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Trends in protected area representation of biodiversity and ecosystem services in five tropical countries

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Trends in protected area representation of biodiversity and ecosystem services in five tropical countries

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ABSTRACT

In late 2020, governments will set the next decade of conservation targets under the UN Convention on Biological Diversity. Setting new targets requires understanding how well national protected area (PA) networks are spatially representing important areas for biodiversity and ecosystem services. We analyzed the representation of biodiversity priority areas (BPAs), forests, forest carbon stocks, non-timber forest products (NTFPs), and freshwater ecosystem services (FES) within terrestrial PA systems in Cambodia, Guyana, Liberia, Madagascar, and Suriname in 2003 and 2017. Four of the countries (all except Suriname) expanded their terrestrial PA networks during the study period. In all five countries, we found that PAs represented BPAs, forests, and forest carbon stocks relatively well, based on their size. PAs did not represent NTFPs and FES particularly

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well, except in Cambodia where FES were well represented. Countries that expanded PA networks during the study period also increased representation of forests, BPAs, and ES; in Cambodia and Madagascar these increases were substantial. Representation could be improved across all five countries, however, indicating that additional efforts are needed to safeguard biodiversity and ecosystem benefits to people in these countries.

1. Introduction

In 2020, governments will convene under the UN Convention on Biological Diversity (CBD) to set a post-2020 global biodiversity framework, which is expected to influence conservation action and investment for the next decade. In order to set meaningful targets, it is necessary to understand whether countries are achieving past conservation commitments. Protected areas (PAs) have long been the primary mechanism for conserving biodiversity (Lewis et al., 2017). There is also a growing interest in the capacity of PAs to secure the sustained delivery of ecosystem services (ES), the benefits that ecosystems provide to people (Ferraro and Hanauer, 2014). Protected areas provide benefits including provision of fresh water (Harrison et al., 2016), carbon storage (Ferraro et al., 2015), and provision of food and livelihoods for local communities (Ivanić et al., 2017). Recognition of these benefits is evident in government commitments such as the CBD and specifically Aichi Target 11, under which 196 countries pledged to protect at least 17 percent of their terrestrial and inland waters, "especially areas of particular importance for biodiversity and ecosystem services" (Convention on Biological Diversity, 2010). These commitments have resulted in an expansion of the global PA network from 8.5% of land and inland waters in 2004 to 14.7% in 2015 (Lewis et al., 2017). Area-based indicators are recognized as insufficient measures of conservation progress, however (Barnes, 2015). Other indicators such as ecological representation and status of key elements of biodiversity are also important (Visconti et al., 2019). Also, while it is often assumed that PAs provide both biodiversity conservation and ES benefits, we have limited knowledge of the extent to which areas important for ES are protected (UNEP-WCMC et al., 2018). The spatial relationship between biodiversity and ES is complex and varies depending on the location and the measures of biodiversity and ES used (Larsen et al., 2012; Naidoo et al., 2008). Therefore, the ability of PAs to achieve both goals is still poorly understood.

PAs have historically been designated for purposes ranging from recreation, aesthetic value, and protection of charismatic wildlife (Phillips, 2004) but their location and configuration has often been driven by opportunity and political expedience (Joppa and Pfaff, 2009). As a result, PA networks in many countries do not adequately represent the highest priority areas for biodiversity (Butchart et al., 2015) nor threatened species (Venter et al., 2014). To be effective at conserving wildlife, PAs must be appropriately resourced and managed (Nolte et al., 2013). Yet even if global PA area targets are met, they will be insufficient to achieve effective conservation of biodiversity and ES (Butchart et al., 2015; Larsen et al., 2014; Venter et al., 2014). The gap in PA coverage is of particular concern in the tropics, which contain large numbers of species at risk of extinction (Rodrigues et al., 2004). In addition, while global PA coverage has increased overall, PA extent has actually declined in some countries due to legal protected area downgrading, downsizing, and degazettement (PADDD) (Qin et al., 2019).

Formal designation of protected areas is a core conservation strategy in diverse political and ecological contexts (Lewis et al., 2017). Understanding whether national PA networks are currently meeting government commitments under the CBD and setting new more meaningful indicators and targets beyond global coverage for the post-2020 biodiversity framework requires spatial information on the location and configuration of biodiversity and ecosystem services. For many countries, national-scale spatial information on biodiversity is patchy and incomplete, and information on ES is nonexistent (Guerry et al., 2015). Spatial data on ES are critically needed, particularly in developing countries where large numbers of people depend directly on ecosystems for food, water, and livelihoods (Naidoo et al., 2019). While PAs clearly play an important role in providing ES, research on the spatial relationship between PAs and important areas for ES is still relatively sparse, particularly in developing countries.

To begin closing this information gap, we mapped biodiversity priority areas and key ecosystem services in five tropical, developing countries: Cambodia, Guyana, Liberia, Madagascar, and Suriname. These countries were selected because they all contain globally significant biodiversity, have human populations with a high level of dependence on natural ecosystems, and represent a diversity of geographic contexts and historic trajectories of protection. All five countries are signatories to the CBD and several of them (Cambodia, Liberia, Madagascar) made additional, explicit commitments to protected area expansion in 2003. We sought to address three questions: 1) Do PA networks spatially represent biodiversity priority areas, forest areas, and important areas for ES? 2) Has spatial representation improved over time? 3) Could PAs represent these areas better, if they had been designed to prioritize these values? While our results cannot be generalized across all countries, they are indicative of some of the trends and challenges facing tropical developing countries as they prepare for the post-2020 conservation agenda. Due to data limitations we rely on spatial representation as an important indicator of overall protection. We recognize that representation does not necessarily translate into effective management (Chape et al., 2005) and that other measures are needed (Watson et al., 2016); nonetheless spatial representation is one of the few measures that can be assessed with currently available data. We hope future research will enable a more complete assessment of the effectiveness of PAs in achieving desired biodiversity and ES outcomes.

2. Materials & methods

We compared the level of spatial representation of biodiversity priority areas (BPAs), forest cover, and areas important for maintaining several ecosystem services (ES) within national protected area networks at two points in time. We mapped these values in five countries: Cambodia, Madagascar, Guyana and Suriname, and Liberia. Each country (or region, in the case of Guyana and Suriname) was mapped independently in a series of case studies designed to inform conservation investment and action in each of the countries, but with similar methods. All five countries contain globally significant biodiversity: for example Cambodia, Liberia and Madagascar all fall within biodiversity hotspots (Myers et al., 2000), while Guyana and Suriname lie within a high-biodiversity wilderness area (Mittermeier et al., 2003). All five countries also have large populations of poor, rural, and/or indigenous people who rely on natural ecosystems for food, water, and livelihoods (Turner et al., 2012). The countries represent different geographic contexts (Asia, Africa, Americas), different forest cover contexts, from large intact forest areas to highly fragmented forest, and different human population densities. They also have different socio-political contexts, threats to biodiversity and ecosystem integrity, and factors determining PA design and land allocation. Looking across these different countries provides preliminary insights about the trends in protected area coverage in a developing, tropical country context. We focused on the period 2003–2017, which captures the time period following commitments to PA expansion made by Madagascar, Cambodia, and Liberia in 2003, and protection goals established by Suriname (2006) and Guyana (2010; Appendix 1). The most recent data available at the time of this analysis were for 2017.

To assess the extent to which ecosystem values are represented, we first compared the observed percentage of BPAs, forest areas, or ES contained within PAs to the percentage of land area encompassed by PAs for each country at two points in time (2013 and 2017). For each point in time, we also compared the observed percentages to a hypothetical maximum percentage which could have been achieved with an equivalent land area under protection. This was calculated by summing the highest value pixels for each ecosystem value (BPAs, forest areas, or ES) until an area equal to the land area under protection was reached. These analyses did not account for PA size or shape and therefore are not intended to represent a realistic protection scenario; they were for comparison purposes only. Though our results are not representative of all tropical nations, we observed trends in PA representation which may hold for other countries. In the future, we hope that greater data availability on ES will enable pan-tropical and even global analyses.

2.1. Mapping PA networks

We collected officially recognized, national government PA data from each country, and identified PAs which had been established as of 2003 and 2017. Data was provided by Conservation International staff from each country, as PA data from the World Database on Protected Areas was in some cases inaccurate or out of date. We selected 2003 because it corresponded to several policy commitments to expand protected areas in Madagascar (Gardner et al., 2018) Cambodia (ICEM, 2003), and Liberia (Ministry of Foreign Affairs, 2003). Guyana also pledged to protect 10% of forested land as part of its Low Carbon Development Strategy (Office of the President, Republic of Guyana, 2010) and Suriname set general protected area representation goals in 2006 and 2013 (Ministry of Labour, Technological Development and Environment, 2013, 2006). We selected 2017 as it was the most recent year for which data was available at the time of our analysis. A complete list of data sources for each country, and maps, can be found in the Appendices.

2.2. Mapping biodiversity & ecosystem services

For all spatial analyses we used a combination of ArcGIS Desktop v10.5 (Esri, 2017) and WaterWorld v2 (Mulligan, 2013). We conducted all analyses at a spatial resolution of one square kilometer, corresponding to the coarsest resolution of the input datasets, and exported results into Microsoft Access 2013 for all calculations. Methods are summarized in Table 1. We conducted similar analyses for all countries, with adjustments to incorporate the best available data for each country, which included a combination of global data and, where available, national-scale data (Appendix 2). Global datasets used as inputs include human population density (Bright et al., 2012), forest cover (ESA Climate Change Initiative-Land Cover project, 2017), forest biomass carbon stocks (Avitabile et al., 2016), and freshwater ecosystem services (Mulligan, 2013).

We relied on the best available data on biodiversity priority areas recommended by experts from each country, several of whom are co-authors on this paper. These included Key Biodiversity Areas (KBAs) from Madagascar (CEPF, 2014), proposed KBAs from Guyana and Suriname (Kasecker et al., 2007), KBAs and Biodiversity and Protected Area Management Project (BPAMP) priority sites from Cambodia (Cutter, 2006), and conservation priority sites defined through systematic conservation planning in Liberia (Junker et al., 2015). KBAs were considered incomplete or outdated for Cambodia and Liberia, which was why experts recommended supplementing them with BPAMP priority sites (in the case of Cambodia) or using priority sites as defined by systematic conservation planning (in the case of Liberia). While the BPAs were therefore defined using different criteria in each country, they all emphasize the presence of species classified by the IUCN Red List as Critically Endangered, Endangered, or Vulnerable. We also analyzed globally consistent biodiversity data, specifically species richness and range rarity calculated from IUCN Red List species range polygons for all mammals, amphibians and birds. We deemed the global data to be inadequate for national-scale analysis; thus the maps are provided in Appendix 5 but the results are not otherwise discussed.

We mapped forest cover using the European Space Agency (ESA) land cover product from 2003 and 2015, the most recent year available (ESA Climate Change Initiative-Land Cover project, 2017). For forest carbon stocks, we used a pan-tropical dataset on aboveground biomass carbon (Avitabile et al., 2016) masked using forest areas from ESA in 2003 and 2015. We compared the global land cover product to national land cover datasets and got similar results, therefore we used the global datasets for consistency. We note that forest cover and forest carbon stocks are spatially associated, but that carbon stocks within forests vary and therefore it is useful to analyze both indicators separately. Forests also harbor biodiversity and provide multiple other ES, also supporting their inclusion in the analysis.

Spatially explicit data on ecosystem services were not available from any of our study countries at a national scale. We therefore conducted spatial analyses to model realized provision of non-timber forest products (NTFPs) and realized freshwater ecosystem services (FES). "Realized" ecosystem service provision refers to services which are being used by people. We selected these two services due to their importance in the study countries and because the results were comparable between countries. We modeled several additional ES where relevant and based on data availability, including coastal protection in Madagascar and Liberia, flood regulation in Guyana, Liberia and Suriname, and fisheries in Madagascar and Cambodia (Conservation International, 2017, 2015a,b,c), but results were not comparable

Table 1
Summarized methods for mapping biodiversity & ecosystem services.

Theme	Summarized methods
Biodiversity priority areas	Existing biodiversity priority such as Key Biodiversity Areas, proposed KBAs, or areas identified using systematic conservation planning. Binary variable (0 or 1)
Forest cover	Areas with forest cover, based on the European Space Agency Climate Change Initiative land cover data from 2003 and 2015 (ESA Climate Change Initiative-Land Cover project, 2017). Binary variable (0 or 1)
Forest carbon storage	Aboveground biomass carbon stocks within forest areas, calculated using global biomass carbon data (Avitabile et al., 2016) and global forest cover data (ESA Climate Change Initiative-Land Cover project, 2017). Continuous variable
Non-timber forest products (NTFPs)	Natural ecosystems derived from land cover data, weighted by (a) level of importance for NTFPs based on literature review (Cambodia), expert ranking (Madagascar), or species composition (Guyana), and (b) proximity to food insecure populations (all countries). Continuous variable
Freshwater ecosystem services	Ecosystems weighted by (a) level of provision of fresh water quantity, quality, or flow regulation services modeled using WaterWorld (Mulligan, 2013) and (b) level of demand. Demand was estimated by identifying watersheds upstream of population centers, irrigated agriculture, and hydropower facilities; and calculating demand per capita (population centers), per hectare (irrigated agriculture), or per megawatt-hour (hydropower facilities). Results were combined in a weighted index of importance for all freshwater ES, for all beneficiaries. Continuous variable ranging from 0 to 1

between countries. National-scale data on cultural ES were not available from any of the study countries. For example, data on nature tourism and cultural/spiritual benefits is available from Madagascar but only for national parks, and thus not allowing assessment of cultural values nationally. Thus no analysis of cultural ES values was included in this study.

We modeled important areas for NTFPs using data on land cover, value of different ecosystem types for NTFPs, and accessibility of natural habitats to people, following methods from Porro et al. (2008). We estimated the value of different natural ecosystems for NTFPs using data available from each country. These included published figures on the economic value of different habitat types for forest products (Cambodia, Hansen and Top, 2006), an expert ranking exercise (Madagascar, Conservation International, 2015c), and occurrence of plant animal species of known importance for food and medicine (Guyana and Suriname, Porro et al., 2008). In Liberia, no data was available so all natural habitat classes were treated as equally valuable. Modeled value of habitat types was then combined with accessibility of habitats to people to create maps of areas of importance for NTFPs.

We modeled ecosystem provision of freshwater quantity, quality, and flow regulation using the WaterWorld model (Mulligan, 2013). We combined the three services into a single index of freshwater services by taking the average values of all pixels. Relevant beneficiaries were identified for each country and included human population centers (all countries), hydropower facilities (all countries), irrigated agriculture (Madagascar and Cambodia), and freshwater fisheries (Cambodia). We estimated demand for freshwater services from each beneficiary type in relevant units (e.g. per capita, per dam production volume, per hectare of irrigated agriculture). We used the most recent data available at the time of analysis for mapping FES and NTFPs, however input datasets and methods varied based on data availability (Appendix 2).

2.3. Data analysis

We analyzed the spatial representation of biodiversity priority areas (BPAs), forest areas, and ES within PAs in the two time periods. For discrete areas (BPAs and forest areas) we first calculated the total area of each per country. This allowed us to calculate the percentage of total national BPAs and forest areas contained in PAs within each country. We looked at forest areas and protected area boundaries in 2003 and 2017 to look at change over time. BPA data was available for only a single time period, therefore we looked at the percentage of BPAs contained within PAs in 2003 and 2017.

For forest carbon, we first calculated the total tonnes of carbon contained in all the forests from each country in 2003 and 2017. For FES and NTFPs, each pixel of habitat was assigned a value ranging from 0 (lowest importance) to 1 (highest) based on their estimated importance as calculated above. NTFPs and FES maps were unitless, as they combined data on the provision of the service (supply) with the estimated level of use of the service (demand). We summed the values of all the pixels of habitat within each country to calculate a total national value of ES. For each ecosystem service (carbon, NTFPs and FES), we then calculated the sum of the of all the pixels contained within PAs. This allowed us to calculate the percentage of total ecosystem service value contained in PAs. We repeated this using PA boundaries from 2003 and 2017.

We compared the observed percentage of BPAs, forest, and ES contained within PAs to the total percentage of land area encompassed by PAs. We also compared the observed percentages to a hypothetical maximum percentage which could have been achieved with an equivalent land area under protection, following methods from Turner et al. (2007). This was calculated by summing the highest value pixels for BPAs, forest areas, and ES until an area equal to the land area under protection was reached.

For example, if PAs represent 10% of the land area of a country, then we calculated the total BPA area of the top 10% of pixels for the country and repeated this calculation separately for forest area and ES values. If hypothetically re-configuring PAs could capture more of these values, then this is an indication that a country might be able to represent them better within the PA network without expanding the total area under protection. We did not combine biodiversity and ES values in this analysis since they measure substantially different ecosystem values. This method does not account for PA size or shape, existing land tenure, political or economic feasibility, nor contiguity of important areas, and therefore is not intended to represent a specific protection scenario; it is for comparison purposes only.

We shared preliminary results with local experts from each country in participatory workshops. Participants included representatives from local conservation organizations, government environmental agencies, and research institutions. We incorporated expert feedback, such as information about newly designated PAs, recently identified BPAs, important ES provision areas, or other suggestions to refine the analyses. Experts also helped validate our results by indicating whether the maps aligned with their understanding of areas important for biodiversity and ES provision. We also compared our results with published statistics on forest cover and protected area coverage from each country, for validation.

3. Results

3.1. Protected area coverage and expansion

The five countries included in our analysis have globally recognized significance for biodiversity, falling within biodiversity hotspots or high biodiversity wilderness areas (Mittermeier et al., 2003; Myers et al., 2000). Four of the five nations (all but Suriname) expanded their terrestrial protected area networks during the study period (2003–2017) (Table 2).

3.2. Forest cover and population

Guyana and Suriname are “frontier-forest” countries which retain

Table 2
Summary statistics on land area, population density, and forest cover of the five countries included in the study. Data sources: Land area, population: World Bank (World Bank, 2017); forest cover: European Space Agency Climate Change Initiative (ESA Climate Change Initiative-Land Cover project, 2017); protected area: World Database of Protected Areas (UNEP-WCMC and IUCN, 2016) updated with more recent, complete protected areas collected from each country. Note ESA forest cover statistics differ from World Bank/FAO forest cover statistics in some countries due to differences in forest definitions and methodologies.

Country	Cambodia	Guyana	Liberia	Madagascar	Suriname
Land area (km^2)	176,520	196,850	96,320	581,800	156,000
Population density 2003 (people/km^2)	73	4	32	30	3
Population density 2017 (people/km^2)	89	4	48	43	4
Forest cover 2003 (% of land area)	37	90	47	26	97
Forest cover 2015 (% of land area)	33	89	45	25	96
Protected area 2003 (% of land area)	21	2	2	4	13
Protected area 2017 (% of land area)	35	9	5	11	13

very high levels of natural forest cover. Cambodia, Liberia, and Madagascar are "fragmented-forest" countries, with intact forest patches interspersed with secondary forest, degraded forest, and cleared areas resulting from a history of deforestation. The two frontier-forest countries also have relatively low population density, growth and recent deforestation rates relative to the other countries (Table 2). All five countries have rural or indigenous populations that are dependent on natural ecosystems for food, fuel, drinking water, and livelihoods (e.g. Golden et al., 2011; Orr et al., 2012). Cambodia is characterized by a particularly high dependence on freshwater resources, due to a heavy reliance on the Tonle Sap Lake freshwater fishery (Ziv et al., 2012).

3.3. Biodiversity priority areas

In Cambodia and Madagascar, in both time periods, PAs spatially represented biodiversity priority areas (BPAs) better than would be expected based on their area alone (Table 3). In Cambodia, PAs encompassed 21% of the land area in 2003, representing 40% of BPAs. By 2017, the country expanded its PA system to cover 35% of the land area, capturing 68% of BPAs. In Madagascar, 4% of land area protected represented 24% of BPAs in 2003; by 2017, PAs covered 11% of the land area, representing 65% of the BPAs. In the other three countries, PAs represented BPAs only slightly better than would be expected based on their size. In Guyana in 2003, PAs encompassed 2% of land area, representing 4% of BPAs; in 2017, the PA network was expanded to 9% of the land area, representing 15% of BPAs. In Liberia in 2003, PAs encompassed 2% of the land area, representing 8% of BPAs; by 2017, PAs had expanded slightly (4% of land area), representing 11% of BPAs. In Suriname in 2003, PAs represented 13% of the land area, representing 19% of BPAs. There was no expansion in PAs in Suriname during the study period, although in 2015 there was a community-led initiative that resulted in the proclamation of a large community conservation area in the south of Suriname, covering 41% of the country (Ramirez-Gomez et al., 2016).

PA systems could hypothetically represent a much larger proportion of BPAs in Cambodia, Liberia and Madagascar, if they had been designed to prioritize these values. In Cambodia, the 2017 PA system (encompassing 35% of the land area) could have represented 99% of BPAs by area, if these areas had been configured to maximize BPA protection. In Madagascar, 11% of land area (the area protected as of 2017) could have represented 73% of BPAs. In Liberia, 4% of land area could have represented 17% of BPAs. Similar increases in representation were not possible in Guyana and Suriname without expanding PA coverage, as PAs were already located within BPAs in both countries.

3.4. Forests and forest carbon stocks

PAs represented forests and forest carbon stocks better than would be expected based on their size in Cambodia and Madagascar in both time periods. In Cambodia, 21% of land area protected in 2003 represented 36% of forest areas and 44% of the forest carbon stocks. By 2017 35% of land area protected represented 57% of the forest areas and 72% of forest carbon stocks. In Madagascar, 4% of land area protected in 2003 represented 11% of forest areas and 19% of forest carbon stocks. By 2017 11% of the land area was protected, representing 30% of the forest and 50% of the forest carbon stocks. In Liberia, PAs encompassed 2% of the land area in 2003, representing 4% of forest areas and 5% of forest carbon stocks; in 2017 PAs encompassed 4% of land area, representing 6% of forest areas, and 7% of forest carbon stocks. In the two frontier-forest countries, PAs represented no more forest area than would be expected based on their size. In Guyana, 2% of the land area under protection captured 2% of forest areas and 3% of the forest carbon stocks. In Suriname, 13% of the land area protected represented 12% of the forest but 18% of the forest carbon stocks.

Madagascar and Cambodia hypothetically could have protected more forest and forest carbon if protected areas had been designed to maximize these values. For example, in 2017 in Cambodia 35% of the land area protected could have represented 100% of remaining forest cover and therefore also 100% of the forest carbon stocks. In Madagascar 11% of the land area protected could have represented as much as 42% of the remaining forest cover and 96% of the country's forest carbon. Similar increases in representation were not possible in Liberia, Guyana, and Suriname without expanding PA size.

3.5. Non-timber forest products

PAs did not represent important areas for non-timber forest products (NTFPs) very well relative to their size in any of the countries. In Cambodia, 21% of land area protected in 2003 represented 23% of important areas for NTFPs, and in 2017 35% of land area protected represented 37% of NTFPs. In Guyana, 2% protection represented 2% of NTFPs in 2003 and 9% protection only represented 5% of NTFPs in 2017. In Liberia, 2% protection represented 0% of NTFPs in 2003; and 4% protection represented 2% of NTFPs in 2017. In Madagascar 4% of land area protected represented 4% of NTFPs in 2003 and 11% protection represented 12% of NTFPs in 2017. In Suriname, 13% protection represented 7% of NTFPs in both years.

PA representation of important areas for NTFPs could have been increased in all countries if PAs were targeted to areas important for this service. In 2017 in Cambodia, 35% protection could represent 45% of NTFPs; in Guyana 9% protection could represent 31% of NTFPs; in Liberia 4% protection could represent 6% of NTFPs; in Madagascar 11% protection could represent 15% of NTFPs; and in Suriname 13% protection could represent 44% of NTFPs.

Table 3
Protected area (PA) representation of biodiversity priority areas (BPAs), forest areas (Forest), forest carbon stocks (Carbon), freshwater ecosystem services (FES), and non-timber forest products (NTFPs). Observed = percentage of each area or value represented within protected areas for a given year. Max = maximum percentage that could have been protected if PAs had been targeted to optimize for a given value.

	Country Year	Cambodia 2003	Cambodia 2017	Guyana 2003	Guyana 2017	Liberia 2003	Liberia 2017	Madagascar 2003	Madagascar 2017	Suriname 2003	Suriname 2017
Protected areas		21	35	2	9	2	5	4	11	13	13
BPAs	Observed	40	68	4	15	8	14	23	59	18	18
BPAs	Max	58	99	4	17	8	21	24	73	19	19
Forest	Observed	36	57	2	9	4	8	11	30	12	12
Forest	Max	57	100	2	10	4	10	14	42	13	13
Carbon	Observed	44	72	3	9	5	10	19	50	12	12
Carbon	Max	85	100	3	13	6	16	48	96	18	18
FES	Observed	29	47	2	9	2	4	3	10	12	12
FES	Max	41	64	2	10	3	8	14	37	14	14
NTFP	Observed	23	37	2	5	0	2	4	12	7	7
NTFP	Max	27	45	7	31	3	7	5	15	44	44

3.6. Freshwater ecosystem services

In Cambodia, PAs represented important areas for freshwater ecosystem services (FES) better than expected based on their size in both time periods, but not in the rest of the countries. In Cambodia in 2003, 21% protection represented 29% of FES, and in 2017, 35% protection represented 47% of FES. In Guyana, 2% protection represented 2% FES in 2003; 9% protection represented 9% FES in 2017. In Liberia in 2003, 2% protection represented 2% of FES; in 2017 4% protection represented 4% of FES. In Madagascar in 2003, 4% protection represented 3% of FES; in 2017 11% protection represented 10% of FES. In Suriname 13% protection represented 12% of FES in both time periods.

If PA systems had been designed to prioritize FES, they could better represent FES in fragmented-forest countries, but not in the frontier-forest countries. In 2017 in Cambodia, 35% of land area under protection could have represented as much as 64% of FES; in Liberia 4% protection could have represented 7% of FES; and in Madagascar 11% protection could have represented 37% of FES. No increases in representation of FES in Guyana or Suriname was possible without expanding PAs.

4. Discussion

4.1. Current protected area representation

We asked, "Do PA networks spatially represent biodiversity priority areas, forest areas, and important areas for ES?" Our results are consistent with evidence that some countries are making concerted efforts to represent forest areas and important sites for biodiversity within PAs. In Madagascar, for example, BPAs were used explicitly to identify and prioritize potential sites for new PAs (Gardner et al., 2018). In Guyana, PAs were proposed in the late 1990s based on biodiversity irreplaceability scores and vulnerability to logging (Richardson and Funk, 1999). In frontier-forest countries (Guyana and Suriname), historic rates of low deforestation have laid a foundation for effective long-term conservation, through PAs or other mechanisms. In Suriname, PAs represented forest carbon stocks better than expected based on their size, indicating that there may have been an effort to protect the oldest forests, where carbon stocks are densest. Policy and financial mechanisms to support conservation, such as Guyana's Low Carbon Development Strategy (Government of Guyana, 2016) and Suriname's commitment to retain 93% forest cover (UNFCCC, 2017), as well as indigenous or local management of biodiversity and ecosystems, provide opportunities for successful conservation of biodiversity and ES in these countries.

In Cambodia, PAs encompass the mountainous areas and watersheds critical for supplying water to Cambodia's major population centers. Cambodia also contains a massive freshwater lake, the Tonle Sap, which is a designated protected area. The lake is a major freshwater resource which provides ecosystem services to millions of people, so its inclusion within the protected area system also contributes to the country's high level of protection of FES.

4.2. Trends in PA representation

We also asked, "Has spatial representation improved over time?" We found that PA networks expanded in four out of five countries during the study period, consistent with global trends. This trend coincides however with a loss of habitat. In fragmented forest countries, biodiversity and forests have become increasingly concentrated within protected areas, as areas outside are converted for agriculture or other uses. Madagascar, for example, has lost much of its original forest cover and remaining forests are under intense pressure due to population growth and poverty (Eklund et al., 2016). Evidence indicates that countries are both losing forests and biodiversity outside of PAs and are also targeting protection to remaining important sites. Habitat loss and degradation is also occurring within PAs. Understanding what drove the trends we observed would require better historic data on biodiversity and ES, spatial dynamics of land cover change, and drivers of these dynamics, all of which was beyond the scope of this analysis. Nonetheless, information on the spatial configuration and representation of important areas in a national PA network such as we provide here can help countries identify potential areas for synergy and tradeoffs between biodiversity and ES, as well as between different ES, in order to optimize protected area investments.

4.3. Gaps in representation

Finally, we asked, "Could PAs represent these areas better, if they had been designed to prioritize these values?" Overall, our results indicate that countries are making efforts to achieve global conservation targets such as those established under the CBD, but there is room for improvement. In four of our study countries (all except Cambodia), PAs did not represent FES particularly well, based on their size. While PAs may be created to protect important water resources, as in the case of the Tonle Sap lake, the consideration of water services in the design of PA networks is a relatively new practice. As water resources become increasingly degraded, the protection of freshwater provisioning areas is becoming more urgent.

We also found that PAs did not represent NTFPs particularly well, based on their size. Our NTFP model, which assumes that natural habitats in proximity to human populations are more important for providing NTFPs, due to their greater accessibility. Accessible areas are also less likely to have PAs (Joppa and Pfaff, 2009) which may explain why we observed a lack of overlap between PAs and ares important for NTFPs. Governments may intentionally avoid siting PAs in areas that local communities depend on for food or livelihoods, in cases where PAs could restrict or prohibit human use. Either way, understanding which areas are important for NTFPs is important for ensuring these resources are not over-exploited. Protection or regulation may be important to ensure the long-term availability of NTFPs for the people who depend on them. In Guyana, for example, one reason for declaring protected areas is to secure resources for communities who have sustainably utilized them for millennia (EPA and NRE, 2014).

Our results were consistent with other studies which evaluated PA representation of biodiversity and ES. Globally, 43% of important bird and biodiversity priority areas are protected, on average (Donald et al., 2019b). In China, for example, PAs encompass 15.1% of the country's land area, representing 8.5–17.9% of threatened species ranges for different taxonomic groups, and between 10.2–12.5% of several ecosystem services (water retention, soil retention, sandstorm prevention, and carbon sequestration) (Xu et al., 2017). In Colombia, PAs have low to intermediate levels of overlap (3–56%) with important areas for sensitive species, ecological systems, habitat quality, scenic beauty and water provision, with water provision the least well protected (García Márquez et al., 2016). There is thus more to be done to safeguard biodiversity and ensure the long-term supply of nature's benefits to humanity.

4.4. Limitations and future research

Our analyses have several key limitations. First, we only included formal PAs in our analysis, since consistent definitions and data relevant to 'other effective area-based conservation measures' (OECMs) are not yet sufficiently developed for comparison among countries (Donald et al., 2019a). Also, our analyses did not account for PA size, shape, or connectivity. Our calculation of a hypothetical maximum possible representation did not account for existing land tenure, political or economic feasibility, or contiguity of important areas. Other aspects of conservation planning such as efficiency, irreplaceability, threats, vulnerability, and flexibility are also relevant to protected area network design (Kukkala and Moilanen, 2013) but were not included here. Also, we analyzed representation of biodiversity, forests, and ES representation individually. Future analyses could examine whether it would have been possible to better represent multiple values simultaneously, through multi-objective optimization analyses. While our analysis looks at spatial representation of PAs, representation alone does not necessarily translate into effective conservation on the ground (Leverington et al., 2010). Both legal and illegal deforestation has occurred within PAs in Cambodia (Davis et al., 2015) and Madagascar (Eklund et al., 2016) and hunting and other threats continue to deplete wildlife in PAs in Liberia (Greengrass, 2016). It was however beyond the scope of this analysis to analyze effectiveness of PA management and enforcement.

We faced many constraints related to data availability. We examined protected areas, forest cover, and forest carbon stocks in two time periods, however due to lack of historic data we were only able to map biodiversity priority areas, freshwater ES, and NTFPs in a single time period. For a discussion of the possible implications of this limitation our results, see Appendix 4. Due to the lack of ES data from our study countries, we often had to combine globally available data, national datasets, and spatial modelling. For example, we included global data on aboveground biomass carbon stocks combined with national land cover products to define aboveground forest carbon stocks. We were however unable to map carbon stored in other ecosystems such as peatlands and mangroves. Accepted methods for calculating belowground forest carbon stocks at the scales addressed here would not change relative proportions of stocks between countries (Mokany et al., 2006). In general, our results should be interpreted as indicative of the relative level of ES provision within a country, and not as absolute estimates. Our spatial models of NTFPs and FES were based on several assumptions, for example we assumed that proximity between people and natural ecosystems (in the case of NTFPs), or the location and population density of people downstream of natural ecosystems (for freshwater services) is an indicator of higher levels of use of ES. Due to financial constraints and the large geographic scope of our analyses (national-level), we were unable to formally validate our models beyond seeking review of our results by experts. Due to limited resources, the expert workshops included representatives from local and international conservation organizations, government environmental agencies, and research institutions, but we recognize that these groups do not represent the full spectrum of stakeholders in each country.

Overall, our results likely underestimate the extent of area important for ES in our study countries, since we were unable to map many services provided by ecosystems. Additional research on ES is needed, particularly on cultural ecosystem services, as well as services supporting agriculture such as pollination and erosion control. Over time, we hope that data availability will improve which will enable more complete accounting of the benefits of nature to people in tropical developing countries and globally.

4.5. Policy implications

In our study countries, conserving priority areas for biodiversity and forests will not necessarily secure the areas which are most important for the supply of freshwater or NTFPs. This has implications for the post-2020 conservation agenda: targets focusing on biodiversity alone will not adequately represent ecosystems providing critical benefits to people. Getting sufficient data to develop and track progress towards ecosystem service targets is challenging, as demonstrated by the limitations we faced in our study countries. There is an urgent need to more robustly map the nature people need, particularly in the developing world where people are most vulnerable. Also, protected areas alone will not be able to fulfill the dual role of conserving biodiversity and maintaining a supply of ES. Other effective area-based conservation measures (OECMs) will have to play a fundamental role in achieving the post-2020 conservation agenda (Watson et al., 2016). Finally, the CBD Secretariat and country governments are demanding that the post-2020 conservation agenda address the needs of people. The only way to accomplish this is to include ecosystem services explicitly in target setting, which will among other things enable the CBD to connect to other international targets such as the UN Sustainable Development Goals and the Paris Climate Agreement.

5. Conclusions

National-scale spatial information on important areas for biodiversity and ecosystem services, such as we provide here, is needed if countries are to measure progress towards past commitments established under the UN CBD or set meaningful targets under the post-2020 agenda. This analysis is a preliminary attempt to fill a gap recognized in CBD progress reports, which call for national-scale identification of important areas for ES (e.g. Secretariat of the Convention on Biological Diversity, 2014). Our study illustrates how different countries might be able to address newly revised indicators as well as challenges that remain in measuring progress towards global conservation targets. The reality is that countries will not take a singular approach to measuring progress. Our framework and these case studies demonstrate a flexible rubric applicable to different contexts and characteristics. While we cannot yet evaluate whether our results are generalizable, we believe the patterns and trends we observed—a focus on forest and biodiversity priority area protection, but still substantial gaps in representation across all values—are likely repeated across much of the tropical developing world. Future efforts should be made to design PA networks to ensure protection of watersheds and other ES, as has been recommended in China, for example (Xu et al., 2017). Other strategies such as payments for ecosystem services (PES) schemes, community-based management, or monitoring and enforcement of environmental regulations should complement traditional protection measures to ensure biodiversity and ES values are also maintained outside of PAs. Achieving international conservation targets will require additional efforts to safeguard biodiversity and benefits from ecosystems to people. Such efforts are urgently needed to avoid catastrophic loss of biodiversity and further degradation of ecosystems supplying clean drinking water, food, fuelwood, and other benefits to the world's most vulnerable people.

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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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2020.101078. GIS data associated with this analysis can be downloaded from: https://www.conservation.org/projects/mapping-natural-capital/mnc-data/.

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