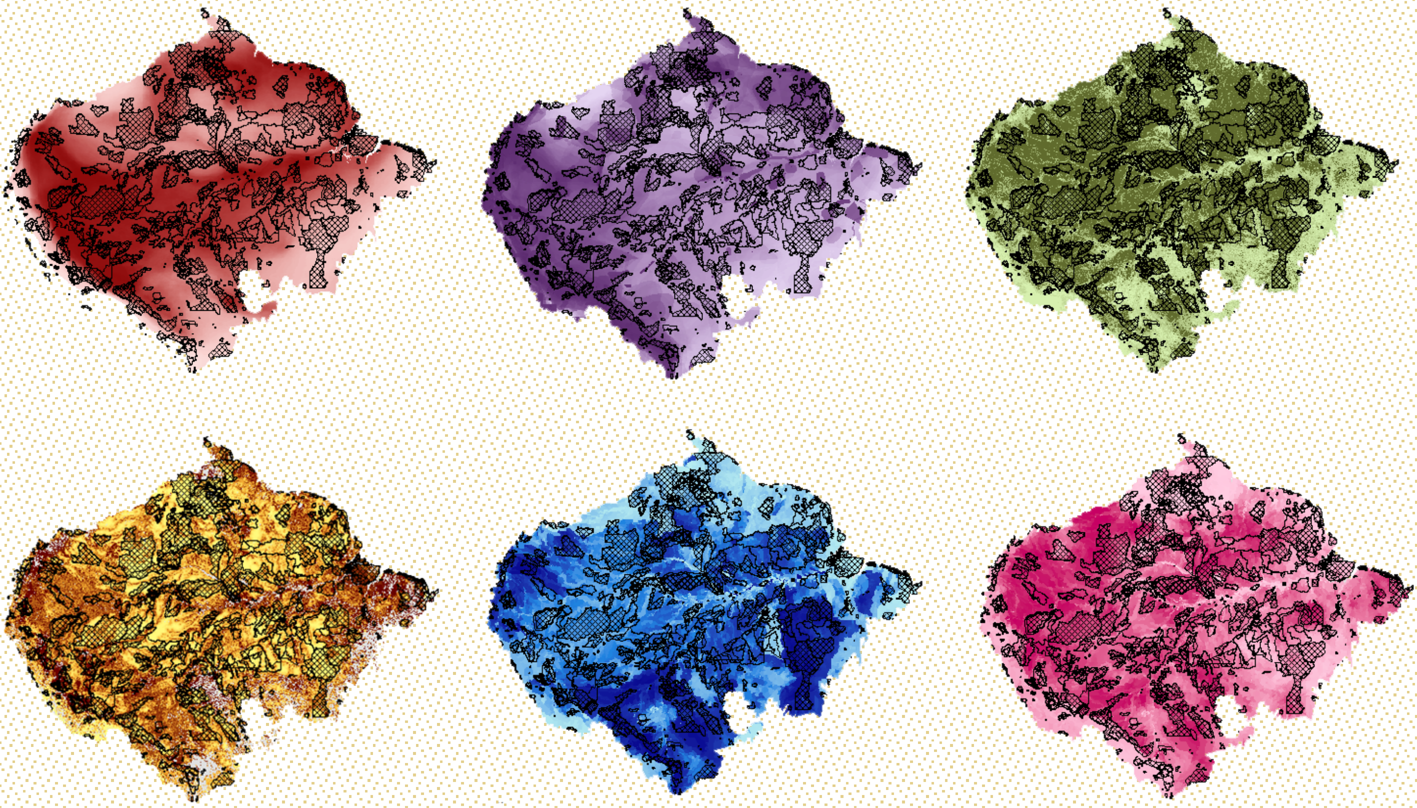

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Spatial Representation of Biodiversity and Ecosystem Services by Protected Areas in Amazonia

Tese de Mestrado em Ecologia Aplicada (International Master of Applied Ecology)

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Abstract

This study utilized an ecosystem services mapping approach to determine the spatial representation of biodiversity and ecosystem services by protected areas in Amazonia. The biodiversity and ecosystem services analyzed included species richness, endemic species, forests and forest carbon stocks, freshwater ecosystem services, flood regulation under climate change, and non-timber forest products (NTFPs). Results indicate that the current protected areas network in Amazonia favours the representation of some elements of biodiversity and ecosystem services, such as forests and forest carbon stocks, over the others included in the analysis. There is also a large difference in spatial representation of biodiversity and ecosystem services between countries, with the best-performing countries being Bolivia, Peru, and Venezuela.

To my parents

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1. Introduction

Ecosystem services and the natural capital stocks that produce them are critical to the functioning of the Earth's life-support system and fundamental to achieving social and economic development (Costanza et al. 1997; MEA 2005). Natural capital refers to the living and non-living components of ecosystems that contribute to the generation of goods and services of value for people (Ekins et al. 2013). Ecosystem services are defined as the processes of ecosystems that generate benefits for people (Ekins et al. 2013). Biodiversity is defined as the gene, species, ecosystem, and functional variability of living organisms (CBD 1992; Elmqvist et al. 2010). Rather than an ecosystem service itself, biodiversity underpins all ecosystem services, as living organisms interact with the abiotic environment to provide benefits to people, such as producing food, pollinating crops, forming soil, recycling nutrients and waste, and many others (CBD 1992; Elmqvist et al. 2010). Habitat degradation and overexploitation of natural resources, climate change, invasive species and pollution all contribute to the loss of natural capital and ecosystem services, exacerbated by a continually increasing global human population (Costanza et al. 2014).

Amazonia is comprised of parts of nine countries in South America: Bolivia (66% of the country is covered by Amazonia), Brazil (49%), Colombia (41%), Ecuador (52%), French Guiana (100%), Guyana (100%), Peru (74%), Suriname (100%), and Venezuela (48%). The region is considered to be one of the world's most important ecological systems and contains the largest remaining area of tropical rainforest globally (Foley et al. 2007). Specifically, the region comprises approximately 25% of the world's forest biomass carbon stocks, 10% of the world's known biodiversity, and the Amazon River is responsible for 20% of the freshwater that reaches the world's oceans (CI 2015; Macedo and Castello 2015). These provide crucial ecosystem services and goods locally, regionally, and globally (Foley et al. 2007). However, the region has been experiencing high rates of deforestation over many years primarily due to infrastructure development, logging, and agricultural expansion, which has led to the loss of over 13% of the region's original forest cover since 1970 (RAISG 2015).

In 1992, the Rio Earth Summit highlighted global environmental destruction and degradation and the need to protect biodiversity hotspots and valuable ecosystems (Hayes and Ostrom 2005). The UN Convention on Biological Diversity (CBD) emerged out of the meeting, where 150 national governments agreed to "establish a system of protected areas or areas where special measures need to be taken to conserve biological diversity" (CBD 1992). In the same year, governments at the Fourth World Congress on National Parks and Protected Areas agreed to designate at least 10% of each biome (forests, oceans, tundra, grasslands, and wetlands) as protected areas (Hayes and Ostrom 2005). The Durban Congress at the Fifth World's Park Congress of 2003 in Durban, South Africa, emphasized the need to expand existing protected areas and that the establishment of future protected areas must be based on practical application at all levels and of the best available scientific data and tools (IUCN 2003).

Protected areas have become an important conservation strategy to minimize the influence of humans on biodiversity and nature (Pyke 2007). Protected areas preserve natural capital that provides ecosystem services that generate important provisioning, regulating, cultural, and supporting benefits (MEA 2005). Specifically, effectively-managed and well-governed protected areas are demonstrably able to deliver important ecosystem services and safeguard habitats and species (Langhammer et al. 2007; CBD 2008a/b/c; Ervin et al. 2010).

While the amount of protected areas has increased over the past century, there are significant shortfalls in the political commitments to enhance the coverage and performance of protected areas (Watson et al. 2014). Protected areas are meant to preserve biodiversity and natural capital, but measures of progress and targets do not reflect this role (Pressey et al. 2014). While international organizations, governments, and non-governmental organizations (NGOs) have focused on measures such as number of hectares protected, it has been proposed that emphasis be placed on the performance of protected areas rather than sheer coverage.

This has been emphasized in the UN Convention on Biological Diversity (CBD) 2011-2020 Strategic Plan for Biodiversity and the corresponding Aichi targets, particularly Target 11, which focuses on the performance of existing terrestrial protected areas rather than further increases in protected areas (CBD 2010). For protected areas, in this study, performance refers to the spatial representation of biodiversity and ecosystem services. Target 11 emphasizes the need to protect areas with particular importance for biodiversity and ecosystem services, including areas which are high in species richness, threatened habitats, areas with particularly important habitats such as Key Biodiversity Areas (KBAs), and areas which are important for the continued provision of ecosystem services, including areas important for water provision (CBD 2010). KBAs are intended to identify and ensure that networks of globally important sites, where unique biodiversity must be conserved immediately, are safeguarded (Eken et al. 2004).

1.1 Research objective and questions

The main objective of this study is to measure the performance of protected areas in spatially representing biodiversity and ecosystem services in Amazonia. The key types of biodiversity and ecosystem services that will be analyzed are species richness, endemic species, forests and forest carbon stocks, freshwater ecosystem services, flood regulation under climate change, and non-timber forest products (NTFPs), respectively. These particular types of biodiversity and ecosystem services were selected because of their importance in Amazonia locally, regionally, as well as globally (Ekins et al. 2003).

Our hypothesis was that current protected areas in Amazonia are better at representing regions which are important for biodiversity and ecosystem services than randomly located sites of equivalent spatial areas. Additionally, it is expected that protected areas in the region have performed better over time in terms of spatial representation, since there is increasing awareness of the importance of biodiversity and ecosystem services (MEA 2005). Furthermore, there have been a rising number of political efforts to protect the provision of ecosystem services, such as programs of payments for environmental services (PES), which have attracted significant attention as a conservation tool in recent years, including REDD (Reducing emissions from deforestation and forest degradation) globally and Bolsa Floresta in Brazil, among others (Pagiola 2011).

We examined two time periods: 2003, the date of the Fifth World Congress on National Parks and Protected Areas, at which many countries committed to expanding their protected areas networks, and 2016, the most recent year for which data was available at the time of this analysis (CBD 2003).

Specifically, the following research questions are addressed:

1. What percentage of biodiversity and ecosystem services did protected areas protect in 2003 and how much do they protect now (in 2016)? That is, to determine whether PAs are better at representing regions which are important for biodiversity and ecosystem services than randomly located sites of equivalent spatial areas.
2. What percentage of biodiversity and ecosystem services would have been protected if protected areas were 'optimally configured' to protect the most biodiversity and ecosystem services? That is, if protected areas were located in the optimal locations, could they be doing a better job of representing biodiversity and ecosystem services?

This study fills a gap in existing research by assessing whether protected areas in Amazonia are located strategically in terms of representing biodiversity and ecosystem services, whether there has been improvement in spatial representation over time, and whether further improvement is possible in the future. To the author's knowledge, no study of this kind exists in the current literature. Specifically, no large-scale assessment of ecosystem services in Amazonia has been done. This is also the first study to examine the spatial representation of protected areas for both biodiversity and ecosystem services together in the region.

1.2 Outline

The thesis is organized in six sections. Section 2 details the study area. Section 3 critically reviews the existing literature on important biodiversity and ecosystem services in Amazonia, biodiversity and ecosystem services mapping, and protected areas and performance. Section 4 describes the methodology of the study. Section 5 presents the results. Section 6 provides a critical discussion and a brief conclusion.

2. The study area

Amazonia (West: 70°21' W, East: 43°34' W, North: 10°37' N, South: 20°28' S) covers nearly 7.4 million km^2 and covers parts of nine countries in South America, including Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname, and Venezuela. It contains the entire tropical rainforest of northern South America, including the forests of the drainage basins of the Amazon River and its tributaries, the southwestern tributaries of the Rio Orinoco, and the forests of the Guianas. Specifically, the boundaries of the region are the Atlantic Ocean in the East and Northeast, the eastern slopes of the Andes that contain the headwaters of the Amazon River in the West, the transition zone between forest and grasslands of Colombia and Venezuela in the Northwest, and the Brazilian Amazon biome in the South (CI 2015) (Figure 1).

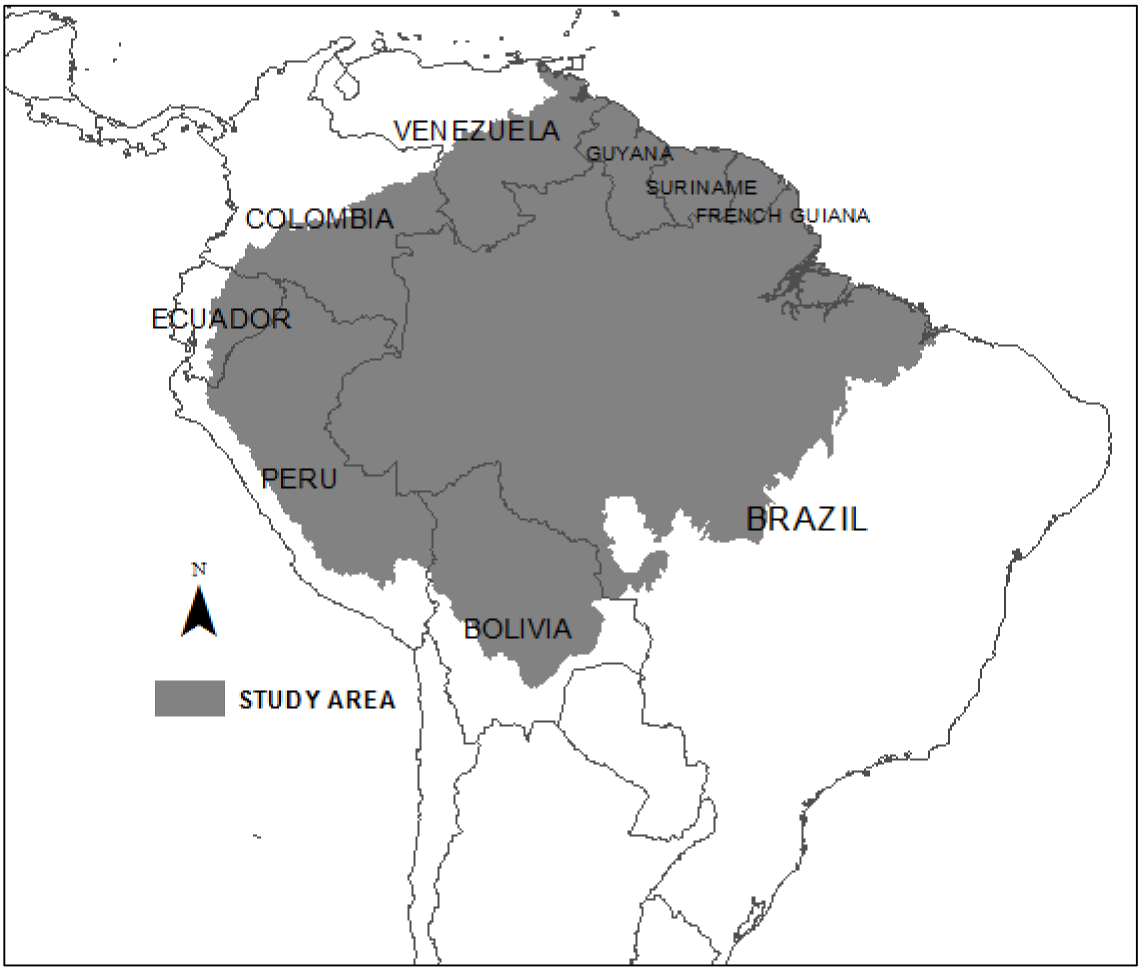

Figure 1: Study area of Amazonia

Amazonia contains 53% of the remaining tropical forests globally and is considered to be one of the world's most important ecological systems (Mittermeier et al. 2003; Foley et al. 2007). It is the largest tropical forest in the world and contains nearly one-third of the world's tropical biomass carbon and 10% of the world's endemic plant species and biodiversity (Mittermeier et al. 2002; Saatchi et al. 2007). Furthermore, the Amazon River contains 20% of the freshwater that reaches the oceans, making it the world's largest river (Macedo and Castello 2015). The region also contains unique ecosystems such as vast regions of wetlands, savannas, and the most well-protected mangroves globally (CI 2015).

Amazonia provides crucial ecosystem services and goods locally, regionally, and globally (Foley et al. 2007). Approximately 34 million people live in the region, including 375 different indigenous groups (CI 2015). At the local and regional scale, Amazonia and its forests, rivers, wetlands, and savannas provide people with freshwater for drinking and hydropower, wild sources of food, raw materials, fuel, and a reduction in impacts from severe flooding (CI 2015), among others. At the global scale, the region's vast tropical forests provide mitigation of global climate change and climate regulation (Foley et al. 2007).

Amazonia and the ecosystem services it provides are facing threats from anthropogenic activities (Foley et al. 2007). The region is characterized by a relatively low rural population density, high poverty, and fast rates of forest loss and degradation (Porro et al. 2008). Deforestation has already resulted in the loss of 13% of the region's original forest cover since 1970, due primarily to agricultural expansion, logging, and infrastructure development (RAISG 2015).

Among the most significant deforestation pressures are roads, which are highly correlated with deforestation. Roads provide incentives to expand human settlements and intensify mining, logging, and farming, among other human activities (RAISG 2013). Approximately 80% of deforestation occurs within 30km from paved roads in the Brazilian Amazon (Barreto et al. 2014). Agriculture, mining, oil and gas exploration, logging, and hydropower dams are also among the most important deforestation pressures in Amazonia (CI 2015). The most significant environmental impacts of deforestation are reduction of water availability, loss of biodiversity, and CO_2 emissions, which exacerbate global climate change (Fearnside 2005). Despite the strong deforestation pressures and threats, Amazonia enjoys a relatively high level of conservation protection and forest cover and more conservation opportunities relative to other tropical regions (Hansen et al. 2013; Macedo and Castello 2015).

3. Literature review

This section critically reviews the literature on biodiversity and the important ecosystem services in Amazonia, ecosystem services mapping approaches, and protected areas establishment and performance. First, biodiversity and the important ecosystem services in Amazonia are reviewed.

3.1 Important biodiversity and ecosystem services in Amazonia

First, biodiversity and the important ecosystem services in Amazonia are discussed, including species richness, endemic species, forests and forest carbon stocks, freshwater ecosystem services, flood regulation under climate change and non-timber forest products (NTFPs).

3.1.1 Biodiversity

Biodiversity can be defined as the gene, species, ecosystem, and functional variability of living organisms (CBD 1992; Elmqvist et al. 2010). Amazonia is one of the most biodiverse regions globally, containing approximately 2.5 million insect species, 2,200 fish, 1,294 birds, 427 mammals, 428 amphibians, 378 reptiles and 40,000 plant species (Mittermeier et al. 2002).

The biodiversity in Amazonia is not yet well understood, and there are many species, taxonomic groups, and areas that have not yet been thoroughly studied (Santos et al. 2015). However, available data suggests that most terrestrial vertebrates are not widely distributed in the region but are present in areas of endemism (Silva et al. 2005). Endemism is defined as restricted to a particular area (Crisp et al. 2001). Measures of endemism are scale-dependent, and species can be endemic at local, regional, and national scales.

Areas of endemism are important because they are home to unique and irreplaceable species, the smallest geographical units for historical biogeography analysis, and the basis for formulating hypotheses about the processes responsible for the establishment of regional biota (Cracraft 1994; Morrone 1994; Morrone and Crisci 1995; Oliveira et al. 2015). Past research in Amazonia has defined the region not as a unique biogeographical entity but as distinct areas of endemism of various species including birds, primates, forest butterflies, and vascular plants, among others (Silva et al. 2005). Given that biota is grouped differently in areas of endemism, the areas must be considered separately as priority zones for conservation action (Stattersfield et al. 1998; Silva 2005; Borges and Silva 2012). Consequently, endemic species highlight these areas and the need for conservation since they are potentially threatened and rare species (CI 2015). Endemic species are therefore species with restricted geographical distribution (Seip and Wenstop 2006).

In addition to areas of endemism, the political context of official biodiversity conservation targets are also important (CI 2015). Global biodiversity conservation prioritization initiatives range in scale from large areas such as Biodiversity Hotspots (Mittermeier et al. 1998) to smaller discrete areas such as Key Biodiversity Areas (KBAs) (Langhammer et al. 2007), Important Bird Areas (BirdLife International 2008), and Alliance for Zero Extinction sites (Ricketts et al. 2005). Their goal is to facilitate the safeguarding of the most important sites through the designation of protected areas (CI 2015).

At the national scale in Amazonia, national governments have established their own prioritization of biodiversity conservation areas, including Brazil (MMA 2007), Bolivia (Araujo et al. 2010), Ecuador (Cuesta et al. 2006), and Peru (INRENA 2008). A regional assessment was also done for Suriname, French Guiana, Guyana, Venezuela and Colombia (Bernard et al. 2011).

3.1.2 Forests and forest carbon stocks

Tropical forests are extremely important for long-term global climate regulation because they sequester and store carbon dioxide (CO_2), which is emitted to the atmosphere by fossil-fuel burning and terrestrial processes (Schimel et al. 2001). After the consumption of fossil fuels, deforestation is the second biggest contributor to global CO_2 emissions and responsible for between 12-20% of global greenhouse gas emissions (Van Der Werf et al. 2009). Amazonia is particularly important because it is the largest contiguous rainforest globally, stores almost one-third of all tropical biomass carbon, and it is essential in the global carbon cycle (Grace et al. 1995; Fearnside 1997; Saatchi et al. 2007).

The forests in Amazonia continue to be lost to agricultural expansion for soy, oil palm plantations, and timber and cattle grazing, despite national and international efforts to stop deforestation in Amazonia (Godar et al. 2014). The ability to quantify the amount of carbon that is stored in the forests of the region and where it is located is crucial for informing national climate policies and international emission targets, as well as for payments for environmental services (PES) programs such as REDD (Reducing emissions from deforestation and forest degradation) (Pagiola 2011; CI 2015).

3.1.3 Freshwater ecosystem services

Freshwater is essential to human life and well-being (Baron et al. 2002). Natural ecosystems provide a range of freshwater ecosystem goods and services, including provision of water quantity, flow regulation, and water filtration, among others (Daily 1997). Ecosystems including forests, wetlands, and rivers are vital for capturing water, filtering contaminants, and allowing it to flow to the people who require it (CI 2015).

Amazonia's river system encompasses 6.9 million km^2 and 13 major tributaries that discharge 6,300 km^3 of water annually, which is 20% of the world's surface water flows to the Atlantic Ocean (D'Almeida et al. 2006; Marengo 2006; Macedo and Castello 2015). The river system provides food, transportation, water for domestic use, water for energy production, and global and regional climate regulation through hydrological feedbacks (Marengo et al. 2011; Macedo and Castello 2015).

3.1.4 Flood regulation under climate change

The Intergovernmental Panel on Climate Change (IPCC) and regional climate models predict that eastern Amazonia may become drier and western Amazonia may have increased precipitation and humidity (Pachauri et al. 2014). Extreme events have become frequent across Amazonia, with increasing amounts of droughts, fires, and floods (Marengo et al. 2013). The Amazonian region has a population of over 33 million, 45% of which are considered to be living in poverty (ARA 2011). The poor are the most vulnerable people to climate change (CI 2015). Climate change is expected to increase the exposure to changes in the water balance across northern and eastern Amazonia. Amazonia's forests and wetlands reduce the impacts from severe flooding by regulating flows of water, capturing water during wet periods and then releasing it during dry periods

(Foley et al. 2007; CI 2015). Natural vegetation regulates water flows in several ways: by directly absorbing water, facilitating the infiltration of surface water into the ground, and by physically slowing the flow of water through its network of roots and other structures (Foley et al. 2007). This reduces vulnerability of people downstream to severe flood events.

3.1.5 Non-timber forest products (NTFPs)

Non-timber forest products (NTFPs) include fruits, nuts, vegetables, medicinal plants, and mammal species, among others, which are important for improving rural livelihoods and providing food security (Porter-Bolland et al. 2012). They are harvested by local households and communities from grasslands, woodlands, and forests (Shackleton and Pandey 2014). In Amazonia, there is an enormous potential for NTFPs to contribute to overall income stability (Grimes et al. 1994).

NTFPs provide multiple important functions in supporting human livelihoods and well-being. First, NTFPs provide direct household consumption for products of food, shelter, medicines, fibres and energy (Kaimowitz 2003). Specifically, NTFPs typically provide 10 to 60% of total household income and constitute a larger proportion of household income for poor than wealthier households (Qureshi and Kumar 1998; Babulo et al. 2009; Asfaw et al. 2013). Second, NTFPs provide many households with primary means of cash generation or supplementary income to other livelihood activities (Babulo et al. 2009; Areki and Cunningham 2010). Third, NTFPs provide a safety-net for use in times of misfortune such as loss of crops or livestock, disease, or flooding (Shackleton and Shackleton 2004). Fourth, NTFPs may also have an important role in local spirituality and culture (Posey 1999; Cocks et al. 2011). Lastly, NTFP use by local households is a cash saving device for both households and the government, since the use of free resources allows poor households to invest scarce cash resources in other livelihood needs (Shackleton et al. 2007). In Amazonia, multiple programs already exist to support the sustainable livelihoods of local and indigenous communities, including Bolsa Floresta in Brazil, among others (Börner et al. 2013).

3.2 Biodiversity and ecosystem services mapping

In order to protect and manage natural capital, maps of the most important natural capital are needed by governments, development banks, conservation organizations, and other actors seeking to meet conservation targets and ensure sustainable development for their people (CI 2015). For this reason, there is rising interest in spatial analyses of ecosystem services using a geographic information system (GIS) approach which recognizes the spatially explicit nature of ecosystem services and incorporates this information into environmental decision-making (Troy and Wilson 2006).

Since biodiversity and the ecosystem services they provide are located in space, and vary from place to place, maps are a powerful way to spatially represent natural capital stocks and ecosystem services flows (Burkhard and Maes 2017). Specifically, ecosystem services maps are effective for organizing, visualizing, and communicating data. Furthermore, there is a strong demand from policy-makers to map ecosystem services and to build natural capital accounts which are based on geo-referenced data of ecosystems (Jacobs et al. 2015; Burkhard and Maes 2017).

The approaches used to map ecosystem services vary depending on the type of ecosystem service. Provisioning ecosystem services are frequently quantified based on indicators for their actual use, while regulating ecosystem services are based on supply indicators that use biophysical models to simulate ecological processes (Burkhard and Maes 2017). Both regulating and provisioning ecosystem services are the most frequently mapped compared to cultural ecosystem services, which are mostly limited to recreation and eco-tourism (Burkhard and Maes 2017). For this reason, most studies involving ecosystem services mapping focus only on a select number of ecosystem services (Kandziora et al. 2013).

Ecosystem services mapping is challenging for a number of reasons. First, there is a significant technical challenge related to what ecosystem services maps should express: potential services, flows of services, or demand for services by people or sectors. Specifically, potential ecosystem services are those that are provided by natural ecosystems, regardless of their actual level of use. Ecosystem services are realized when humans benefit from them, where supply meets demand and ecosystem services flow from where they are generated to where they are received (Burkhard and Maes 2017).

Such flows are dynamic over time and difficult to map, while stocks are less dynamic and therefore more straight-forward to map.

Second, the selection of a suitable spatial scale remains a challenge in ecosystem services mapping studies. Specifically, ecological processes occur at different temporal and spatial scales and therefore require different quantification approaches and spatial units. To make different ecosystem service maps consistent and harmonized requires spatial operations including upscaling, downscaling, and spatial statistics, all which may introduce uncertainties. Existing studies of ecosystem services mapping differ in spatial scales (Palomo et al. 2013), ranging from global (Naidoo et al. 2008), national (Egoh et al. 2009), to local scales (Kroll et al. 2012).

Third, there are significant data limitations and gaps related to ecosystem services mapping. While wealthier countries and regions with advanced economies often have more accurate spatial data and higher data resolution, lower-income regions typically lack ecosystem service data (Burkhard and Maes 2017). Studies have been filling such data gaps using a range of alternative approaches, including remote sensing, participatory mapping, land-use proxies, and lower resolution global-scale datasets.

3.2.1 Mapping biodiversity and ecosystem services in Amazonia

While many studies have mapped biodiversity and some studies have mapped individual ecosystem services at the site or country-level, only one study has been done that mapped both biodiversity and ecosystem services in Amazonia. Specifically, Conservation International has mapped essential natural capital in Amazonia, which are the most important areas for biodiversity and ecosystem services (CI 2015). The analysis used existing biophysical and socioeconomic data and ecosystem service modeling tools to conduct spatial analyses to identify areas important for biodiversity, freshwater, climate mitigation and adaptation, and non-timber forest products (NTFPs).

The approach used to map ecosystem services in Amazonia included several components. First, beneficiaries were identified in order to quantify actual service provision rather than potential ecosystem service provision. Second, several types of natural capital and ecosystem services were selected because of their importance in Amazonia. Essential natural capital was based on the concept of critical natural capital, which is the sub-set of all natural capital that cannot be substituted or replaced (Ekins et al. 2003). Third, existing spatial data was collected, followed by desktop modelling and GIS analysis. Lastly, expert workshops were held to validate the resulting maps. The maps have a number of limitations, constraints and challenges, which are discussed in Appendix I as well as in CI (2015) in detail.

3.3 Protected areas

Protected areas are critical for conservation because they harbour biodiversity and natural capital that is responsible for providing ecosystem services to people. The International Union for Conservation of Nature (IUCN) defines a protected area as a "clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (IUCN 2008).

While traditionally, protected areas have often been set aside for the purpose of conserving biodiversity, preserving iconic landscapes for scenic value and human recreation opportunities, charismatic species and their habitats, and biodiversity hotspots, the increasing human transformation of the biosphere has to led to paradigm shifts in how conservation is approached (Rands et al. 2010; Kareiva and Marvier 2012; Ellis et al. 2013). Increasingly, the new conservation paradigm involves coupling humans and nature and includes safeguarding human well-being in biodiversity conservation plans. Consequently, protected areas serve to conserve biodiversity in addition to protecting ecosystem services provision that contribute to human well-being, including important provisioning, regulating, cultural, and supporting benefits (MEA 2005; Watson et al. 2014). Furthermore, there is significant evidence that protected areas provide social and economic benefits to society which can be used to raise funds for conservation and build political support (TEEB 2012).

More recently, research has demonstrated that the long-term political sustainability of protected areas also depends on the support of overlapping and adjacent human communities, which is further enhanced when protected areas foster community development and equity (Naughton-Treves et al. 2008). Both positive and negative spillover effects are possible in the buffer zones of protected areas. Positive spillover effects may include reduced rates of natural vegetation cover loss around protected areas as a result of new economic opportunities for nature-based tourism (Andam et al. 2008). Negative spillover effects, known as leakage, may include elevated levels of forest loss in buffer zones as a result of human activities being displaced from within parks (Ewers and Rodrigues 2008).

Globally, protected areas have been seen as one of the leading ways to protect wildlife, forests, and nature (Hayes and Ostrom 2005). Today, approximately 209,000 sites are given protected areas status in the world, covering around 15.4% of the world's land and inland water areas, and 3.4% of the oceans (Juffe-Bignoli et al. 2014). Despite the importance of protected areas, major challenges remain. The existing protected areas network does not cover all species and biomes (Getzner et al. 2010). Furthermore, protected areas are frequently not able to fulfil their biodiversity conservation objectives and many protected areas have not yet been fully implemented or managed (CBD 2010).

Since protected areas are established for varying reasons, IUCN identifies six categories of protected areas based on their particular management objectives, which provide a global standard for defining, recording and communicating about protected areas (IUCN 2008). The categories vary in terms of the level of human access and use that is allowed, ranging from strict nature reserves and wilderness areas to protected areas with sustainable use and natural resources. All protected area categories were included in the analysis.

3.3.1 Performance of protected areas

Protected areas are meant to preserve biodiversity and ecosystem services, but measures of progress and targets do not reflect this role (Pressey et al. 2014). While international organizations, governments, and NGOs have focused on measures such as number of hectares protected, which are politically powerful, it has been proposed that emphasis be placed on the effective performance of protected areas rather than sheer coverage. For this study, performance refers to the spatial representation of biodiversity and ecosystem services in Amazonia.

One related study focused on the spatial representation of both biodiversity and ecosystem services in China's nature reserves (Xu et al. 2017). It overlaid a map of nature reserves with the habitat map of threatened species and of four major regulating ecosystem services. It found that China's nature reserves perform moderately well for mammals and birds, but not for other major taxa and neither for key regulating ecosystem services.

This analysis also focuses on spatial representation, which is important for asking certain questions about protected areas, such as whether they are in the right places and whether they are large enough to capture important biodiversity and ecosystem services that humans depend on. However, it is also important to understand whether protected areas are effective at conserving biodiversity and ecosystem services, which is what many other studies related to protected area effectiveness have focused on.

Other studies have focused extensively on the ecological effectiveness of protected areas and measured in relation to habitat loss within protected areas and surrounding buffer zones (Liu et al. 2001; Leroux and Kerr 2013; Geldmann et al. 2013). Meta-analyses of such studies have shown that while protected areas generally reduce forest loss within the protected areas, high rates of forest loss are increasingly common in buffer areas due to leakage (Joppa and Pfaff 2010). However, direct comparisons between protected and unprotected areas are biased because protected areas are frequently not randomly assigned but usually determined by characteristics that also affect deforestation such as accessibility and land productivity (Andam et al. 2008). Specifically, global and national studies have found that many protected areas are not suitable for human use and therefore protected and unprotected lands differ in characteristics that also affect deforestation (Brandon et al. 1998; Sánchez-Azofeifa et al. 2003; MEA 2005). Furthermore, humans may also respond to protected areas by changing land uses in buffer areas which will bias the estimates of the protection’s impacts (Andam et al. 2008). For these reasons, this study chose to focus on spatial representation of biodiversity and ecosystem services as a performance measure rather than comparing habitat loss within and outside protected areas.

3.3.2 Protected areas in Amazonia

Relative to other tropical regions, Amazonia has a high level of conservation protection and forest cover and more conservation opportunities relative to other tropical regions (Hansen et al. 2013; Macedo and Castello 2015). Specifically, the large network of formally-designated protected areas which includes 980 strict nature reserves, indigenous territories and sustainable use areas cover approximately 47% of Amazonia, or 3.4 million km^2 (Figure 2). Specifically, 682 protected areas cover 33% and 298 indigenous territories cover 14% of Amazonia. However, when accounting for the overlap between protected areas and indigenous territories, all formally-designated protected areas cover 41% of Amazonia, or 3.0 million km^2.

Because of a historical focus on terrestrial biodiversity conservation, and limitations in available data on most taxonomic groups, a significant part of the protected area network in Amazonia was designed based on the biogeography of only a few taxa of birds, lizards, butterflies and woody plants (Peres and Terborgh 1995, Abell et al. 2007). The Amazon Region Protected Areas (ARPA) program established by Brazil is the largest protected areas network in the region and remains vital to forest conservation in the entire region (Macedo and Castello 2015).

Approximately 46% of Amazonia remains covered by forest or other natural habitat and is currently unprotected, which includes government-owned areas, private lands, concessions, and other land-uses (CI 2015). These areas present opportunities for protection, restoration, community conservation agreements, payments for ecosystem services, and integrated conservation projects. The remaining 7% of Amazonia has already been converted into agriculture, developed into urban areas, or degraded, which presents an opportunity for restoration or agricultural intensification in order to relieve pressure from the remaining natural habitats (CI 2015).

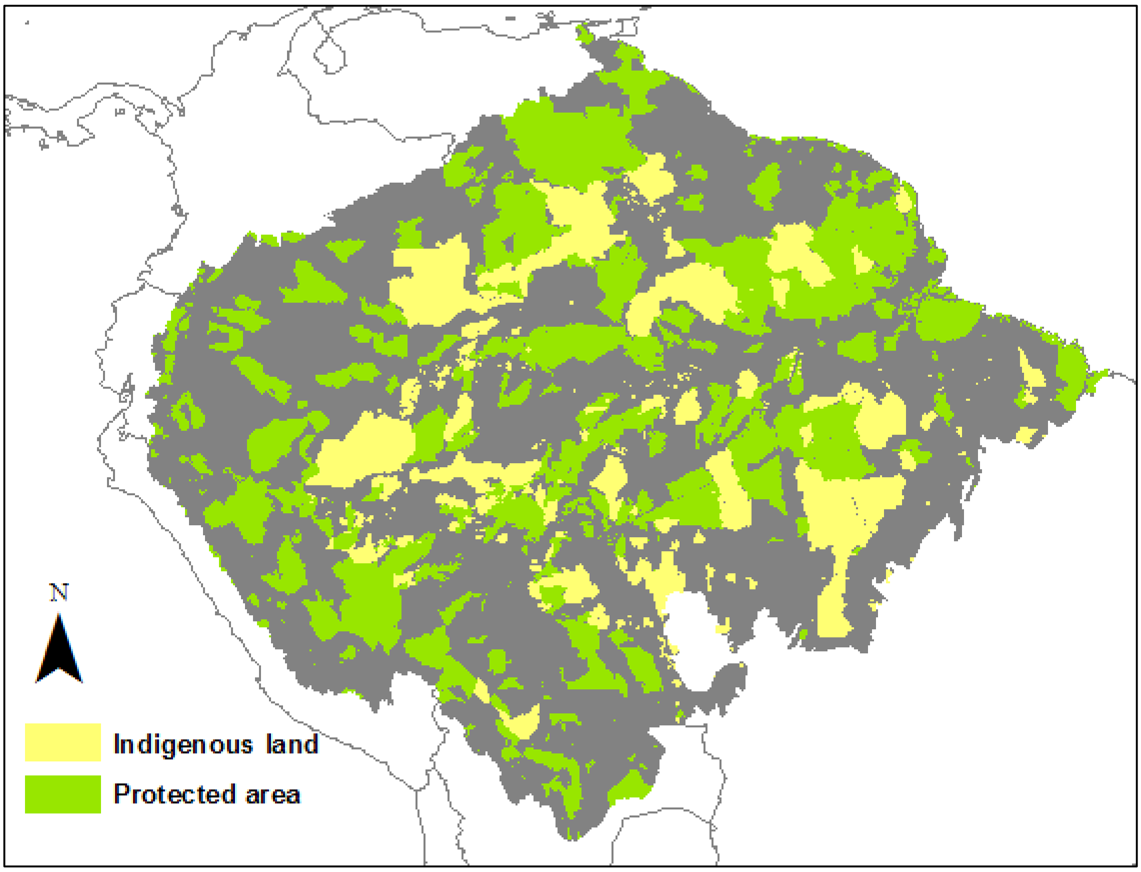

Figure 2: Protected areas and indigenous lands in Amazonia[1]

[1] Own figure based on data from IUCN and UNEP-WCMC 2016.

4. Methodology

The methodology of the biodiversity and ecosystem services mapping and the protected area representation calculations are presented in this section.

4.1 Biodiversity and ecosystem services mapping

In this study, the biodiversity and ecosystem services mapping data is used directly from Conservation International (CI 2015), which in turn used data sources summarized in Table 1 below. The key biodiversity and ecosystem services that were mapped included weighted endemism (a measure of endemism), species richness, forests and forest carbon stocks, freshwater ecosystem services, and non-timber forest products (NTFPs). The methods used by CI (2015) are briefly summarized in Appendix I. For a more thorough discussion of the methods used for the biodiversity and ecosystem services mapping, see CI (2015).

Table 1: Original data sources for analyses*

Category	**Original data sources**
Biodiversity	IUCN Red List database (IUCN 2015); Bird species database (BirdLife International and NatureServe 2014); Species richness calculations (CI 2015); Weighted endemism calculations (CI 2015, following methods from Crisp et al. 2001); Endemism centers (CI 2015).
Forests and forest carbon	Forest land-cover (Hansen et al. 2013; Chen et al. 2014); Above ground biomass (Mokany et al. 2006).
Freshwater ecosystem services	Eco-hydrological model WaterWorld (Mulligan 2013); Estimated water use and hydropower dams (CI 2015); LandScan population data (Bright et al. 2015).
Flood regulation under climate change	Eco-hydrological model WaterWorld (Mulligan 2013); General Circulation Models (GCMs) (IPCC 2014).
Non-timber forest products	Modelling approach (CI 2015, following methods from Porro et al. 2008).
Protected areas	World Database on Protected Areas (WDPA) (IUCN and UNEP-WCMC 2016).

* All data provided by CI (2015)

4.2 Protected areas representation

The maps of biodiversity and ecosystem services were overlaid with the protected areas boundaries from 2003 and 2016. The data for the protected areas was taken from the

World Database on Protected Areas (WDPA) (IUCN and UNEP-WCMC 2016). This allows for the calculation of the level of representation of biodiversity and ecosystem services in the current protected areas network in Amazonia and how it has evolved over a 13-year period. Furthermore, it also allowed for the calculation of the percentage of biodiversity and ecosystem services that could be represented if protected areas were optimally configured to capture it. This enables the estimation of how well the current protected areas are representing biodiversity and ecosystem services, relative to what they could be doing under a hypothetical scenario in which protected areas were spatially targeted for biodiversity and ecosystem services.

The natural capital maps are raster images at a 1 km^2 resolution. The raster information was extracted using a 1 km^2 fishnet grid and centroids using ArcGIS (Figure 3) (ESRI 2014). The ArcGIS tool "extract values to points" was used to identify the numerical value of each of the 1 km^2 raster images from each of the natural capital maps. These centroids were spatially joined with the World Database on Protected Areas shapefile and country borders in order for the centroids to also have protected area and country information. These centroid values were exported as tables and imported into Microsoft Access, where all subsequent calculations were made.

Due to disagreements between the WDPA (IUCN and UNEP-WCMC 2016) and the VMAP0 (NGA 2005) country boundaries, the VMAP0 country boundaries were used by default for all countries. Furthermore, The Suriname country boundaries were adjusted to include those territories which Suriname legally claims. The results were rounded to the nearest percent to account for map agreement error and for the fact that the biodiversity and ecosystem services maps have some uncertainty. Several of the countries (French Guiana, Guyana, and Suriname) fall completely within the study area, and therefore the results include the entire countries. For the other countries, however, the results only reflect the portion of the country contained within Amazonia.

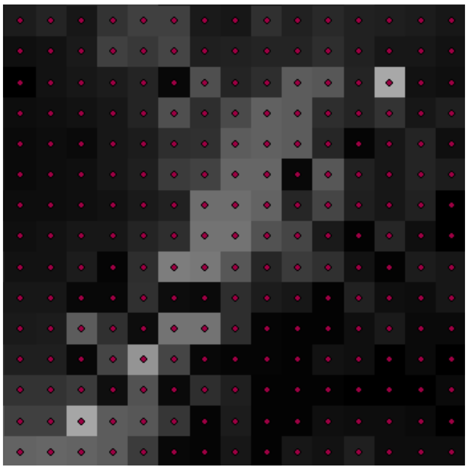

Figure 3: Example of 1 km^2 fishnet grid and centroids

The level of representation of biodiversity and ecosystem services was calculated as follows for each ecosystem service and for each time period, before 2004 and until 2016 (Equation 1):

$$Level\ of\ representation\ (\%) = \frac{\sum centroid\ values\ in\ protected\ areas}{\sum centroid\ values\ in\ Amazonia\ or\ country} \qquad \text{(Equation 1)}$$

In order to calculate the percentage of biodiversity and ecosystem services that could be represented if protected areas were optimally configured to capture it, the following equation was used (Equation 2):

$$Max\ representation\ (\%) = \frac{\sum top\ \mathrm{x}\ centroid\ values\ in\ protected\ areas}{\sum centroid\ values\ in\ Amazonia\ or\ country} \qquad \text{(Equation 2)}$$

where x refers to the number of centroids that are contained in the protected areas for each of the time periods, before 2004 and until 2016. These equations enabled the calculation of biodiversity and ecosystem services representation at both the regional and national level.

Where protected areas are capturing a larger percentage of the total value of an ecosystem service, relative to their area, they are considered to be over-representing that ecosystem service. And vice versa, where protected areas are capturing a smaller percentage relative to their area, they are considered to be under-representing that service. For example, if a protected area network represents 10% of a given country's land area, but only 5% of the forest carbon contained within that country, then the protected areas network is considered to be under-representing the service of forest carbon.

5. Results

5.1 Protected area expansion

The proportion of Amazonia that is protected area has significantly increased in the last 13 years, from 25% in 2003 to 41% in 2016 (Table 3 and Figure 4). The largest relative protected area expansions in the region occurred in Guyana, French Guiana, the Peruvian Amazon, and the Brazilian Amazon (Table 3). Smaller relative protected area expansions occurred in the Bolivian Amazon, the Ecuadorian Amazon, and the Colombian Amazon. The smallest relative protected area expansions occurred in Suriname, while in the Venezuelan Amazon there was no expansion.

Table 3: Protected areas in Amazonia, 2003 to 2016, by country, percent

	Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2003	*25%*	20%	28%	17%	22%	13%	2%	11%	12%	66%
2016	*41%*	24%	49%	20%	26%	51%	9%	33%	14%	66%
change	*64%*	*20%*	*69%*	*18%*	*18%*	*292%*	*350%*	*200%*	*17%*	*0%*

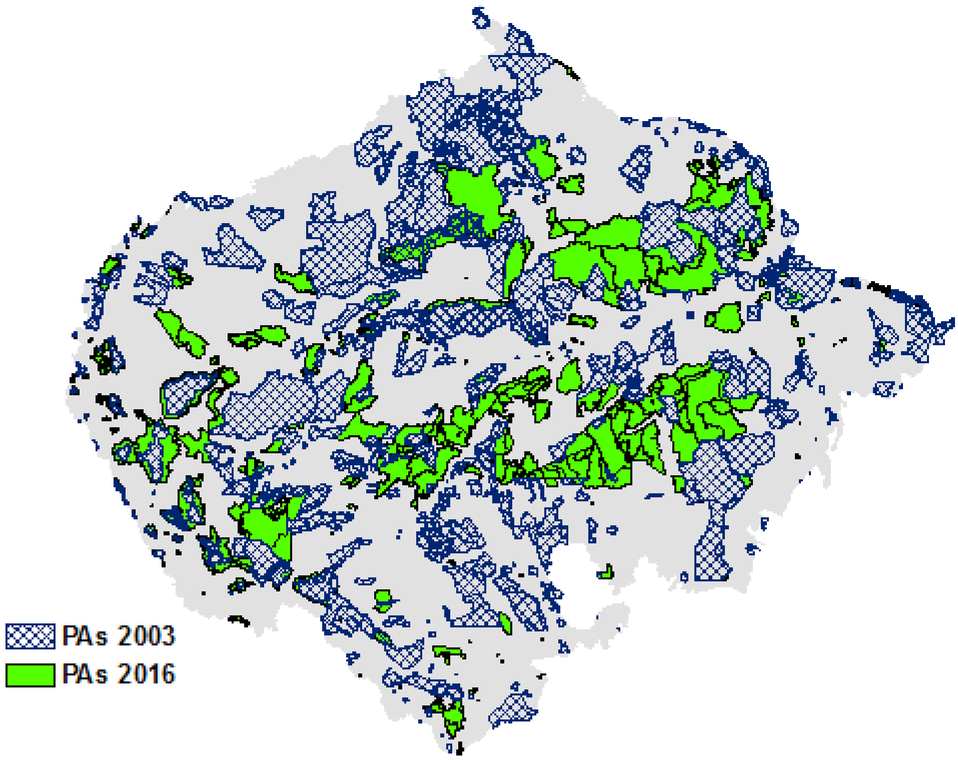

Figure 4: Protected area expansion between 2003 and 2016

Comparing protected area size in Amazonia (Table 3) to reported protected area size for the entire countries (Table 4) shows that, in general, more land is protected within Amazonia than outside of it. While protected areas cover 49% of the Brazilian Amazon in 2016, only 28% of Brazil's entire land area was reportedly protected in 2014 (UNEP-WCMC 2014). Similarly, protected areas cover 66% of the Venezuelan Amazon in 2016, while only 54% of Venezuela's land area was reportedly protected in 2014. The other countries indicated similar proportions to their reported protected area size for the country as a whole and the percentage of its Amazonia part that was protected. French Guiana was not reported. Since the entire countries of French Guiana, Guyana, and Suriname fall within Amazonia, it is expected that the protected area size found in the analysis (Table 3) is the same or similar to the reported protected area size (Table 4). The numbers are indeed similar but not exactly the same, due to differences in methods used for calculating areas, mapping error, and incomplete data.

Table 4: Reported protected area, 2014, by country, percent (UNEP-WCMC 2014)

	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2014	25%	28%	23%	26%	N/A	9%	31%	15%	54%

5.2 Representation of biodiversity and ecosystem services in Amazonia's protected areas

Results indicate that Amazonia's protected area network currently represents weighted endemism (40%), species richness (42%), forested areas (47%), carbon stock (49%), freshwater ecosystem services (42%), flood regulation under climate change (41%), and non-timber forest products (NTFPs) (33%), respectively (Figure 5 and Table 5). These results are detailed by ecosystem service below.

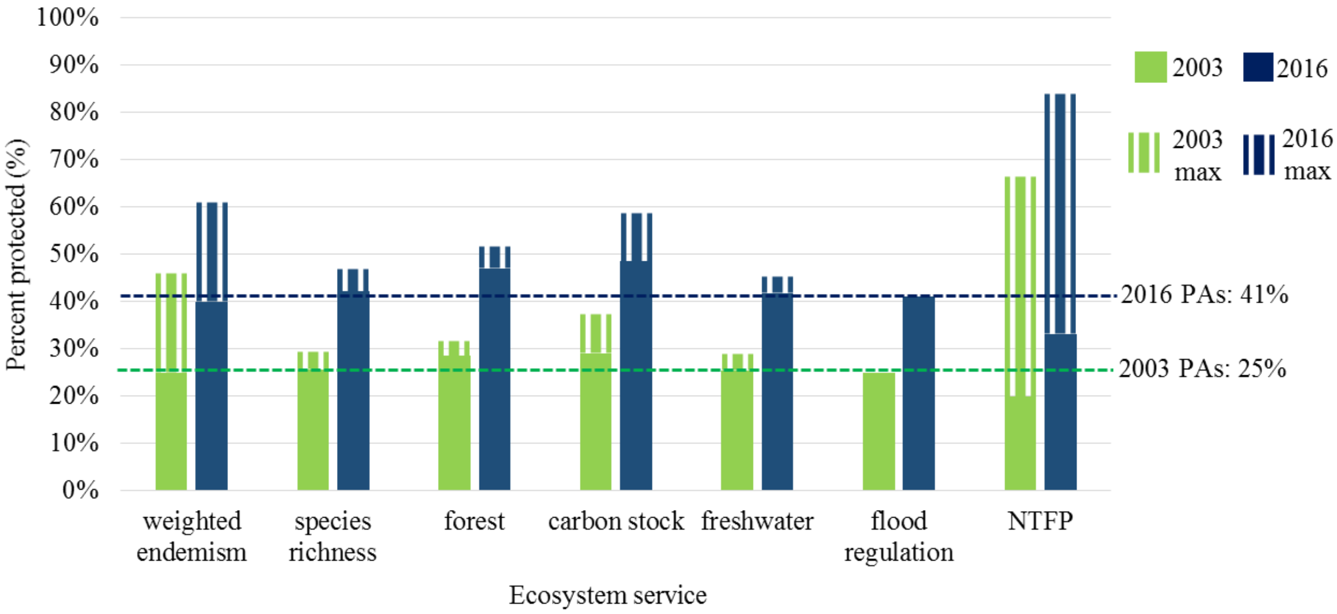

Figure 5: Representation of biodiversity and ecosystem services in Amazonia's protected areas, percent*

* Dotted lines represent the percentage of total land area protected in a given year. Solid bars represent the percentage of each ecosystem service represented by protected areas in a given year. Where the bars fall below the dotted lines, the ecosystem service is under-represented in protected areas, and vice versa. Striped bars represent the percentage of the ecosystem service that could have been captured, if protected areas had been spatially configured to maximize that ecosystem service.

Table 5: Representation of biodiversity and ecosystem services in Amazonia's protected areas, percent, by country*

Country	Year	protected area	weighted endemism	species richness	forest	carbon stock	freshwater	flood regulation	NTFP
Amazonia	2003	*25%*	25%	26%	28%	29%	25%	25%	20%
	2016	*41%*	40%	42%	47%	49%	42%	41%	33%
Bolivia	2003	*20%*	24%	21%	25%	26%	21%	20%	18%
	2016	*24%*	29%	25%	29%	31%	25%	24%	22%
Brazil	2003	*28%*	29%	28%	32%	33%	28%	29%	23%
	2016	*49%*	49%	49%	56%	58%	49%	50%	37%
Colombia	2003	*17%*	18%	17%	18%	18%	18%	16%	15%
	2016	*20%*	22%	20%	20%	21%	20%	19%	17%
Ecuador	2003	*22%*	21%	22%	23%	22%	22%	23%	17%
	2016	*26%*	28%	25%	27%	26%	26%	26%	19%
French Guiana	2003	*13%*	14%	14%	12%	11%	13%	10%	14%
	2016	*51%*	48%	50%	51%	51%	51%	54%	53%
Guyana	2003	*2%*	3%	2%	3%	3%	2%	2%	2%
	2016	*9%*	8%	9%	10%	10%	10%	11%	5%
Peru	2003	*11%*	12%	12%	13%	13%	12%	11%	12%
	2016	*33%*	33%	37%	39%	40%	34%	34%	37%
Suriname	2003	*12%*	13%	12%	12%	12%	12%	11%	6%
	2016	*14%*	16%	14%	14%	15%	14%	13%	7%
Venezuela	2003	*66%*	70%	67%	69%	71%	67%	65%	55%
	2016	*66%*	71%	67%	70%	71%	67%	65%	56%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

5.2.1 Biodiversity

Taking Amazonia as a whole, in 2003 weighted endemism was neither over nor under-represented and species richness was over-represented (Table 6 and Figure 6). In 2016 weighted endemism was under-represented and species richness was over-represented in Amazonia's protected area network. Weighted endemism was over-represented in Bolivia, Colombia, Suriname, and Venezuela in both 2003 and 2016, while species richness was over-represented for both time periods in Bolivia, Peru, and Venezuela. In French Guiana, weighted endemism and species richness was over-represented in 2003 and under-represented in 2016, indicating a declining level of representation over time. Similarly, in Guyana, weighted endemism was over-represented in 2003 and under-represented in 2016. Contrastingly, in Ecuador, weighted endemism was under-represented in 2003 and over-represented in 2016, indicating an increase in representation. In Ecuador, species richness was neither under nor over-represented in

2003 and under-represented in 2016. In Brazil, Guyana, Colombia, and Suriname, species richness was neither under nor over-represented in both 2003 and 2016. Furthermore, we found that large gains are possible in the representation of biodiversity by Amazonia's protected areas, and particularly in Bolivia, Colombia, Ecuador, French Guiana, Guyana, and Peru, if the protected areas were relocated to places that optimize biodiversity (Table 7).

Table 6: Representation of biodiversity in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2003	protected area	*25%*	*20%*	*28%*	*17%*	*22%*	*13%*	*2%*	*11%*	*12%*	*66%*
	weighted endemism	25%	24%	29%	18%	21%	14%	3%	12%	13%	70%
	species richness	26%	21%	28%	17%	22%	14%	2%	12%	12%	67%
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	weighted endemism	40%	29%	49%	22%	28%	48%	8%	33%	16%	71%
	species richness	42%	25%	49%	20%	25%	50%	9%	37%	14%	67%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

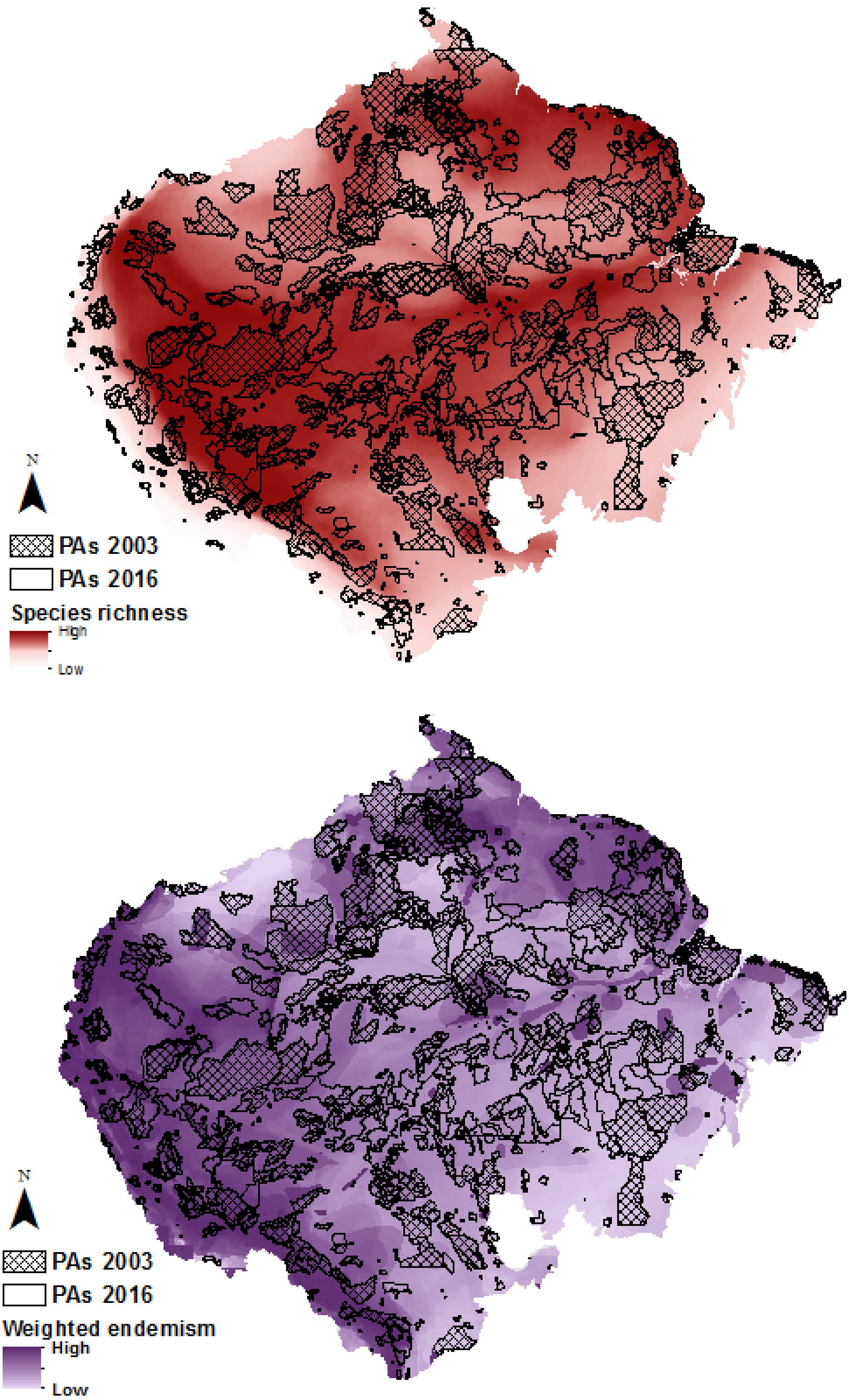

Figure 6: Spatial representation of biodiversity in Amazonia's protected areas

Table 7: Maximum possible representation of biodiversity in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	weighted endemism	40%	29%	49%	22%	28%	48%	8%	33%	16%	71%
	species richness	42%	25%	49%	20%	25%	50%	9%	37%	14%	67%
max 2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	weighted endemism	61%	48%	58%	40%	46%	60%	25%	51%	21%	78%
	species richness	47%	30%	53%	22%	33%	53%	10%	43%	16%	69%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

5.2.2 Forests and forest carbon stocks

For Amazonia as a whole, both forests and forest carbon stocks were over-represented in both 2003 and 2016 (Table 8 and Figure 7). Specifically, forests and carbon stocks were over-represented in Bolivia, Brazil, Guyana, Peru, and Venezuela in both time periods. In Colombia, forests were over-represented in 2003 and neither under nor over-represented in 2016, while carbon stocks were over-represented in both time periods. In Ecuador, while carbon stocks were neither over nor under-represented in both time periods, forests were over-represented in 2003 and 2016. In French Guiana, both forests and carbon stock were under-represented in 2003 and neither over nor under-represented in 2016. In Suriname, forests were neither over nor under-represented in both years, while carbon stocks were neither over nor under-represented in 2003 and over-represented in 2016. Gains are possible in the representation of forests and forest carbon in Amazonia's protected areas, and particularly in Bolivia, Brazil, and Venezuela (Table 9).

Table 8: Representation of forests and forest carbon in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2003	protected area	*25%*	*20%*	*28%*	*17%*	*22%*	*13%*	*2%*	*11%*	*12%*	*66%*
	forest	28%	25%	32%	18%	23%	12%	3%	13%	12%	69%
	carbon stock	29%	26%	33%	18%	22%	11%	3%	13%	12%	71%
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	forest	47%	29%	56%	20%	27%	51%	10%	39%	14%	70%
	carbon stock	49%	31%	58%	21%	26%	51%	10%	40%	15%	71%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

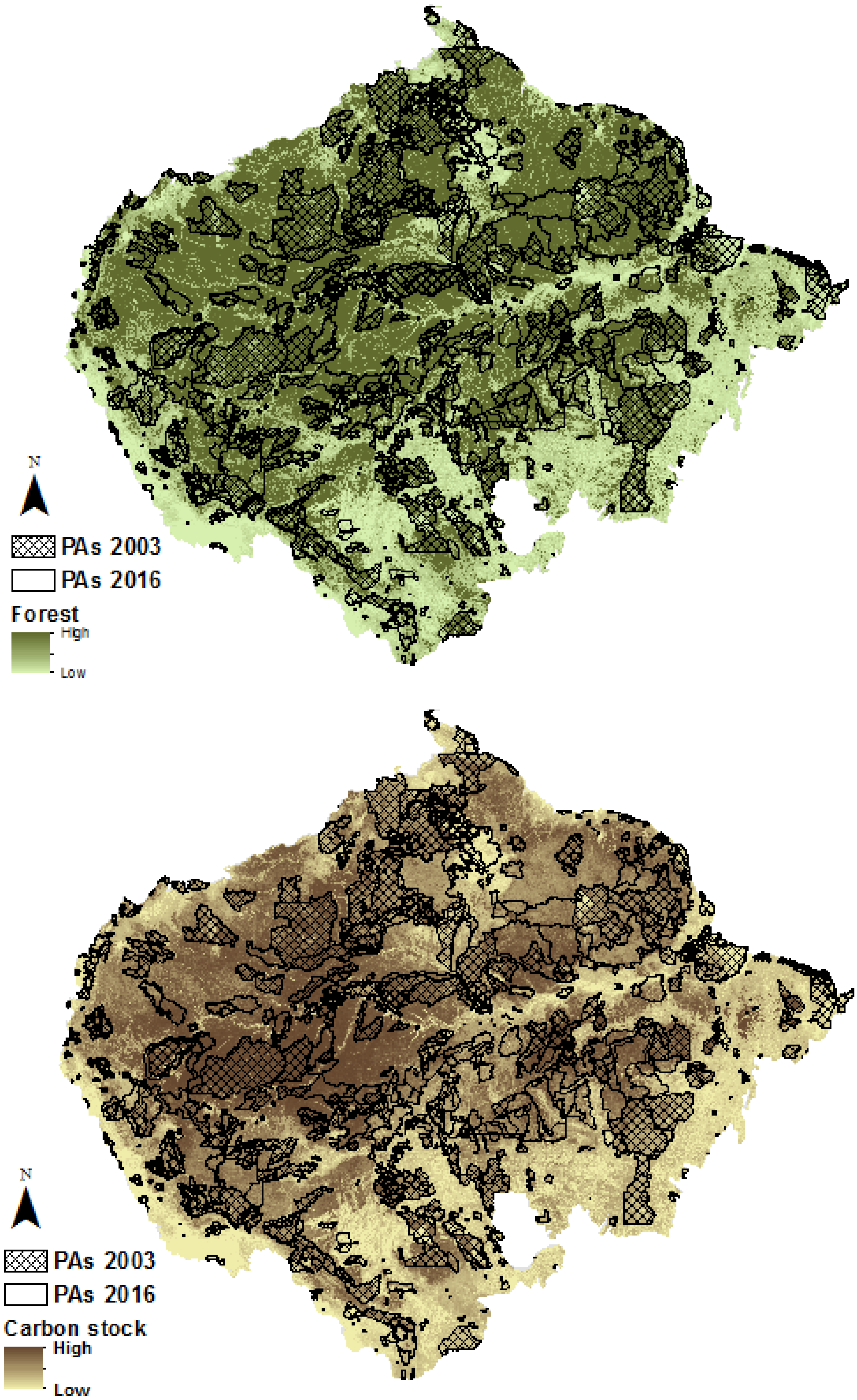

Figure 7: Spatial representation of forests and forest carbon in the Amazonia's protected areas

Table 9: Maximum possible representation of forests and forest carbon in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	forest	47%	29%	56%	20%	27%	51%	10%	39%	14%	70%
	carbon stock	49%	31%	58%	21%	26%	51%	10%	40%	15%	71%
max 2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	forest	52%	38%	61%	21%	31%	52%	10%	43%	15%	77%
	carbon stock	59%	46%	68%	25%	36%	57%	12%	48%	18%	83%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

5.2.3 Freshwater ecosystem services

For the entire region, realized freshwater services were neither over nor under-represented in 2003 and were over-represented in 2016 (Table 10 and Figure 8). In Bolivia, Peru, and Venezuela, realized freshwater services were over-represented in both time periods. In Brazil, Ecuador, French Guiana, and Suriname, realized freshwater services were neither over nor under-represented in both 2003 and 2016. In Colombia, realized freshwater services went from being over-represented in 2003 to neither over nor under-represented in 2016, while Guyana showed the reverse trend. Only small gains are possible in the representation of realized freshwater services in Amazonia's protected areas (Table 11).

Table 10: Representation of freshwater services in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2003	protected area	*25%*	*20%*	*28%*	*17%*	*22%*	*13%*	*2%*	*11%*	*12%*	*66%*
	freshwater services	25%	21%	28%	18%	22%	13%	2%	12%	12%	67%
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	freshwater services	42%	25%	49%	20%	26%	51%	10%	34%	14%	67%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

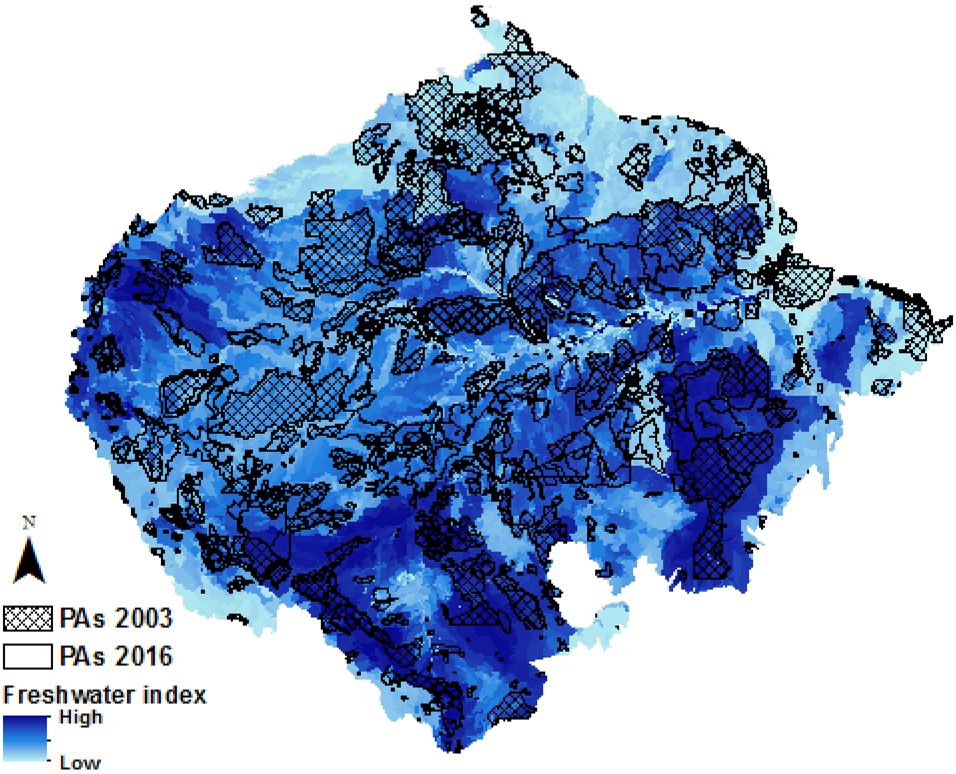

Figure 8: Spatial representation of freshwater services in Amazonia's protected areas

Table 11: Maximum possible representation of freshwater services in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	freshwater services	42%	25%	49%	20%	26%	51%	10%	34%	14%	67%
max 2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	freshwater services	45%	27%	52%	22%	29%	52%	11%	36%	16%	70%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

5.2.4 Flood regulation under climate change

For Amazonia as a whole and in Bolivia, flood regulation under climate change was neither over nor under-represented in both time periods (Table 12 and Figure 9). In Colombia, Suriname, and Venezuela, flood regulation under climate change was under-represented in both time periods. In Guyana and Peru, flood regulation under climate change was neither under over nor under-represented in 2003 and over-represented in

2016. Flood regulation under climate change in Brazil was over-represented in both time periods. In Ecuador, flood regulation under climate change was over-represented in 2003 and neither over nor under-represented in 2016. In French Guiana, flood regulation under climate change was under-represented in 2003 and over-represented in 2016. Gains are possible in the representation of flood regulation under climate change in Amazonia's protected areas and all countries (Table 13).

Table 12: Representation of flood regulation under climate change in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2003	protected area	*25%*	*20%*	*28%*	*17%*	*22%*	*13%*	*2%*	*11%*	*12%*	*66%*
	flood regulation	25%	20%	29%	16%	23%	10%	2%	11%	11%	65%
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	flood regulation	41%	24%	50%	19%	26%	54%	11%	34%	13%	65%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

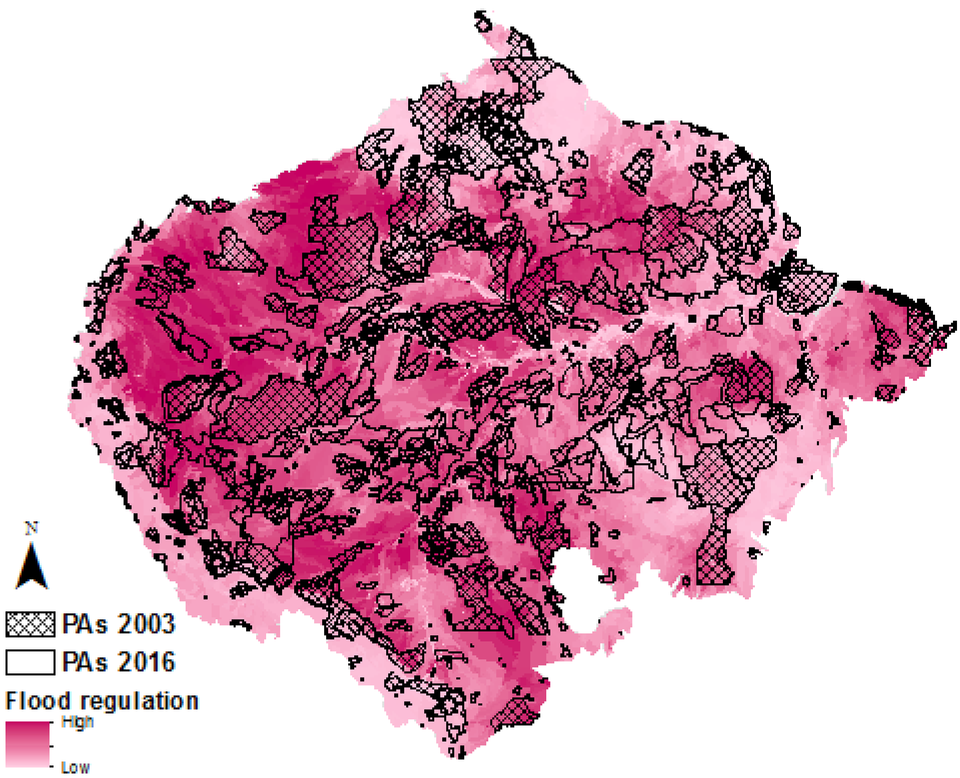

Figure 9: Spatial representation of flood regulation under climate change in Amazonia's protected areas

Table 13: Maximum possible representation of flood regulation in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	flood regulation	41%	24%	50%	19%	26%	54%	11%	34%	13%	65%
max 2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	flood regulation	49%	29%	55%	22%	32%	59%	15%	40%	18%	76%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

5.2.5 Non-timber forest products (NTFPs)

For Amazonia as a whole, non-timber forest products (NTFPs) were under-represented in both 2003 and 2016 (Table 14 and Figure 10). Similarly, in Bolivia, Brazil, Colombia, Ecuador, Suriname, and Venezuela, non-timber forest products (NTFPs) were under-represented in both time periods. French Guiana and Peru were the only countries where non-timber forest products (NTFPs) were over-represented in both time periods. In Guyana, non-timber forest products (NTFPs) were neither over nor under-represented in 2003 and under-represented in 2016. Large gains are possible in the representation of non-timber forest products (NTFPs) in Amazonia's protected areas and all countries (Table 15).

Table 14: Representation of non-timber forest products (NTFPs) in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2003	protected area	*25%*	*20%*	*28%*	*17%*	*22%*	*13%*	*2%*	*11%*	*12%*	*66%*
	NTFP	20%	18%	23%	15%	17%	14%	2%	12%	6%	55%
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	NTFP	33%	22%	37%	17%	19%	53%	5%	37%	7%	56%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

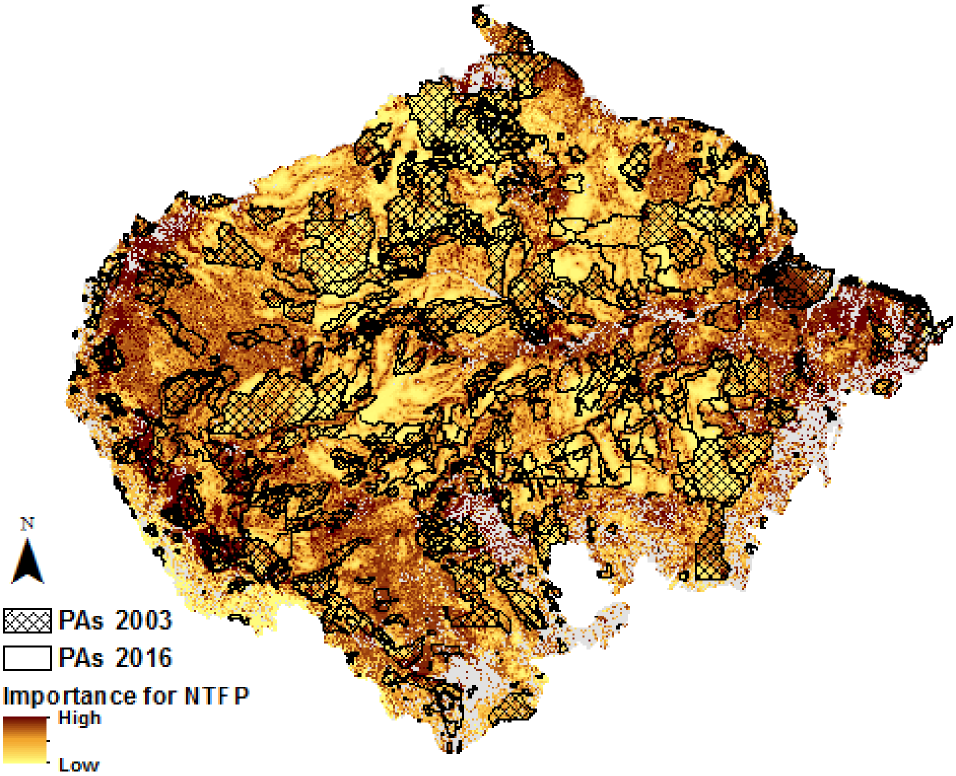

Figure 10: Spatial representation of non-timber forest products in Amazonia's protected areas

Table 15: Maximum possible representation of non-timber forest products in Amazonia's protected areas, percent, by country*

		Amazonia	Bolivia	Brazil	Colombia	Ecuador	French Guiana	Guyana	Peru	Suriname	Venezuela
2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	NTFP	33%	22%	37%	17%	19%	53%	5%	37%	7%	56%
max 2016	protected area	*41%*	*24%*	*49%*	*20%*	*26%*	*51%*	*9%*	*33%*	*14%*	*66%*
	NTFP	84%	59%	89%	56%	60%	87%	32%	69%	47%	97%

* Legend: green: over-represented; grey: neither over nor under-represented; orange: under-represented

6. Discussion and conclusion

The current protected areas network in Amazonia favours the representation of some elements of biodiversity and ecosystem services over others. Forests and forest carbon stocks are well represented by protected areas, over-represented at the regional level as well as in six and seven countries, respectively. This is likely because both protected and forested areas tend to be located in more remote areas with low productivity where there is little conflict with human land uses (Joppa et al. 2008; Joppa and Pfaff 2009). Furthermore, given the value of protecting tropical forests for climate-change mitigation through payment for ecosystem services schemes such as reducing emissions from deforestation and degradation (REDD+), growth in protected area coverage for tropical forests is likely to continue (Brooks et al. 2009). Given that the most imminent and visible threat to the forests of Amazonia is direct deforestation, it is an important and positive result that forests and forest carbon are over-represented by protected areas (Betts et al. 2008).

Few large-scale assessments of forests and forest carbon covered by protected areas exist due to the lack of data, and therefore assessments of spatial representation by protected areas are usually done at more local scales (Juffe-Bignoli et al. 2014). However, one related study of carbon stock found that protected areas in humid tropical forests contain 3.5% of global terrestrial carbon stocks (Scharlemann et al. 2010). Another study found that 20.1% of the world's natural forests are covered by protected areas (Juffe-Bignoli et al. 2014). Specifically, the Neotropics, which contain all of Amazonia, have a very high level of spatial representation of forests in protected areas (39.6%) compared to other realms such as the Nearctic (10.2%), Palearctic (13.4%), and Oceania biogeographic realms (13.4%) (Juffe-Bignoli et al. 2014). This is in line with our findings that show a strong over-representation of forests and forest carbon stocks by protected areas in Amazonia.

Weighted endemism was under-represented in the current protected areas network at the regional level likely due to the fact that the analyzed species in Amazonia have very large distribution ranges, and therefore protected areas would not be able to over-represent endemic species very well at the regional level (Rodrigues et al. 2004b). Nevertheless, it was over-represented in five countries, also suggesting that protected areas represent endemic species relatively well. Several gap analyses showed that the existing protected areas in Amazonia are frequently inadequate in conserving biodiversity (Scott et al. 2001; Ochoa-Ochoa et al. 2007). Another study which disaggregated results by taxa found that China's nature reserves represent mammals and birds well, but not other major taxa (Xu et al. 2017). Another study found that biodiversity was poorly-represented in Chile's existing terrestrial protected areas (Durán et al. 2013). These studies suggest that it is possible for the spatial representation of biodiversity in protected areas in Amazonia to vary between different taxa.

However, even if protected areas are representing endemic species well, declines in biodiversity within these protected areas are still possible as a result of extinction debts which are produced by a possible lack of connectivity with other populations and natural habitats (Saura et al. 2017). Furthermore, even though protected areas have been reported to have higher species richness than unprotected sites globally, biodiversity declines still do occur within protected areas, possibly as a result of changes outside of protected areas such as deforestation, which may increase the isolation of protected areas (Laurance et al. 2012). It has been estimated that protected areas are only 41% effective at retaining species richness and only 54% effective at retaining local species abundance (Gray et al. 2016). However, at the scale of Amazonia, the effectiveness of protected areas to retain biodiversity would likely be unfeasible to study given the severe data limitations in the region.

Similar to forests and forest carbon, few large-scale assessments of biodiversity representation by protected areas exist due to lack of data. However, several studies have assessed the global coverage of protected areas of species distributions and determined that species ranges are insufficiently covered by protected areas (Rodrigues et al. 2004a). Furthermore, only birds 56% are adequately covered by protected areas globally while fewer than half of the species in most other taxa groups are sufficiently represented by protected areas (Butchart et al. 2015). Another related study found that 85% of all globally threatened mammals, amphibians, and birds were not adequately represented by protected areas (Venter et al. 2014).

Freshwater services were only moderately well represented by protected areas, over-represented only slightly at the regional level and in four countries. This confirms findings from other studies which suggest that protected areas in Amazonia were originally and primarily established to protected terrestrial taxa from deforestation and overharvesting (Peres and Terborgh 1995; Fagundes et al. 2016). Specifically, protected areas that focus on the conservation of terrestrial ecosystems and species frequently do not effectively conserve freshwater ecosystems (Thieme et al. 2007; Castello et al. 2013).Furthermore, existing protected areas frequently ignore river catchment sites and threats to the provision of freshwater ecosystem services (Wishart and Davies 2003; Fagundes et al. 2016).

The worst-represented ecosystem service was non-timber forest products (NTFPs), which was under-represented in protected areas in Amazonia as well as in seven countries. The reason that non-timber forest products (NTFPs) are the worst-represented ecosystem service is likely due to the model used. Specifically, the map of non-timber forest products (NTFPs) shows high values in areas close to population centers; such areas tend to be less well represented by protected areas, since they tend to be concentrated in more remote areas (Joppa et al. 2008).

In addition to differences in spatial representation between biodiversity and different ecosystem services, there is also a large difference between countries. The protected area network in the Peruvian Amazon over-represents six of the seven biodiversity and ecosystem services analyzed. The protected area networks of Bolivia and Venezuela within Amazonia over-represent five of the seven biodiversity and ecosystem services analyzed. Guyana and the Brazilian Amazon over-represent four and three biodiversity and ecosystem services, respectively. The Colombian and Ecuadorian Amazon, French Guiana, and Suriname over-represent two biodiversity and ecosystem services. Colombia, Suriname, and Venezuela are the only countries whose protected areas under-represented two biodiversity and ecosystem services, while Peru is the only country that did not under-represent any of the biodiversity and ecosystem services analyzed. As a whole, most countries in Amazonia are performing better than would be expected by chance in terms of spatial representation of biodiversity and ecosystem services in Amazonia. However, our analyses indicate that significant gains are possible, with an equivalent area protected, if protected areas were relocated to optimize biodiversity and ecosystem services representation.

The reason for these disparities could likely be the large heterogeneity in national policy targets for protected areas, biodiversity, and ecosystem services in Amazonia countries (CI 2015). In terms of protected area expansion, only Brazil, Ecuador, Guyana, and Peru have set quantitative goals in line with the Aichi Target 11, while Colombia, Suriname, and Venezuela refer to protected areas being important for biodiversity conservation and ecosystem services provision (CI 2015). National policy targets for ecosystem services are addressed by only Brazil, Colombia, and Suriname, and often in vague terms (CI 2015).

Compared to other tropical regions, Amazonia has a high level of conservation protection and forest cover, which our study confirms (Hansen et al. 2013; Macedo and Castello 2015). The Neotropics, which contain all of Amazonia, is the only biogeographic realm globally that is meeting Aichi Target 11: to increase by 2020 the terrestrial area under protection to at least 17% of well-connected systems of protected areas (CBD 2010). Our study demonstrated that within Amazonia, only Guyana and Suriname are short of meeting the 17% target, while all other seven countries are above the 17% threshold already, which is confirmed by officially reported protected area size (UNEP-WCMC 2014). However, despite making global commitments to increasing size and effectiveness of protected areas, some governments are increasingly decreasing their commitments to support protected areas, which could potentially result in worse representation as well as protected area downgrading, downsizing, and degazettement (PADDD) over time (Watson et al. 2014).

The present analysis is faced with several limitations. First, the biodiversity and ecosystem services analyzed were only mapped or modelled for one time period (using the most recent data available as of 2015) which does not coincide with the time periods of the protected areas coverage data (2003 and 2016). This is due to data limitations, since data for several of the biodiversity and ecosystem services is not available for 2003. However, for forests, data is available for 2003 and an analysis comparing forest representation within protected areas in the two time periods would be appropriate to provide context for the current results.

With the current limitation, it is possible that the results over or under-estimate the actual level of biodiversity and ecosystem services protection at both the regional and country-level in 2003. For example, we know that natural ecosystems were lost during the study period, therefore the overall level of biodiversity and ecosystem services provided in Amazonia was lower in 2016 than in 2003. Thus, our analysis might over-estimate the level of biodiversity and ecosystem services represented in protected areas in 2003. However, the human population in Amazonia has increased in recent decades; thus while natural habitat was lost, the benefits to people might have actually increased or stayed the same, due to the larger number of beneficiaries (Caviglia-Harris et al. 2016). Thus, without historic data it is not easy to ascertain whether our analysis over- or under-represents spatial representation of ecosystem services in 2003.

The interpretation of the results is also highly model-dependent for some of the biodiversity and ecosystem services. Specifically, the non-timber forest products (NTFPs) model assumed that higher accessibility of natural habitat to people leads to higher ecosystem service provision, using the logic that more people can access the products and therefore benefit from them. The opposite assumption (more remote areas provide more non-timber forest products, because they have not been over-harvested) changes the results significantly. Third, the country-level analyses for Bolivia, Brazil, Colombia, Ecuador, and Peru are limited because the biodiversity and ecosystem services mapping only focused on the parts of each country that fall within Amazonia, and neglects biodiversity and ecosystem services provision that occurs outside of the region. This doesn't affect our results for Guyana, French Guiana, or Suriname, which fall completely within the study area.

The current analysis also does not provide any information about what targets are actually needed to achieve effective protection of biodiversity and ecosystem services in the region. Unfortunately, quantitative information on the level of demand for ecosystem services is not currently available, but future research could shed insights on, for example, how much forest area is actually needed to ensure ongoing provision of freshwater to population centers.

Another key limitation of the analysis is that it examines spatial representation, but not other measures of protected area performance, such as avoided species extinctions and integrity of ecosystems. Future analyses should examine ecological outcomes of protected areas, to provide a more complete picture of protected area performance.

Furthermore, good spatial representation by protected areas does not indicate whether protected areas are managed effectively, which is essential to protect the biodiversity and ecosystem services they are representing. Research suggests that only 20 to 50% of protected areas are effectively managed (Watson et al. 2014). Lastly, the maximum possible representation for biodiversity and ecosystem services assumes that protected areas could be relocated anywhere within the region, an assumption that disregards significant considerations of protected area design, including trade-offs with other land uses, contiguity, feasibility, opportunity, and cost.

This study is the first analysis of the spatial representation of biodiversity and ecosystem services of protected areas in Amazonia. It highlights conservation successes at the regional level such as forests and forest carbon stocks and countries which protect most of the biodiversity and analyzed ecosystem services, including Bolivia, Peru, and Venezuela. It also highlights some of the gaps in the current protected areas network in Amazonia, particularly by identifying those biodiversity and ecosystem services that are not well-represented, including non-timber forest products (NTFPs). This information can inform efforts to target future conservation to the most important places. Lastly, it can help countries understand whether they are achieving the CBD Aichi Target 11, in terms of representing biodiversity and ecosystem services in their protected area systems.

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Appendix I: Summary of methodology for biodiversity and ecosystem services mapping

Biodiversity

The two approaches that were used by CI (2015) to map biodiversity were endemism and species richness.

Weighted endemism

A common approach to mapping biodiversity involves using endemism, which is one of biodiversity's fundamental dimensions (Myers et al. 2000). Endemism refers to species that are restricted to a particular area. Principally, areas with high endemism are home to unique and irreplaceable species. In Amazonia, some species are range-restricted, which is one way to measure endemism. CI (2015) used the bird species databases from BirdLife International and NatureServe (2014) and the mammal, reptile, and amphibian databases from the IUCN RedList database (2015) were used to identify areas with the largest number of range restricted species, which is a proxy for endemism. Specifically, CI (2015) calculated the distribution area of each species, followed by calculating and summing all species' range rarity indices (see Crisp et al. 2001 and CI 2015 for detailed methodology). The result by CI (2015) is a map of weighted endemism which highlights areas with larger numbers of range-restricted species and provides an indicator of the importance of an area for biodiversity across Amazonia (Figure 11).

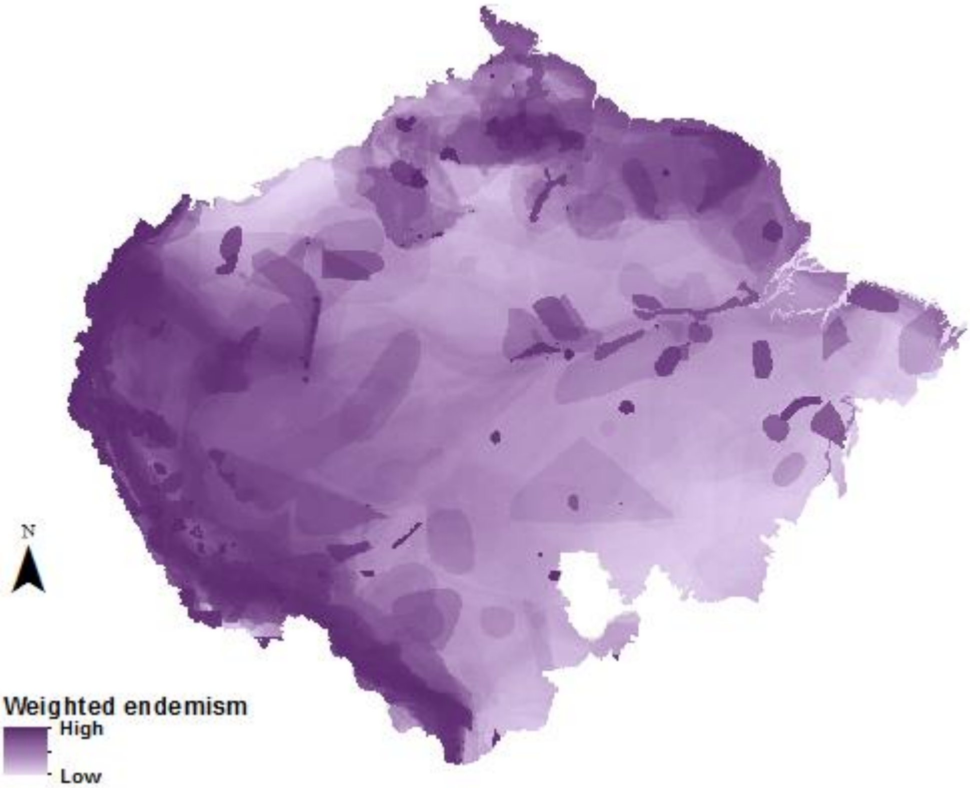

Figure 11: Weighted endemism (CI 2015)

Species richness

Like the weighted endemism, CI (2015) produced the species richness map using the same species distributions to count the number of overlapping species distributions for each pixel, providing a species richness in terms of species per km^2 (Figure 12).

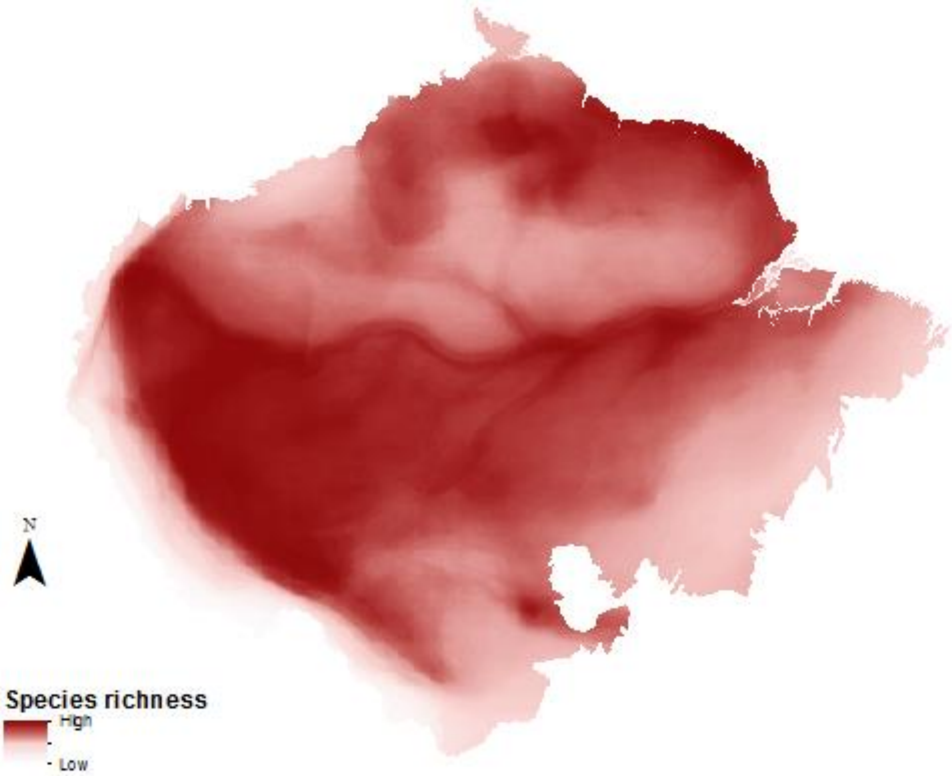

Figure 12: Species richness (CI 2015)

Forests and forest carbon stocks

Mapping important areas for climate mitigation includes identifying areas of importance for the long-term maintenance of biotic carbon stock in Amazonia. CI (2015) mapped forest biomass carbon stock (Figure 13) using current land cover and the density of vegetation biomass (Baccini et al. 2012). CI (2015) considered both aboveground and belowground biomass, but soil carbon was not considered because even though soils hold two to three times more carbon than that stored above ground in forest vegetation, much of the carbon in soils is physically and chemically protected and not easily oxidized (Davidson and Janssens 2006). CI (2015) also mapped forest area (Hansen et al. 2013) (Figure 14).

CI (2015) calculated the standing forest carbon stock (tonnes) using maps of both forest area (ha) and biomass density (tonnes/ha) as inputs at a 1km^2 resolution (Hansen et al. 2013; Chen et al. 2014). Firstly, CI (2015) created a forest biomass layer based on a biomass density layer by identifying 1km grid cells that are 99% or greater forest, which are considered "pure forest pixels". Secondly, CI (2015) interpolated the above ground biomass (AGB) density values from the pure forest pixel values to all 1km pixels using an inverse weighted distance (kriging). Thirdly, CI (2015) multiplied the interpolated AGB density by the 2014 forest area per 1km grid cell to determine the tonnes of AGB per grid cell. Lastly, CI (2015) converted the AGB values to carbon (Equation 3), calculated the below ground biomass, and converted the biomass weight to carbon weight (Mokany et al. 2006):

$$Carbon\ (tonnes) = \frac{AGB + ((0.489) * (AGB)^{0.89})}{2} \qquad \text{(Equation 3)}$$

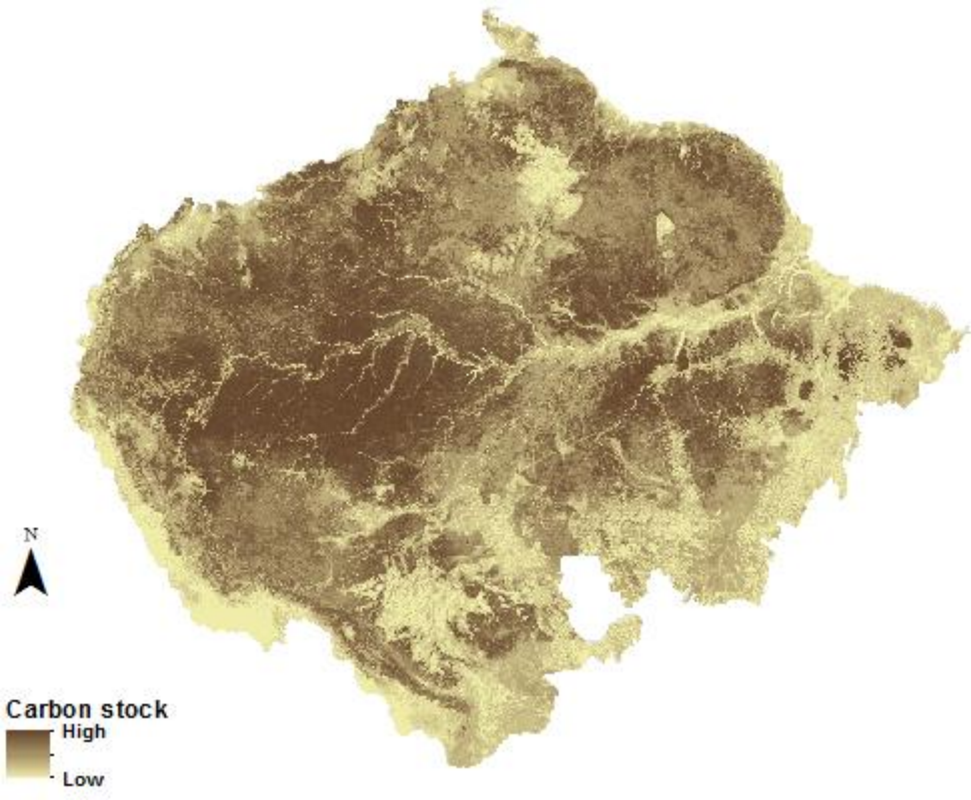

Figure 13: Forest biomass carbon stock (CI 2015)

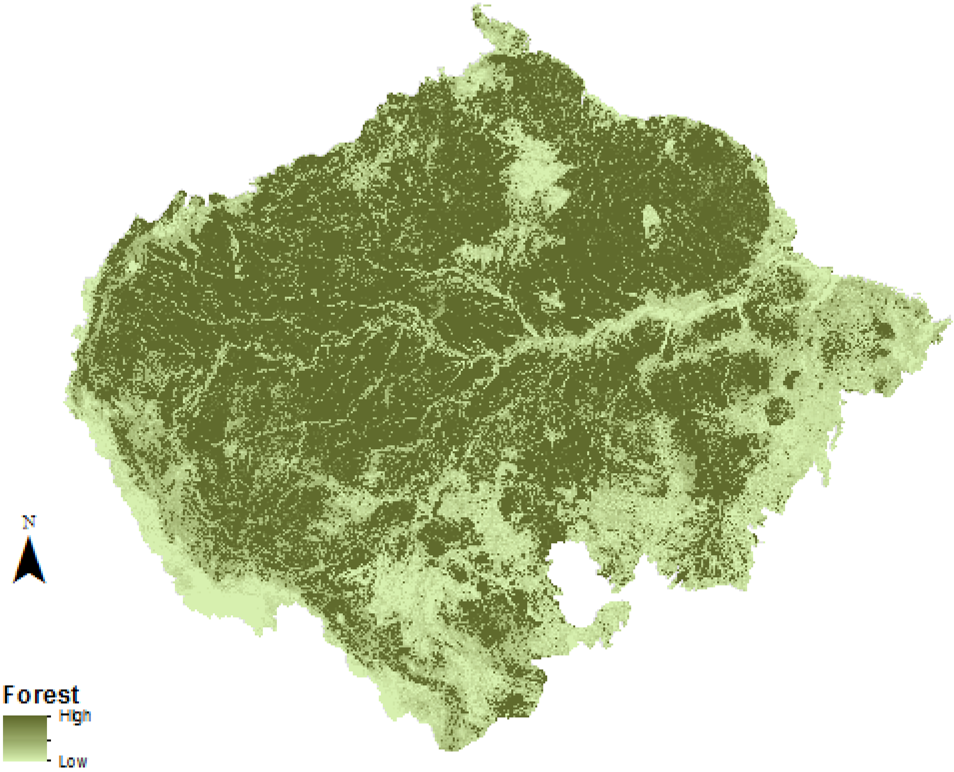

Figure 14: Forest (CI 2015)

Freshwater ecosystem services

The important areas for freshwater includes areas that are important for the provision of realized freshwater services related to water quality, quantity, and flow regulation that is supplied by upstream ecosystems. Specifically, such ecosystems support a high provision of water for human use or hydropower production (water quantity), avoided erosion and sedimentation (water quality), or provide a stable flow of water (flow regulation).

CI (2015) mapped freshwater provision using the eco-hydrological model WaterWorld (Mulligan 2013). The model depends on biophysical variables including temperature, precipitation, land cover, solar radiation, and topography to map ecosystems that are important for providing potential freshwater services. CI (2015) weighted the areas of potential freshwater services by the amount of service demanded by downstream water users (population centres and hydropower dams) in order to identify areas important for realized freshwater ecosystem services (Figure 15) (for detailed methodology, see Mulligan 2013 and CI 2015).

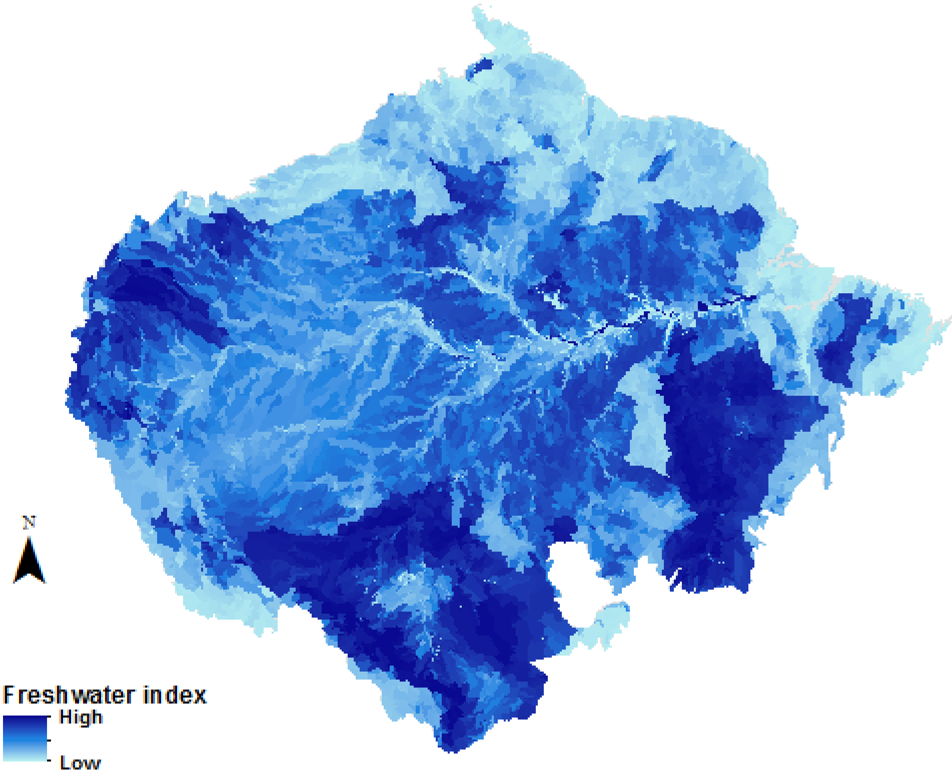

Figure 15: Importance for freshwater ecosystem services (CI 2015)

Flood regulation under climate change

To identify important areas for flood regulation under climate change, CI 2015 mapped the impacts on water availability of a hypothetical drastic land use change scenario under the ensemble of climate change scenarios (Figure 16). This ensemble included the mean of outputs from 17 of the General Circulation Models (GCMs) of the IPCC Fifth Assessment Report (Pachauri et al. 2014). The eco-hydrological model WaterWorld (Mulligan et al. 2013) was used to determine changes to the water balance due to climate change, accumulate outputs downstream and focus on the projected changes in seasonable run-off.

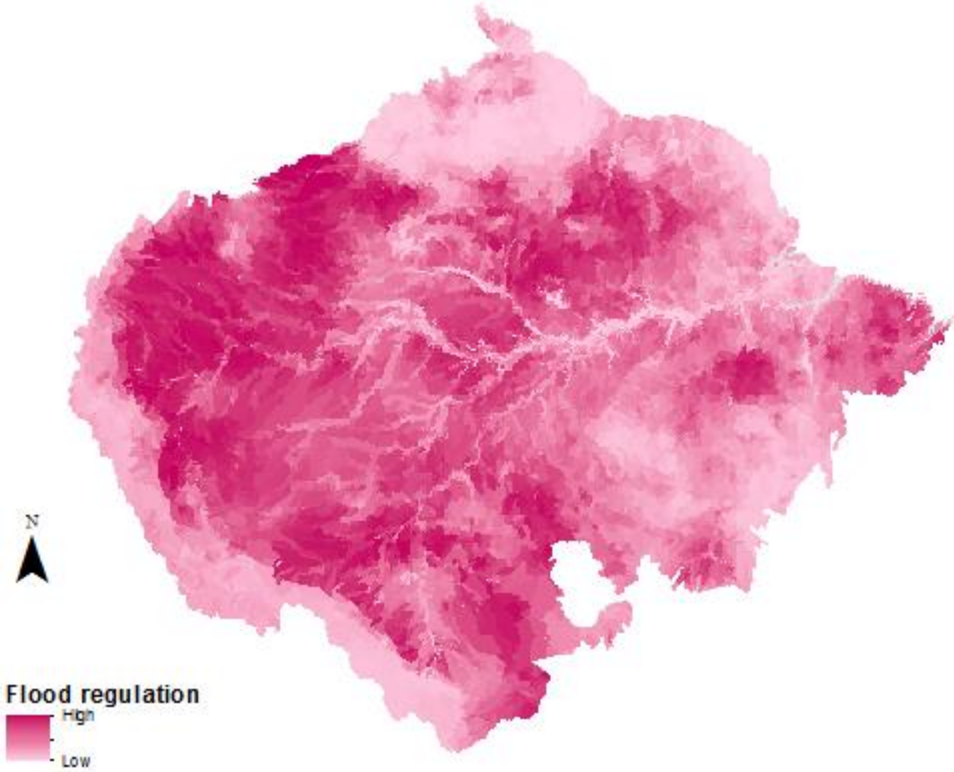

Figure 16: Importance for flood regulation under climate change (CI 2015)

Non-timber forest products (NTFPs)

CI (2015) mapped non-timber forest products (NTFPs) using a model that combines the species occurrence data from species of known importance for NTFPs and accessibility to people, which is an approach adapted from the Ecosystem Services for Poverty Alleviation (ESPA) (Porro et al. 2008). The species occurrence data combines wild species important for food security in Amazonia, including plant species such as fruits and nuts, as well as several animal species (see CI 2015 for a detailed list). CI (2015) created the species occurrence map using spatial data on ecosystem services and habitat types, including forest, woodland, mangroves, grassland, and wetland (for detailed methodology see CI 2015).

CI (2015) created the accessibility map using spatial data on roads, rivers, train tracks, land cover, urban areas, international borders, elevation, and slope and modeled in ArcGIS' Model Builder (Porro et al. 2008; ESRI 2014). All of these features influence travel time, which is a key aspect of accessibility. CI (2015) converted all the spatial features to numeric values of travel time to yield a velocity surface to indicate the minutes required to cross a given pixel. Finally, the resulting velocity, elevation, and slope layers were multiplied together to create a final accessibility map.

CI (2015) multiplied the species occurrence and accessibility maps by each other to create the final non-timber forest products (NTFP) map that indicates the areas with a relatively large number of species of known importance for NTFPs and which are more accessible to people (Figure 17). Specifically, CI (2015) combined the species occurrence and accessibility inputs for the final map by rescaling each input from 1 to 100 using a linear transformation so they would equally factor, and using the Equation 4:

$$Importance\ for\ NTFPs = Species\ Occurrence * \frac{1}{Accessibility} \quad \text{(Equation 4)}$$

Accessibility is the inverse of travel time and the areas with a higher number of known NTFP species that are more accessible to people are given a higher value.

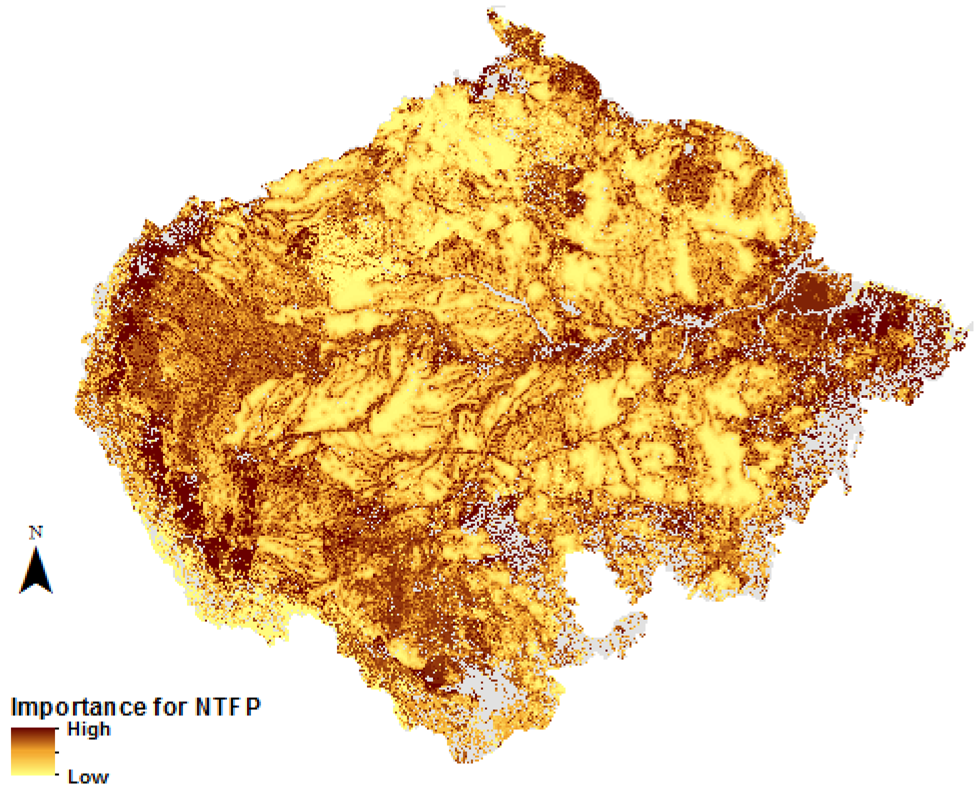

Figure 17: Important areas for non-timber forest products (NTFPs) (CI 2015)

Limitations

The mapping of biodiversity and ecosystem services in Amazonia faced several constraints and challenges. They are discussed in detail in CI (2015) but also highlighted below.

First, there were significant data constraints for the analysis. Therefore, several of the maps relied on global datasets, including forest carbon stocks as well as the modeling of freshwater ecosystem services, because consistent regional-level data was not available for the region (CI 2015). These data would be more robust if they were validated using ground-based sampling techniques and local datasets, however, this was impractical given the size of the Amazonian region and the number of services analyzed. Furthermore, in the case of forest carbon stocks, multiple global forest biomass datasets exist and there is some level of disagreement between them (CI 2015). Hydropower demand for freshwater was also underestimated due to lack of data on production capacity for some of the dams, which results in an underestimation of demand.

Second, several regional datasets were incomplete. Specifically, the analysis for both species richness and weighted endemism (a measure of endemic species) is missing taxonomic groups including plants and invertebrates, and some species distributions may be out of date or incomplete due to the lag time involved in updating the IUCN Red List database (CI 2015). Similarly, the non-timber forest products (NTFPs) analysis included only those species for which there was spatial data available, which is far from comprehensive.

Lastly, the constraints faced in terms of data and time dictated which analyses, modelling tools, and assumptions were used. For example, endemism and species richness are only two ways of prioritizing important areas for biodiversity. Other methods and components can consider threatened and protected species, rare ecosystems, migratory species, as well as spawning grounds, which would provide for a more comprehensive assessment of priority areas for biodiversity in Amazonia (CI 2015). Similarly, a key assumption in the non-timber forest products (NTFPs) model is that ecosystems with a large number of known NTFP species, which are more accessible to people, are assumed to be more important for NTFPs. This may not always be accurate since the quantity of NTFPs contained in an ecosystem may be higher than the number of different species in determining its importance (CI 2015).

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