Using nighttime lights to assess infrastructure expansion within and around protected areas in South America

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Abstract
Protected areas (PAs) are important mechanisms for conserving biodiversity and buffering anthropogenic pressures, but the expansion and intensification of human activities within and around PAs are threatening the biological diversity they are designed to protect. In South America, a region which includes many biodiversity hotspots (e.g., Atlantic Forest, Andes), agriculture, mining, oil and gas exploitation, dam construction, and settlements have been expanding and intensifying within and around PAs. These human activities need infrastructure (e.g., buildings, logistic facilities, ports), which leads to increased pressure on PAs. In this study, we used nighttime light data and the World Database on Protected Areas to evaluate the extent of intrusion of infrastructure in PAs in South America between 2001 and 2011. Our results show that in general PAs in all of the seven IUCN categories are buffering the intrusion of infrastructure within them, but this was not the case for PAs in multiple-use categories where there was a considerable increase in infrastructure within these PAs. The largest increase in infrastructure occurred within the first 60 km from the border of the PAs, and for multiple-use categories, the peak occurred in the first 10 km. In addition, infrastructure expansion around PAs in category I showed more variability and the largest extent. Infrastructure expansion within and around PAs varied among countries. There were only 23 of the 2,902 PAs with zero expansion, 16 were located in Brazil, four in Colombia, and one in Suriname, Venezuela, and French Guiana. Ecuador and Venezuela were the two countries that had the most infrastructure expansion within and around their PAs, while Guyana and French Guiana had the least development. Presently, South America has ~22% of the land area under some type of protection. Hopefully, the management of PAs will improve to help buffer the impacts of human activities and improve biodiversity conservation. Unfortunately, our results show that opposite, infrastructure is expanding within and around the PAs, which will most likely lead to ecological degradation and isolation of many of these PAs.

1. Introduction
Protected areas (PAs) are important in situ mechanism to conserve biodiversity and buffer a wide range of anthropogenic pressures [1]. For instance, PAs can reduce deforestation [2–4], noise and nighttime light pollution [5, 6], and slow the rate of species extinction [7]. However, many PAs are not meeting their conservation goals [8] because of insufficient funding, and poor management and enforcement [8, 9]. In addition, changes in policies to remove legal protection of PAs through downgrading, downsizing, and deagazettement is opening up these area for development [10]. Consequently, human encroachment within PAs and the expansion and intensification of human activities around PAs are threatening the biodiversity and the ecological processes that PAs are designed to protect [1, 11].
South America has a high level of biodiversity [12] and includes a wide variety of ecosystems, and globally important areas for conservation [13], many of which are partly protected within PAs. Regrettably, this diversity is associated with productive and fertile systems and highly valued natural resources. Agriculture, forestry, mining, oil and gas exploitation, dam construction, and settlements are some examples of human activities and land-uses that have been expanding and intensifying across South America [14–19] as a consequence of the increase in human population and their needs for natural resources and consumption patterns. The expansion of these and other land-uses have reduced forest cover around many PAs [16, 20, 21]. In addition, these activities all require infrastructure (e.g. logistic facilities, buildings, silos), which has increased considerably and much of the expansion has occurred in rural areas away from major urban centers [22]. As human infrastructure continues to expand and the distance between PAs and urban areas decline [23], it will be a challenge to maintain the integrity of PAs across South America as a reduction in the surrounded natural habitats can increase the spillover of negative effects into PAs [24].

In this study, we evaluate the expansion of infrastructure in and around terrestrial PAs in South America between 2001 and 2011. We specifically answer the following questions: (1) is infrastructure expanding within and around PAs?; (2) is infrastructure expansion related to the IUCN management category?; (3) how does infrastructure expansion associated with PAs vary within and among countries? The answers to these questions allowed us to respond to our final question, (4) are PAs effectively managing infrastructure development? The answers to these questions, integrated with detailed studies of the direct impacts of infrastructure on the biota and ecosystem services, are essential for informing management strategies to guarantee the conservation of the biological diversity within and around PAs.

2. Methods

2.1. Nighttime light (NTL) data

To evaluate infrastructure expansion in South America, we used an infrastructure change map (2001–2011) created by Andrade-Núñez and Aide [22]. We define infrastructure following the definition of built-up structure used in the Global Human Settlement Layer (GHSL) which is defined as an ‘enclosed construction above ground intended or used for the shelter of humans, animals, things or for the production of economic goods or the delivery of services’ [25, 26]. The infrastructure change map was created using nighttime lights (NTL) data derived from the Defense Meteorological Satellite Programs Operation Linescan System (DMSP-OLS) and intercalibrated by Zhang et al [27]. NTL images have a spatial resolution of approximately 1 km × 1 km and use digital number (DN) value of each pixel in a range from 0 (no lights) to 63 (brightest lights) to represent light intensity (or brightness) of anthropogenic lights from human settlements, industrial lights, and other sites with persistent light [28]. The countries of South America have high levels of electrification (70%–100%), facilitating the use of NTL data as a proxy for the built environment (e.g., cities, towns, farms, hydroelectric dams, mining and industrial areas) [22]. NTL data were classified into three classes along an infrastructure compactness gradient: no-development (ND) (DN = 0), scattered (SC) (DN > 0 and <30), and aggregated (AG) (DN ≥ 30) (figure S1 is available online at stacks.iop.org/ERC/2/021002/mmedia). The ND class corresponded with areas with no or minimal infrastructure such as forests, grassland, and plantations. The SC class corresponded with areas of low infrastructure compactness, such as rural areas, towns, farms (e.g., agriculture fields with human infrastructures), and sprawling suburban areas. Finally, the AG class was defined as areas where infrastructure dominates the landscape. This class was mainly represented by cities where infrastructure ranges from intermediate to high compactness. Using the information of the infrastructure change map (2001–2011) we extracted the extent of the following infrastructure expansion transitions: from no-development to scattered (ND-SC), from no-development to aggregated (ND-AG), and from scattered to aggregated (SC-AG) which we summed and considered as infrastructure expansion (EXP) (figure 1(b)). In addition, we used the scattered to scattered (SC-SC) and aggregated to aggregated (AG-AG) ‘transitions’ to represent the area of each infrastructure class that did not change between 2001 and 2011 (figure 1(b)). A detailed explanation of the methodology used to create the map can be obtained in Andrade-Núñez and Aide [22].

2.2. Protected areas (PAs)

To evaluate infrastructure expansion within and around PAs, we used spatial data from the World Database on Protected Areas (WDPA) accessed in September 2018 (https://protectedplanet.net/). We extracted the data for South America which comprise a total of 4,503 PAs. In the analyses, we excluded PAs that were less than 2 km² of extent, islands, or with more than 50% extent in the ocean using geoprocessing tools in ArcGIS. We used a total of 2,902 PAs, and we grouped them based on the following IUCN (International Union for Conservation of Nature) categories: Category I (PAs in IUCN categories Ia and Ib), Category II, III, IV, V, VI, and Category Others (PAs not assigned to any category, not reported, or no IUCN category is applicable; these include PAs
such as Ramsar sites, UNESCO MAB areas, private conservation areas, and indigenous areas. The management objectives of a PA (e.g. strict protection, multiple-uses) is the basis for assigning the IUCN PA categories (figure 1(a), table 1) [29].

To obtained the total PA coverage by country (table 2) we followed a similar procedure used by the WDPA (https://protectedplanet.net/c/calculating-protected-area-coverage). However, we included some PAs that we categorized as Others (e.g., proposed, not reported, and UNESCO Man and Biosphere Reserves) that WDPA did not consider in their calculations. Therefore, the total coverage by country could differ from those reported in the WDPA and in official country reports due to difference in methodologies and datasets used (e.g., we excluded PAs with <2 km$^2$). Specifically, we used the Geoprocessing tool Dissolve in ArcGIS 10.6 to eliminate overlaps between PAs with different categories to avoid double counting. Then, we checked and repaired the geometry of the resulting shapefile, and we finally extracted country coverage by using the Union tool with a shapefile of South America countries boundary.
In South America, PAs cover 3,959,461.7 km² comprising approximately 22.3% of its extent (figure 1(a)). The median size of the PAs of the seven IUCN categories was 104 km², but the size of the PAs varied greatly (figure 2). The largest was the Yanomami indigenous area in Brazil (Other category) with an extent of 95,563 km².

### 2.3. Analysis

#### 2.3.1. Infrastructure expansion within and around protected areas by IUCN categories

To understand the potential impact of infrastructure on PAs, we determined the extent of infrastructure expansion between 2001 and 2011 within and around (in a 100 km buffer) each PA. Each protected area and the buffer area around it was the unit of analysis. We choose a 100 km buffer because important sources of negative impacts to PAs such as edge effects, fire ignitions, exotic species establishment, nighttime lights, water pollution, and illegal logging usually occur within 100 km of the PA [24]. The buffer area was calculated from each PA border, and because PAs vary in shape and sizes, the area of the buffers varied in total extent. We extracted the expansion area (EXP) and the area of scattered (SC-SC) and aggregated (AG-AG) infrastructure within and around each PA and grouped them based on IUCN categories. All spatial analyses were done using ArcGIS 10.6.

| IUCN category | Number of protected areas | Area protected (km²) | Percent of country area |
|---------------|---------------------------|----------------------|-------------------------|
| Brazil        | 110 186 18 74 165 174 896 | 1,623 2,451,418.82   | 28.90                   |
| Venezuela     | 0 33 10 8 41 10 12        | 114 369,433.77       | 40.58                   |
| Argentina     | 15 70 10 16 14 138 57     | 320 277,773.97       | 9.99                    |
| Bolivia       | 0 0 0 5 0 0 135           | 140 258,307.40       | 23.81                   |
| Peru          | 0 14 13 3 2 30 89         | 151 237,954.82       | 18.43                   |
| Colombia      | 2 68 2 9 10 204 1         | 296 156,776.79       | 13.78                   |
| Chile         | 0 26 7 71 0 0 26          | 130 51,187.93        | 6.84                    |
| French Guiana | 1 0 0 8 2 0 2            | 13 43,506.64         | 52.25                   |
| Ecuador       | 0 0 0 0 0 0 44           | 44 42,326.70         | 17.06                   |
| Paraguay      | 0 10 2 9 1 2 8           | 32 20,675.51         | 5.18                    |
| Guyana        | 0 1 0 0 0 0 5 0          | 6 18,348.46          | 8.76                    |
| Suriname      | 0 2 0 7 0 2 6           | 17 17,899.04         | 12.25                   |
| Uruguay       | 0 2 0 3 4 3 4          | 16 13,844.67         | 7.77                    |
| **Total**     | **128 412 62 213 239 568** | **1,280 2,902** | **22.37** |

Table 2. Number of protected areas and the area under protection in the 13 South American countries. The number of protected areas (PAs) under the different IUCN categories is provided. This information is based on the 2,902 PAs evaluated (PAs with > 2 km², no islands, and with less than 50% of their extent in the ocean).

Figure 2. Boxplots showing the variability in size of protected areas based on IUCN categories in South America. The black line within each box is the median, and grey circles represent the outliers.

In South America, PAs cover 3,959,461.7 km² comprising approximately 22.3% of its extent (figure 1(a)). The median size of the PAs of the seven IUCN categories was 104 km², but the size of the PAs varied greatly (figure 2). The largest was the Yanomami indigenous area in Brazil (Other category) with an extent of 95,563 km².
2.3.2. Spatial gradient of human infrastructure expansion in and around protected areas by IUCN categories
To determine the spatial gradient of infrastructure expansion within and around PAs by IUCN category we performed the following steps: (1) we created a distance allocation map from PAs using the Euclidean distance tool, which calculates for each pixel the distance to a source (i.e., PA border) based on the straight-line distance. We set the maximum distance to 100 km. The final map showed positive distance values for those pixels outside the PA; the value 0 corresponded to the pixels located in the PA border, and negative values for those pixels located within the PA. (2) We overlaid the distance map for each PA with the infrastructure change map to estimate the distance of scattered (SC-SC), aggregated (AG-AG), and infrastructure expansion (EXP) for each PA. (3) To extract the distance of the three infrastructure classes for each PA, we performed buffer and spatial join analyses. (4) We obtained the number of pixels of SC-SC, AG-AG, and EXP at 10 km intervals ranging from −60 km to 100 km. All spatial analyses were done using ArcGIS 10.6. Once we obtained the number of pixels (≈1 km²) in each distance class for each PA, we calculated the mean and standard deviation for each distance class for each of the seven IUCN categories.

2.3.3. Infrastructure expansion within and around protected areas at the country level
To assess the variation in infrastructure expansion associated with PAs within and among countries, we calculated the total infrastructure expansion in each of the 2,902 PA as the sum of infrastructure expansion within and around (100 km buffer area). In addition, we classified infrastructure expansion within and around PAs into different expansion classes. We defined different threshold values for the within and the around expansion classes as the expansion extent varies greatly between both areas (within and around). Therefore, we identified the following infrastructure expansion classes within PAs: (1) 0, no infrastructure expansion, (2) >0 to 50 km², (3) >50–200 km², (4) >200–500 km², (5) >500–1,000 km² and (6) >1,000–2,000 km². Similarly, we classified infrastructure expansion extent around PAs as followed: (1) 0, no infrastructure expansion, (2) >0 to 500 km², (3) >500 to 2,000 km², (4) >2,000–5,000 km² and (5) >5000 to 11,000 km². Finally, we determined the number and percent of protected areas within each expansion class (for within and around PAs) for each of the 13 South American countries.

3. Results

3.1. Infrastructure expansion within protected areas
Infrastructure expansion between 2001 and 2011 occurred within PAs regardless of the IUCN category (figure 3(a)). Infrastructure expansion occurred in 67.36% of PAs under the most strict conservation categories (I, II, III, and IV), while 81.93% of PAs under the multiple-use categories (V, VI, and Others) showed an increase of infrastructure within their boundaries. However, strictly protected PAs had less infrastructure expansion within their borders (from 0 to 704 km²) than multiple use categories (from 0 to 1960 km²) (figure 3(a)). In addition, strictly protected PAs had in general relative smaller scattered and aggregated areas than multiple use categories (figure S2). PAs in Category V had the largest median value (145 km²) of infrastructure expansion within them (figure 3(a)) and had the largest median values of scattered and aggregated infrastructure classes within their borders (353 km², and 30 km² respectively) (figure S2).

3.2. Infrastructure expansion around protected areas
Similarly, infrastructure expansion around PAs varied among PA categories (figure 3(b)). However, PAs in category I showed more variability and the largest extent (excluding outliers) in comparison with the other categories, with a median value of 1,833 km². PAs in Category V also showed a large extent of infrastructure expansion around them, with a median value of 1,597 km² (figure 3(b)), and also showed the largest extent of scattered and aggregated areas (figure S2). The Others category is composed by PAs with different national categories (and hence different degree of protection, and human presence) which could explain the large numbers of outliers in this class (figure 3(b)).

3.3. Spatial gradient of infrastructure expansion around protected areas
In almost all categories there was a clear increase in infrastructure expansion as soon as the border is passed (figure 4). The distance to PAs where infrastructure expanded most between 2001 and 2011 varied among IUCN categories (figure 4). In the categories I, II, III, and IV, the peak in infrastructure occurred approximately 30 km from the PA boundary (figure 4). Specifically, for PAs in category I the peak (mean infrastructure expansion 315.92 km²) occurred around 30 km, and for PAs in category II the peak was 255.8 km² and was reached at approximately 20 km. Infrastructure expansion around PAs in category III reached a peak (mean infrastructure expansion 191.96 km²) at about 60 km, while in category IV the peak (mean infrastructure expansion 162.11 km²) occurred at approximately 40 km (figure 4). In the multiple use categories V, VI, and Others, the largest expansion
area (mean infrastructure expansion of 375.55, 189.09 and 272.37 km² respectively) was located within the first 10 km from the PA border. In general, the distance at which infrastructure expansion reaches a peak also showed the largest median values of scattered and aggregated infrastructure classes (figure S3).

Regarding the distance gradient of infrastructure expansion within PAs, the peak expansion occurred mainly in the first 10 km from the edge inwards (figure 4). At this distance, PAs in categories I, III, and IV had less than 16 km² of infrastructure expansion (mean area); while PAs in categories II and VI had 45 km² and 47.5 km² respectively, and PAs in category Others and V had larger increases in infrastructure expansion with 100 km² and 290.5 km² respectively (figure 4).

3.4. Infrastructure expansion within and around protected areas at the country level
The number of PAs and the extent of PAs vary greatly among countries (table 2). The country with the largest percent of its area under some kind protection is French Guiana with 13 protected areas that cover approximately 52% of the country, followed by Venezuela (n = 1,114, 40.58%), Brazil (n = 1,623, 28.9%), and Bolivia (n = 140, 23.81%). In contrast, the country with the lowest percent of area protected was Paraguay (n = 32, 5.18%), followed by Chile (n = 130, 6.84%), Uruguay (n = 16, 7.77%), and Guyana (n = 6, 8.75%) (table 2).

Infrastructure expansion within and around PAs varied among countries. However, all countries had some infrastructure expansion within and around their PAs (figure 5). There were only 23 of the 2,902 PAs with zero expansion (within and around), 16 were located in Brazil, four in Colombia, and one in Suriname, Venezuela, and French Guiana (figure 5). Many PAs with a large extent of infrastructure expansion (within and around) were located near urban areas (figure 5).

When analyzing infrastructure expansion within and around PAs separately, Guyana was the only country where infrastructure expansion did not occur within their PAs, followed by Peru and Uruguay where infrastructure expansion between 2001 and 2011 did not occur inside of 38.4%, and 37.5% of their PAs, respectively (figure 6(a)). In contrast, Ecuador was the country with less PAs free of infrastructure expansion (2.27% of PAs), followed by Suriname (5.88%), and French Guiana (7.69%) (figure 6(a)). In general, most PAs in

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**Figure 3.** Infrastructure expansion between 2001 and 2011 within (a) and around (b) protected areas in South America. Protected areas (PAs) are grouped based on the IUCN categories. Category Others represent those PAs not assigned, not reported or that an IUCN category is not applicable. Infrastructure expansion was assessed in a 100 km buffer around PAs.

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most of the countries had up to 50 km² of infrastructure expansion within them (figure 6(a)), except for Venezuela where 33% of PAs showed an expansion between 50 and 200 km², and Ecuador where 34% of PAs had between 200 to 500 km² of infrastructure expansion during the study period (figure 6(a)). Only a few PAs in Brazil, Venezuela, and Peru had infrastructure expansion within their borders greater than 1,000 km² (2.53%, 0.877%, and 0.66% respectively) (figure 6(a)), and all these PAs were category V or Others.

Regarding infrastructure expansion around PAs, only four countries had PAs without infrastructure expansion within the 100 km buffer: Suriname (5.88%), Colombia (1.35%), Brazil (0.98%), and Venezuela (0.87%) (figure 6(b)). In general, in most countries, most of PAs had infrastructure expansion of 500–2,000 km² around them, except Ecuador where 50% of PAs had infrastructure expansion between 2,000 to 5,000 km² around them. Other exceptions were French Guiana, Guyana, and Brazil. All PAs in French Guiana, and Guyana, and 40% of PAs in Brazil had >0 to 500 km² of infrastructure expansion around them (figure 6(b)). In addition, four countries had PAs with extreme values (>5,000–11,000 km²) of infrastructure expansion around them, Ecuador (9.09%), Brazil (5.48%), Venezuela (1.75%), and Argentina (0.65%) (figure 6(b)).

4. Discussion

4.1. Infrastructure expansion within and around protected areas

Human infrastructure is considered a major threat to biodiversity conservation, as its establishment and expansion are associated with a large variety of direct and indirect negative impacts [30]. Some of these impacts include: deforestation, water and air pollution, illegal hunting, biota homogenization, and noise and light pollution [31–35]. At the continental scale, our results show that in general the PAs system in South America is buffering the intrusion of infrastructure within PAs. Between 2001 and 2011, while some infrastructure expansion occurred within PAs, the majority occurred around the PAs (figures 3, and 4). A similar pattern was observed at the global scale between 1993 and 2012, with low levels of NTL within and much greater levels of NTL around PAs [36].

Although PAs are buffering the increase in infrastructure, there was still considerable infrastructure expansion within PAs (figure 3). Similarly, Gaston et al. [37] reported a 38% increase in NTL with 3,045 PAs.
between 1992 and 2010 in South America. In general, the increase of infrastructure (and NTL) within PAs could be associated with urban expansion [38] in those PAs near urban areas and to mining projects [16, 39], oil and gas projects [19] and dams constructions [18] in PAs located far from large urban centers. For example, in the Amazon region, dams construction and oil and gas projects are established or planned to occur within PAs (of all IUCN categories) and indigenous territories (categorized as Others in this study) [18, 19]. In addition, tourism facilities and buildings could also explain the expansion of infrastructure within PAs, specifically in some National Parks and other strictly PAs with touristic opportunities. For example, the Iguazu National Park (IUCN category II), which receives approximately 1 million visitors per year, unplanned infrastructure development for tourism concessions could explain infrastructure expansion within its borders [40].

Considering that most PAs are relatively small in size, even a smaller increase in infrastructure inside a PA could trigger a large cascade of direct and indirect impacts. For instance, road construction within PAs often stimulates deforestation even if there are no or few human settlements [41].

We expected differences in infrastructure expansion within PAs among the IUCN categories due to the different management objectives associated with each category (table 1). In general, our results supported this expectation. For instance, strictly protected PAs (I, II, III, and IV) were more successful in regulating...
infrastructure expansion than multiple-use PAs (V, VI, Others). Protected areas in the multiple-use categories initiated the study with large extent of infrastructure within them (figure S2), and during the study period, the extent of infrastructure expanded greatly (figure 3). The large increase in infrastructure within and around PAs in category V is not surprising given that they permit intensive use of natural resources (e.g., agriculture, forestry, and tourism). Nevertheless, several PAs in category II had large areas of infrastructure expansion inside their borders (figure 3, outliers). For example, the Parque Estadual Da Serra Do Mar located in Sao Paulo, Brazil (categorized in II) had 704 km² (∼22% of its area) of infrastructure expansion during the study period. This infrastructure expansion within the PA was associated with urban expansion from the nearby city of Cubatao and the construction of roads inside the PA [38].

Surprisingly, PAs in category I (strict nature reserve, and wilderness areas) showed the largest extent in infrastructure expansion around the PAs (figure 3(b)). Given that many of these PAs are small, this increase in infrastructure could increase isolation by eliminating corridors and habitat patches in the surrounding landscape.

4.2. Spatial gradient of infrastructure from protected areas
Protected areas attract people, and consequently, human activities and encroachment have intensified at their boundaries [17, 36, 42]. Globally, PAs have experienced significant increases in urban land within 50 km of their boundaries [17]. South America is not an exception, as we found that the largest increase on infrastructure between 2001 and 2011 occurred within the first 60 km from the PA borders, and for multiple-use categories, the peak occurred within the first 10 km (figure 4). This differences in the distance at which infrastructure expansion reaches a peak between strictly protected and multiple-use IUCN categories is likely related to the differences in management objectives of each category [29]. In addition, the expansion of infrastructure around PAs could be

Figure 6. Percent of protected areas in each South America country with different infrastructure expansion (within and around) extent (km²). (a) Percent of protected areas (PAs) with different extent of infrastructure expansion within PAs. (b) Percent of protected areas with different extent of infrastructure expansion around PAs. Percent was calculated based on the total number of PAs of each country (table 3).
related to touristic facilities [40], and the intensification of land uses such as agriculture [21, 43] which includes the construction of roads, silos, sheds, mills, and factories. Furthermore, the fact that the peaks in infrastructure expansion occurred near the borders of most PAs suggests the proximity to urban areas and the possible shortening of the distance between urban areas and PAs over time [23]. This situation highlights the need to incorporate management activities at landscape level which include urban planning strategies that reduce the impacts of urban areas on nearby PAs [24].

4.3. Spatial distribution of infrastructure expansion within and around protected areas at the country level

South American countries varied in terms of their capacity to minimize infrastructure expansion both within and around their PAs (figures 5 and 6). These differences could be explained by a combination of socio-economic, demographic, and biogeographical factors. Although an analysis of the drivers of infrastructure expansion within and around each PA is beyond the scope of this paper, here we describe three groups of countries with the intent of encouraging more detailed research.

The first group includes French Guiana, Guyana, Suriname, and Uruguay, which had the lowest percent of infrastructure expansion within and around PAs (figure 6). The low level of transformation in these countries is mainly due to small population size, few large urban areas, and low rates of urban expansion. In addition, these countries have few PAs (n \(\leq 17\)).

The second group includes the Southern Cone countries of Argentina, Chile, and Paraguay, which had high levels (>500 km\(^2\)) of infrastructure expansion around 75% of their PAs (figure 6). The major drivers of infrastructure expansion in these countries are agriculture, cattle ranching, exotic tree plantation [44–46], and urban sprawl [47].

The third group includes Venezuela, Colombia, Brazil, Ecuador, Peru, and Bolivia, all relatively large countries with high levels of biodiversity, but they vary greatly in terms of infrastructure expansion (figure 6). Peru had the largest percent of PAs with no infrastructure expansion within their borders (38%). This is probably related to high levels of rural-urban migration [48] and many PAs located far from urban areas. In contrast, although \(\sim 18\%\) of Ecuador is classified as a PA, it was the country with the highest percent of PAs with infrastructure expansion within and around them. This expansion appears to be driven by an increasing urban and rural population coupled with urban expansion [48], and the exploitation of natural resource (e.g. mining, and hydroelectric dams) near and within PAs [49]. Brazil, Venezuela, Colombia, and Bolivia had a similar pattern with no or little infrastructure expansion near isolate PAs in the Amazon, but higher levels of impact in PAs near urban centers and agricultural frontiers [21, 50–54].

5. Conclusion

Between 2001 and 2011 PAs across South America experienced different degrees of infrastructure expansion as a result of human population and economic growth. We expect that as the human population and consumption continue to increase infrastructure will continue to expand across South America to fulfill housing, livelihoods, and commodities demands. Although PAs in South America are presently buffering infrastructure expansion within their borders, the landscape around PAs will experience increasing pressure as infrastructure expand [21]. With the increase in infrastructure (and related land-uses) around PAs, it is expected that species within PAs will become more isolated [55], as the quality of the surrounded landscape (i.e., matrix) decreases and reducing their ability to move and survive [43]. In addition, the increase in infrastructure around PAs will exacerbate the negative impacts (e.g. water, light, and sound pollution) from the surrounded matrix [24, 56]. These trends suggest that land uses outside PAs are the main threat to the biodiversity conservation within PAs.

Unfortunately, most PAs managers have no control over the activities occurring outside PAs. Therefore regional-scale land use planning [57] which includes the conservation and management of private, and productive lands around PAs is needed [58]. In addition, analysis of the cumulative long-term impacts of human activities around PAs, and the development of strategic planning at different scales (i.e., regional, national, and international) are important for the long-term protection of biodiversity. In addition, international landscape planning that includes countries agreements is critical to create a network of PAs across South America. A large scale network of PAs is necessary not only to protected biodiversity from human activities, but also to account for the potential consequences of climate change in species and ecosystems [59, 60].

Institutional capacity and adequate financial resources are essential to ensure the effective management [61] of the PAs and the surrounding lands in South America. Unfortunately, the effective management of many PAs often conflicts with a country political agenda, development goals, and international commitments. For example, in 2007 the Ecuadorian government decided not to exploit oil in the more remote and intact parts of the Yasuni Park (i.e. the Yasuni-ITT Initiative) to mitigate climate change and protected biodiversity [62]; however, the initiative was canceled five years later, and presently the future of one of the most biodiversity PAs
on Earth is uncertain [63]. Similarly, the fate of several indigenous reserves in Brazil is in peril due to changes in national policies [10]. In an era where many governments are exploiting natural resources in PAs with high biodiversity value, it is important for scientists, managers, stakeholders, and international organizations to work together to ensure the long-term conservation of biodiversity in these areas.

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