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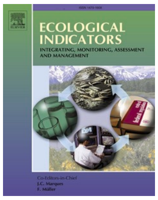

Original Articles

Assessing variation in the effectiveness of IUCN protected area categorisation. What remotely sensed forest integrity and human modification reveals across the major tropical forest biomes

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ABSTRACT

One of the major threats facing protected areas (PAs) in hyper-diverse tropical forest ecosystems is human modification of their natural habitats. With a focus on forested PAs situated across three of the world's major tropical regions, the Congo Basin, insular Indonesia Malaysia and the Tropical Andes. We analyse their representation of identified ecoregions and remote sensing data of human modification and forest integrity levels within PAs and used a generalized linear modelling approach to estimate the influences on these pressures, with a particular focus on IUCN management categorisation, PA size, and geographic location. Representation of key ecoregions varied with 7%, 11% and 22% of named ecoregions being unprotected within each major region. Overall, the IUCN management category allocation played a minor role in influencing the modification and forest integrity observed within PAs. Instead, PA size was the most important determinant of these variables across the different regions under consideration. This work provides further evidence to suggest that the assignment of PAs to IUCN categories in their current form is not interpreted consistently across different regions and does not correspond to the conservation benefits expected to be conferred by this categorisation.

1. Introduction

Tropical forest ecosystems cover approximately 1,172 million hectares globally (FAO and UNEP, 2020) and harbour as much as half of the world's biodiversity (Gibson et al., 2011; Bonan, 2008; FAO and UNEP, 2020). These are, however, threatened by a combination of demographic pressures and economic drivers such as expansion of agriculture, extractive industries, and urban development (Nkem et al., 2010; Barlow et al., 2018). Owing to the interactive and cumulative effects of these drivers, tropical forests lost 1.1million km^2 globally between 2000 and 2012 (Hansen et al., 2013). Now, the Amazon Basin, the Congo Basin, and South Asia contain the only remaining substantial and contiguous forest blocks (Brandon, 2014).

Protected areas (PAs) are widely regarded as the cornerstones of global biodiversity conservation efforts, especially for stemming tropical forest loss (Cazalis et al., 2020). These PAs represent one of the most important tools for maintaining functioning ecosystems and represent a core component of national and international biodiversity conservation strategies (Coetzee et al., 2014; Watson et al., 2014; Maxwell et al., 2020). The 196 parties to the Convention on Biological Diversity (CBD) adopted Aichi Target 11, which sets a target to conserve at least 17 % of the world's terrestrial ecoregions within PA systems by 2020 (Convention on Biological Diversity. 2010), with this target set to increase to 30 % coverage of land by 2030 (Convention on Biological Diversity., 2020). Such goals outlined have been successful in driving the rapid expansion of PAs in all regions of the world during the last decade and this terrestrial coverage target has all but been achieved, with the global PA network covering ∼ 16 % of the world's land mass (UNEP-WCMC, 2019).

Since their establishment, research has examined the link between the effectiveness of PAs across their IUCN management categories and their conservation value (Elleason et al., 2021; Leberger et al., 2020). However, truly evaluating the effectiveness of PAs is extremely challenging and multifaceted (Rodrigues & Cazalis, 2020). Much of the previous analyses of PA effectiveness have focused PA extent (Mascia et al., 2014), management (Coad et al., 2019), and what they represent

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with regard ecoregions, species, or key biodiversity areas (Oliveira et al., 2017; Kullberg et al., 2019; Singh, Griaud & Collins, 2021a,b). Other studies instead focus on impact evaluation and assessing the relative performance of PAs in relation to different conservation indicators, estimating reductions of threats inside PAs (Adnam *et al.*, 2008) and their biodiversity outcomes (Cazalis et al., 2020) by using a counterfactual approach i.e., by comparing outcomes across a PA network to those at matched, unprotected sites over a set time-period, therefore providing an indication as to what may have happened at protected sites in the absence of protection (Pressey et al., 2021). While PA networks have had measurable impacts in reducing habitat loss and the prevalence of harmful human activities within their boundaries (Tilman et al., 2017; Ribas et al., 2020) some have failed to provide concrete evidence regarding the effectiveness of PAs in safeguarding biodiversity against increasing anthropogenic threats (Craigie et al., 2010; Jones et al., 2018).

Meanwhile, substantial deterioration and biodiversity loss has been reported in half of PAs studied during the past 30 years, resulting primarily from increases in hunting and exploitation of forest-products (Laurance et al., 2012). Therefore, assessing forest quality and integrity within PA networks is an important component of efficacy evaluation. Recently, a global scale analysis identified that globally, only 40.5 % of forests have high landscape-level integrity and only 27 % of this area is found in nationally designated protected areas (Grantham et al., 2020).

Protected Area efficacy depends on multiple factors, including the management interventions to which the PAs are subject and the enforcement of restrictions. The International Union for Conservation of Nature (IUCN) has developed a system for classifying PAs based on their management objectives. This system forms an important global standard for conservation planning and includes six PA management categories, plus one subcategory (Ia; Ib; II; III; IV; V; VI) defined by the primary objectives set for that area (Table 1). These categories have been grouped according to their expected degree of naturalness (Leroux et al., 2010; Nelson et al., 2011). The management intentions of categories I - IV focus explicitly on the conservation of biodiversity or natural features and are restrictive in terms of human use, especially categories Ia and Ib. While these PAs are often considered to offer the greatest levels of nature protection (Riggio et al., 2019; Leberger et al., 2020), only 5 % of global lands at high risk of development are covered by strict PAs (I-IV) (Oakleaf et al., 2019). Conversely, PAs designated as category V or VI have a multiple-use management strategy with the aim of promoting a balance between nature conservation and human development. The management of such PAs will thus be more lenient in respect of land use practices allowed within reserve boundaries. Critics of the multiple-use categories argue that these categories are incompatible with biodiversity conservation (Locke & Dearden, 2005; Gardner, 2011), however conservation benefits such as avoided habitat loss have been widely reported within less strictly managed PAs, (Porter-Bolland et al., 2012; Schleicher et al., 2017). These less strictly managed PAs, principally category VI areas, are rapidly expanding in numbers and area within the global PA network (Shafer, 2020).

Table 1
IUCN protected area management categories and their management priorities (modified from Dudley et al., 2018).

Category	Name	Description
Ia	Strict Nature Reserve	Strictly managed to protect biodiversity. Large restrictions on human visitation and recreational use.
Ib	Wilderness Area	Large unmodified areas. Managed to preserve natural condition.
II	National Park	Managed to protect large-scale ecosystem processes and biodiversity. Permits visitor use for scientific, educational, and recreational purposes.
III	Natural Monument	Managed for the conservation of a specific natural monument.
IV	Habitat/Species Management Area	Managed primarily to protect particular species or habitats.
V	Protected Landscape/Seascape	A landscape/seascape with significant interaction between humans and natural processes. Managed to conserve these interactions.
VI	Managed Resource Protected Area	Permits the sustainable use of natural resources within an area, while also conserving biodiversity and ecological processes.

While PA management categories have attracted a lot of attention, the current literature concerning which factors play an important role in driving conservation outcomes in PAs is rapidly expanding and is spread across multiple disciplines. These include biophysical properties of individual PAs themselves, including PA size (Maiorano et al., 2008; de Carvalho et al., 2017), geographical location (Joppa et al., 2009), connectivity (Santini et al., 2016) and fragmentation (Durán et al., 2016). Plus, the local socioeconomic and political contexts in which PAs are set (Barnes et al., 2017). While multiple factors drive PA performance, distinguishing which characteristics may be the most influential is difficult and results are often contradictory depending on the metrics used to measure PA performance.

In this study we seek to find out how well PA networks across select countries within three megadiverse tropical regions, the Congo Basin, Indonesia-Malaysia, and the Tropical Andes represent different ecoregions present in these locations. This will enable us to assess which regions are closest to meeting the Aichi Target 11 aim of having 17 % of terrestrial protection coverage by 2020 and will highlight where protection gaps exist for certain ecoregions. Additionally we investigate the relationship between PA characteristics and human modification of natural landscapes and of forest integrity within PA boundaries across theses three regions, with a particular focus on IUCN management categorisation, PA size, and geographic location. This assessment will reveal which PA traits have the biggest influence on positive conservation outcomes and add to the evidence base on the applicability of the IUCN management categories.

2. Methods

2.1. Site descriptions

This study compares nationally designated PA networks across three distinct tropical megaregions, the Congo Basin, Indonesia-Malaysia, and the Tropical Andes which cover three different continents and comprise the latitudinal expanse of the Tropics. These megaregions were chosen because they are of global conservation importance, being ranked amongst the most biodiverse areas in the world and encompassing numerous biodiversity hotspots (Myers et al., 2000; Mittermeier et al., 2011). They are also experiencing increasing anthropogenic pressures, particularly deforestation resulting from timber extraction, urban expansion, and agricultural development (Laurance & Balmford, 2013; Gibbs et al., 2010; Tyukavina et al., 2018).

2.1.1. Congo Basin

Spanning from the Gulf of Guinea in the west to the highlands of the Albertine Rift mountains in the east, the Congo Basin covers an estimated 180 million hectares across several Central African countries making it the second-largest expanse of tropical forest on Earth (Aveling, 2010). At its core, the Congo River regulates moist forest ecosystems which dominate the basin and supports the world's largest assemblage of tropical forest vertebrates. In this paper, the Democratic Republic of Congo (DRC), Republic of Congo (Congo) and Gabon were specifically assessed as contiguous countries containing 84 % of the Congo Basin moist forests (Bele, Sonwa & Tiani, 2015). These countries have experienced consistently high population growth rates; >2% increases in population size per year over the past 20 years (World Bank, 2021), and pressures on the forests have mirrored this population growth. Subsistence farming is believed to be the primary driver of forest disturbance in the region with annual rates of small-scale clearing for agriculture in primary forests and woodlands doubling between 2000 and 2014 (Tyukavina et al., 2018). For this study 81 PAs covering a total area of 503,185 km^2 were assessed within the region (Fig. 1; Supplementary Table 1).

2.1.2. Indonesia-malaysia

Indonesia and Malaysia lie in Insular Southeast (SE) Asia and cover the major biogeographic units of Sundaland and Wallacea which are considered as some of the most diverse regions of the planet (Myers et al. 2000). The region is a global deforestation hotspot with approximately 60 % of forest loss between 1990 and 2010 occurring in Indonesia alone (Stibig et al., 2014). These high levels of deforestation have arisen primarily as a result of an increase in demand for commodities such oil palm (Gaveau et al., 2019), while a weak regulatory framework combined with local socio-economic conditions have resulted in an increased encroachment and deforestation in Indonesia's PAs (Levang et al., 2012; Brun et al., 2015). For this study 827 PAs covering a total area of 257,836 km^2 were assessed within this region (Fig. 1; Supplementary Table 2).

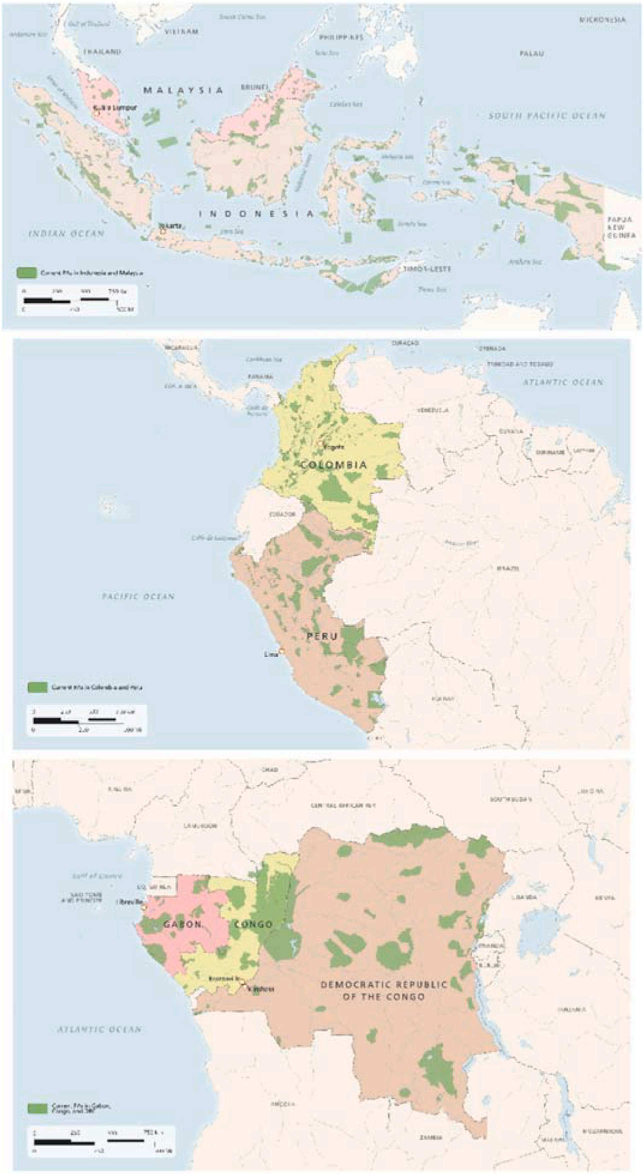

Fig. 1. Political Boundaries of the study areas (highlighted countries) within (Top to Bottom) Indonesia-Malaysia (Indonesia and Malaysia), Tropical Andes (Colombia and Peru), and Congo Basin (Gabon, Congo, and Democratic Republic of Congo). The extent and location of current PA networks in each of the three regions are displayed in green. Data derived from the World Database on Protected Areas (WDPA), accessed December 2020[1]. [1]https://www.protectedplanet.net/en.

2.1.3. Tropical Andes

The Tropical Andes region comprises the longest and widest cool region in the tropics covering 158.3 million hectares along the Andes Mountain chain from Venezuela through Colombia, Ecuador, Peru, Bolivia, to the northern tropical portions within Argentina and Chile. But while the Tropical Andes covers only 1 % of the Earth's land area, it one of the most diverse hotspots in the world in terms of species richness and endemism (Myers et al., 2000) supporting c.15 % of all known plant species and c.12 % of all known vertebrate species (Bax & Francesconi, 2019). Although forest loss and fragmentation in the in the region is predominantly driven by agricultural expansion, deforestation rates in montane and lowland forests vary as a result of differing socio-economic, demographic and biophysical factors at the local level (Armenteras et al., 2011). This study focuses on the nationally designated PA networks of Colombia and Peru, which cover most of the northern section of the region. These countries were chosen because they are of global conservation importance and are ranked amongst the most biodiverse countries in the world (Mittermeier et al., 2011) and encompass two of the world's pre-eminent biodiversity hotspots: the Tumbes-Chocó-Magdalena and the Amazon lowland rainforests (Myers et al., 2000; Jenkins, Pimm & Joppa, 2013). For this study a final number of 1349 of PAs covering a total area of 517,295 km^2 were assessed within this region (Fig. 1; Supplementary Table 2).

2.2. PA selection & grouping

Once data for PAs in each country was downloaded from the World Database on Protected Areas (WDPA) processing was required to extract data appropriate to the purposes of this work. Only terrestrial PAs were considered and internationally designated areas (e.g., UNESCO Man-Biosphere reserves and Ramsar Wetlands of International importance) were excluded from further analysis. Additionally, areas of PA overlap were removed to avoid double counting in the analysis following established cleaning methods (UNEP-WCMC, 2019).

We grouped PA management categories by expected degree following the classifications established in other studies investigating the impacts of IUCN categories (Leroux et al., 2010; Ferraro et al., 2013). Category Ia (Strict Nature Reserve) and Ib (Wilderness area) are strictly protected and focus on preserving vital biodiversity and severely restrict human activity within their boundaries in order to preserve their integrity for future generations. Categories II, III and IV were grouped together as they contain PAs for which the primary management objectives also focus explicitly on the conservation of biodiversity but instead permit varying levels of human influence. Meanwhile category V and VI PAs were grouped together representing reserves with multiple-use management strategies. Finally, PAs categorized as 'Not Applicable', 'Not Assigned', or 'Not Reported' were grouped together as these PAs meet the selection criteria but have not been formally designated under any IUCN management categories so are likely to be important components of regional PA systems. This final group is referred to as 'Nots' throughout the rest of the paper). The characteristics of the PA network within each region varied markedly. In the Tropical Andes and, to a lesser extent, Indonesia-Malaysia, PA networks are made-up of many, smaller reserves relative to PAs in the Congo basin that were fewer in number, though many magnitudes larger (Fig. 2a). Reserve designation within different IUCN management categories also varied between the regions. Indonesia-Malaysia contained a large proportion of PAs in the

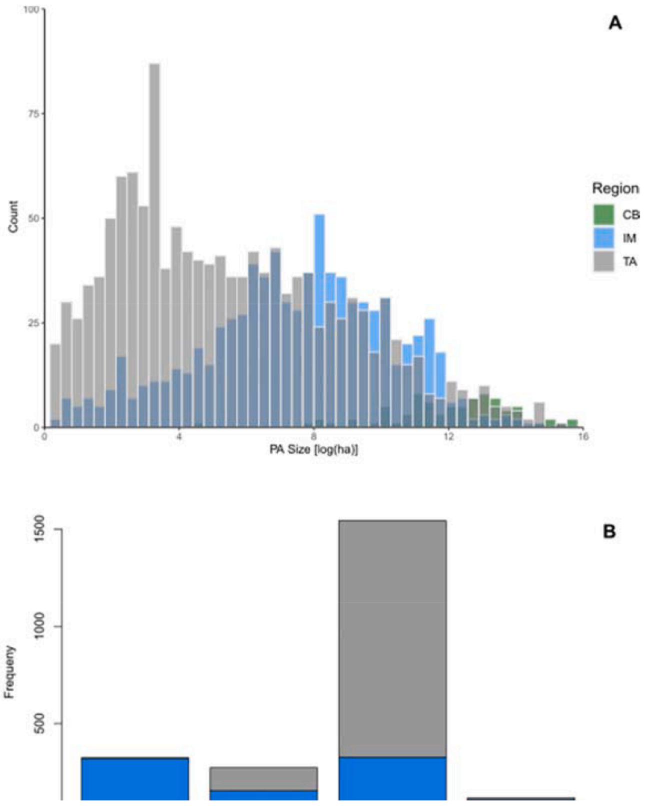

Fig. 2. Size distribution of PAs (A) and the number of PAs in each IUCN management category grouping (B) across the different tropical megaregions. CB = Congo Basin, IM = Indonesia Malaysia and TA = Tropical Andes. ‘Nots’ are PAs that are Not assigned/applicable/reported.

‘strictest’ management categories (Ia & Ib), while management categories VI and V were the most frequent amongst PAs in the Tropical Andes (Fig. 2b).

Before analysis, we also omitted PAs of<1 ha in size (n = 39) as these represented areas which were substantially below the resolution of the human modification and FLII data used (both 1 km^2) and so were thought unlikely to play a substantive role in influencing values in the raster data – these were principally in the TA (Fig. 2a). While many PAs present in our study region exist within forest biomes, PAs without any discernible forested area, i.e. where mean FLII values were estimated to be zero (n = 159) were removed from the final forest integrity analyses. The dataset downloaded from the WDPA contained 2,257 PAs, covering the three study regions/seven countries, with a total area of 1,278,315 km^2 (Supplementary Table 1). This dataset was reduced further to 2,069 PAs once all of the smallest reserves (<1ha), and PAs with forest integrity values = 0, were removed for consequent analyses.

2.2.1. *Ecoregions, human Modification, and forest integrity*

To evaluate how representative PA networks were across each tropical region, we estimated PA coverage of the terrestrial ecoregions (Olson et al., 2001) present in each country to assess how well PA networks meet Aichi Target 11 aim of having 17 % of land protected by 2020 (Convention on Biological Diversity, 2010). Ecoregions are spatial planning units at a smaller spatial resolution than biomes. They are important for informing regional conservation strategies and highlighting priority areas for protection. A selection of the ecoregions included in this analysis have been given further designation as ‘Global 200′ ecoregions. Global 200 ecoregions are distinguished by the fact that the biodiversity they are highly distinctive and irreplaceable, so are considered priority regions when developing conservation strategies (Olson & Dinerstein, 2002). Therefore, we also considered the extent the extent to which PA networks represented these important ecoregions independently.

To evaluate the effectiveness of existing PA networks in mitigating anthropogenic pressures we used the most recent cumulative measure of human modification of terrestrial lands, the Global Human Modification of Terrestrial Systems, v1 (Kennedy et al., 2020). This dataset is available at 1 km^2 resolution and models the physical extents of 13 anthropogenic stressors and their estimated impacts using spatially explicit global datasets with a median year of 2016 (Kennedy et al., 2019). Meanwhile we quantified the degree of ecological integrity of forested areas inside PAs using the recently developed Forest Landscape Integrity Index (FLII), a continuous index of forest condition using a resolution of 1 km^2 (Grantham et al., 2020). The FLII considers forest extent, observed pressure from high impact, localized human activities, inferred pressure associated with edge effects and anthropogenic changes in forest connectivity.

2.3. *Statistical modelling*

The two human pressure datasets were overlaid with the final set of PAs in each megaregion and mean human modification and forest integrity index values were extracted for individual PAs. Forest integrity and human modification levels within PA networks are likely to vary spatially due to differences in regional context and the individual characteristics of a PA, therefore we adopted a generalized linear modelling approach to estimate the influence of these pressures at a global and regional scale. For the global model, calculated human modification and forest integrity mean values for each distinct PA were used as the response variable and three potentially explanatory variables were used in the analysis. These were geographic region [tropical ‘megaregion’: Congo Basin (CB), Indonesia-Malaysia (IM), Tropical Andes (TA)], PA size [continuous, in log(ha)], plus the four PA management category groups: [Ia + Ib; II – IV; V + VI; Not Assigned/Applicable/Reported]. We also created separate regional models to account for the differing patterns of PA size plus the intrinsic variation in the level of anthropogenic pressures faced across each megaregion. Therefore, regional models were considered best to understand human pressure trends at regional scales. A similar generalized linear modelling approach was employed but the explanatory variable of megaregion was replaced by the individual country as a predictor variable [Gabon, Congo, DRC; or Indonesia and Malaysia; or Colombia and Peru].

Generalized linear models were fit to the human modification and forest integrity data to include the three main factors of interest and their two-way interactions. These interactions were believed to be important due to the regional variation in the relative proportion of each PA management category groups and in the PA size distributions. Stepwise deletion was used to identify factor effects on forest integrity and human modification values within PAs. Within each megaregion, and where a visual inspection of the data suggested it was appropriate, a polynomial function was also fit to estimate whether there was a curve to the relationship between the human modification level and PA size. Statistical analysis and graphics were completed using R (R Core Team, 2021).

3. Results

3.1. *Ecoregion coverage*

The PA network of the Congo Basin was most comprehensive in meeting Aichi coverage targets when considering protection afforded to terrestrial ecoregions: 10 out of 18 (55 %) distinct ecoregions present across Gabon, Congo and DRC have > 17 % of their area covered by PAs. The PA systems currently established within Indonesia-Malaysia and the Tropical Andes both afforded much lower levels of protection to terrestrial ecoregions in general with only 15 out of 45 ecoregions (33 %) in IM and 14 out of 46 ecoregions (30 %) in the TA considered to have met the Aichi 11 target of > 17 % of their area formally protected by PAs. Conversely, within in the Congo Basin ~ 22 % of ecoregions (n = 4) were seriously underrepresented by its PA network with no coverage by PAs; the proportion of uncovered ecoregions lower in the Tropical Andes was ~ 11 % (n = 5) and was lowest in Indonesia-Malaysia at ~ 7 % (n = 3). Nine of these unrepresented ecoregions across the three megaregions only existed within small fragments of the megaregions studied (e.g., <1000 km^2) and were thus less likely to be covered by existing PAs. Many larger ecoregions, however, were also poorly represented by regional PA networks, with examples present across each of the tropical megaregions: the Angolan Miombo woodlands (CB, no protection), Western Java rainforests (IM, 0.4 % of area protected) and Rio Negro campinarana (TA, no protection) (Supplementary Table 2).

Seventy-five WWF Global 200 Ecoregions are present to some extent across the tropical biomes studied (13 in CB, 25 in IM, and 37 in TA) and cover a substantial 77 % of the region. Of these 31 (~41 %) are considered to have been well represented by PA networks, but 10 Global 200 Ecoregions were afforded no protection within the most strictly managed PA types (IUCN categories I-IV). PAs in the Congo Basin were found to be best at protecting Global 200 Ecoregions with 54 % well represented within the region compared to 40 % in Indonesia-Malaysia and 38 % in the Tropical Andes.

3.2. Human modification

The human modification level within PAs varied between megaregions, with PAs in the Congo Basin being less modified by people while those in Indonesia-Malaysia and the Tropical Andes revealed much higher modification values (Fig. 3a).

As expected from the variation in PA size between megaregions, the highest order, three-way interaction was statistically important [F (6,2201) = 4.60, p= <0.001]. There was a decline in human modification with rising PA size in all regions, although the interaction term indicated that the slope was different [F(2,2207) = 19.96, p= <0.001] in each region (Fig. 4). The main effects were all individually significant (Megaregion: [F(2,2218) = 40.05, p= <0.001]; Management category group: [F(3,2218) = 27.22, p= <0.001]; PA size: [F(1,2218) = 627.66, p= <0.001]), though the PA size was most influential and accounted for ~ 20 % of the variation in the model with PA management category and Region (both responsible for ~ 3 % of variation in the model) far less influential (Table 2).

3.2.1. Regional analysis

When the data for each megaregion was analysed separately, PA size was consistently found to be the greatest determinant of modification levels within PA networks while the effects of the other variables (country and management grouping) were relatively weak.

In the Congo Basin, a quadratic function led to improved model fit and PA size accounted for ~ 38 % of the variation [F(1,74) = 16.57, p= <0.001] (Table 2). Variation in human modification of land also varied between the countries in this region [F(2,74) = 9.3, p = <0.001], with PAs in Gabon being least modified (mean = 0.11 ± 0.04) and those of the Congo the most (mean = 0.28 ± 0.08). This, however, accounted for substantially less variation than size directly (~10 %) while the effect of PA management category in the Congo Basin was not detected to have an effect [F(3,74) = 1.1, p = 0.35].

In Indonesia-Malaysia, the interaction between country and protection category influenced the degree of modification observed [F(3,801) = 5.79, p = <0.001]. Although this may be driven by the high modification value of ‘Nots’ in Malaysia which is at odds with other categories which are more modified in Indonesia (Fig. 5a). All main effects were individually influential (Country: [F(1,808) = 59.27, p = <0.001]; Management category group: [F(3,808) = 18.05, p = <0.001]; PA size [F(1,808) = 499.34, p = <0.001]) though PA size was most influential accounting for ~ 34 % of the variation within the model (Table 2).

In the Tropical Andes, the interaction between country and PA management categories was statistically influential though may be driven by a lack of Ia and Ib PAs in Peru [F(2,1318) = 5.27, p = 0.05] (Fig. 5b). The interaction between PA size and designated management category group was also influential [F (2,1318) = 13.35, p = <0.001] though accounted for only ~ 2 % of variation detected and is thought to

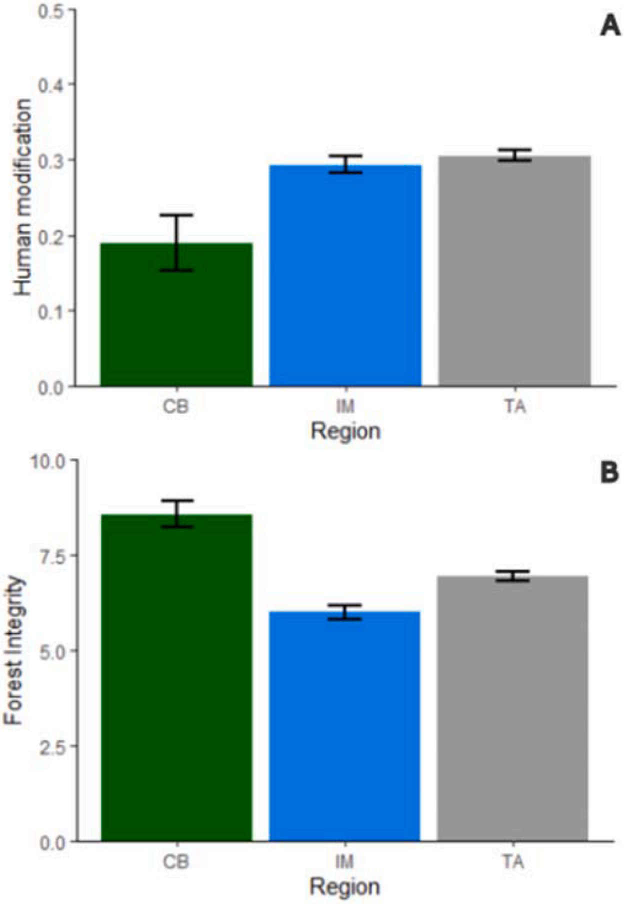

Fig. 3. (A) Average extent of human modification of land and within PAs across the tropics with error bars displaying 95 % confidence intervals. (B) Average forest integrity within PAs across the tropics with error bars displaying 95 % confidence intervals. CB = Congo Basin, IM = Indonesia Malaysia and TA = Tropical Andes.

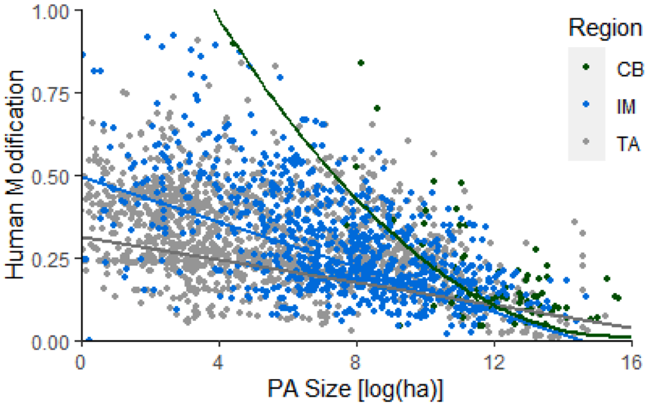

Fig. 4. Human modification as a function of PA size across each tropical megaregion. Relationships are displayed by different coloured regression lines - polynomial regression in the case of the Congo Basin (dark green: $y = 1.74–0.22x + 0.007x^2$). CB = Congo Basin, IM = Indonesia Malaysia and TA = Tropical Andes.

Table 2

Summary statistics of Generalized Linear Models of Global Human Modification as a function of megaregion or country, management category and PA size. All main effects analysed here and interactions between them are included with ANOVA output statistics and Coefficient of Determination (R^2) displayed. Significant terms are presented in **bold**.

Region	Interactions	F	df	p	R^2
All	**Megaregion + Category + PA size**	4.60	6,2201	**<0.001**	0.009
	Megaregion + Category	0.79	6,2207	0.576	0.002
	Category + PA size	2.62	3,2207	0.049	0.003
	Megaregion + Size	19.96	2,2207	**<0.001**	0.01
	Megaregion	40.05	2,2218	**<0.001**	0.03
	Category	27.22	3,2218	**<0.001**	0.03
	PA Size	627.66	1,2218	**<0.001**	0.2
Congo Basin	Country + Category + PA size	0.36	3,63	0.79	0.006
	Country + Category	0.19	3,66	0.92	0.003
	Category + PA size	1.17	3,66	0.33	0.02
	Country + PA size	3.7	2,66	0.03	0.04
	Country	9.3	2,74	**<0.001**	0.10
	Category	1.1	3,74	0.35	0.02
	PA Size	69.64	1,74	**<0.001**	0.38
Indonesia-Malaysia	Country + Category + PA size	4.58	2,799	0.01	0.006
	Country + Category	5.79	3,801	**<0.001**	0.012
	Category + PA size	2.58	3,801	0.05	0.005
	Country + PA size	2.29	1,801	0.13	0.002
	Country	59.27	1,808	**<0.001**	0.04
	Category	18.05	3,808	**<0.001**	0.04
	PA Size	499.34	1,808	**<0.001**	0.34
Tropical Andes	Country + Category + Size	0.14	1,1317	0.712	0.00007
	Country + Category	5.27	2,1318	**0.005**	0.006
	Category + Size	13.35	3,1318	**<0.001**	0.02
	Country + Size	2.71	1,1318	0.1	0.001
	Country	173.67	1,1324	**<0.001**	0.09
	Category	4.27	3,1324	**0.005**	0.007
	PA Size	113.76	1,1324	**<0.001**	0.06

be driven by the small numbers of Ia and Ib PAs present in the region (n = 2). The country [F(1,1324) = 173.67, p = <0.001], the management category group [F(3,1324) = 4.27, p = 0.005] and the PA size [F (1,1324) = 113.76, p = <0.001] all influenced the degree of human modification observed. Here though, PA size was found not the strongest influence, accounting for ~ 6 % of the variation within the model, and instead between country variation dominated, accounting for ~ 9 % of variation in the human modification values observed (Table 2).

3.3. *Forest integrity*

Human modification and forest integrity were negatively correlated (t = 8.38, d.f = 2067, p < 0.001), though the line fit was poor indicating that they may provide different views on this area (Fig. 6).

Inter-regional analysis of mean forest integrity values within PAs revealed many of the same trends as the human modification analysis. There was no identifiable three way interaction, though the interactions between PA size and IUCN category [F(3,2051) = 3.79, p = 0.01] and PA size with megaregion [F(2,2051) = 4.81, p = 0.008] were important (Table 3). Smaller reserves in Indonesia-Malaysia had less forest integrity than those of the Tropical Andes and the Congo Basin.

Each of the main effects; geographic region [F(2,2062) = 127.34, p = <0.001], PA management category [F(3,2062) = 8.5, p= <0.001], and PA size [F(1,2062) = 451.44, p= <0.001] were found to influence forest integrity levels inside PAs, with PA size the most influential, accounting for ~ 16 % of variation in the model (Table 3). Across the tropics, mean forest integrity within PA boundaries was highest in the Congo Basin, while that of Indonesia-Malaysia was the lowest (Congo Basin = 8.56 ± 0.35, Indonesia-Malaysia = 6.00 ± 0.18, Tropical Andes = 6.90 ± 0.13) (Fig. 5b).

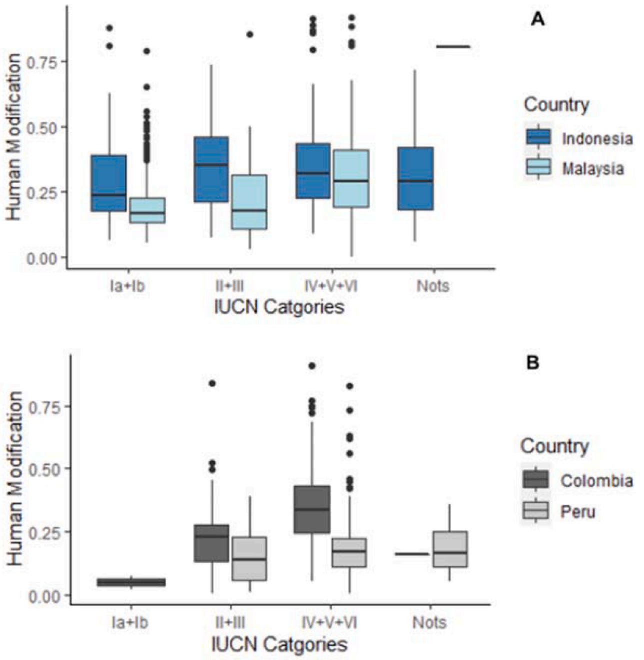

Fig. 5. Modification of protected land designated under different IUCN management categories across Indonesia and Malaysia (A), and Colombia and Peru (B). The influence of PA on Human Modification varied with country within these megaregions, though this was not the case in the Congo Basin (See Fig. 3).

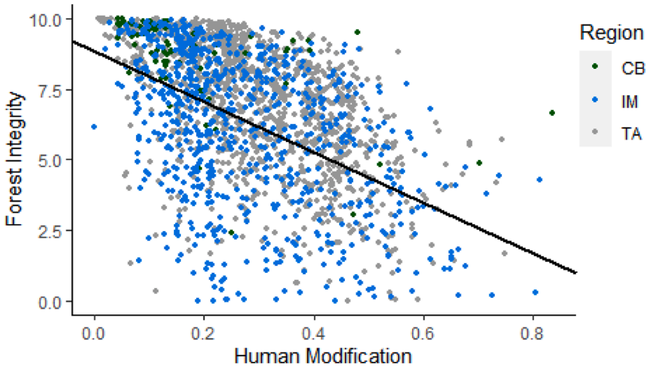

Fig. 6. Forest integrity as a function of human modification within PAs. The black trend line (y = 9.07–8.38x) denotes the linear relationship between forest integrity and human modification values. CB = Congo Basin, IM = Indonesia Malaysia and TA = Tropical Andes.

3.3.1. *Regional analysis*

When the data for each megaregion was analysed separately, PA size was consistently discovered to be the greatest predictor of forest integrity within regional PA networks while the effects of the other variables (country and management grouping) were relatively weak in comparison.

In the Congo Basin there were no important interactions between the main effects. In which country a PA was established was the strongest influence on forest integrity values within a PA [F(2,73) = 11.75, p = <0.001] and accounted for ~ 21 % of the variation in the model (Table 3). PAs in Gabon had forest integrity scores (mean FLII = 9.40 ± 0.20), whilst this was lowest in the DRC (mean FLII = 8.06 ± 0.63). PA

Table 3
Table of GLM model runs of Forest Integrity findings across all PAs combined and for PA networks in each of the megaregions presented separately. All explanatory variables (megaregion or country, management category, and PA Size) and interactions between them are included with ANOVA output statistics and Coefficient of Determination (R^2) displayed. Significant factors are highlighted in **bold**.

Region	Interactions	F	df	p	R^2
All	Megaregion + Category + PA size	0.1	6,2045	0.999	0.0002
	Megaregion + Category	0.35	6,2051	0.912	0.0007
	Category + PA size	3.79	3,2051	**0.01**	0.004
	Megaregion + PA size	4.81	2,2051	**0.008**	0.003
	Megaregion	127.34	2,2062	**<0.001**	0.09
	Category	8.5	3,2062	**<0.001**	0.009
	PA Size	451.44	1,2062	**<0.001**	0.16
Congo Basin	Country + Category + PA size	0.9	3,62	0.44	0.03
	Country + Category	1.51	3,65	0.22	0.04
	Category + PA size	1.27	3,65	0.29	0.03
	Country + Area	0.73	2,65	0.49	0.01
	Country	11.75	2,73	**<0.001**	0.21
	Category	1.58	3,73	0.2	0.04
	PA size	12.26	1,73	**<0.001**	0.11
Indonesia-Malaysia	Country + Category + PA size	2.2844	2,763	0.103	0.004
	Country + Category	0.9429	3,765	0.419	0.003
	Category + PA size	2.3373	3,765	0.072	0.007
	Country + Area	1.7762	1,765	0.183	0.002
	Country	1.344	1,772	0.25	0.001
	Category	7.47	3,772	**<0.001**	0.02
	PA size	246.82	1,772	**<0.001**	0.24
Tropical Andes	Country + Category + PA size	2.09	1,1198	0.15	0.001
	Country + Category	4.29	2,1199	0.01	0.005
	Category + PA size	0.11	3,1199	0.95	0.0002
	Country + PA size	28.66	1,1199	**<0.001**	0.02
	Country	3.9	1,1205	0.05	0.003
	Category	4.43	3,1205	**0.004**	0.009
	PA size	167.22	1,1205	**<0.001**	0.11

size was also influential [F(1,73) = 12.26, p = <0.001], but accounted for a smaller proportion of variation (~11 %) within the model.

In Indonesia-Malaysia there were no important interactions between the main effects though differences in management categories accounted for a small portion (~2%) of the variation in forest integrity levels inside PAs [F (3,772) = 7.47, p = <0.001] (Table 3c). There was no identifiable difference between the countries, with mean forest integrity inside PAs in Indonesia (mean FLII = 6.06 ± 0.25) similar to that of Malaysia (mean FLII = 5.93 ± 0.27). PA size was the best predictor of forest integrity values within the PA network in the region [F (1,772) = 246.82, p = <0.001] accounting ~ 24 % of the variation within the model (Table 3).

In the Tropical Andes there was an identifiable interaction between country and PA size on forest integrity [F (1,1199) = 28.66, p = <0.001], however, the effect size was small, ~2% of variation detected. As with Indonesia - Malaysia, individually the PA size was the strongest predictor of forest integrity inside the PAs in the Tropical Andes accounting for ~ 11 % of the variation in the model [F (1,1205) = 167.22, p = <0.001]. Forest integrity also varied with the management category [F (3,1205) = 4.43, p = 0.004] although the influence of country itself was not identifiable at this level. (Table 3).

4. Discussion

4.1. *Ecoregion coverage*

The pattern of unequal ecoregion protection between each tropical biome within the regional PA networks reflects the strategies and constraints of PA creation in these different geographies. Overall, the PA network in the Congo Basin provided a high level of protection of the greatest proportion of ecoregions present in the region while Indonesia-Malaysia and the Tropical Andes performed poorly in coverage terms. While certain ecoregions had > 90 % of their land area protected, less than half of those occurring within the study area were comparatively well-represented, and 14 ecoregions received no PA coverage at all (Supplementary Table 2). The unequal representation of ecoregions within PAs exposed here mirrors documented global trends (Schmitt et al., 2009). These findings reveal that despite Aichi targets being achieved at national scales, there is still a long way to go before 17 % coverage targets are realised at smaller, relevant ecoregional scales.

Understanding how PAs represent key biogeographic regions, which share a distinct assemblage of vegetation types and associated biodiversity, is important to identify priority areas for protection. Here several large ecoregions were identified as particularly poorly protected: the Angolan Miombo woodlands (CB), Western Java rainforests (IM) and Rio Negro campinarana (TA). Future conservation strategies involving the expansion of PA networks should be targeted at these and at those that are most pressured by human activities if the aim is to maximise the impact of protection (Venter et al., 2018).

4.2. *Is PA categorisation useful?*

Composite remote sensing data sets of forest integrity and human development pressures demonstrated clearly that levels of human modification and forest integrity of land inside PAs varied widely across the study regions. The IUCN management category allocated, however, consistently played only a minor role in influencing the modification and forest integrity observed within PAs. That management category, in current form, accounted for little weight in the models, and a clear pattern of naturalness did not emerge across PAs of different category in all megaregions. But since our study did not factor in changes over time, it is difficult to conclude whether IUCN management category influences human disturbance or forest integrity as current patterns could conceivably reflect past management prior to PAs designation rather than indicating the results that occurred after PAs were established. Our results do however align with a wider body of research. Previous studies analysing the Human Footprint Index (Jones et al., 2018; Anderson & Mammides, 2019), development of human settlements (Guan et al., 2021), and deforestation rates within PA networks (Porter-Bolland et al., 2012; Miranda et al., 2016) have also provided evidence to support the claim that there exists no obvious association between the designation of PA management categories and improved outcomes for conservation or minimisation of anthropogenic pressures. The reasons behind this pattern are harder to evaluate remotely and local-scale understanding is clearly vital (Singh et al., 2021a,b). However, these rapidly achieved analyses are necessary in providing broad-scale guidance and will continue to be important as researchers evaluate whether management designation will be a better predictor of future patterns than current ones.

Though they were strongly correlated, the variance between human modification and forest integrity is likely the result of national income and population density differences between the megaregions (Bradshaw et al., 2015), parameters not assessed during this study. Cases, therefore, where PAs with varying management categories were associated with lower human modification or improved forest integrity (i.e., more optimal conservation outcomes) may not be driven by the regulatory strictness *per se*, but rather arose because of where the stricter protection was assigned i.e., in places experiencing lower human pressures (Ferraro et al., 2013; Pfaff et al., 2014). Additionally, while the PA management system sets out clear objectives for each category in terms of conservation of natural features or a multiple-use strategy, we would not always expect reductions in human pressures. For example, categories II, III, and IV all allow for tourism activities which require the inward migration of people and infrastructure development which will influence the human development and forest integrity scores in composite remote sensing data sets. This is one reason why the PA management categories are so contentious and there has been little evidence to show that theoretical 'strictness' in categorisation directly influences conservation benefits derived from PA networks (Shafer, 2015; Elleason et al., 2021). To improve the conservation effect of the system, it has been proposed that that the category definitions should be updated to explicitly define the role of individual PAs in biodiversity conservation i.e., the species and vegetation types contained and the management objectives for their conservation, rather than associated with features contained, management priorities, and degree of human use in different protected as in their current state (Boitani et al., 2008). For effective conservation, this level of detail matters.

Despite the IUCN PA category system being widely adopted internationally as the basis for categorising PAs (McDonald & Boucher, 2011; UNEP-WCMC, 2019), they do not appear to have been interpreted consistently across the globe (Leroux et al., 2010). Across our study regions, clear disparities were identified in the relative frequency of, and terrestrial area covered by PAs under different management category types across each tropical biome (Fig. 2). The principal trends delineated were that all but three of the category Ia/Ib PAs studied were in either Indonesia or Malaysia; that the majority of PAs in categories IV - VI were designated in Colombia and Peru, and finally that a disproportionate number of PAs in the Congo Basin were simply not designated as one of the recognised IUCN management categories (Supplementary Table 1). While variation in management categories would be expected between geographically distinct regions, such large discrepancies would be unlikely if categorisation was interpreted and allocated consistently. For example, while categories Ia ('Strict Nature Reserves') and Ib ('Wilderness Areas') represent the most ecologically intact regions with minimal human disturbance (Dudley et al., 2018), is it accurate to assume that the designation of 100x more sites as either Ia or Ib in Indonesia-Malaysia than in Columbia and Peru reflects a real difference in the number of ecologically intact reserves between those two areas? Although the designation of IUCN categories is voluntary, with no central body presently evaluating category designations administered by local or national governments (Leroux et al., 2010) such an obvious mismatch in interpretation of categories may indicate a systemic issue. It may be that the category system is more usually applied as a basis for determining future intended activities in PAs, rather than their present conservation needs and objectives.

While designated PAs are undoubtedly a vital cornerstone of efforts to conserve biodiversity in the tropics, many have pointed to the emerging importance of 'Other effective area-based conservation measures' (OECMs). These are areas with a local designation that are achieving effective in-situ conservation of biodiversity outside of protected areas. These, such as indigenous territories and private lands have received substantial interest as they may ensure longer term conservation of nature, plus preservation of human rights and livelihoods (Dudley et al., 2018; Donald et al., 2019). Such protected areas are a growing component of the global protected area (Bingham et al., 2017; Garnett et al., 2018) and it is likely that many OECMs are yet to be officially recorded. As social and economic conflicts can arise when trying to protect regions with competing land uses, using OECMs that explicitly integrate local people as stakeholders may be the optimal strategy for promoting mutual biological conservation and socioeconomic development outcomes (Oldekop et al., 2016). Some evidence now suggests that OECMs can be as effective as PAs in harbouring biodiversity and avoiding deforestation in locations with high deforestation pressures (Schleicher et al., 2017). Current PA management category classification can seem arbitrary and may not correlate with improved conservation outcomes, we suggest that the definition of PAs should be widened to include OECMs that provide conservation value in regions under pressure from anthropogenic threats. An integration of OECMs into the PA network may help ensure that they provide a long-term commitment to conservation. Such designation would help to reduce the likelihood of conversion of these lands in the future.

4.3. *The value of large PAs*

The'SLOSS' (Single Large or Several Small) discussion has long been present in conservation ecology theory (Diamond, 1975; Lindenmayer et al., 2015) and in this study, PA size was the most important correlate of variation in human modification across PA networks in both the Congo Basin and Indonesia-Malaysia (c30%), remaining consistently more influential than management category grouping. Similar was seen, though less emphatically (11–24 % across megaregions), when assessing forest integrity levels with smaller reserves experiencing lower forest integrity. Few studies have explicitly considered PA size in relation to their capacity to minimise the extent of human activities and land-use change within PA networks despite the large body of research focused PA size in relation to their efficiency in preserving biodiversity as part of SLOSS debate (Ovaskainen, 2002; Hammill et al., 2020). Despite a general sense that large PAs are invariably better, studies investigating the role played by protected area size in ensuring conservation outcomes present contrasting results. Recent research has indicated that protected area size played no role in mediating deforestation dynamics within protected area boundaries in Ecuador (Van Der Hoek, 2017) while larger PAs appear to have suffered highest forest loss rates globally, although this trend was less obvious in the Tropics (Wolf et al., 2021). Global scale analyses, however, suggest that the capacity of PAs to slow down habitat degradation is mediated by their size (Maiorano et al., 2008) and that size is a strong predictor of species richness contained within PAs (Durán et al., 2016). Additionally, there is a clear pattern of large PAs being established in regions of high altitude, low productivity, and lower accessibility for humans (Joppa et al., 2009; Sayre et al., 2020; Singh, Griaud & Collins). So, while it may look as though large PAs reduce human impacts, it may just be that large PAs have been established in places where human impacts were minimal for other reasons. A focus on longitudinal outcomes will help understand if size genuinely influences human impacts and forest integrity into the future.

4.4. *PA location*

The establishment of large PAs has been linked to better outcomes for biodiversity in both marine and terrestrial realms (Geldmann et al., 2013; Edgar et al., 2014) and the need to create larger reserves as part of wider PA networks has become a high-profile recommendation in national conservation policy. Where they are placed, however, matters. As mentioned previously, there exists clear correlation between the biophysical properties of PAs and their location, with inhospitable areas receiving disproportionate levels of protection by large PAs (Joppa et al., 2009; Sayre et al., 2020; Singh et al., 2021a,b). In contrast, many diverse regions subject to significant anthropogenic pressures are often underrepresented, as land here is subject to many competing pressures e.g., deforestation and agricultural expansion (Venter et al., 2018; Visconti et al., 2019). Because the establishment of PAs is partly driven by land availability and acquisition cost (Baldi et al., 2017), factors heavily influenced by the extent of human activities already carried out in a region, the question remains whether larger PAs are placed in regions of low human development and high forest integrity because it's easy to establish large reserves in these areas or whether they are in themselves driving positive conservation outcomes in these areas? Future research comparing the average human modification and forest integrity scores within PAs and surrounding buffer areas could help reveal the true impact of PAs encompassing these areas and studies that directly compare outcomes within matched PA and non-protected areas will become the 'gold standard' for assessing PA performance and other conservation measures (Ferraro, 2009; Ferraro & Pressey, 2015).

Such location bias can mask the real effects of land protection (Joppa et al., 2009), therefore, more rigorous impact evaluation studies are required to determine the real influence of PA size on reducing human pressures within reserves and maintain forest integrity (Ferraro & Pressey, 2015) in regions subject to similar levels of human pressure. Such analysis will be particularly important for investigating how PA networks can be expanded in deliver the greatest benefits for conservation at a time when megadiverse tropical biomes are under increasing pressures from deforestation (Hansen et al., 2013) and budgets for PA expansion and management are often restricted (Watson et al., 2014). Additionally, greater efforts need to be made in identifying the contexts in which PAs of any size will be most effective in regions where competing land uses are high, and in assessing their ability to buffer future threats, such as climate change.

5. Conclusions

While many nations may meet large scale PA coverage targets set out by the CBD, we show that at a local level, protection is extremely unequal. Across the tropical biomes studied, many regions of global importance containing highly distinctive and irreplaceable biodiversity are seriously underrepresented by the current spatial layout of PA networks. These critical ecoregions identified should therefore be priorities for future PA establishment.

Although a strict counterfactual approach was not utilised to assess PA performance in this study, our results illustrate that IUCN management categorisation in itself does not play a large role in influencing human modification and forest integrity values observed within PAs and instead highlights clear differences in interpretation of management categories across different regions. These findings question the local interpretation, enforcement, and effectiveness of the IUCN classification system for PAs in its current form. The categories may not align with present conservation objectives and are likely impacted by other drivers (e.g., PA location/human pressures/local governance) rather than significantly affecting the conservation performance of PAs. We highlight the strong positive association of PA size with forest integrity and human modification. While we are unable to evaluate whether these findings are generalisable across other regions, we believe that the establishment of large PAs along with OECMs in diverse tropical regions will be vital to mitigate harmful human activities and maintain high levels of forest integrity. More rigorous impact evaluation studies will be needed to distinguish the true effect of PA size on reducing human pressures within reserves. Further research should also consider what sizes of PAs can maximise performance in different socioeconomic and governance contexts. This future research will be vital to safeguard tropical forest ecosystems and the vast array of biodiversity that they hold.

CRediT authorship contribution statement

Samuel Hirons: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **C. Matilda Collins:** Writing – review & editing, Supervision. **Minerva Singh:** Supervision, Writing – review & editing, Visualization.

Declaration of Competing Interest

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

Data availability

Data present in the Supplementary

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109337.

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