LETTER

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An ecosystem risk assessment of temperate and tropical forests of the Americas with an outlook on future conservation strategies

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Abstract

Forests of the Americas and the Caribbean are undergoing rapid change as human populations increase and land use intensifies. We applied the IUCN Red List of Ecosystems (RLE) criteria and simple cost-efficiency analyses to provide the first regional perspective on patterns of relative risk integrated across multiple threats. Based on six indicators of ecosystem distribution and function, we find that 80% of the forest types and 85% of the current forest area is potentially threatened based on RLE criteria. Twelve forest types are Critically Endangered due to past or projected future deforestation, and Tropical Dry Forests and Woodland have highest threat scores. To efficiently reduce risks to forest ecosystems at national levels, scenario analyses show that countries would need to combine large forest protection measures with focused actions, tailored to their sociopolitical context, to help restore ecological functions in a selection of threatened forest types.

KEYWORDS

conservation actions, conservation goals, cost-efficiency analysis, ecosystem collapse, ecosystem risk assessment, forest management and conservation, IUCN Red List of ecosystems, threat score, temperate forest, tropical forest

1 | INTRODUCTION

Tropical and temperate forests host an immense share of terrestrial biodiversity, play a critical role in global climate regulation, represent a foundation for the provision of ecosystem services such as clean and reliable water and timber, and provide animal and plant resources of high commercial and cultural value (Levis et al., 2017; Naidoo et al., 2008).

Forests are under great pressure from cumulative direct and indirect effects of human activities through time. A combination of hunting, timber extraction, wildlife trade and land use change driven primarily by agricultural expansion affect more than 75% of tropical and temperate forests worldwide, and now interact with global climate change (Lewis, Edwards, & Galbraith, 2015; Watson et al., 2016). Although current threats are diverse, global forest transformation also involves long, historical legacies. Major shifts from mostly wild to human-dominated landscapes occurred in some regions over the last two centuries (Ellis, Goldewijk, Siebert, Lightman, & Ramankutty, 2010), and strong human imprints are evident even in remote areas of the Amazon (Levis et al., 2017).

Forest management must balance economic growth, social development and the conservation of biodiversity and ecological services. International commitments, including the Aichi targets and the Sustainable Development Goals, establish a common set of conservation objectives (Brooks et al., 2015). Quantitative analyses of potential benefits and costs of conservation and management can offer valuable insights for national strategic planning, even when based on simplified assumptions. For example, ecosystem stewardship for conservation, restoration, and improved land management practices, can make cost-effective contributions to global climate change goals, while providing food, other natural products, and services (Griscom et al., 2017). To meet these challenges with effective conservation strategies, we need systematic risk assessments to analyze diverse threats and legacies.

We undertook a systematic risk assessment using the International Union for the Conservation of Nature (IUCN) Red List of Ecosystems criteria (RLE, http://www.iucnrle.org) to identify the most threatened forests of North, Central, and South America, and the Caribbean ("Americas region"; IPBES, 2018). Specifically, we sought to answer three main questions: which ecosystems are more at risk, where do they occur, and what kinds of strategies would reduce the risks most effectively? This region includes a wide diversity of forest types with large natural distributions, transformed to varying degrees over the last three centuries, and with contrasting contemporary rates of loss (Ellis et al., 2010; Hansen et al., 2013; Lewis et al., 2015). We first applied the RLE criteria across the entire region to assess relative risks of collapse and document spatial patterns of forest ecosystems most at risk. We then undertook national-scale assessments to explore variation in forest ecosystem status across the

diversity of policy contexts within the region (IPBES, 2018). Risk assessments at these different scales provide complementary insights: a regional overview informs allocation of international resources (e.g., from United Nations, international NGOs), whereas national assessments inform on-ground action, which is mostly implemented within national and subnational jurisdictions. Finally, we compared scenarios of potential conservation actions (i.e., in the absence of legal, social, or economic constraints) and analyzed which combinations would be required to reduce the threat to ecosystems at the national level. We believe this is the first continental-scale risk assessment of forest ecosystem conservation that integrates multiple threatening processes.

2 | METHODS AND MATERIALS

We based our analysis on 136 vegetation macrogroups with mesomorphic tree vegetation in the tropical and temperate (excluding boreal) portions of North, Central, and South America and the Caribbean. Macrogroups were suitable proxies for forest ecosystem types because they are characterized by diagnostic plant species and growth forms that reflect biogeographic differences in composition and subcontinental to regional differences in mesoclimate, geology, substrates, hydrology, and disturbance regimes (Faber-Langendoen et al., 2014). We follow nomenclature of the International Vegetation Classification (Faber-Langendoen et al., 2014); descriptions, hierarchical classification of related macrogroups into formations (Table S1) and working maps of their potential distribution were provided by NatureServe (http://natureserve.org).

We assessed 11 of the 13 IUCN RLE subcriteria (Bland, Keith, Miller, Murray, & Rodríguez, 2017; Keith et al., 2013) using six indicators developed from available spatial data derived from remote sensors, cartographic reconstruction, and interpolation and modeling of climatic variables (Table 1, full details in Supporting Information). Changes in ecosystem distribution and function were assessed over three different time periods ("present": 1950–2000, "future": 2000–2050 and "historic past": from 1750; Bland et al., 2017).

For all macrogroups, we used a historical time series of land transformation from natural to anthropogenic biomes (Ellis et al., 2010) to estimate change in distribution over present and past time frames (subcriteria A1 and A3; Bland et al., 2017; Table 1). From the same source, we used estimated change in human density and land use pattern within the remaining wooded area to assess changes in biotic composition and processes over present and past time frames (subcriteria D1 and D3; Barlow et al., 2016; Table 1).

We used time series of forest cover from 2000 to 2012 (from remote sensing layers of tree cover and land use; Friedl et al., 2010; Hansen et al., 2013) to predict future declines

TABLE 1 Risk indicators used in Red List assessment of forest ecosystems in tropical and temperate Americas. Refer to Supplementary Information for further details

Indicator	IUCN RLE subcriteria	Analysis	Assessed	Data source
Woodland cover change	A1 and A3 - Contemporary and historical change in forest distribution	Potential macrogroup distribution intersected with time series of "woodland" cover 1700–2000 and 1950–2000 to calculate proportional rate of change	All 136 macrogroups	Ellis et al. (2010)
Trends in current tree cover	A2b—Future change in forest distribution	Rate of change in forest extent modelled from two remote sensing time series 2000–2014 and extrapolated to 2000–2050	All 136 macrogroups	Friedl et al. (2010); Hansen et al. (2013)
	B1—Extent of occurrence	Area of convex hull fitted to intersection between potential macrogroup distribution and mean tree cover for 2001–2012 with values higher than 25%, and evidence of continuing decline in forest area (any significant negative trend from A2b).	All 136 macrogroups	
	B2—Area of occupancy	Number of 10 × 10 km cells overlaying intersection between potential macrogroup distribution and mean tree cover for 2001–2012 with values higher than 25%, and evidence of continuing decline in forest area (any significant negative trend from A2b).	All 136 macrogroups	
	B3—Small number of locations and prone to serious immediate threats	Number of patches of contiguous 10 × 10 km cells as proxies for locations (from B2), and evidence of strong continuing decline in forest area (significant negative trend leading to declines higher than 20%, from A2b).	All 136 macrogroups	
Change in climate suitability	C2a—Future environmental degradation	Rate of change in modelled climatic suitability (19 bioclimatic variables, Random Forest) from 2000 (fitted) to 2050 (projected from five Global Circulation Models and four Reference Concentration Pathways)	34 macrogroups with good-fit models	Hijmans et al. (2005)
Change in surface water	C2b—Contemporary-future environmental degradation	Rate of change in surface water extent from 1984–1999 to 2000–2015 based on remote sensing time series and extrapolated to 50 years	47 flood-prone macrogroups	Pekel et al. (2016)
Potential defaunation	D2b—Contemporary disruption of biotic processes	Response ratios for hunted cf. unhunted based on accessibility, market proximity and land tenure, extrapolated to 50 years using land use time series 2001–2012	83 macrogroups with tropical mainland distribution	Benítez-López et al. (2017); Friedl et al. (2010)
Resource use	D1 and D3—Contemporary and historical forest structural change	Potential macrogroup distribution intersected with time series of ordinal "woodland" cover classes 1700–2000 to calculate proportional rate of change	All 136 macrogroups	Ellis et al. (2010)

in macrogroup area by extrapolation from models of proportional decline (subcriterion A2b; Table 1). We used the same data to estimate the current Extent of Occurrence (minimum convex polygon enclosing all occurrences) and Area of Occupancy (sum of 10×10 km grid cells containing at least 1 km^2 of forest) for each macrogroup (Bland et al., 2017). We combined these estimates with evidence of continuing decline in macrogroup area (from the subcriterion A2b analysis), and the number and size of forest patches to evaluate subcriteria B1, B2, and B3 (Table 1).

For forested wetland macrogroups subject to flooding we used a remote sensing time series of surface water (Pekel, Cottam, Gorelick, & Belward, 2016) to estimate future trends (subcriterion C2b; Table 1).

We projected future changes in bioclimatic suitability using machine-learning classification methods applied to 19 bioclimatic variables and calibrated with present environmental conditions within the potential distribution of each macrogroup. We used the estimated likelihood that bioclimate would become more suitable for a different macrogroup to assess future environmental degradation (subcriterion C2a; Table 1).

Finally, to assess disruption of biotic processes (subcriterion D2b; Table 1) for tropical mainland macrogroups we inferred the potential severity of defaunation (overexploitation of large mammals due to hunting and poaching; Dirzo et al., 2014), from a combination of spatial proxies that have been shown to relate to recent declines in large mammal abundance (Benítez-López et al., 2017; Supporting Information).

For all indicators, we estimated uncertainty by propagating plausible bounds through the analyses (Supporting Information).

We first assessed the indicators across the entire extent of each macrogroup ("regional assessment") and summarized patterns across formations; we then calculated indicator values for the distribution of each macrogroup in each country ("country-level assessment"). We used current threat score, T (a weighted sum of the number of macrogroups in each category using equal step weights; Butchart et al., 2007), to summarize ecosystem status in each country. Data Deficient or Not Evaluated macrogroups were excluded from this calculation.

To explore alternative scenarios of conservation action at the country level we evaluated the potential effect of controlling single or multiple threats influencing the assessment outcome for each macrogroup and the resulting national threat scores. We calculated a proxy for "intervention cost" as the minimum area that needs to be managed in order to downlist the threat level for one criterion by one step (i.e., from CR to EN, from EN to VU, and from VU to LC). For each country, each macrogroup was reassessed assuming one or more hypothetical actions were implemented. We determined whether

the overall category and the overall threat score improved with each combination of actions. The actions included seven types of interventions: reforest and restore historical forest distribution (addressing subcriteria A1 and A3); halt current deforestation (A2b); protect restricted distributions (B1, B2, B3); climate change adaptation (C2a); protection/restoration of water resources (C2b); control natural resource use (D1, D3); and control overexploitation of animal resources (D2b). We repeated this process 100,000 times with random combinations of interventions per macrogroup and country and identified the optimal combination with the lowest relative costs (combined area for all interventions for the country) and greatest effect (proportional change in threat score) among all combinations. For the optimal combination, we calculated the relative importance of each of the seven types of interventions.

3 | RESULTS

Historical declines in woodland cover between 1700 and 2000 (subcriterion A3) are unevenly distributed among and within formations (Figure 1). The three most extensive formations still retain a large proportion of their original cover. The other five formations have lost more than 50% of their original cover, and in the most extreme case, Tropical Dry Forest and Woodland has lost almost 80% of its historic range. Historical changes have accelerated in tropical formations and slowed in temperate ones, but current rates of change are much more variable (Figure 2). Significant declines in forest cover were observed in around half of the macrogroups.

Mean severity for most indicators of environmental degradation or biotic disruption showed no pattern across the formations in which they could be applied (Figure 2). Only one indicator–changes in intensity of human use in the last century–showed significantly higher mean severity values in tropical than in temperate forest formations (18.68 ± 8.0 and 9.71 ± 4.6, respectively; $t = 7.44$, d$f = 106.15$, $P < 0.001$; Supporting information).

Integrating all criteria, approximately 79.5 % (97 of 122 evaluated) of the tropical and temperate forest macrogroups of the Americas and Caribbean were eligible for threatened status, with 12 (9.8 %) being Critically Endangered (CR; Figure 3). In both regional and national-level assessments, the overall risk category is determined by spatial criteria A and/or B (60.6%), functional criteria C and/or D (20.6%), or combinations of both (18.8%). The proportion of macrogroups threatened exclusively by current and future declines (43.1%) is similar to those suffering historical declines (41.3%); 15.6% are threatened by both.

Risk of collapse is spatially variable. Seventeen macrogroups not threatened at the regional scale were threatened in at least one country. Country-level threat score

FIGURE 1 Historical changes in area covered by tropical and temperate (excluding boreal) forest formations between 1700 and 2000. Bar width is proportional to the estimated original area in 1700 (0.1 million km^2 for mangrove formation and 5.4 million km^2 for Tropical Lowland Humid Forest formation), light and dark grey portions represent the percentage of the original area loss prior to 1900 and after 1900, respectively, white is the proportion remaining in 2000
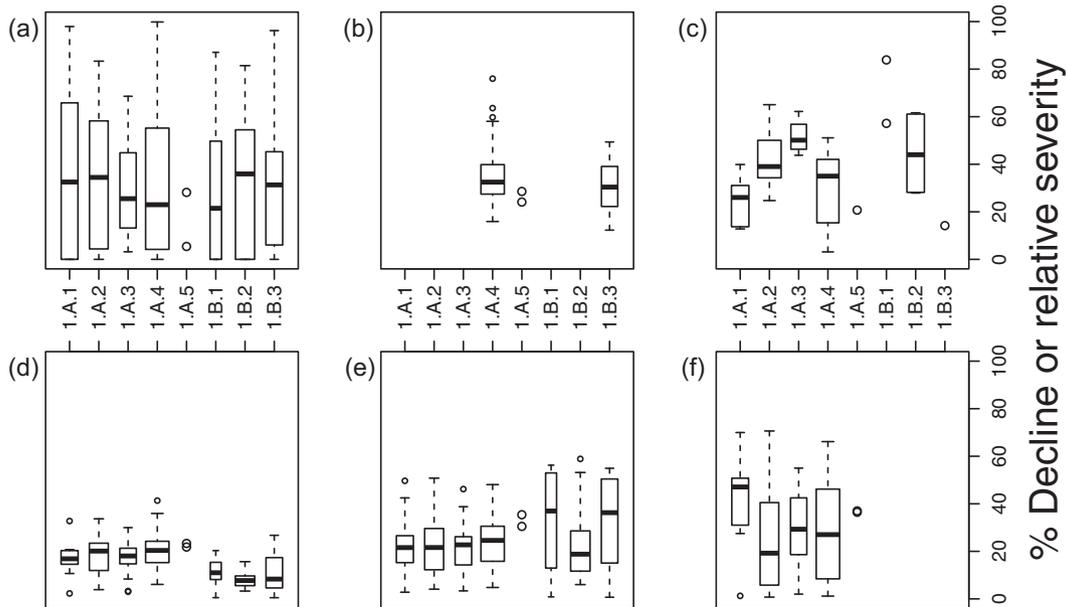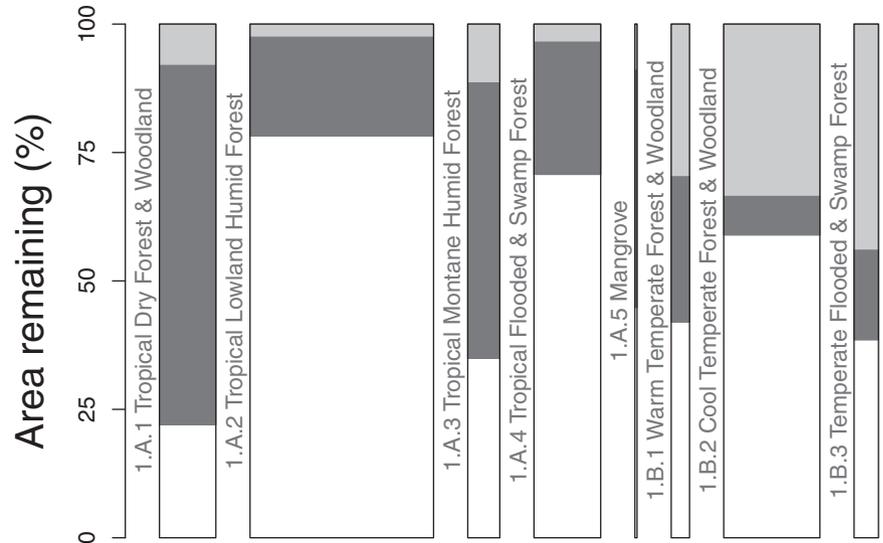
FIGURE 2 Estimated decline in area or mean relative severity for different indicators in different time-frames and summarized per formation. Values are scaled between zero (no decline or change) and 100 (collapse in area or function). (a) Current and future (2001–2051) change in forest cover extrapolated from models of proportional decline, (b) mean relative severity of projected future climate change (2000–2050), (c) mean relative severity of recent and future changes in surface water (2000–2050), (d) mean relative severity of historical increase in natural resource use due to increased human population (since 1750), (e) mean relative severity of recent increase in natural resource use (1950–2000), and (f) mean relative severity of current and future risk of defaunation (2000–2050). Formation codes correspond with formation names in Figure 1

was weakly rank-correlated with the threat score based on the regional assessment ($\tau = 0.290$, $z = 2.916$, $P < 0.01$; Figure 4).

The optimal strategies suggested by the cost-efficiency analysis could bring significant reductions in threat scores per country (Paired t-test for a difference >0.5 units, t = 1.808, df = 46, $P < 0.05$). Thirty four countries (72%) would require large investments in forest protection (halting deforestation and protecting remaining forest) and/or in forest recovery (reafforestation and restoration), but need less investment (between 0% and 40% of the total area cost) to counteract

ecosystem degradation in selected threatened forest types. However, at least 10 countries (21%) would need to focus predominantly on reversing ecosystem degradation (between 60% and 100% of total area cost) (Figure 5).

4 | DISCUSSION

Our risk analysis integrated diverse threatening processes (contemporary land use, historic legacies, changes in flood regimes, pressures from hunting and future climate change)
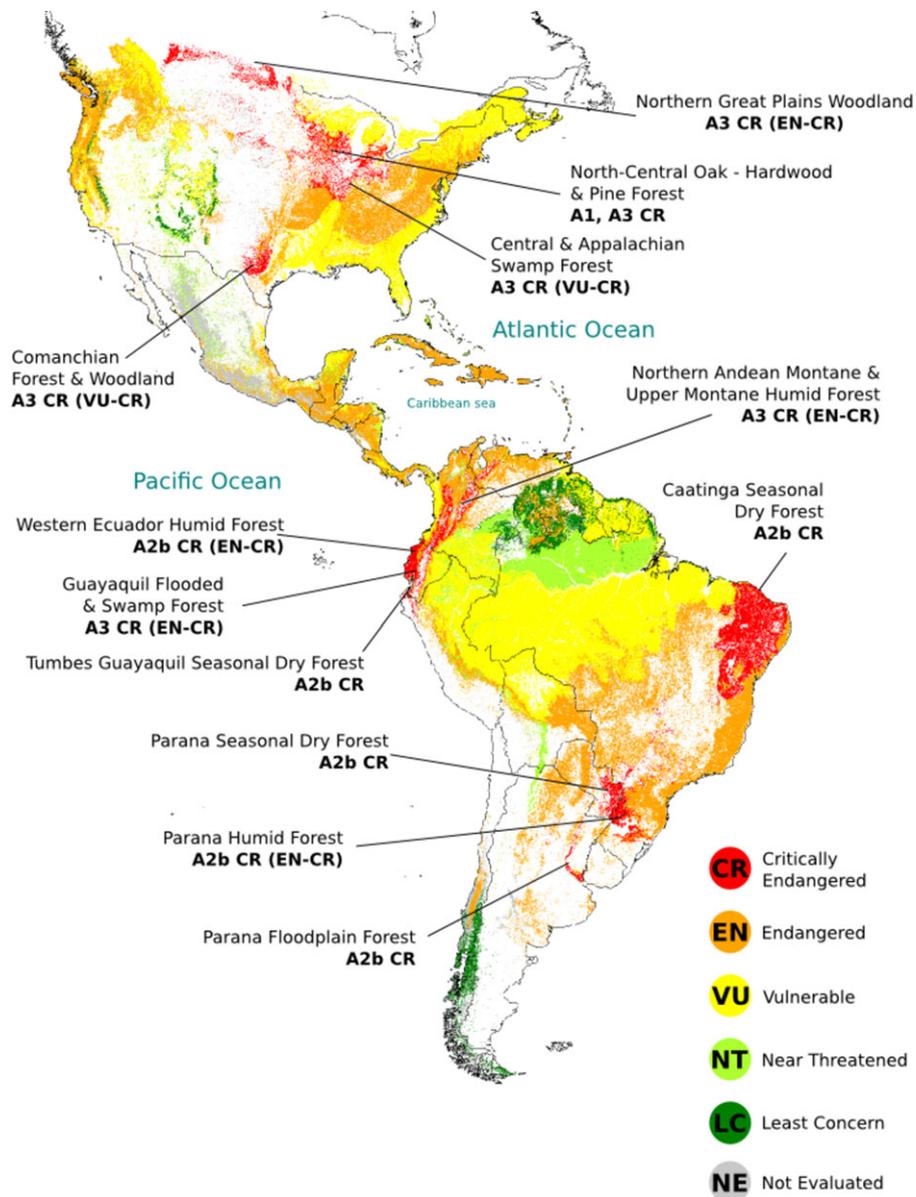
FIGURE 3   Map of potential distribution of tropical and temperate forest macrogroups in the Americas (boreal forests not included). Colors correspond to the IUCN Red List of Ecosystems categories assigned after applying eleven subcriteria. The 12 macrogroups with the highest risk of collapse are indicated along with plausible bounds and the subcriterion determining overall status. Potential distribution map was originally provided by NatureServe

across the full range of forest ecosystems in tropical and temperate Americas. Implementing risk assessments at two thematic levels allowed us to place countries in a regional context. Use of a relatively detailed ecosystem classification at these scales, multiple indicators of diverse processes, a systematic risk assessment that deals with uncertainties and our scenario analysis for conservation action enables a significant advance on previous global and regional risk assessments (Portillo-Quintero & Sánchez-Azofeifa, 2010; Tovar, Arnillas, Cuesta & Buytaert, 2013; Watson et al., 2016).

Although previous national risk assessments provide important insights from more detailed ecosystem classifications, they use noncomparable assessment units (Crespin &

Simonetti, 2015; Etter, Andrade, Amaya, & Arévalo, 2015; Herrera-F., 2015; Pliscoff, 2015; Rodríguez, Rojas-Suárez, & Hernández, 2010). Conversely, the broader units assessed here might overlook local trends and the lack of validation data can lead to exclusion of locally important macrogroups. Furthermore, our estimates of defaunation are coarse and only likely to be indicative of patterns across large regions. Future work needs to combine finer-resolution units of a common typology to fill gaps in the coverage of national assessments, while applying a suite of indicators to represent different threatening processes. Because most conservation action occurs at a national level, our cost effectiveness analysis was based on country-level assessments. We recognize that
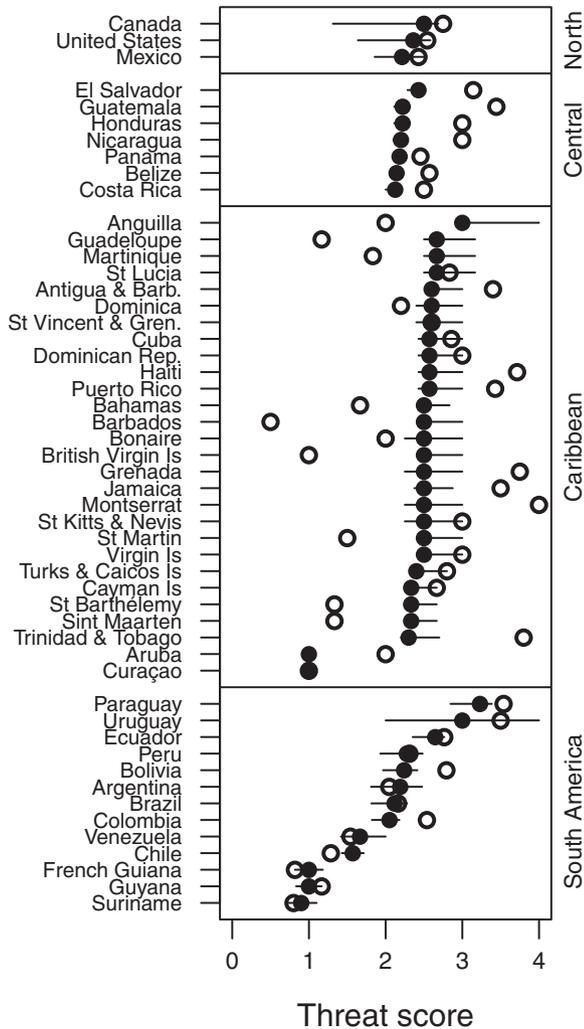
FIGURE 4 Ranking of countries according to the threat scores of tropical and temperate forest macrogroups (Boreal forests not included) based on country-level assessment (open circles), and compared with the threat score based on the regional-level assessment (closed circles). A value of $T = 0$ means all macrogroups are Least Concern, and a value of $T = 4$ means that all macrogroups are Critically Endangered. Uncertainty in regional-level assessment is represented by bars around estimate, uncertainty in country-level assessment is not shown

our conclusions are based on simplistic measures of costs (intervention area) and benefits (reduced threat score), and future analyses should complement them with information on national legal frameworks, economic constrains, cultural values, and social contexts of each country (IPBES, 2018).

Our regional risk assessment suggests that contemporary rates of forest decline and degradation not only exacerbate past impacts, but also affect a broadening suite of previously unexploited forest types in the Americas and the Caribbean. Among the different forest formations, Tropical Dry Forests and Woodland appear to face a double challenge, in addition to historical legacies of clearing, their distribution continues to be rapidly eroded by contemporary land use intensification. High levels of risk combined with low levels of protection

consign them to an ecological crisis (DRYFLOR et al., 2016; Portillo-Quintero & Sánchez-Azofeifa, 2010; Watson et al., 2016).

The most threatened forest macrogroups are not necessarily the most diverse or endemic. Three CR forest types are related to the Atlantic Forest and Cerrado biodiversity hotspots in Brazil, and four overlap with the Tropical Andes and Tumbes-Chocó-Magdalena hotspots (Mittermeier, Myers, Thomsen, da Fonseca, & Olivieri, 1998), but the rest are located in less diverse regions (e.g., Central Midwest Oak Forest, Woodland and Savanna in North America). Surprisingly, we found an overall lower threat score, and no CR forest types, in the hotspots of the California Floristic Province and the Chilean Winter Rainfall and Valdivian Forests. This was partly because we lacked an indicator of fire regimes, a major threat in these regions, and because macrogroups may be too coarse a proxy to detect the ecosystems at highest risk. Setting conservation priorities requires combined information on risk and conservation values (Marchese, 2015), but should also consider local constraints and opportunities (Bicknell et al., 2017).

Uneven deforestation rates are averaged in regional-level analyses, and those countries with lower local threat scores than their regional average therefore represent important conservation opportunities for widely depleted forest types. Some countries in the Caribbean, within the Amazon basin and the Guiana Shield may have an optimistic outlook on the status of their forests, with low threat scores (IPBES, 2018; Mittermeier et al., 1998). Other Caribbean and Central American countries, as well as Paraguay and Uruguay, have very high threat scores due to combined effects of high exposure to spatially clustered threats, high fragmentation and high pressure for agricultural development (Hansen et al., 2013; Nolte, le Polain de Waroux, Munger, Reis, & Lambin, 2016).

Protecting forest remnants and diversifying forest management practices, if effectively implemented, could reduce current and future declines and bring short- to medium-term changes in threat status. Accelerated reafforestation provides some ecosystem services (soil stabilization, carbon sequestration), but costs are high and full ecosystem restoration is unlikely (Cunningham et al., 2015; IPBES, 2018; Pinto et al., 2014). For temperate forests that show high historical loss with less severe current declines, or even positive current trends, the best approach is to promote reafforestation. For special cases, such as the deciduous forests of northeastern United States, which re-established after extensive historic conversion to cropfields and are now entering a second era of depletion (Thompson, Carpenter, Cogbill, & Foster, 2013), a mixed strategy of reafforestation and protection of regrowth is appropriate. These and other regenerating forests are likely to have undergone major changes in composition due to legacy effects of historical land conversion, timber harvesting and/or wildlife use. Historic impacts on the Atlantic forests and
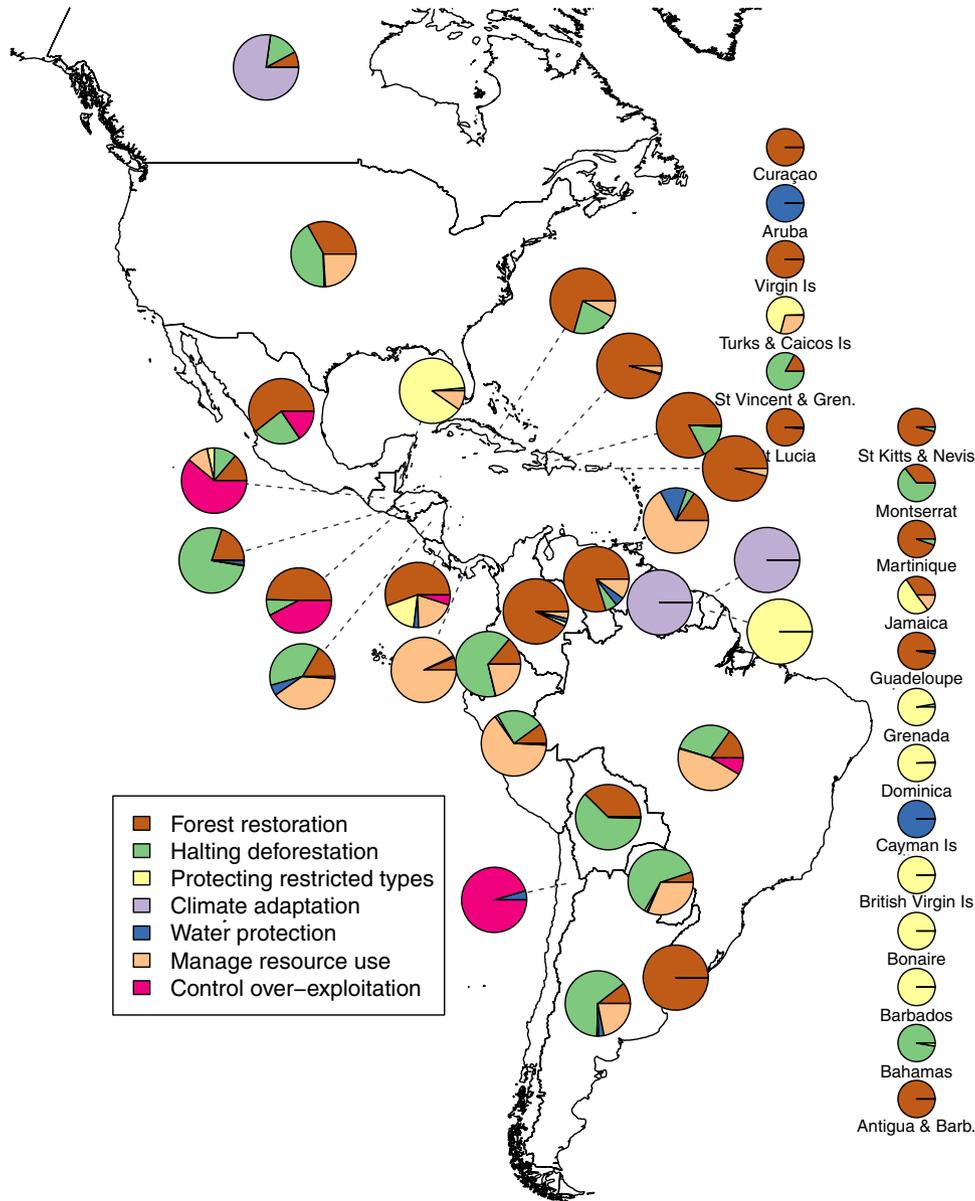
FIGURE 5 Map showing the optimal combination of strategies for each country. Smaller Caribbean countries are shown on the right. The pie represents the percentage area for different strategies for the optimal cost/effectiveness combination

Chaco region of South America were less severe, but these have undergone rapid depletion and fragmentation in the contemporary era (Ellis et al., 2010; Nolte et al., 2016; Pinto et al., 2014). New policies and effective monitoring have significantly reduced forest loss rates in the Brazilian Amazon (Hansen et al., 2013). However, success of antideforestation policies depends on several economic and social conditions, and, even within a country, similar policies can have contrasting results. Thus, compensation and incentives for private and public sectors have to be adapted to local frameworks (Gustafsson et al., 2012; Nolte et al., 2016; Pinto et al., 2014).

Degradation of environmental conditions or disruption of biotic processes are emerging risks to American forests, but their effect is often underestimated due to the lack of appro-

priate indicators and monitoring tools (Barlow et al., 2016). We approached these threats using indirect indicators of complex environmental processes including responses to changing water regimes in flooded forests and shifts in species composition, vegetation structure or vegetation phenology due to climate change (Keddy et al., 2009; Tovar, Arnillas, Cuesta, & Buytaert, 2013). Even with these limitations, our analysis found that functional symptoms contribute to the overall risk of collapse in almost 40% of threatened macrogroups.

These findings have implication for national-level conservation strategies. Assuming no economic, political, or social constraints, the optimal conservation strategies involve forest conservation, reafforestation, or restoration. However, certain countries will have to focus predominantly on managing other

threats. For example, controls of overexploitation will reduce risks to forests on the Caribbean coast of Mesoamerica, the Choco-Darien region and the Amazon (Brashares et al., 2014; Cooney et al., 2015). For countries in the Guiana Shield, our analysis for criterion C showed that climate change is the most urgent threat. Future expansion of protected area networks to include potential refuges would therefore enhance their adaptive capacity (Bicknell et al., 2017; Hannah et al., 2007).

By identifying and interpreting multiple threats, we can highlight effective actions to reduce risk of collapse by focusing on underlying causes and their spatial or functional symptoms. However, management of natural resources in human-dominated landscapes is often laden with conflicts. Transition from intensive land use to multifunctional landscapes offer one option for diversifying nature's contributions to improved livelihoods and human well-being (Griscom et al., 2017; IPBES, 2018). Strategies for effective action must be aligned with the broader social and natural context of each region or country, and consider practicalities of implementation (cost and opportunities), along with the social, political, or economic values of alternative actions.

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SUPPORTING INFORMATION

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