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Informing forest conservation planning with detailed human footprint data for Argentina

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ABSTRACT

Conserving the remaining wildest forests is a top priority for conservation, and human footprint maps are a practical way to identify wild areas. However, available global assessments of wild areas are too coarse for land use decisions, especially in countries with high deforestation rates, such as Argentina. Our main goal was to map the human footprint in Argentina's forested areas to improve conservation planning at regional and country levels. Specifically, we quantified the level of human influence on the environment and mapped the wildest native forests (i) across forest regions, and (ii) in the different land-use categories of the National Forest Plan, which is a key policy instrument for conserving the nation's native forests through zoning, and (iii) identified wildest forests that are at risk due to human activities. We analyzed detailed spatial data on settlements, transportation, energy, and land use change, and estimated the areal extent to which these various human activities disrupt natural processes. We defined pixels with human footprint index of zero as wildest areas. We found that a substantial portion (43%) of Argentina's forested area remains wild, which suggests there are opportunities for conservation. However, levels of human influence varied substantially among forest regions, and Atlantic and Chaco forests have the highest levels of human influence. Further, we found that the National Forest Plan does not conserve the wildest forests of the nation, as most (78%) of the wildest native forests are located in zones that allow silvopasture, timber production, and/or forest conversion to crops, thus potentially threatening biodiversity in these areas. Our map of wildest forests is an important, but first, step in identifying wildland forests in Argentina, as available spatial data layers of human activities capture many, but not all, human influences on forests. For instance, small human features, like certain rural roads, trails, and rural settlements exist in our wildest areas. Our study provides new datasets to assist land use planners and conservationists, and identifies areas for

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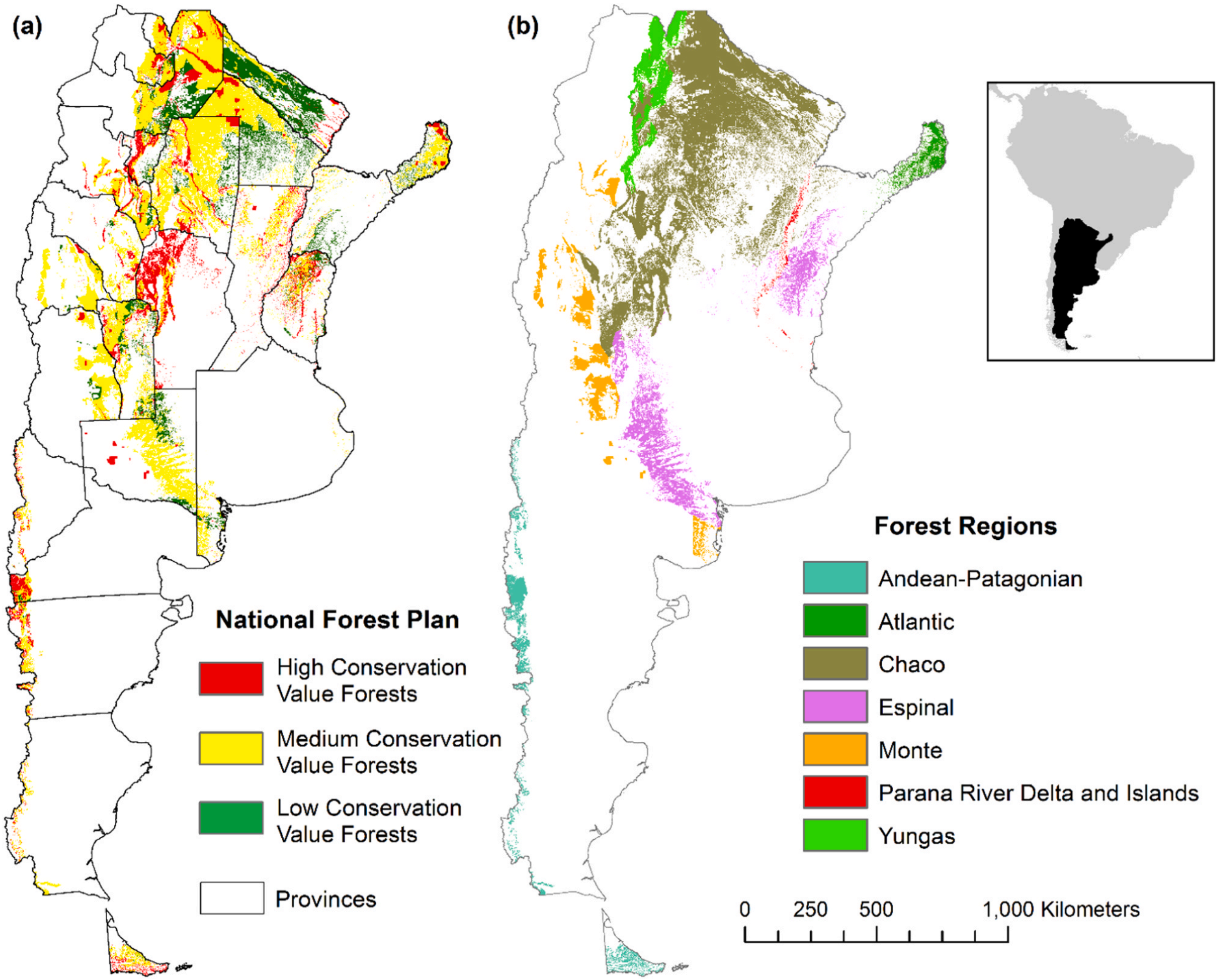

Fig. 1. Forested area of Argentina classified according to the National Forest Plan (a) and forest regions (b) (MAyDS, 2017).

conservation attention in Argentina. More broadly, our analyses highlight the value of detailed human footprint data to support conservation decisions in forest landscapes.

1. Introduction

Land use and infrastructure pose major threats to biodiversity when they cause habitat loss, fragmentation, and species declines (Foley, 2005; Rands et al., 2010). More than 75% of Earth's ice-free land has been altered by human land use, and less than a quarter remains wild (Ellis and Ramankutty, 2008). Roads fragment the Earth's terrestrial ecosystems into small patches, causing habitat degradation and species loss (Ibisch et al., 2016). Rapid expansion of forest plantations and energy development (e.g., oil and gas) threatens wild areas and biodiversity conservation even further (Vijay et al., 2016; Harfoot et al., 2018). Conserving biodiversity in the 21st Century thus requires a detailed assessment of human influence across landscapes, including the identification of the remaining wildest areas (Kennedy et al., 2019; Williams et al., 2020).

Mapping the human footprint both quantifies human influence across landscapes and identifies the remaining wildest areas (Sanderson et al., 2002; Venter et al., 2016; Kennedy et al., 2019). Maps of the human footprint integrate spatial information on land use, infrastructure, and human access to capture the cumulative human pressure on the environment on a relative scale of 0–10 (or any other scale), where 0 corresponds to low human influence and 10 to high human influence (Sanderson et al., 2002). Wild areas are those where human influence levels are minimal or zero (Sanderson et al., 2002; Kennedy et al., 2019). However, global maps of human footprint have limited value for regional or local applications because the global datasets from which they are developed are typically poor in terms of accuracy, completeness, and spatial resolution (Sanderson et al., 2002; Woolmer et al., 2008). In southern Chile, for example, the global human footprint map underestimates the extent of human influence when compared with a human footprint map derived from local data (Inostroza et al., 2016). In contrast, in Puerto Rico, global maps overestimate the human footprint (Guzmán-Colón et al., 2020). Thus, for regional or local applications, maps of human footprint based on relevant and accurate data mapped at finer resolutions are needed (Woolmer et al., 2008; González-Abraham et al., 2015; Martinuzzi et al., 2018).

Evaluating the level of human influence and identifying the wildest areas across regions (e.g., ecoregions, forest types, etc.) is important for conservation of biodiversity (Ellis and Ramankutty, 2008; Venter et al., 2016). Across the globe, temperate grasslands, tropical coniferous forests, and tropical dry forests have the highest levels of human influence, while boreal forests, montane grasslands and tundra contain much of the remaining wild areas (Riggio et al., 2020). However, more detailed information, both in terms of spatial resolution, and for different habitat types that are locally relevant, is needed to guide on-the-ground conservation efforts.

Land-use plans are a commonly used instrument for balancing nature conservation and economic growth (e.g., Knaap et al., 2015; Chiavari and Lopes, 2017, see Table S1 in Martinuzzi et al., 2018). Land-use plans establish "zones" for specific use (e.g., agriculture, residential, forestry, open space, etc.) and may be applied by governments to both private and public lands. However, land use plans are often based on incomplete information and may not explicitly identify, and therefore may not conserve, the remaining wildest areas, particularly when developed at national scales. Protected areas such as parks and refuges are one specific form of zoning that does protect wild areas, but protected areas are typically limited to public lands and are of limited extent (Dietz et al., 2015; Anderson and Mammides, 2020). Zoning on private land has been effective at reducing large-scale deforestation (Nolte et al., 2017), at protecting riparian areas from development (Dempsey et al., 2017), and has been recommended for protecting the habitat of large carnivores in key biodiversity places like the Greater Yellowstone Ecosystem (Shafer, 2015), but it is not clear if zoning applied at broad scales, such as within states, provinces, or nations, conserves the remaining wildest land. For example, among the world's forests, the majority of the remaining wildest areas are located outside of protected areas (73%; Grantham et al., 2020).

At the same time, some wildlands are more likely to be lost in the future than others, due to a lack of proper protection, or to high likelihood of increases in future human pressures, or both. Identifying the wildest areas that are at risk from human activities is thus essential in order to prioritize mitigation actions (Brooks et al., 2006; Moran and Kanemoto, 2017; Allan et al., 2019; Carter et al., 2019). Between 2000 and 2013, 1.9 million km^2 of wildlands—an area the size of Mexico—became highly modified across the globe (Williams et al., 2020), underscoring the pace and scope of degradation and loss of this critical resource.

Forests harbor the majority of terrestrial species, and maintaining substantial areas of wild forest is essential for maintaining biodiversity and ecosystem functioning (Mittermeier et al., 2003; Belote et al., 2016; Di Marco et al., 2019). Argentina, in southern South America, needs effective forest conservation because its forests are increasingly under development pressure. Argentina supports a variety of forest regions, ranging from the highly diverse Atlantic Forest in the northeast, to cold Andean-Patagonian Forest in the south. However, Argentina lost 15% of its tree cover between 2001 and 2018 alone, due mostly to the expansion of row-crop agriculture and pastures (Hansen et al., 2013; Global Forest Watch, 2020). To regulate deforestation Argentina passed the Native Forest Law in 2007 and established a National Forest Plan, which mandates the partitioning of the forested area in each province into three land-use zones: (i) *high conservation value forests*, where only minimally altering practices, such as gathering of non-timber forest products, scientific research, and ancestral use are allowed; (ii) *medium conservation value forests*, where productive activities such as silvopasture and tourism under the guidelines of conservation plans are allowed; and (iii) *low conservation value forests*, where timber production and conversion to other land uses such as agriculture are allowed (Seghezzo et al., 2011; García Collazo et al., 2013; Núñez-Regueiro et al., 2019; see Fig. 1a). Unfortunately, detailed, nation-wide spatial information on human influence and on the location of the remaining wildest forests was lacking when the National Forest Plan was enacted, and when the provinces allocated forest to land-use zones. While localized analyses have mapped the human footprint and revealed the presence of wild forests outside protected areas (Martinuzzi et al., 2018; Carrasco et al., 2021; Rosas et al., 2021a, 2021b), these studies encompassed only 12% of the forested area covered by the National Forest Plan. Consequently, the level of human influence in different forest regions, the location of the wildest forests in relationship to National Forest Plan zones, and the location of the wildest forests at risk of degradation or conversion from human activities, is largely unknown. This is a problem because some uses allowed by the National Forest Plan, like silvopasture, timber production, and/or land conversion to crops, are direct threats to wild ecosystems (Frey et al., 2012; Macchi et al., 2013; Baldassini et al., 2020).

Argentina is similar to many developing countries in that detailed spatial data on human influence are urgently needed to support biodiversity conservation and land use planning (Stephenson et al., 2017; Rochette et al., 2019). The increased availability of spatial data on human infrastructure and GIS capabilities in many developing countries (Scott and Rajabifard, 2017; Amade et al., 2018; Coetzee et al., 2020) provides opportunities to incorporate information on human influence into the land use planning process.

Our main goal was to map the human footprint in Argentina's forested areas to improve conservation planning at the regional and country levels. Specifically, we quantified human influence and mapped the wildest native forests (i) across the major forest regions, and (ii) in the three zones of the National Forest Plan, and (iii) identified the wildest forests that are at risk due to human activities.

2. Materials and methods

2.1. Study area

We analyzed the native forested areas delimited by the National Forest Plan, which encompass 541,350 km^2 (19% of Argentina; Fig. 1). According to the National Forest Plan, 20% of the forested area has low conservation value, 60% has medium conservation value, and 20% has high conservation value (Fig. 1a). The Argentinean government also distinguishes seven major forest regions: Andean-Patagonian, Atlantic, Chaco, Espinal, Parana River Delta and Islands, Monte, and Yungas (Fig. 1b).

In the National Forest Plan, different provinces used different definitions of "forests" (e.g., differences in the minimum height of dominant trees, or in the minimum percentage of canopy cover in the stand, or in the minimum patch size of a group of trees to be considered as a forests), as well as different mapping approaches to delimit their forested area dominated by native species, resulting in some inconsistencies between provincial and national forest inventories (MAyDS, 2017). Further, the classification of forests into high, medium, and low conservation value zones was based on different sets of ecological, environmental, and socio-economic criteria in different provinces, according to availability of data, resulting in additional inconsistencies across provinces (García Collazo et al., 2013; MAyDS, 2017). However, the National Forest Law demands that each province's plan be updated every five years. This requirement provides opportunities to adjust zone delineation, incorporating new information like the location of the wildest areas, wildlife presence and richness patterns (Martinuzzi et al., 2018).

2.2. Approach

2.2.1. Human footprint mapping

We mapped the human footprint following the method of Sanderson et al. (2002) and applied elsewhere (Woolmer et al., 2008; González-Abraham et al., 2015; Venter et al., 2016). The process included: (i) selecting the spatial resolution of the analysis, (ii) selecting datasets capturing different types of human pressures, (iii) assigning human influence scores (from 0 to 1) to each dataset, and (iv) combining human influence scores across datasets, resulting in the map of the human footprint.

We applied a spatial resolution of 100 m (1 ha) following our prior work in northern Argentina (Martinuzzi et al., 2018). We compiled datasets on human settlements (urban and rural settlements), transportation (e.g., primary roads, secondary roads, trails, etc.), energy infrastructure (e.g., oil and gas wells, pipelines, etc.) and land use (e.g., forest plantations, deforestation) from governmental databases and previous studies (Table A.1). We assigned human influence scores to each dataset ($n = 19$) on a scale of 0–1 taking into account the direct effect (i.e., the level of land transformation within our 100 m pixel), and the estimated distance to which substantial ecological effects extend outward from each human feature. We assigned scores and distances based on precedent, using examples from Argentina when possible (Table A.1). For example, we assigned urban pixels the maximum score of 1 (as in González-Abraham et al., 2015; Martinuzzi et al., 2018) because urban pixels are dominated by non-vegetated (e.g., concrete, asphalt) surfaces. High-voltage power lines, on the other hand, received a score of 0.3 because they result in forest cleanings that are narrower than our 100-m resolution pixel and remain vegetated (Woolmer et al., 2008). At the same time, the distance extent of influence varied according to the type of human feature. For example, we assigned to roads an influence distance between 1 and 3 km depending on whether they were minor, secondary, or primary roads (as in Woolmer et al., 2008). Similarly, within energy infrastructure, compressor stations received larger distances of influence than wells, because compressor stations emit substantial noise, which can alter wildlife communities up to 700 m away (Bayne et al., 2008), compared to an influence distance of 100–250 m for wells, which do not produce noise (Barton et al., 2016; Farwell et al., 2019). For all variables, we applied a decay function to reflect the declining human influence with increasing distance, setting a steeper decline close to the source, and a more gradual decline further from the source (Table A.1).

We refined variables and scores to reflect both the characteristics of our study area and the intended use of our human footprint map, improving conservation of forests. For example, in previous studies mapping the human footprint, vegetated land uses such as pasture, agriculture, and forestry plantations received substantially lower scores than urban lands (e.g., 0.4–0.7 vs 1 for urban; Woolmer et al., 2008; González-Abraham et al., 2015; Venter et al., 2016; Martinuzzi et al., 2018). However, we assigned higher scores, i.e., 0.8 for forestry plantations (which are all composed of exotic species) and 0.9 for forest conversion to pasture or agriculture, because these uses fully replace the native forest cover, and our main focus was on the conservation of the native forest. In addition, small rural settlements consisting of one or a few houses clustered around an artificial water source for livestock (known as *puestos*), or clusters of a few rural houses plus a first-aid post and a small school (known as c*aseríos*) are common human features in forested areas of Argentina, yet puestos and caseríos are not well captured by land cover maps or satellite-derived nighttime lights products. To map rural settlements, we combined governmental GIS layers of puestos, estancias (e.g., ranches) and schools, and assumed that schools are proxies for caserios. Additional information on the variables and scores can be found in Table A.1.

Some factors were not included due to lack of data. Forest degradation due to selective logging (for charcoal, fences, wood, etc.) and grazing (by cattle, goat, sheep) are important pressures in Chaco, Espinal, and Monte (Martínez Pastur et al., 2020), and streams and rivers are often used as off-road routes for movement of humans and livestock across mountainous terrain. However, spatial data on these activities was either too coarse or was unavailable. In addition, the distances of influence are based on literature review, which for several of our variables (e.g., wells, trails, deforestation, forest plantations, etc.) are based on studies of birds, plants, or are an average of multiple vertebrate species. For many large mammals these distances are likely conservative (Núñez-Regueiro et al., 2015).

To map the cumulative human footprint, we combined the human influence scores across the different datasets using Theobald's fuzzy algebraic sum of human modification scores (Theobald, 2013) as in González-Abraham et al. (2015) and Martinuzzi et al. (2018). The values in the final map range from 0 to 1, and pixels with human footprint value = 0 correspond to our wildest areas. To verify the need for a human-footprint map for Argentina, we also compared our footprint map with those available globally (Venter et al., 2016; Potapov et al., 2017; Jacobson et al., 2019; Kennedy et al., 2019). Further, because some of the distances of influence might be conservative for large mammals, we conducted a sensitivity analysis and increased the distance of influence for one of our variables, deforestation, three levels, from the current 300-m to 1 km, and calculated the change in area with human footprint = 0.

2.2.2. *Analysis of human footprint in each forest region*

We evaluated the human footprint in the seven forest regions (i.e., Atlantic Forest, Espinal, etc.; see Fig. 1b). For each forest region we reported the mean human footprint (from 0 to 1), and the extent of the wildest areas (human footprint = 0) both in km^2 and as a percentage of the total forest area.

2.2.3. *Analysis of human footprint across the National Forest Plan zones*

Next, we evaluated the human footprint in the three zones designated in the National Forest Plan; areas of high, medium, and low conservation value (Fig. 1b). For each zone we reported the mean human footprint (0−1), and the extent of the wildest areas (human footprint = 0) both in km^2 and as a percentage of the total forest area.

In addition, we estimated how well the wildest forests in each forest region (i.e., in the Atlantic Forest, Yungas, etc.) are protected under the National Forest Plan. Thus, we calculated the percentage of the wildest areas classified as low, medium, or high conservation values in each forest region. Our assumption was that the wildest areas are better protected if they are located in zones designated by the National Forest Plan as high conservation value, where minimal or no human land-use is allowed, followed by medium conservation value, where uses like silvopasture (which maintain some level of tree cover) are allowed, and have least protection in low conservation value zones, where deforestation is allowed.

2.2.4. *Identification of wildest forests that are at risk due to human activities*

Identifying the wildest forests that are at risk due to human activities is key for guiding land use decisions. We defined at-risk forests as areas where a high concentration of wild pixels (human footprint = 0) was located in areas zoned as low or medium conservation value by the National Forest Plan. Our assumption was that the activities allowed in those two zones pose risk of degradation and land conversion.

We conducted this analysis at the province level. We used a hexagonal grid of 635 km^2 to identify areas of at-risk forests in each province (n = 23), which is an effective shape and resolution for informing regional conservation planning (White et al., 1992). For each hexagon we first extracted the wildest areas (human footprint = 0) located in low and medium conservation value forests. Then we extracted those wildest areas that were forest according to a 30-m resolution forest cover layer (Hansen et al., 2013). This was necessary because provinces used different definitions of forest area, as well as different mapping approaches, and we wanted to limit our analyses to forest cover consistently. After tallying the number of wild pixels of low or medium conservation values in each hexagon we arranged the hexagons in a rank order. For each province, we identified the top ten at-risk hexagons, including the five hexagons with the largest wild area in low conservation value lands, and the five hexagons with the largest wild area in medium conservation value lands. In certain cases, the total number can be lower than ten, for example if a province has no wild area in low conservation value lands, in which case we only reported the five hexagons with the largest wild area in medium conservation values lands.

To further assist forest planning at the province level, we also reported the mean human footprint (from 0 to 1) and the extent of wild pixels (human footprint = 0) in the forest area of each province.

2.2.4.1. Accuracy assessment of wildest areas. We defined wildest areas as those with human footprint = 0. However, these areas may still support some level of human presence, as our definition and identification of wildest areas is based on available spatial data layers that can be imperfect, and human effects on forests could extend beyond what can be detected from existing data layers. We therefore conducted an accuracy assessment of our wildest areas based on visual interpretation of high spatial resolution imagery from Google Earth. We selected 150 random pixels with human footprint = 0 (i.e., our validation points). We then used the high spatial resolution imagery to search for human features in the area around each validation point that were not included in our spatial data layers, for example a missing minor road, a missing deforestation patch, etc., within 1-km of the pixel. Finally, we measured if the validation point was located within the distance of influence of the human features (based on the influence distances reported in Table A.1), in which case the value of zero human footprint in our map is incorrect. We repeated this step for each validation point (n = 150) and reported the number of times the validation point was correctly or incorrectly classified with human footprint = 0, including the main reason(s) for the incorrect classification.

We analyzed the area within 1-km around each validation point because most human features in our study have up to 1-km

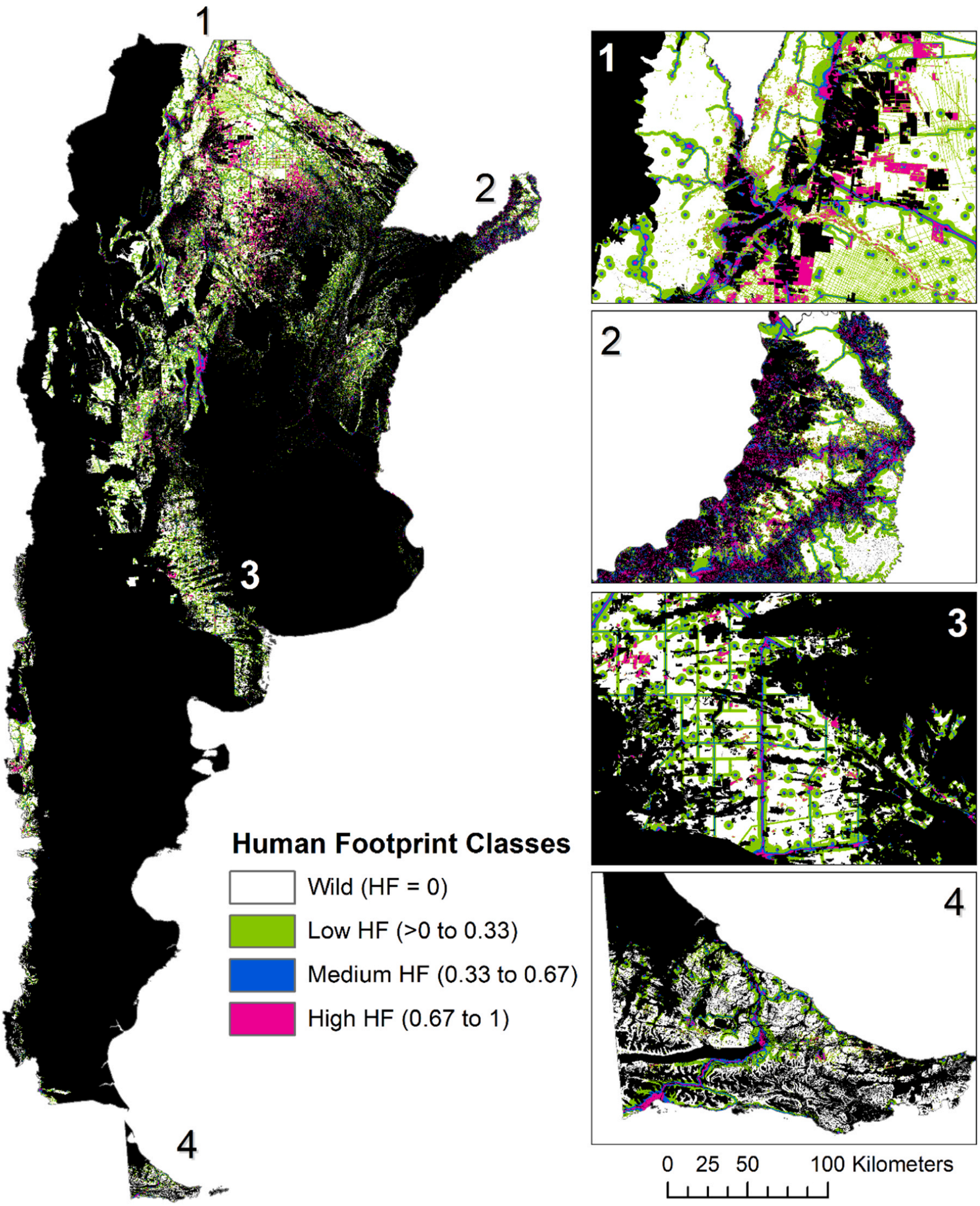

Fig. 2. Human footprint classes in the native forest areas of Argentina. Subsets: 1. Yungas/Chaco, 2. Atlantic, 3. Espinal, and 4. Andean-Patagonian Forests.

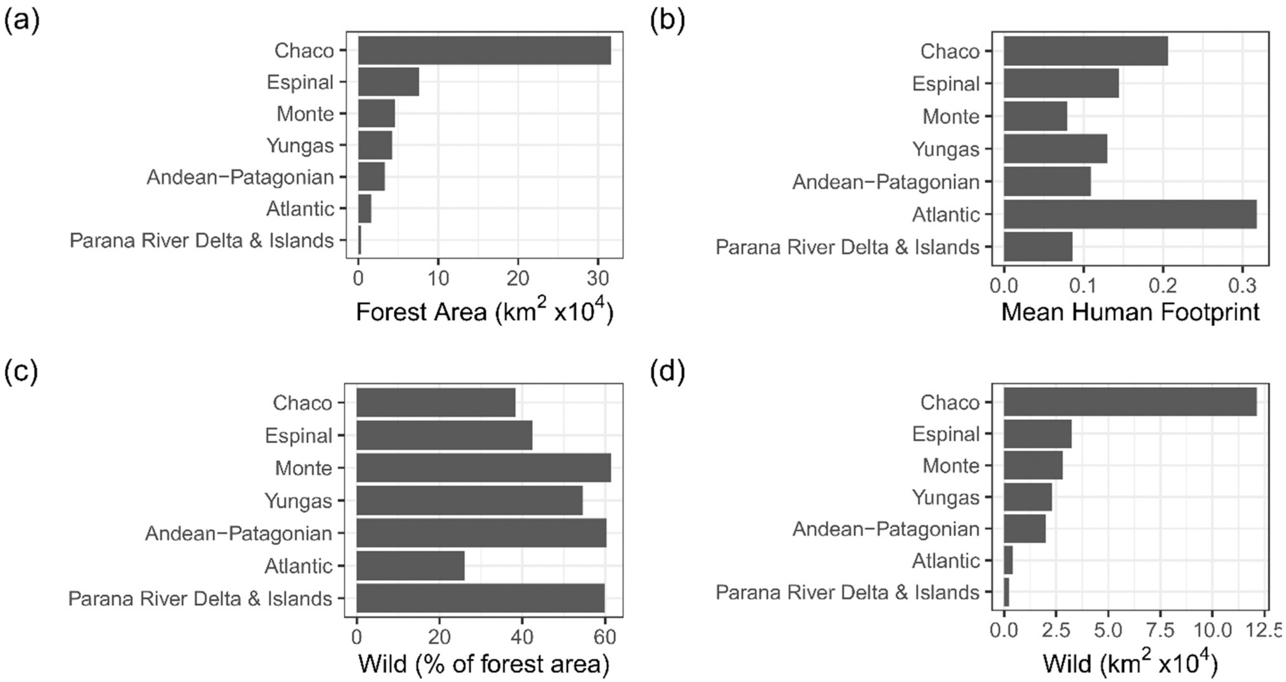

Fig. 3. Human footprint in the different forest regions. (a) extent of each forest region based on the National Forest Plan, (b) average human footprint (0−1), and the extent of wildest areas (areas with human footprint = 0) in (c) percent and (d) in km^2.

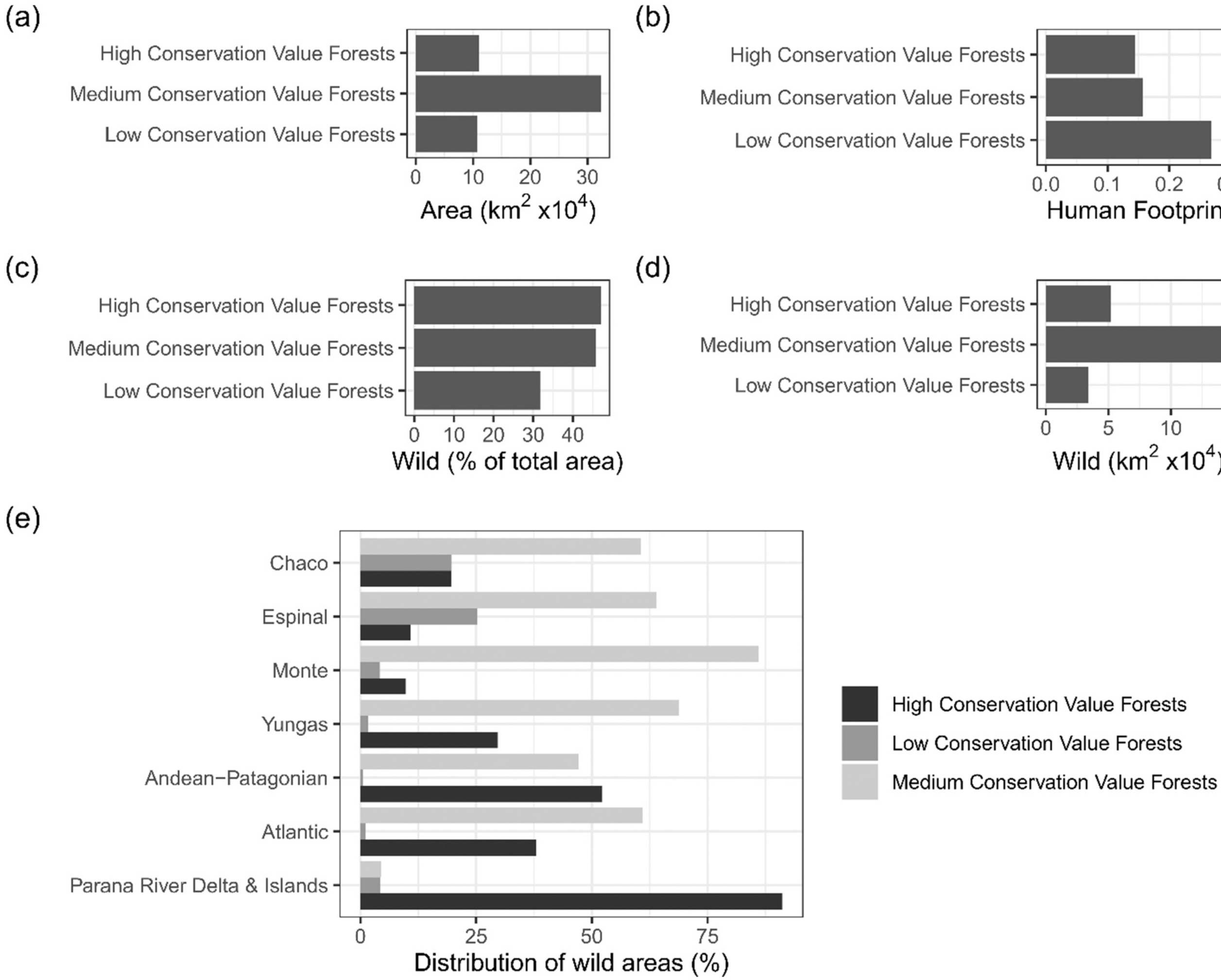

Fig. 4. Human footprint in low, medium, and high conservation value zones designated by the National Forest Plan. (a) areal extent of each zone, (b) average human footprint in each zone, and the extent of wildest areas (areas with human footprint = 0) in (c) percent and (d) in km^{2}in each zone; (e) proportion of wild forest within the three zones, by forest region.

influence distance, particularly for the smaller features like trails, minor roads, etc., which are the most likely to be imperfect in the spatial data layers. Large features such as urban centers or primary roads have a much larger influence distance (up to 15 km) but they are unlikely to be missing in the spatial data layers. The only exception is puestos, which have a 3-km influence distance, but this spatial data layer was assessed for accuracy separately (see Table A.1). Finally, we did not assess whether the forest was degraded or not, because forest degradation can be difficult to infer from high spatial resolution imagery, especially in forests that are naturally open or shrub-dominated, which is the case for some forests of Argentina.

3. Results

3.1. Human footprint map

Human footprint values in the forested area encompassed by the National Forest Plan ranged from 0.0–1.0, with an average value of 0.18. The wildest areas (human footprint index = 0) covered 43%, or 234,048 km^2 of the forested area. Areas of low, medium, and high human footprint, defined as index values < 0.33 (low), 0.33–0.67 (medium), and 0.67–1 (high), covered 37%, 10%, and 10%,

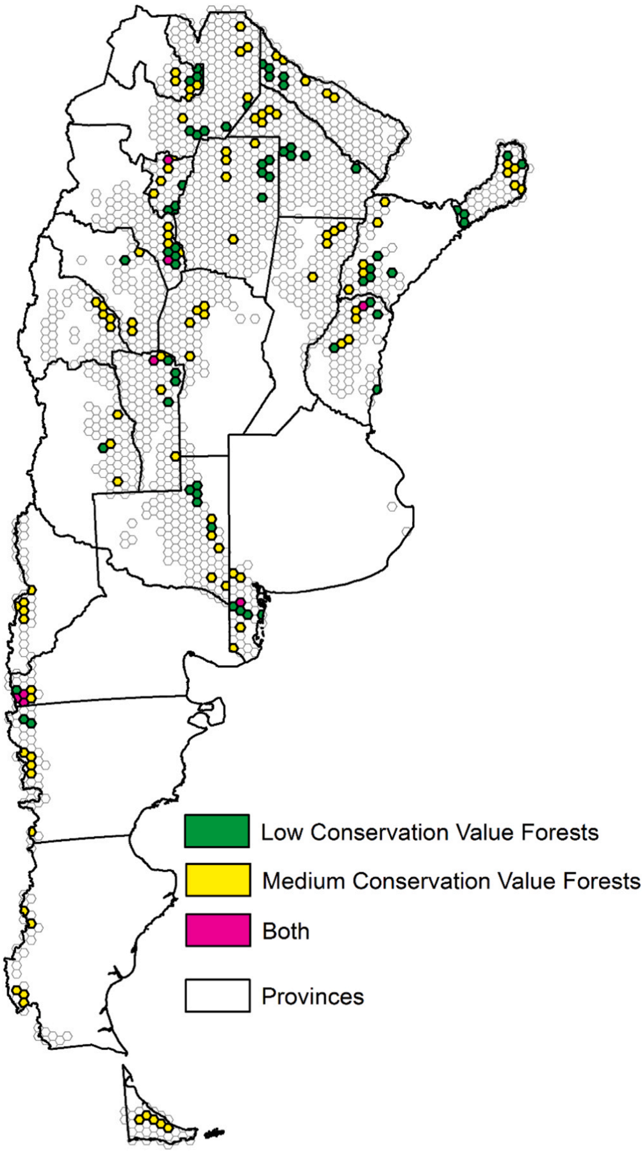

Fig. 5. Wildest forest that are at risk due to human activities. These areas correspond to the highest concentrations of wild areas (human footprint index = 0) in areas of medium or low conservation value (or both) by the National Forest Plan, in each Province. Activities allowed in these lands, like silvopasture and land conversion constitute potential threats to wild areas. The hexagons indicate the forested areas according to the National Forest Plan.

respectively (Fig. 2). Areas with high human footprint values were concentrated near settlements and roads, as well as in areas corresponding to recent forest clearings for agriculture or pasture (Fig. 2).

The visual comparison of our human footprint map with global products showed substantial differences (see Fig. A.1). In particular, our map depicted the influence of many settlements, roads, and other features of small extent (e.g., oil and gas infrastructure) that are not captured by the global products. In addition, our sensitivity analysis showed that increasing the distance of influence of deforestation three times changed the area with human footprint = 0 from 43% to 34%.

3.2. Human footprint across forest regions

We compared the seven forest regions (Andean-Patagonian, Atlantic, Chaco, Espinal, Parana River Delta and Islands, Monte, and Yungas) in terms of mean human footprint and amount of wildest areas. The Atlantic Forests had by far the largest mean human footprint (0.32) followed by Chaco Forests (0.21), while the other five forest regions had lower values that ranged from 0.08 to 0.15 (Fig. 3b). The forest regions with the greatest proportions of wild areas included Monte, Andean-Patagonian, and Parana River Delta & Islands with 60–61% of their forested area classified as wild, while Atlantic Forests had the lowest amount with only 26% classified as wild (Fig. 3c). In absolute terms (km^2) though, Chaco Forests had the largest extent of wild areas with 121,335 km^2, vs 2260–32,353 km^2 for the other forest regions (Fig. 3d) because of the much larger area of the Chaco Forests compared to the rest (Fig. 3a).

3.3. Human footprint across the National Forest Plan zones

The National Forest Plan classifies the native forested areas into zones of low, medium, and high conservation values. We found that low conservation value forests had the highest mean human footprint (0.27), while medium and high conservation value forests had lower, but very similar mean human footprint (0.16 and 0.15 respectively; Fig. 4b). Furthermore, about two thirds of all wildest forests were located in the medium conservation value zone (148,100 km^2, or 63%), 22% in the high conservation value zone, and 15% in the low conservation value zone (Fig. 4c and d).

Among the seven forest regions, five had most of their wildest areas in the medium conservation value zone (61%−86%, Fig. 4e). However, a substantial amount of the wildest areas in Chaco and Espinal Forests (20% and 25%) were located in areas designated as low conservation value, compared to only 1–4% for the other forest regions (Fig. 4e).

3.4. Wildest forests at risk due to human activities

For ease of use by policy makers and conservationists, we: (i) identified at-risk forests in each province, and (ii) summarized the human footprint in the forested areas of each province (n = 23). At-risk forests, defined as high concentration of wild pixels (human footprint index = 0) located in low or medium conservation value areas, tended to be spatially dispersed, indicating that conservation attention is required in multiple locations within each province and not just in one concentrated area (Fig. 5).

Among provinces, Misiones (NE Argentina, containing most of the Atlantic Forests) had the highest human footprint (0.32), followed by Santiago del Estero, Córdoba, and Chaco, located in north and central Argentina, which had human footprint values between 0.23 and 0.24 (Fig. A.2). All provinces also had some wild pixels, with proportions ranging substantially from ∼25% in Entre Rios and Misiones (E and NE Argentina) to 68% in Tierra del Fuego, located in the southern-most part of Argentina. Similar to our findings at the regional forest level, in most of the provinces the majority of wildest areas were outside of areas zoned as high conservation value, i.e., the areas with the maximum protection by the National Forest Plan. Of particular concern, in the provinces of Corrientes and Formosa (which harbor Espinal and Chaco Forests), most of the wildest forests (56% and 82%) are zoned as low conservation value, and thus are areas where deforestation is allowed under the National Forest Plan (Fig. A.3).

3.5. Accuracy assessment of wildest areas

We conducted an accuracy assessment based on 150 validation points. We found that 104 (69%) validation points were correctly classified as wild (human footprint index = 0), and 46 (31%) were incorrectly classified (Table 1). The main reason for the incorrect classification was the presence of small features like rural roads, puestos, trails, and tracks that were visible in the high-resolution imagery but missing in the existing spatial data layers.

Table 1
Results from the validation of wild areas.

Wild classification	Number of validation points	Description
Correct	104 (69%)	N/A
Incorrect	46 (31%)	Twenty validations points were < 1 km from a rural road (i.e., minor road). Eleven validation points were < 1 km from puestos or other small rural settlements. Eleven validation points were < 100 m from a trail or track. Other (n = 4).
Total	150 (100%)	

4. Discussion

Conserving the remaining wildest areas is a top priority for conservation, both for maintaining biodiversity and for the provision of ecosystem services, and human footprint maps are a practical way to identify those wildest areas. We mapped the human footprint in native forested areas of Argentina and found that while forested areas with a human footprint index of zero (i.e., our indicator of wild) remain relatively common, most of them lack protection under the National Forest Plan. Further, the level of human influence varies substantially among different forest regions. We identified priority areas for potential conservation actions, and provide new datasets of use to national and provincial land use planners and conservationists. Our map of the wildest forests is a first step in identifying wildland forests of Argentina, as the identification of wild areas is based on available spatial data layers, which capture many, but not all, human influences on forests. Overall, our study highlights the value of detailed human footprint data for informing conservation decisions at regional to national scales.

Our human footprint map revealed that a substantial proportion (43%) of the native forested areas of Argentina had a human footprint index of zero, i.e., our indicator of wild areas. The relatively high proportion of remaining wild native forest is encouraging from the perspective of conservation planning. It suggests that despite the high deforestation rates in Argentina, there are still many forests with minimal or low human influence, based on the set of variables used in our study. Having a substantial proportion of native vegetation under minimal or low human influence allows for flexibility in protecting the wildest forests, which is a main strategy for conserving biodiversity (Venter et al., 2016; Watson et al., 2018; Williams et al., 2020).

We found that the Atlantic and Chaco Forests have the highest levels of human influence among Argentina's forest regions, as reflected by both their high mean human footprint values and low proportion of wild forests. This finding is important because the Atlantic Forest is one of the smallest regions in terms of total area, but it supports the highest diversity of plants and animals in Argentina (Giraudo et al., 2003). Forest plantations of non-native species, deforestation associated with subsistence agriculture, and a dense road network all contribute to the high levels of human footprint found in the native forests of this region. On the other hand, the Chaco Forest region is a large area with some of the highest deforestation rates in the world (Gasparri and Grau, 2009; Hansen et al., 2013), and a region of major conservation concern (Mastrangelo and Gavin, 2012; Torres et al., 2014; Kuemmerle et al., 2017). Deforestation due to the expansion of the agricultural frontier, plus a substantial network of roads and settlements are responsible for the high levels of human footprint in this region.

We found that the National Forest Plan is not conserving the nation's wildest forests based on the current zoning of native forest cover. The great majority (78%) of the wildest forest area is located in areas designated as medium or low conservation value by the National Forest Plan, where allowed activities such as silvopasture or deforestation degrade or eliminate those important areas (Peri et al., 2016; Martínez Pastur et al., 2017). This might be explained by the lack of spatial information for supporting land use planning by the provinces (MAyDS, 2017; Martínez Pastur et al., 2020), in this case about the location of the wildest forests. Our findings corroborate those from a small area of northern Argentina (Martinuzzi et al., 2018) and suggest that, unless improved, the current National Forest Plan zonation contributes to risk of loss of remaining wildest forests.

To advance forest conservation planning under Argentina's National Forest Plan, we suggest provinces consider additional steps in their current zoning processes. These include: (i) incorporate spatial data on human influence, for example, on the location on the remaining wildest areas, and (ii) upgrade the conservation status of those wildest forests designated as low or medium conservation value, either by changing the designation status to high conservation value, or by restricting the type of productive activities that can be allowed there (e.g., allowing tourism but not silvopasture). In addition, our human footprint map can be combined with information on wildlife species and richness for assisting in the identification of potential ecological corridors (e.g., Belote et al., 2016) and proposals of new forest conservation areas.

All studies have limitations, and ours is no exception. For instance, information on forest degradation due to selective logging or grazing, which are important human pressures on forests, was too coarse or unavailable. Similarly, while we incorporated data on row-crop agriculture and pasture using a layer of deforestation, we did not incorporate effects from existing agricultural lands and pastures that penetrate hundreds of meters into adjacent forest (Zurita et al., 2012; Pfeifer et al., 2017). This limitation was due to the variation in the definition of forest among different provinces and because several provinces considered portions of non-tree vegetation (e.g., shrubs, herbaceous wetlands) as part of the forest ecosystem, which precluded a consistent assignment of edge effects across all provinces. In addition, the use of our human footprint map to support analyses related to large mammals should be conducted with caution, as the distances of human influence for some of our variables were developed using information about smaller-bodied animals and plants, and large mammals may be affected at even larger distances. A distance of influence that extends further from the source of disturbance would reduce the amount of wild forest. For example, tripling the influence distance of deforestation changed the area with human footprint = 0 by less than 10% points, from 43% to 34%, suggesting also that our general conclusions are robust. At the same time, we quantified the amount of wildest forests based on the number of pixels with human footprint = 0 without considering patch size (e.g., Potapov et al., 2017). We did so because different provinces define their forest areas based on different thresholds for tree height, canopy cover, and minimum patch size, so that a consistent threshold across the country would have removed areas legally considered forests by those regions with a smaller threshold. Furthermore, our accuracy assessment revealed that some puestos, rural roads, tracks, and trails exist in our forest areas classified as wild, highlighting the need to map these features in more detail to advance conservation planning in Argentina. Our estimates of the distance extent of various human influences may be more conservative than the on-the-ground reality. And finally, we acknowledge that wild area is not a full proxy for value to biodiversity, as differences in site productivity, elevation, and the spatial relationship of pixels designated as wild to areas of importance to wild species, all shape the relative contribution of individual wild area pixels to biodiversity persistence. For all of these reasons, our estimate of the extent of remaining wild forest should be considered an optimistic one, and may not reflect the actual behavior of wild species. However, our map is a consistent nation-wide assessment of human footprint using the best data available.

4.1. Conclusions

Overall, forty-three percent of Argentina's native forests remain wild (human footprint = 0), although within the seven major forest regions, the proportion that is wild varies substantially. Our assessment of the human footprint in native forest of Argentina identified wildest areas that are subject to potential degradation or conversion under the National Forest Plan, as well as areas of wildest forests that are protected. The pace of forest loss is rapid, and we suggest that evaluation and strong consideration of increasing the conservation status of remaining wildest forests should be a top priority of forest planners in Argentina, before options are more restricted and forest loss more extensive. This will go far toward securing the future of Argentina's native forest species. Our study provides detailed human footprint data in support of conservation decisions in forest landscapes.

[The human footprint map we developed for Argentina will be freely available upon publication at http://silvis.forest.wisc.edu/data/].

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01787.

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