance, cultural significance, aesthetics, or scientific interest, and the lists were established using expert knowledge and literature review. We obtained species occurrence records from the Global Biodiversity Information Facility (GBIF, for 2008-present), from Argentina's Second Native Forests Inventory 2015–2020 (Ministry of the Environment and Sustainable Development of Argentina), Sistema de Información de Biodiversidad (SIB; National Parks Administration), Fundacion CEBio database (www.cebio.org.ar), and other sources (e.g., PEBANPA network; Peri et al., 2016). We included records from Argentina plus a 200-km buffer around the country limits to increase sample size for the parameterization of our models. We removed occurrence records with wrong coordinates (e.g., due to data entry errors) and used the 'spThin' package (Aiello-Lammens et al., 2015) to spatially thin the data so as to reduce potential geographic bias (Beck et al., 2014). Specifically, we excluded records that were <2 km apart because our environmental data had 1-km resolution, and greater distances than 2 km would dilute environmental changes associated with steep elevational gradients, like in the Andes mountains. Further, because we were interested in modeling species distributions in forests, we restricted the species observation records to those occurring within forest pixels, defined as containing >50 % forest cover based on satellite data (Hansen et al., 2013), or located in close proximity (within a 5-by-5-km window) to a forest pixel. We only retained species with a final number of records equal to 30 or more, which is the minimum sample size necessary for running species distribution models using various methods (Soultan and Safi, 2017; Støa et al., 2019; Wisz et al., 2008).

2.2.2. *Environmental predictor variables*

To model the potential distribution of the species of regional importance we used six climatic and seven remotely-sensed predictor variables at 1-km resolution. We first downloaded the 19 standard bioclimatic variables from WoldClim (Fick and Hijmans, 2017) at 1-km resolution, and eliminated those that were highly correlated, using Spearman's correlation coefficient > 0.8 estimated based on 5000 random points within the forested area (Fig. S1). We retained six bioclimatic variables as predictors: mean diurnal temperature range (mean of monthly maximum and minimum temperature, BIO2); isothermality (BIO3); temperature seasonality (BIO4); maximum temperature of warmest month (BIO5); precipitation seasonality (BIO15); and precipitation of the warmest quarter (BIO18). Our remote sensing predictor variables, also with Spearman's correlation coefficient < 0.8, included two components of the Dynamic Habitat Indices (DHIs) based on MODIS data from 2003 to 2014 (Hobi et al., 2017; Radeloff et al., 2019), including cumulative DHI, which is a proxy for the productive capacity in an area, and variation DHI, which measures the seasonal (intra-annual) variability in productivity; as well as three phenological variables also derived from MODIS 16-days Vegetation Indices (MOD13Q1-collection 6; EVI 250-m resolution), including the start of the growing season, defined as the first day of the year when vegetation greenness reached >25 % of the annual maximum, the end of the growing season, which is the first day of the year in autumn when vegetation greenness was <25 % of the annual maximum, and the length of the growing season, which is the number of days between the start and end of season dates. We also used two thermal heterogeneity variables derived from Landsat-8 TIRS data, including thermal heterogeneity in summer, i.e., the spatial variability of land surface temperature values within 1-km pixels in summer months (November to February); and thermal heterogeneity in winter (May to August), i.e., the spatial variability of land surface temperature values within 1-km pixels in winter months. We resampled the MODIS-derived variables from 250 m to 1-km to match the resolution of our coarsest dataset. To do so, we generated a 1-km grid and calculated mean values within the grid. More information on the remote sensing variables can be found in Hobi et al. (2017), Radeloff et al. (2019), and Silveira et al. (2021).

2.2.3. Human footprint

We identified the most-intact forests in each forest region based on a human footprint map at 100-m resolution developed for the native forests of Argentina by Martinuzzi et al. (2021). The map reflects the combined pressure of human settlements (urban and rural settlements), transportation (primary roads, secondary roads, etc.), energy infrastructure (oil and gas wells, pipelines, etc.) and land uses (forest plantations, deforestation) across the landscape with pixel values ranging between 0 and 1, where 0 corresponds to the areas with the lowest potential human influence and 1 the highest. To map the human footprint, first, the pixels in each GIS layer (e.g., primary roads, urban settlements, etc.) were assigned values between 0 and 1 taking into account: (i) the level of land transformation by the human feature in question, and (ii) the distance to which substantial ecological effects extend outward from each human feature (Martinuzzi et al., 2021). Specifically, a decay function was used to reflect the declining level of human influence with increasing distance, with a steeper decline near the source, and a more gradual decline further from the source. Then, to map the cumulative human footprint, the human influence scores across the different datasets were combined using Theobald's fuzzy algebraic sum of human modification scores. Additional information on the human footprint map creation can be found in Martinuzzi et al. (2021). Finally, for the purpose of easier data handling in this study, we rescaled the human footprint map values from 0–1 to 0–10.

2.3. Analysis

2.3.1. Species distribution modeling and creation of richness maps

To identify areas with high numbers of species of regional importance, we first mapped the potential habitat distribution for each species using species distributions models, and then stacked the maps to create "richness" maps for each forest regions. We modeled the species' potential distributions using ensemble modeling with the R package biomod2 (Thuiller et al., 2020; Thuiller et al., 2009) following precedent of recent studies (Bellard et al., 2014; Hao et al., 2019; Loiseau et al., 2020; Zhang et al., 2017). Rather than using a single algorithm, like maxent, or GLM, ensemble modeling combines predictions from multiple algorithms into a single output (i.e., an ensemble). Our ensemble included projections from eight modeling algorithms: generalized linear model (GLM), generalized boosting model (GBM), generalized additive model (GAM), classification tree analysis (CTA), multiple adaptive regression splines (MARS), random forest (RF), surface range envelope (SRE), and maximum entropy (Maxent). For each species, we evaluated the predictive power of each of the eight models using 80 % of the data for training and 20 % for testing, which was repeated four times using different sets of randomly-selected training and testing samples (Loiseau et al., 2020; Zhang et al., 2017), and we evaluated models' accuracy based on the area under the receiver operating characteristic curve (AUC; Fielding and Bell, 1997) and the true skill statistics (TSS; Allouche et al., 2006). In addition, because the models require both presence locations and pseudo-absences, we randomly generated five sets of 1000 pseudo-absences within 1000 km of presences and gave equal weight to presences and pseudo-absences (Bellard et al., 2014). As recommended by VanDerWal et al., 2009, we also tested the results of using different numbers of pseudo-absences (1000 vs. 10,000) generated within different distances from the presence points (ranging from 50 km to >2000 km), and found that 1000 pseudo-absences generated within 1000 km best differentiated the environmental conditions under which species occur in Argentina. To make the final prediction for each species, we used all the available data but only retained output from modeling algorithms for which the predicted power indicated by the TSS and AUC values was higher than 0.6 and 0.8, respectively (e.g., Bellard et al., 2014), and we obtained the ensemble distribution using the weighted average consensual approach and the TSS as weight (Hao et al., 2019).

We then created "richness" maps (i.e., one for each forest region) based on the species of regional importance specific to that region. To do so, we converted the species' potential distribution maps from continuous values to binary maps of presence-absence of suitable habitat using the threshold that maximized the TSS value (Bellard et al., 2014; Zhang et al., 2017), and clipped the maps by the limits of the forest area, since the species used in our analysis are forest-affiliates. Lastly, we summed the individual species distributions for each forest region, resulting in a richness map in which the value of each pixel corresponds to the number of species of regional importance predicted to have suitable habitat in that pixel.

2.3.2. Identification of priority conservation areas

We defined priority conservation areas as the 30 % of area of each forest region with the highest number of species of regional importance and the lowest human footprint per pixel. We chose 30 % to be consistent with an International Union for Conservation of Nature (IUCN) initiative to protect 30 % of Earth's land area by 2030 (a.k.a. "30 × 30"; https://www.iucn.org/). For each forest region (n = 5), we first rescaled the richness map linearly from 0 to 10 to make it consistent with the scale of the human footprint, and then extracted for each pixel the values of species richness and human footprint. To identify the priority conservation areas, we quantified the areal extent (km^2) occupied by the pixels with the highest species richness (i.e., value 10) and the lowest human footprint (i.e., value 0), and then added more pixels by including the next-highest species richness and next-lowest human influence scores (i.e., 9–0, 10–1, 9–1, and so forth), until the areal extent reached 30 % of the forest area of a given region.

2.3.3. Protection status of the priority conservation areas

Our third objective was to evaluate the protection status of the priority conservation areas based on the forest zone designation under the Native Forest Law (Fig. 1a). For each forest region, we calculated the proportion (km^2 and %) of the priority conservation areas within the three different zonation categories (I, II, and III). We assumed that the threat of forest loss or degradation, and of logging within priority conservation areas, is highest in Category III lands (green, indicating few restrictions on human activities), followed by Category II (yellow, intermediate restrictions), and then Category I (red, indicating highest protection of natural features and processes, including legally declared protected areas). Meeting IUCN's 30 % conservation target requires priority conservation areas to be fully (i.e., 100 %) in Category I lands, since our priority areas represent 30 % of the forest in each region.

2.3.4. Species richness and human footprint outside of priority conservation areas

Because our definition of priority conservation areas required pixels with both high number of species *and* low human influence, it is theoretically possible to find areas with high number of species of regional importance *but* high human footprint, or with low human footprint *but* low species richness, outside our priority conservation areas. Knowing this is important for conservation and management, as areas with high species richness and high human influence would be candidate areas for enforcement of natural resource laws (e.g., protection from illegal logging and poaching). Areas with low human influence and low species richness can be important as they may serve as connectors/corridors between high quality habitat or for the provision of ecosystem services. To address this objective we quantified, for each forest region, the area (km^2) occupied by pixels with species richness scores >8 on the 0–10 scale (i.e., our indicator for species hotspots), and the area occupied by pixels with human footprint value equal to zero (our indicator for wilderness), outside of the priority conservation areas.

3. Results

3.1. Species distribution modeling

We modeled the potential distribution of 70 of the 80 species of regional importance included in our initial list, including 17 of 17 of the species in the Andean-Patagonian region, 20 of 23 (87 %) in the Atlantic region, 12 of 17 (71 %) in Chaco, 12 of 13 (92 %) in Espinal, and 15 of 16 (94 %) in Yungas (Table S1). The final number of observations per species after thinning ranged between 34 and 2861 with a median of 139 (Table S1). The ten species that we did not model had fewer than 30 observations, our minimum sample size for modeling. The process of data thinning reduced the total number of usable species observations by 63 %, from 77,493 before thinning, to 28,891 after thinning.

3.2. Species richness and human footprint patterns across forest regions

We found that patterns of predicted richness values of the regionally important species varied across regions. In the Andean-Patagonian, Atlantic, and Yungas regions there were large areas of forest with high species richness values. For example, in the Andean-Patagonian and Yungas regions the pixel-level richness values ranged between 0 and 15, and about half of the forest in each region (or ~ 22,000 km^2) had richness values of 10 or more (Fig. 2, Fig. S2). In contrast, in Chaco and Espinal there were small areas of forest containing high richness values of regionally important species. In Chaco, the richness map peaked at medium levels (i.e., richness value of five, with 51,000 km^2). In Espinal, 41 % of the forest area (31,000 km^2) was predicted to have habitat for zero species of regional importance (i.e., richness value of zero), and the richness values followed a rather uniform distribution (Fig. 2, Fig. S2). All forest regions had some areas with zero predicted species richness, but in less proportion than Espinal (i.e., in other forest regions zero species richness areas were equivalent to 1 %–16 % of the forest area).

On the other hand, in all regions the values of human footprint maps were heavily skewed towards the lower end of the range, meaning that most forest pixels had low human footprint (Fig. 2, Fig. S2). The proportion of forest area with human footprint equal to zero varied from 26 % in the Atlantic region to 61 % in the Andean-Patagonian.

3.3. Priority conservation areas

The distribution of the priority conservation areas, defined as the 30

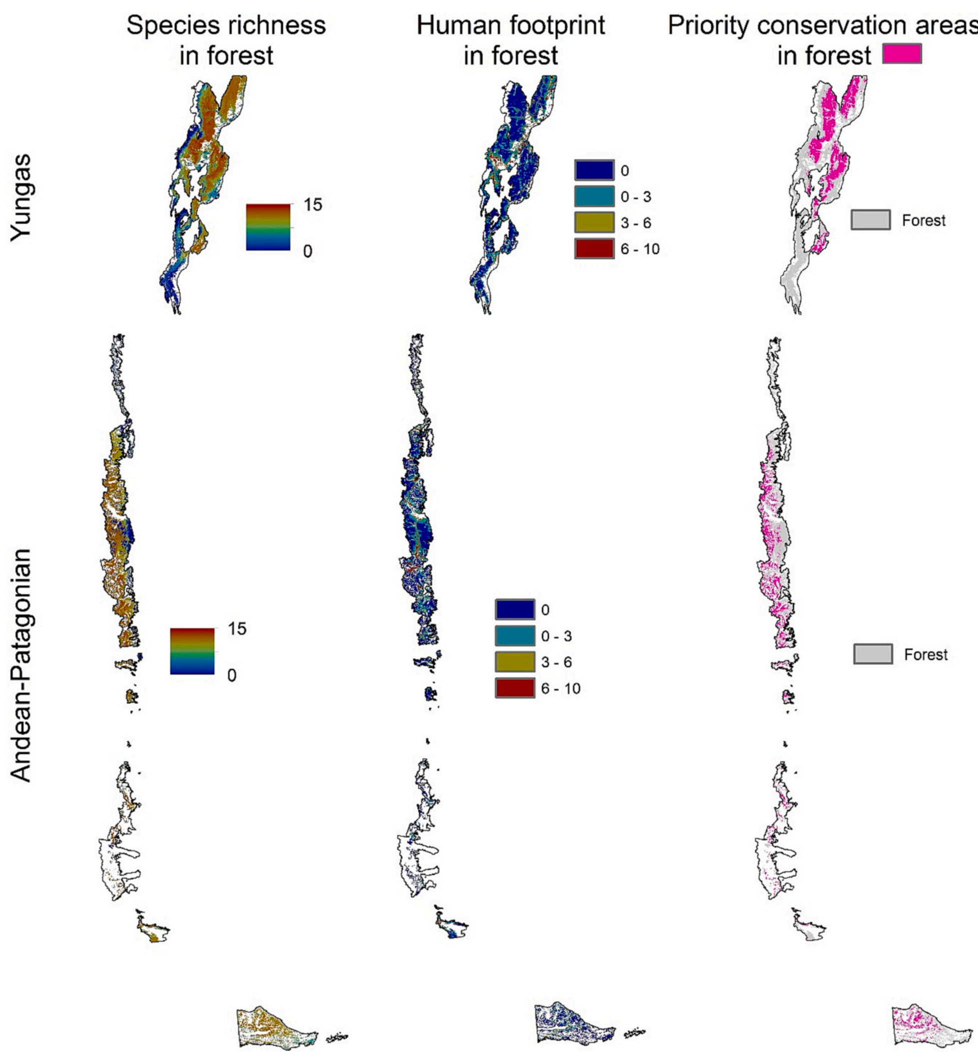

Fig. 2. Species richness, human footprint, and priority conservation areas in the forest areas of the different regions. Priority conservation areas (in pink color) correspond to the 30 % forest area of each forest region with the highest number of species of regional importance and the lowest human footprint per pixel. Forests outside of priority conservation areas are shown in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

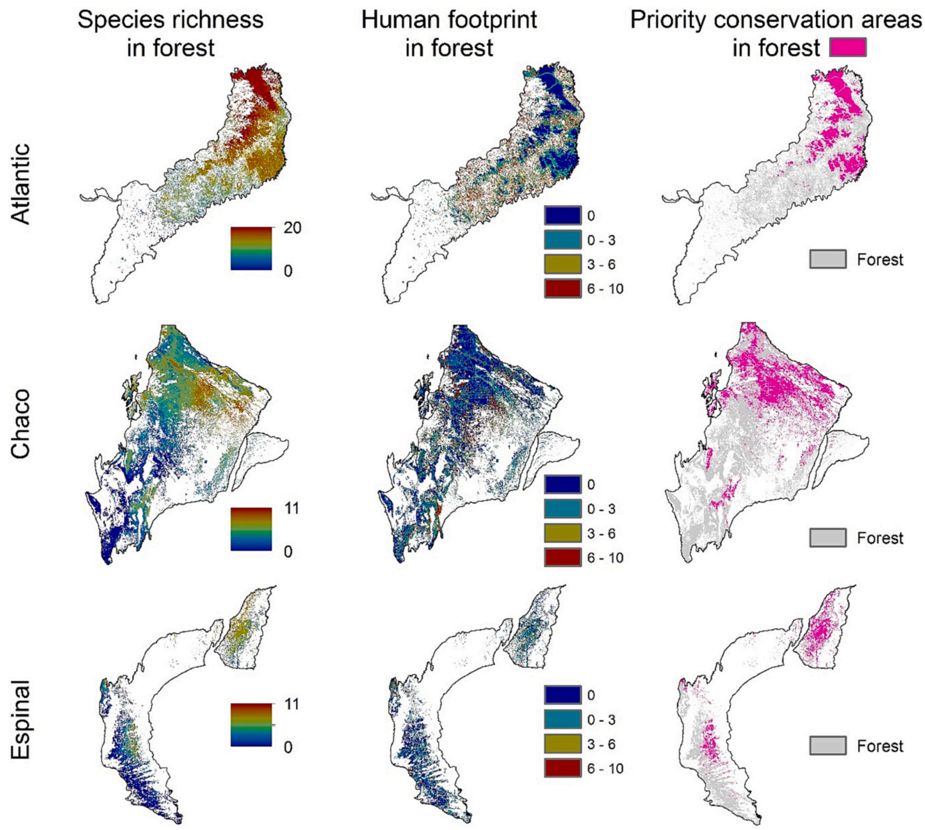

Fig. 2. (*continued*).

% of each forest region with the highest richness of species of regional importance *and* the lowest human influence, varied across regions. In Atlantic and Chaco regions, priority conservation areas were concentrated in northern areas of forest (Fig. 2). Espinal had two areas of high species richness, one in northeast and one in the south-central part. In Yungas, priority conservation areas were concentrated in the northern and eastern-central parts. In the Andean-Patagonian region, which occurs along the eastern edge of the Andes and into Tierra del Fuego, priority conservation areas were distributed throughout the west of the Andean forest and northern part of Tierra del Fuego (Fig. 2).

The values of species richness and human footprint that comprised the 30 % areal extent designated as priority conservation areas also varied across regions (Fig. 3). In the Andean-Patagonian, Atlantic, and Yungas regions, priority conservation areas included human footprint values of 0 to 2 and species richness of 7 to 10 (on the 0–10 scale; Fig. 3). In Espinal and Chaco, however, in order to reach the 30 % target area, the range of values of species richness and human footprint was much wider, and included areas with substantially higher human footprint (values 0 to 7) and lower species richness (values 2 to 10 on the 0–10 scale).

3.4. Protection status of the priority conservation areas

We evaluated the protection status of the priority conservation areas based on the Native Forest Law's land zone designation. We found that (i) IUCN's 30 % target was not met, (ii) the results varied by region, and (iii) priority conservation areas in Chaco and Espinal regions are under higher threat that priority conservation areas in other forest regions.

Meeting IUCN's target of protecting 30 % of the land requires priority conservation areas to be fully (i.e., 100 %) in Category I lands, the highest level of land protection under the Native Forest Law. In all regions, the proportion of priority conservation area in Category 1 lands were much lower than that; for example in Andean-Patagonian 57 %, in Atlantic 37 %, in Yungas 27 %, in Espinal 26 %, and in Chaco 16 % of our calculated priority conservation areas were designated as Category 1 (Fig. 4). At the same time, Andean-Patagonian, Atlantic, and Yungas regions all had very small proportions (<2 %) of their priority conservation area in Category III (green), the category in which forests can be converted to other uses. In contrast, Chaco and Espinal had 36 % and 39 % of their priority conservation areas in Category III (Fig. 4). Finally, all regions have a substantial proportion of the priority conservation area (35 % to 72 %) in the medium protection level, Category II (yellow).

3.5. Species richness and human footprint outside of priority conservation areas

We quantified the area (km^2) occupied by pixels with relative species richness scores >8 on the standardized 0 to 10 scale (i.e., our indicator for species hotspots), and the area occupied by pixels with human footprint value equal to zero (i.e., our indicator for wilderness), in relation to the priority conservation areas. We found that all forest regions have some pixels with relative species richness scores >8 or with human footprint equal to zero outside of our priority conservation areas, and that patterns varied among regions (Fig. 5). For example, in the Atlantic region, a similar amount of high species richness pixels occurred inside (4659 km^2) and outside (4385 km^2) the priority conservation areas (Fig. 5a). In Andean-Patagonian and Yungas, about 20 % of the high species richness pixels were located outside the priority conservation areas, representing 3462 km^2 and 2480 km^2 respectively. On the other hand, in Espinal and Chaco pixels with relative species richness values >8 were rare, and most of them (>85 %) occur inside the priority conservation areas (Fig. 5a).

On the other hand, pixels with human footprint value equal to zero were common both inside and outside the areas of conservation importance in Andean-Patagonian, Chaco, Espinal, and Yungas (Fig. 5b). However, in the Atlantic region, most (87 %) of the pixels with

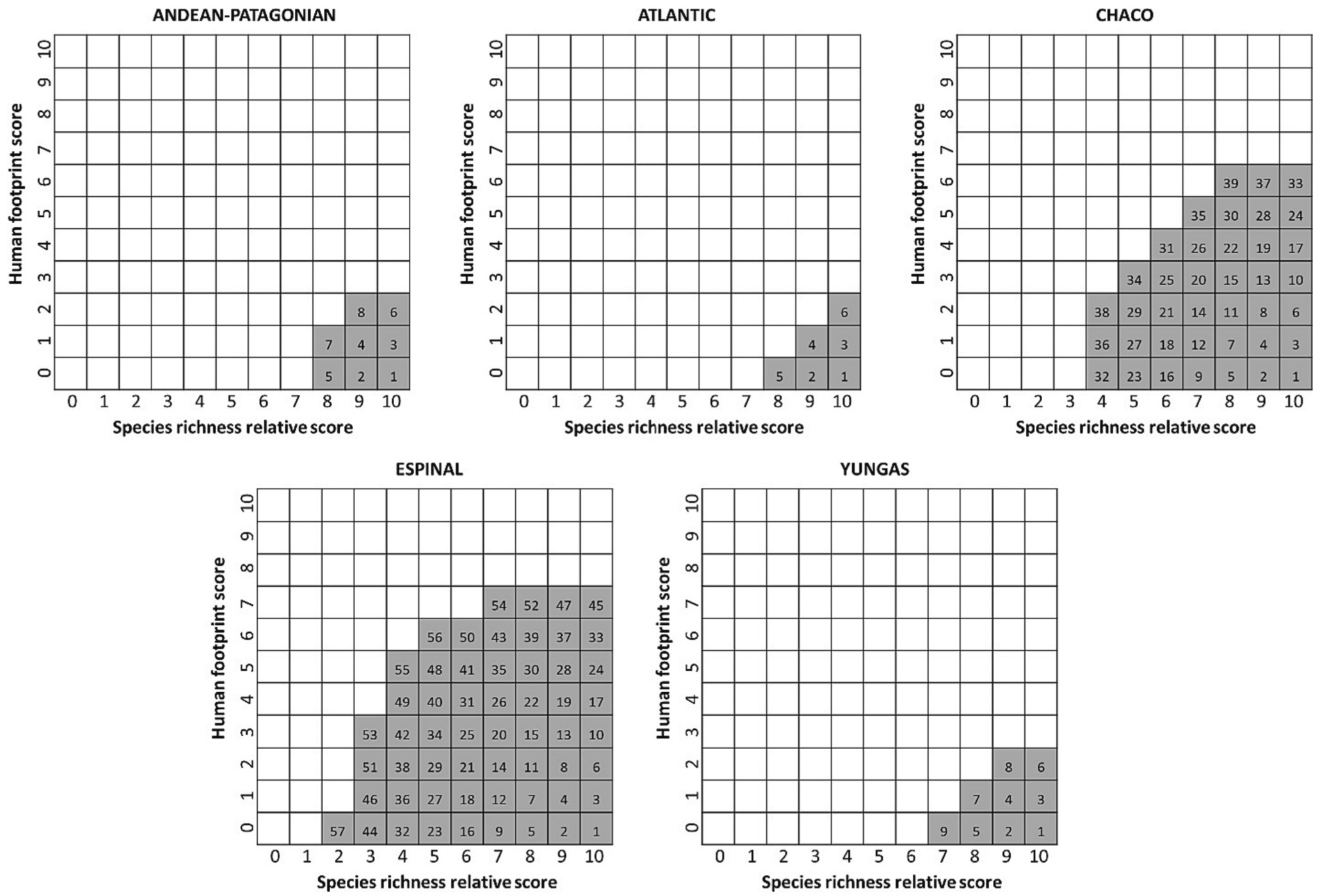

Fig. 3. Combination of human footprint and species richness scores that comprised the 30 % priority conservation area in each forest region (shown in gray). Relative scores range between 0 and 10. The numbers in cells indicate the order in which the combinations of species richness and human footprint values were added in priority conservation areas, starting with "1", then "2", "3", etc.

human footprint value equal to zero were located inside the priority conservation areas (Fig. 5b).

4. Discussion

We identified priority conservation areas in five forested regions of Argentina where modeled richness of species of regional importance was high and human footprint was low. A novel aspect of our approach is that we integrated data for species that are societally important according to both social and ecological criteria, which can be useful for countries that do not have comprehensive presence data for the full assemblage of biodiversity. Including socially important species may have the advantage of garnering wide buy-in by the populace at large for priority areas because a number of the included species are widely recognized. Our resulting maps identified areas of conservation importance where the existing Native Forest Law zoning designation is commensurate with the value of the land areas for biodiversity, as well as areas where there is a conflict between an area's designated forest protection status and its conservation importance. Our analyses were made for each region independently, highlighting priority areas according the particularities of the region. The biodiversity values varied greatly across range of ecosystems, from rainforests in the north to temperate forests in the south (Matteucci et al., 2021), and also varied within each region. Our maps help close the research-implementation gap by providing spatially detailed information at management relevant scales about species habitat value, human influence, and current land zoning. The maps reveal where prioritizing high vulnerability sites or low vulnerability sites (a la Brooks et al., 2006) may be undertaken in updates to provincial land use plans.

Our maps of potential distribution for 70 regionally important species revealed substantial variation in richness among forest regions. While Andean-Patagonian, Atlantic, and Yungas supported relatively large areas of forest with high species richness values, in Espinal and Chaco, forest areas with high richness of regionally important species were rare. This is likely due to extensive land cover conversion and forest degradation in Espinal and Chaco (Peri et al., 2021) plus the large areal extent and relatively low productivity of these regions, which may contribute to fewer overlapping distributions. In Chaco, most bird species have a narrow rather than wide range size, and occupy a total area less than half of the entire region (Názaro et al., 2020). In Andean-Patagonian forests, the bird species of regional importance are mostly generalists, which locally migrate among the seasons in relation to food availability. However, there are also specialists in Andean-Patagonian forests that need mature forest structure to meet food and nesting requirements (e.g., Magellanic woodpecker, *Campephilus magellanicus*) (Schlatter and Vergara, 2005; Vergara and Schlatter, 2004), are associated to old-growth unmanaged forests (e.g., *Dysopsis glechomoides*, family Euphorbiaceae) (Lencinas et al., 2017), or occur in a narrow area (e.g., huemul, *Hippocamelus bisulcus*) (Rosas et al., 2017).

We also found that within priority conservation areas the range of species richness and human footprint values varied substantially. In the Andean-Patagonian, Atlantic, and Yungas, hotspots of species richness and the location of the wildest forests (i.e., those with the lowest potential human footprint) share many of the same places, and thus, priority conservation areas in these three regions have both very high species richness (i.e., values of 7 to 10 on the 0–10 scale) and large numbers of pixels with human footprint equal to zero (~80 % of the total area). This can be explained by different factors depending on the

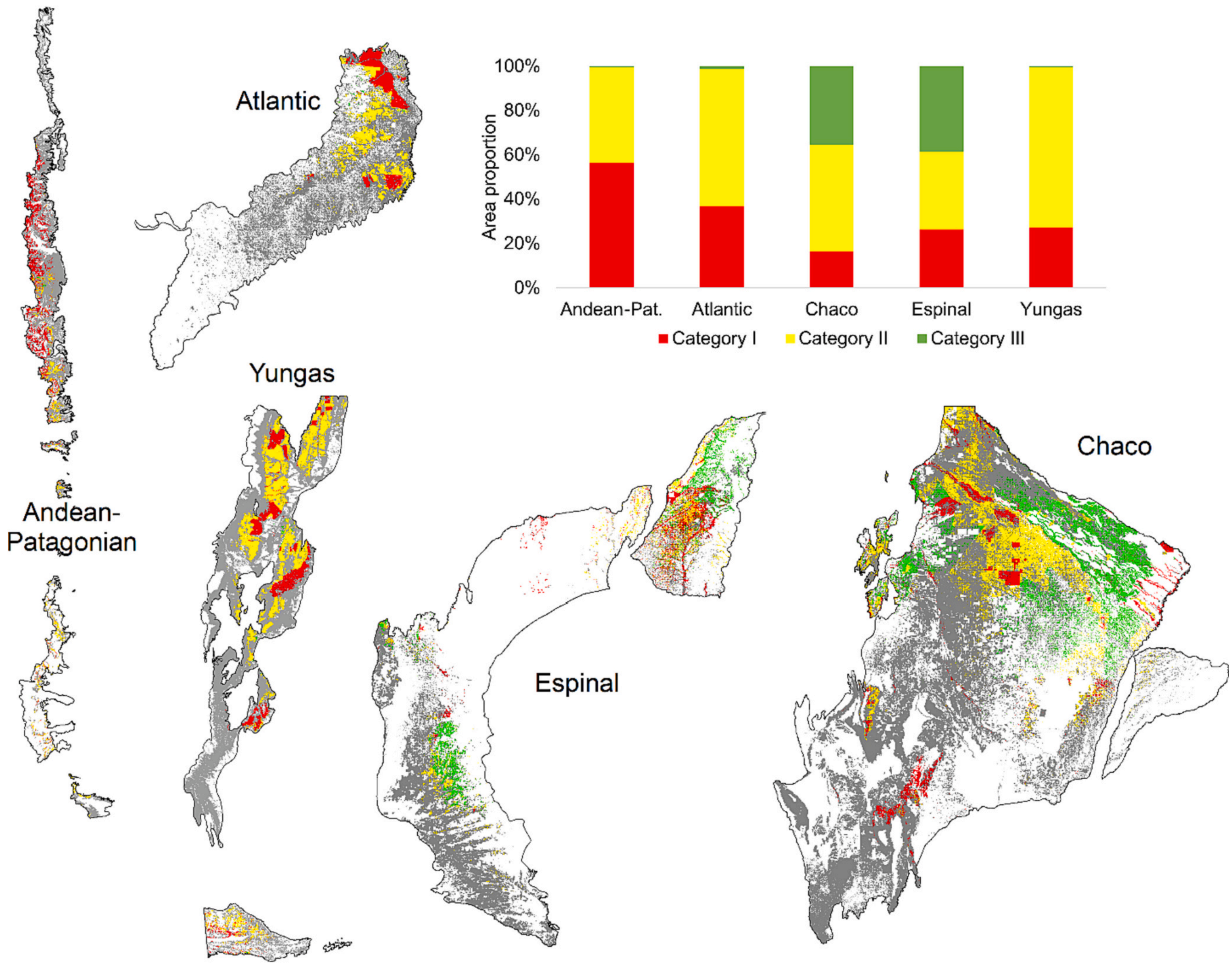

Fig. 4. Priority conservation areas within five forest regions shown according to how that are currently zoned under the Native Forest Law. Forests outside the priority conservation areas are shown in gray.

region. In Andean Patagonian and Yungas, complex topography makes landcover conversion beyond the lowlands difficult, resulting in the presence of large tracts of relatively continuous forests in the mountains that are also suitable habitat for the species of regional importance, and are relatively safe from encroachment, as has been found in other ecosystems (e.g., Wilson et al., 2005b). In the highly transformed rolling hills of the Atlantic region, large protected areas (e.g., Iguazú National Park, Urugua-í Provincial Park, Yabotí Biosphere Reserve) seem to play a key role as they both contain much of the remaining wildest forests of the region and are suitable habitat for many species of regional importance. On the other hand, priority conservation areas in Chaco and Espinal show much wider ranges of species richness and human footprint values, which is in part expected considering the lack of large hotspots of species richness in these regions. Further, visual inspection of the human footprint map for Chaco and Espinal shows that roads, recent deforestation, and small rural settlements represented by "puestos" (i.e., small rural settlements consisting of one or a few houses clustered around an artificial water source for livestock) and "caseríos" (i.e., clusters of a few rural houses plus a first-aid post and a small school) are responsible for the presence of positive human footprint values inside the priority conservation areas, and substantially increase exposure to threatening processes (a la Wilson et al., 2005a). Thus, our study highlights that conserving and managing priority conservation areas in Espinal and Chaco must include the local people, reinforcing findings of previous studies (Marinaro et al., 2020; Nunez Godoy et al., 2022; Torres et al., 2014; Vallejos et al., 2022).

The human footprint characterizes the pressure on native forest from both modern society, as well as local people's activities and land use changes. The actions of local indigenous communities, both now and presumably in past centuries also, depends within each region on opportunities for obtaining wild resources. Rural families of indigenous and other ethnic backgrounds harvest plants and animals available in native forests (Schaumberg, 2020; Vallejos et al., 2022), but to our knowledge there is no past record of extensive fires in Argentina's forests set by indigenous people. In addition to the human footprint of local communities, there is also pressure from people living in urban areas through poaching and illegal harvesting (Aguiar et al., 2022; Mosciaro et al., 2023). This great variety of human pressures are integrated in the human footprint.

We examined the allowable use designations of the priority conservation areas under both the Native Forest Law zonation scheme and IUCN's goal of protecting 30 % of the land. Although IUCN's goal was not met because no region had their entire priority conservation areas designated as Category I lands, our analysis identified some regions where the land use designation correspond to the value of the forest for biodiversity. In the Andean-Patagonian and Atlantic regions a large proportion (57 % and 37 %) of priority conservation areas were designated as Category I (red) under the Native Forest Law, indicating that

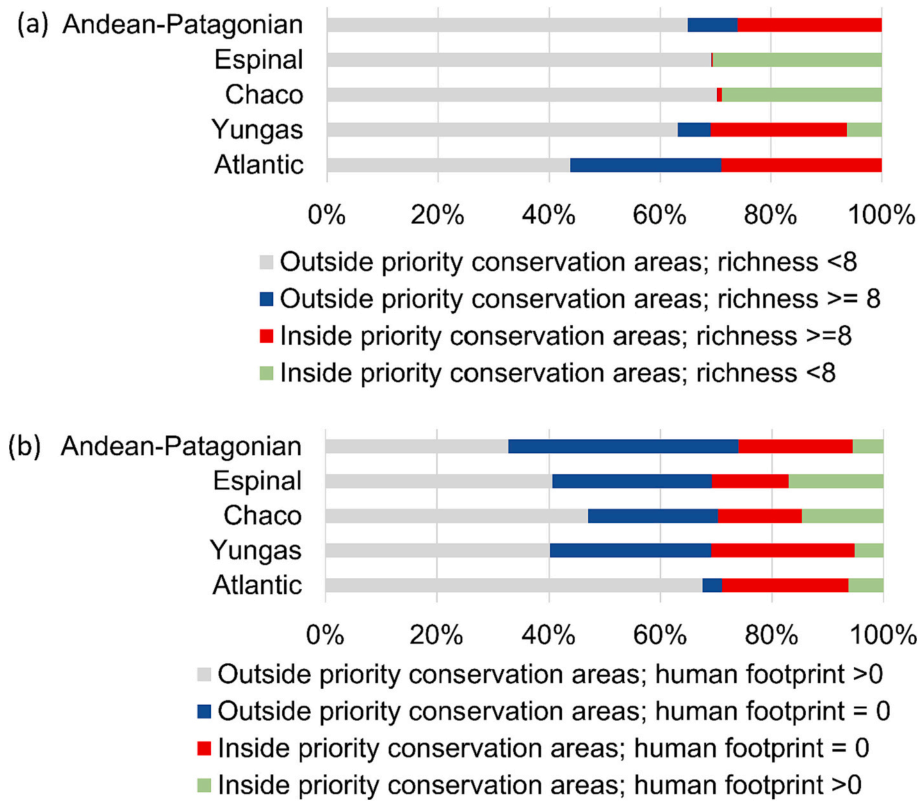

Fig. 5. Percent of pixels with relative species richness scores >8 on the standardized 0 to 10 scale (i.e., our indicator for species hotspots), and percent of pixels with human footprint value equal to zero (i.e., our indicator for wilderness), in relation to the priority conservation areas.

there is some level of protection, and further, these regions had practically no lands of priority areas designated as Category III (green), where deforestation is allowed. Thus, the prospects for long-term persistence of biodiversity in the Andean-Patagonian and Atlantic regions are more promising than for other forest regions of Argentina. However, we also found regions in which there was substantial conflict between the designated forest protection status and conservation importance. The most notable of these was in Chaco and Espinal, where more than a third of their priority conservation area was designated in the lowest conservation Category III (green), and another ~40 % was designated as Category II (yellow), where activities that could degrade the ecological integrity of forests are allowed, thus leaving a huge proportion of their priority conservation areas (84 % and 74 %, respectively) vulnerable to degradation or loss. Our results therefore indicate an urgent need to revisit the current zoning structure, especially in Chaco and Espinal regions.

Our study is also subject to limitations. Our strategy of using species of regional importance has several advantages over modeling all biodiversity for countries that lack spatially detailed survey data for the majority of species, which is the case of many developing countries such as Argentina. Advantages include widespread recognition of the selected species, which is likely to inspire widespread support for their conservation, as well as the need for survey data on many fewer species than other approaches require, and computationally simpler analyses (Martínez Pastur et al., 2016; Martinuzzi et al., 2018; Pidgeon et al., 2015; Rivera et al., 2021; Rosas et al., 2022). A major caveat of our study, however, is that we do not have empirical evidence that the regionally important species are adequate proxies for less well-known species in all cases. However, by choosing a set of ~10–20 species of regional importance, several of which require large home range (Noss et al., 2003) or disperse over large areas during the annual cycle (Keuroghlian and Eaton, 2008; Rivera et al., 2020), and from both plant (including trees and understory plants) and animal taxa, we believe there is high likelihood that an umbrella effect (Politi et al., 2021) is achieved, by which many species gain habitat protection under this strategy. At the same time, our human footprint map does not reflect the effect of some important drivers of forest degradation, such as grazing and logging, because detailed, spatially-explicit data on these activities for the country does not exist or is not available. Incorporating these data could help refine our current understanding of human pressures within priority conservation areas (Martinuzzi et al., 2021; Rosas et al., 2021a, 2021b).

An important challenge of the implementation of the Native Forest Law is that different provinces weighted the set of environmental criteria established by the Native Forest Law differently, and used different datasets for creating their zoning maps, and as a result there is low agreement on the categorization of forest among provinces (Ceddia et al., 2022; García Collazo et al., 2013). Our priority conservation areas developed at the scale of the forest regions can reduce these artifacts, by providing consistent environmental information across political boundaries. However, we also recognize that individual provinces might want to use or explore our data in different ways (e.g., use of continuous species distributions maps instead of binary maps, explore other ways of combining species with human footprint, etc.) as this can help refine the location of priority areas (Belote et al., 2021; Muscatello et al., 2021). Our research is timely, since provinces have to update their zoning plan every five years. Our spatial data will be available online (see Data availability).

Our study provides several recommendations for policy makers and forest managers. While the ideal conservation action would be to reclassify all priority conservation areas as Category I (red) lands, i.e., the maximum level of protection, this option might be difficult to implement, at least in the short term. Alternatively, substantial progress can be made by: (i) Increasing the protection level of Category III (green) lands that overlap priority conservation areas. This will be particularly important for Chaco and Espinal. (ii) Improving the management of activities allowed in Category II lands within priority conservation areas. Activities that often degrade ecological function like silvopasture, logging, and hunting should be permitted only after rigorous sustainability planning (Macchi et al., 2019). Adaptive management strategies that favor the conservation of forest areas and the use of silvopastoral practices that use local tree species (e.g., Sánchez-Romero et al., 2021) should be promoted. And (iii), encouraging forest restoration projects within priority conservation areas, which can provide added benefit to local communities through forest carbon markets. Further, our study can also increase awareness and support for on-going conservation efforts relevant for policy makers and forest managers. For example, in the Atlantic region, our findings highlight the value of the Green Corridor of Misiones, an area designated for the conservation and sustainable use of the forests, and which contains much of the priority conservation areas identified in our study.

Closing the research-implementation gap is crucial to advance biodiversity conservation and management planning (Ferreira and Klütsch, 2021; Whitehorn et al., 2019), and this is especially important in developing countries (Josse and Fernández, 2021; Stephenson et al., 2021). Our study provides practical information for informing forest conservation in Argentina in the context of the Native Forest Law, and identifies places where current zoning can, and should, be improved. Our map products in support of sustainable management of Argentina's forests (Martinuzzi et al., 2021; Silveira et al., 2021, 2022, 2023) are being requested by provinces and are being downloaded frequently, suggesting that they are functioning to close the research-implementation gap. Overall, our study highlights the value of integrating species distributions and human footprint maps for guiding conservation, as well as for developing management-ready information critical to close the research-implementation gap.

Author statement

The material presented in this manuscript is original and it has not been published nor is it being considered for publication elsewhere, and all co-authors have agreed to the submission of this version of our manuscript to Biological Conservation.

Declaration of competing interest

The authors report no competing interests.

Data availability

Our spatial data will be available at http://silvis.forest.wisc.edu/ (University of Wisconsin-Madison, USA) and https://sib.gob.ar/novedades/modelando-habitat (National Parks Service, Argentina)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110257.

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