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CONTRIBUTED PAPER

Global drivers of mangrove loss in protected areas

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Abstract

Despite increasing efforts and investment in mangrove conservation, mangrove cover continues to decline globally. The extent to which protected area (PA) management effectively prevents mangrove loss globally across differing management objectives and governance types is not well understood. We combined remote sensing data with PA information to identify the extent and the drivers of mangrove loss across PAs with distinct governance types and protection levels based on categories developed by the International Union for Conservation of Nature (IUCN). Mangrove loss due to storms and erosion was prevalent across all governance types and most IUCN categories. However, the extent of human-driven loss differed across governance types and IUCN categories. Loss was highest in national government PAs. Private, local, shared arrangement, and subnational government agencies had low human-driven mangrove loss. Human-driven loss was highest in PAs with the highest level of restrictions on human activities (IUCN category I) due to mangrove conversion to areas for commodity production (e.g., aquaculture), whereas PAs that allowed sustainable resource use (e.g., category VI) experienced low levels of human-driven mangrove loss. Because category I PAs with high human-driven loss were primarily governed by national government agencies, conservation outcomes in highly PAs might depend not only on the level of restrictions, but also on the governance type. Mangrove loss across different governance types and IUCN categories varied regionally. Specific governance types and IUCN categories thus seemed more effective in preventing mangrove loss in certain regions. Overall, we found that natural drivers contributed to global mangrove loss across all PAs, whereas human-driven mangrove loss was lowest in PAs with subnational- to local-level governance and PAs with few restrictions on human activities.

KEYWORDS

coastal, conservation outcomes, IUCN management categories, management effectiveness, marine conservation

INTRODUCTION

Mangroves are highly productive coastal ecosystems that provide a range of ecological, economic, and social benefits, such as flood risk reduction, fish habitats, and carbon storage (Barbier et al., 2011; Donato et al., 2011; Laegdsgaard & Johnson, 2001; Menéndez et al., 2020). In recent years, global interest in, and funding for, mangrove conservation has also increased rapidly, particularly in the context of blue carbon (Macreadie et al., 2021), including a pledge of an estimated US\$4 billion

for securing a global coverage of 15 million ha of mangroves for carbon mitigation (Climate Champions, 2023; Global Mangrove Alliance, 2023). At the same time, mangrove cover continues to decline globally and mangrove forests are considered one of the world's most threatened ecosystems (Carugati et al., 2018; Worthington & Spalding, 2018). Furthermore, these declines are predominately driven by growing human pressure in coastal areas, including coastal development, pollution, and conversion of mangroves for aquaculture and agriculture production (e.g., rice farming) (Friess et al., 2019; Románach et al., 2018). Loss

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of mangroves also comes with an increase in ecosystem fragmentation and degradation (Bryan-Brown et al., 2020). The conservation of mangrove forests is thus critical to maintaining these ecosystems and the benefits they provide coastal communities. Therefore, the creation of effective strategies to promote mangrove conservation is needed (Roy, 2014). Multiple global agreements, such as the Convention on Biological Diversity (CBD), and international targets, such as the United National Sustainable Development Goals (SDGs), have played an important role in increasing the number and extent of protected areas (PAs). However, PA extent is not always a good measure of conservation success in achieving positive outcomes. A large number of PAs are not managed well and fail to achieve desired conservation goals (Gill et al., 2017; Joppa et al., 2016).

Deforestation in PAs remains high, and research is expanding on identifying patterns and drivers of protected forest loss and degradation in terrestrial forests (Wolf et al., 2021). Mangroves are a unique ecosystem in this regard because they are in intertidal zones and may be classified as either terrestrial forests or coastal and marine ecosystems (Friess et al., 2016). Mangrove loss is also less severe in PAs compared with unprotected areas (Turschwell et al., 2020). Yet, not much is known about the variables that shape the effectiveness of PA management to prevent mangrove loss in PAs at the global scale.

In particular, the type of governance has been increasingly noted as critical for positive conservation outcomes (Archibald et al., 2020; Muñoz Brenes et al., 2018). Governance of PAs refers to how decisions are being made and how power and responsibilities are exercised within PA boundaries (Golebie et al., 2022; Laffoley et al., 2019). Although decision-making bodies have some autonomy, their decision are often shaped by interactions with other decision-making entities (Fortnam et al., 2022). Governance of mangrove ecosystems is particularly complex as mangroves are in the intertidal zones and need to be governed across the marine and terrestrial interface as well as across multiple actors (Friess et al., 2016; Rog & Cook, 2017), depending on PA legal frameworks and resource tenure and rights that apply to PAs (Slobodian et al., 2018).

Although governance arrangements in mangrove PAs can be diverse and complex, the International Union for Conservation of Nature (IUCN) recognizes 4 main governance types, depending on who has control over decision-making, management authority, and responsibility for a PA: governance by the government (federal or national government or subnational government), shared governance (collaborative and joint governance), governance by private entities (nongovernmental organizations and private landowners), and governance by Indigenous peoples and local communities (IPLCs) (Bingham et al., 2017; Clements et al., 2018; Dudley, 2008; IUCN, 2022; Mitchell et al., 2018). Governance by government can refer to decision-making at a wide range of levels from national to local government. PAs governed by federal or national governments often have a centralized managed structure and thus in some cases have been criticized for being less embedded in the local context compared with those governed by local communities or Indigenous peoples or privately, which often allow for more stakeholder engagement and integration of

TABLE 1 Overview of International Union for Conservation of Nature (IUCN) protected area categories (Day et al., 2012).

Category	Description
Ia	Strict protection of biodiversity and possibly geological and geomorphological features; human visitation, use, and impacts are strictly controlled and limited to ensure protection of the conservation values; can serve as reference areas for scientific research and monitoring
Ib	Usually large, unmodified, or slightly modified areas; retain natural character and influence; no permanent or significant human habitation; protected and managed to preserve their natural condition
II	Large natural or near natural areas for protection of largescale ecological processes and their complement of species and ecosystems characteristic; provide a foundation for environmentally and culturally compatible spiritual, scientific, educational, recreational, and visitor opportunities
III	Protect a specific natural feature (e.g., landform, sea mount, submarine caverns, geological feature, or living feature, such as an ancient grove); generally small with high visitor value
IV	Protected and managed for a particular species or habitat; many need regular interventions to address requirements of particular species or to maintain habitats, but this is not a requirement of the category
V	Interaction of people and nature over time has produced an area of distinct character with significant ecological, biological, cultural, and scenic value; safeguarding the integrity of the interaction is vital to protecting and sustaining the area and its associated nature conservation and other values
VI	Conserve ecosystems, habitats, associated cultural values, and traditional natural resource management systems; generally large with most of the area in natural condition; proportion is under sustainable natural resource management; low-level nonindustrial use of natural resources is compatible with nature conservation and seen as one of the main aims of the area

local knowledge (Worboys et al., 2015). Governance by government, however, also includes PAs that are governed at the subnational scale (e.g., at the district or provincial governmental level), where ultimate governance authority may be held by locally based decision-makers (Borrini et al., 2013). The involvement of local levels of government thus could be important for effective protection, and conservation success may differ across government PAs at different levels based on the specific government decision-making authority and the subsequent management actions. However, there has been no global assessment of differences in mangrove protection outcomes in PAs across different IUCN governance types or between governance by government agencies at the national or subnational level.

Just as governance can influence conservation success, the management objectives of individual PAs also play a critical role in effective conservation. The IUCN defines 7 types of PAs based on management objectives, which are expected to translate into differing protection levels (Table 1) (Day et al., 2012, 2019). These range from strict reserve (Ia) and protected wilderness areas (Ib), which would be expected to have the highest

levels of restrictions on human activities and focus on protecting biodiversity, to protected landscape or seascape (V) and sustainable natural resource area (VI), which are managed for a range of human activities, including natural resource extraction, and aim to balance sustainable use of natural ecosystems with biodiversity protection (Day et al., 2019).

Effectively implemented PAs with high levels of protection, such as IUCN category I, are theoretically more effective in maintaining or increasing protected species abundance because they have the highest restrictions on human activities and do not allow extractive uses, such as forestry or agriculture (Edgar et al., 2014; Gill et al., 2017; Sala et al., 2018). Yet, highly protected PAs often face challenges associated with equity and well-being of people and have sometimes been criticized for having poor compliance because of inadequate management resources and failures to account for the local context of PAs, such as high local dependency on natural resources or traditional uses (Andradi-Brown et al., 2023; Campbell & Gray, 2019; Woodhouse et al., 2018). In contrast, there has been an ongoing debate regarding biodiversity outcomes of PAs with low levels of protection (e.g., categories V and VI) and whether these areas should be counted toward global protection targets as given that they allow for extractive resource use to support local community well-being (Locke & Dearden, 2005; Shafer, 2015). However, these areas can deliver biodiversity benefits, albeit at lower levels than highly PAs (Andradi-Brown et al., 2023). However, empirical research is lacking that explores mangrove conservation outcomes across PAs with different levels of protection.

Thus, we explored whether there are differences in drivers of mangrove loss based on PA governance and management. We combined a 16-year global time-series data set on mangrove loss and its drivers with data on global PA coverage and characteristics to assess mangrove cover change in PAs across different governance and management types over time. We hypothesized that mangrove loss varies across different governance types and that governance types that place governance authority at more local levels have a greater ability to reduce mangrove loss. We also hypothesized that mangrove loss is low in PAs with high protection status (IUCN categories I & II) because these areas have high restrictions on human use, which we expected to reduce impacts on protected ecosystems. Given the importance of different drivers of mangrove loss in different regions globally (Friess et al., 2019) and differences in mangrove governance systems in different continents (Slobodian & Badoz, 2019), we also tested the hypothesis that effects of PA governance types and PA categories vary by region. We sought to provide novel insights into the type of governance and protection levels on mangrove conservation.

METHODS

Mangrove loss drivers

The mangrove loss time series was estimated from 2000 to 2016 based on a combination of historical Landsat satellite imagery

(Giri et al., 2011) and mangrove forest change detection models (Goldberg et al., 2020; Lagomasino et al., 2019) (workflow in Appendix S11). The Landsat surface reflectance tier 1 data archive and all remote sensing analyses were completed end-to-end in Google Earth Engine, given its capacity to process large volumes of global-scale analysis-ready Landsat data (Gorelick et al., 2017). All satellite imagery was preprocessed to surface reflectance (Vermote et al., 2016). Clouds and cloud shadows were masked following methods outlined in Foga et al. (2017). The resulting Landsat images were corrected for differences in sensor configurations between Landsat 5TM, 7 ETM+, and 8 OLI with harmonization algorithms developed by Roy (2014). The normalized difference vegetation index (NDVI), a metric closely associated with forest condition (Pettorelli et al., 2005), was calculated based on the difference in near-infrared and red spectral reflectance bands divided by the sum of the 2 values for every preprocessed Landsat image in the collection. We derived a reference map for 2000 based on the median NDVI value across all valid pixels (e.g., those not removed during cloud and shadow masking) from January 1998 through December 2001 covering Landsat 5 TM and Landsat 7 ETM+ images. Individual pixels with <10 quality Landsat observations were removed from the analysis. The reference NDVI map for 2000 was then subtracted from all individual NDVI images calculated for each satellite observation between January 2001 through December 2016 based on an iterative approach as outlined in Goldberg et al. (2020). We summed all the differences between the reference period and each individual image during the observation period for each overlapping pixel. This produced a cumulative anomaly that was normalized based on the total number of images with non-null values for individual pixels returning an average long-term NDVI change over the observation period. The resultant long-term NDVI change was used to separate permanent loss from intact mangrove forest with a change threshold of -0.2 that occurred in the Global Mangrove Forests Data set (Giri et al., 2011) as defined previously (e.g., Goldberg et al., 2020; Lagomasino et al., 2019).

We used a machine-learning-based classification approach to map spectral-based land cover in all areas marked as loss. We generated a 2016 Landsat image mosaic from imagery between 2014 and 2018, employing a similar image preprocessing approach. A visual interpretation of the 2016 Landsat Mosaic and high-resolution imagery from Google Earth was used to categorize multiple land-cover types based on dominant visual characteristics: wetland, dry land, and open water. We selected training points distributed across $1168\ 1\times 1^\circ$ grid cells containing mangrove forest in the year 2000. The predictor variables—NDVI, normalized difference moisture index, modified normalized difference water index, green chlorophyll vegetation index, surface reflectance, ratio54, and ratio35—were extracted for each training point and applied to a random forest classifier to run the final global classifications, owing to its comparatively high performance on global classification problems (Gareth et al., 2013) and mangrove mapping (Mondal et al., 2019). A single global classification of the 3 land-cover types was generated for 2016 that captured land-cover change from mangroves in 2000 to other land covers in 2016.

Based on the spectral signatures, classified from the random forest modeling and a novel recursive partition model with several open-source data sets, we separated each land-cover category into one of 5 loss driver categories: erosion, commodities production (i.e., aquaculture and agriculture), settlement, non-productive conversion, and extreme weather events. Detailed instructions on the method are in Goldberg et al. (2020). Briefly, erosion was defined as loss intersecting a river or coastline connected to the open ocean, as derived from the 30-m-resolution global forest change 2016 (Hansen et al., 2008) water mask and the JRC global surface water 2016 occurrence layer (Pekel et al., 2016). Human settlement-driven conversion to impervious surfaces was identified based on the global human settlement layer (GHSL) (Pesaresi & Freire, 2016). The conversion to commodities production used the Global Food Security-Support Analysis Data Cropland Extent 30-m (GFSAD-30) layer (38–44) to mask all agricultural areas. The remainder of the wet-soil-converted pixels were assigned to the dieback class (Thenkabail et al., 2021). To identify the potential extent of human intervention, we derived a human influence layer based on a 5.5-km zone around the GRIP-4 global roads data set (Meijer et al., 2018) and the GHSL human settlement data set (Pesaresi & Freire, 2016). The additional zone helped capture mangrove losses associated with small-scale cutting near roads or settlements and hydrologic changes resulting from built environments. We defined a nonproductive conversion from mangrove to an unused land type as one that had not been converted to commodities production or settlement or that transitioned to open water or mudflat through natural processes, such as erosion. Losses that occurred outside the human influence zone were assigned to the extreme weather events class on the basis that losses occurring at a significant distance from human settlements likely saw little direct anthropogenic influence; thus, the loss was assumed to result from an extreme event, such as a drought or cyclone.

Protected areas

To assess mangrove loss in existing PAs, we acquired data on PAs from the World Data Base on PAs (WDPA) (UNEP-WCMC & IUCN, 2020). We used the database to extract information on PA location, size, designation year, governance type, and IUCN category for all PAs that contained mangroves in AD 2000, that is, at the start of our mangrove loss time series.

We included all 4 IUCN governance types in our analyses (national and subnational government, shared governance, private entities, and IPLCs [Borrini et al., 2013]). Following IUCN guidelines (Borrini et al., 2013), shared governance included joint and collaborative governance arrangements, and private governance included private landowners, nonprofit organizations, and for-profit organizations. Although national and subnational governance are both governance by government, we kept these types separate to examine whether there is a difference in mangrove loss in PAs governed by government agencies at the national level compared with the local and municipal levels.

Data analyses

All statistical tests were run in R (R Core Team, 2021). All spatial analyses and maps were produced in ArcGIS 10.6.1. We combined the WDPA layer with a spatial mangrove layer from 2000 (Giri et al., 2011), which also formed the basis for the mangrove loss data set, to identify PAs that contained mangroves in 2000. This resulted in the selection of 3010 PAs. We further selected PAs with a minimum mangrove extent of 1 ha that were established before or in 2000 and had at least one of their IUCN category or governance type reported. The 1-ha area corresponded to approximately 11 Landsat nominal 30 × 30-m pixels. This threshold is a common forest area minimum mapping unit and allows potential change to occur in at least one pixel (Giri & Muhlhausen, 2008; Morin et al., 2021). Selection of PAs reported as established before or in 2000 was done to ensure that all PAs analyzed for mangrove loss existed throughout the analysis period. Out of the 3010 PAs, 1260 PAs were established before or in 2000 for the governance analyses and 980 PAs for the IUCN analyses. The PAs for the governance analyses included PAs with national government ($n = 770$), subnational government ($n = 309$), shared governance or joint governance ($n = 114$), private entities ($n = 42$), and IPLCs ($n = 25$). The 980 PAs selected for the IUCN analyses included category I ($n = 135$), category II ($n = 175$), category III ($n = 60$), category IV ($n = 227$), category V ($n = 255$), and category VI ($n = 128$).

We evaluated the presence or absence of mangrove loss in each PA (0,1) to detect the PAs that had lost mangroves over the 16 years. We calculated the percentage of mangrove loss in each PA by dividing the total amount of mangrove loss between 2000 and 2016 in each PA by the initial mangrove area in 2000. In addition, we divided the total loss of mangrove area in each governance type and each IUCN category over the 16 years by the initial mangrove cover in 2000 to calculate the percentage of mangrove area that has been lost in each type and category globally.

We fitted a generalized linear model (GLM) with family = binomial and link = logit to identify differences in the proportion of PAs that lost mangroves in each governance type and IUCN category. A Tukey test was used to make pairwise comparisons to identify differences in the proportion of mangrove loss between each combination of governance type and each combination of IUCN category.

To test for differences in percent mangrove loss, we employed a modified Kruskal–Wallis for zero-inflated data (ZIKW) in the ZIR package to account for the high number of PAs with zero or very low loss values (Wang et al., 2023). A Mann–Whitney U test with Bonferroni correction was employed to assess pairwise comparisons or percent mangrove loss between each combination of governance type and each combination of IUCN category.

To detect regional differences in mangrove loss within distinct governance types and IUCN categories, we created 3 governance categories, including government (national and subnational), nongovernment (IPLCs and private), and shared governance to ensure an adequate number of PAs in each cell

TABLE 2 The distribution of protected mangroves per governance type ($n = 2347$) and International Union for Conservation of Nature (IUCN) category ($n = 2000$).

	No. of PAs	Area of PAs (km ²)	Mangrove area in PAs (km ²)	Percentage of total protected mangrove area
Governance				
National government	770	849,996	24,522	62.3
Subnational government	309	130,829	5337	13.5
Shared	114	222,164	8307	21.1
Private	42	6728	93	0.2
IPLC	25	30,953	1129	2.9
IUCN				
I	135	55,245	6100	18.9
II	175	214,003	8672	26.9
III	60	4218	205	0.6
IV	227	46,371	3055	9.5
V	255	193,557	7441	23.1
VI	128	321,648	6775	21.0

Abbreviations: IPLC, Indigenous peoples and local communities; IUCN, International Union for Conservation of Nature; PA, protected area.

in our analyses. For IUCN categories, we created 3 categories ranging from high levels of protection to low levels of protection by combining categories I and II, categories III and IV, and categories V and VI. We then used a ZIKW with a Bonferroni-corrected Mann–Whitney U test to detect statistical differences between each combination of the 3 governance types and each combination of the 3 IUCN categories.

RESULTS

Mangrove protection based on governance and IUCN category

Global coverage of mangrove protection was uneven across the 5 governance types ($H = 45.023$, $df = 4$, $p < 0.001$) (Appendix S1). The majority of mangroves globally were protected by national (62.3%) and subnational government agencies (13.5%), followed by shared governance arrangements (21.1%) (Table 2). Privately governed areas contained the smallest percentage of protected mangroves (0.2%) and most of these PAs were in North America (Figure 2a). The IPLCs contained 2.9% of protected mangroves and most of these were in Oceania and Southeast Africa (Figure 2a).

Global coverage of protected mangroves across IUCN categories differed significantly ($H = 68.581$, $df = 5$, $p < 0.001$) (Appendix S1). Mangrove protection was almost equally split between PAs with either high (45.8%, category I and II) or low levels of protection (44.1%, categories V & VI) (Table 2). Only 10.1% of protected mangroves were in PAs with medium levels of protection, including category III (0.6%) and IV (9.6%). The majority of categories I and II PAs were in Asia, whereas most PAs in categories V and VI were in North America (Figure 2b).

Mangrove loss across governance types

Across governance types, private PAs performed the best with regard to mangrove loss. In terms of the total area of mangroves lost in each governance type, private PAs lost the least area of mangroves from 2000 to 2016 (0.88 km² lost) and national government PAs the most (342.63 km² lost). (Figure 1a). In terms of percent loss of mangrove cover, subnational government areas (1.82%) and IPLCs (1.67%) lost the highest percentage of their mangrove cover, whereas private PAs lost the smallest percent (0.95%) (Figure 1b).

Governance type predicted the frequency with which PAs lost mangroves from 2000 to 2016 (Table 3). Subnational PAs had significantly lower frequencies of loss compared with national PAs ($Z = -4.531$, $p < 0.001$) and IPLCs ($Z = 2.763$, $p = 0.039$). Of subnational PAs, 19.4% exhibited mangrove loss, whereas 33.5% of national PAs and 44.0% of IPLCs lost mangrove cover (Table 3).

National government PAs had the highest mangrove loss from human drivers in terms of area and percent loss, mainly from the conversion of mangroves to commodities production. Three national PAs lost more than 50% of their mangrove cover; one PA lost 95% of mangrove cover (Appendix S12). All other governance types mainly lost mangroves due to natural drivers, including erosion, and, in the case of IPLCs and private PAs, extreme weather events (Figure 1a,b).

Governance type significantly influenced mangrove loss for both categories of loss drivers: human-driven loss and natural-driven loss. Percent mangrove loss was statistically different across governance types for both human-driven loss ($H = 179.989$, $df = 4$, $p < 0.001$) and natural-driven loss ($H = 351.347$, $df = 4$, $p < 0.001$). Percent loss in national government PAs was significantly different from percent loss

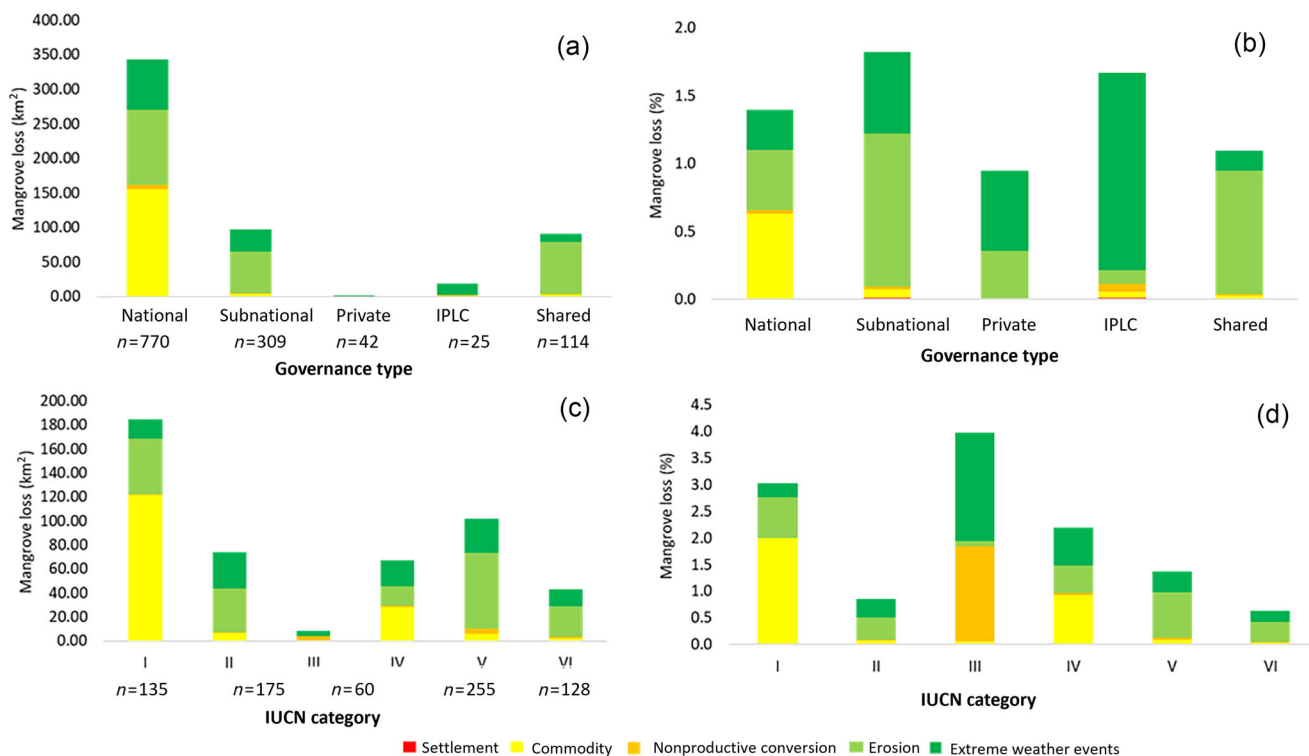


FIGURE 1 (a) Mangrove loss under each governance type; (b) total percent loss of mangrove cover in each governance type; (c) mangrove loss for each International Union for Conservation of Nature (IUCN) category; and (d) total percent loss of mangrove cover in each IUCN category (IPLC, Indigenous peoples and local communities).

in subnational PAs for both human-driven loss ($U = 4.471$, $p = 0.001$) and natural-driven loss ($U = 4.732$, $p = 0.001$) (see Appendices S2 & S3).

At the level of individual drivers of loss, mangrove loss was different across governance types for all drivers (see Appendix S4). Pair-wise comparisons showed that national government PAs were again significantly different from subnational PAs for mangrove loss due to extreme weather events ($U = 3.189$, $p = 0.020$), erosion ($U = 3.571$, $p = 0.010$), and commodities production ($U = 5.949$, $p < 0.001$). Private PAs were significantly different from national PAs ($U = 3.875$, $p < 0.001$), IPLCs ($U = -2.584$, $p < 0.001$), and shared governance PAs ($U = -2.757$, $p = 0.026$) for loss to commodities production. Private PAs were also significantly different from IPLCs for loss due to settlement ($U = -0.977$, $p < 0.001$) (Appendix S5).

Mangrove loss across IUCN categories

The number of PAs that lost mangroves differed significantly by IUCN category (Table 3). The IUCN category VI had the largest proportion of PAs that lost mangroves (44.5%) and was statistically significantly different from PAs in category I ($Z = 2.875$, $p = 0.043$), in which 24.9% of PAs had loss. Category III ($Z = 4.104$, $p < 0.001$) had 11.7% of PAs showing loss, and category V ($Z = 3.897$, $p = 0.001$) had 24.7% of PAs with mangrove loss. The PAs in category III also had a significantly

different frequency of loss compared with PAs in category IV ($Z = 3.188$, $p = 0.016$; 33.9% of PAs with loss) and category II ($Z = -3.236$, $p = 0.014$; 35.9% of PAs with loss) (Table 3).

However, in terms of total mangrove loss, I PAs performed the worst. Category I PAs had the highest loss (185 km²) followed by PAs in category V (102 km²) (Figure 1c). PAs in category III had the lowest loss in terms of area (8.21 km²). Yet, PAs in category III had the highest percent loss (3.97%) followed by PAs in category I (3.03%) (Figure 1d). A small number of PAs in categories I and IV lost a high percentage (i.e., >20%) of their mangrove cover (Figure 3). These PAs were governed by national and subnational agencies.

The 6 IUCN categories significantly affected mangrove loss for both human ($H = 257.191$, $df = 5$, $p < 0.001$) and natural ($H = 417.742$, $df = 5$, $p < 0.001$) loss drivers. Specifically, regarding human-driven loss, I PAs did not perform well. Human-driven loss was highest in category I in terms of area (122.6 km²) and percentage of human-driven loss (2%), as well as in terms of human-driven loss as a percentage of overall mangrove loss in this category (66.1%). In comparison, human-driven loss accounted for 8.2% of total mangrove loss in category VI and 10.0% in category V, even though PAs in both these categories had typically lower levels of restrictions regarding human use compared with category I.

For natural-driven loss, PAs in IUCN categories II and III performed well relative to other IUCN categories. Natural-driven loss was lowest in PAs in category III (Figure 3), and

TABLE 3 Tukey contrasts comparing the proportion of protected areas losing mangroves among different governance types and International Union for Conservation of Nature (IUCN) protected area categories.

First governance type	Second governance type	Estimate	SE	ζ	p
Subnational government	National government	−0.73774	0.16282	−4.531	<0.001*
Private	National government	−0.76155	0.4003	−1.902	0.285
IPLC	National government	0.4442	0.41008	1.083	0.793
Shared	National government	−0.12873	0.21693	−0.593	0.972
Private	Subnational government	−0.02381	0.41844	−0.057	1.000
IPLC	Subnational government	1.18195	0.42781	2.763	0.039*
Shared	Subnational government	0.60901	0.24882	2.448	0.089
IPLC	Private	1.20576	0.5628	2.142	0.179
Shared	Private	0.63282	0.44231	1.431	0.574
Shared	IPLC	−0.57294	0.45118	−1.27	0.681
First IUCN category	Second IUCN category				
II	I	0.34872	0.24979	1.396	0.716
III	I	−1.05033	0.44604	−2.355	0.161
IV	I	0.30722	0.23851	1.288	0.780
V	I	−0.14031	0.24148	−0.581	0.992
VI	I	0.75442	0.26241	2.875	0.043*
III	II	−1.39906	0.4323	−3.236	0.014*
IV	II	−0.04151	0.21171	−0.196	1.000
V	II	−0.48904	0.21505	−2.274	0.193
VI	II	0.4057	0.23831	1.702	0.513
IV	III	1.35755	0.42588	3.188	0.016*
V	III	0.91002	0.42755	2.128	0.258
VI	III	1.80475	0.43972	4.104	<0.001*
V	IV	−0.44753	0.20183	−2.217	0.216
VI	IV	0.4472	0.22646	1.975	0.341
VI	V	0.89473	0.22959	3.897	0.001*

Note: Percentage of PAs with mangrove loss: national, 33.5%; subnational, 19.4%; private, 19.0%; IPLCs, 44.0%; shared, 30.7%; IUCN I, 27.4%; IUCN II, 34.9%; IUCN III, 11.7%; IUCN IV, 33.9%; IUCN V, 24.7%; IUCN VI, 44.5%.

Abbreviation: IPLC, Indigenous peoples and local communities.

*Significant comparisons.

percent loss in category III differed significantly from PAs in categories I ($U = -3.438$, $p = 0.034$), II ($U = -4.96$, $p < 0.001$), IV ($U = 3.968$, $p = 0.009$), and VI ($U = 6.569$, $p < 0.001$) (see Appendix S6). Naturally driven loss differed significantly between category II and category VI PAs ($U = -3.886$, $p = 0.004$) and between category V and category VI PAs ($U = 5.489$, $p < 0.001$) (Appendix S7). Natural-driven losses were also lower in category II PAs and category V PAs than in category VI PAs (Figure 3).

We also detected statistical differences for all individual drivers of loss across IUCN categories. Specifically, for commodity-driven loss, category IV PAs showed the highest loss relative to other IUCN categories. Pairwise comparisons indicated that loss to commodities production was statistically different and higher in PAs in category IV compared with both categories II ($U = -4.193$, $p = 0.006$) and V ($U = 3.674$, $p = 0.014$). PAs in category IV also had higher loss due to non-

commodities compared with PAs in category I ($U = -3.367$, $p = 0.033$) (Appendix S8 contains detailed comparisons of individual drivers).

Spatial differences in drivers across governance types and IUCN categories

Mangrove loss in PAs was more prevalent in Asia than in other regions. Specifically, mangrove loss in national and subnational PAs due to human drivers was more prevalent in Asia compared with PAs in these categories in Oceania ($U = -7.831$, $p \leq 0.001$), North America ($U = -5.33$, $p < 0.001$), and Africa ($U = -6.516$, $p < 0.001$) (Appendices S10 & 13). Mangrove loss in national and subnational government PAs in Asia was predominantly driven by the conversion of mangroves to commodities production, such as rice and aquaculture (Figures 2c

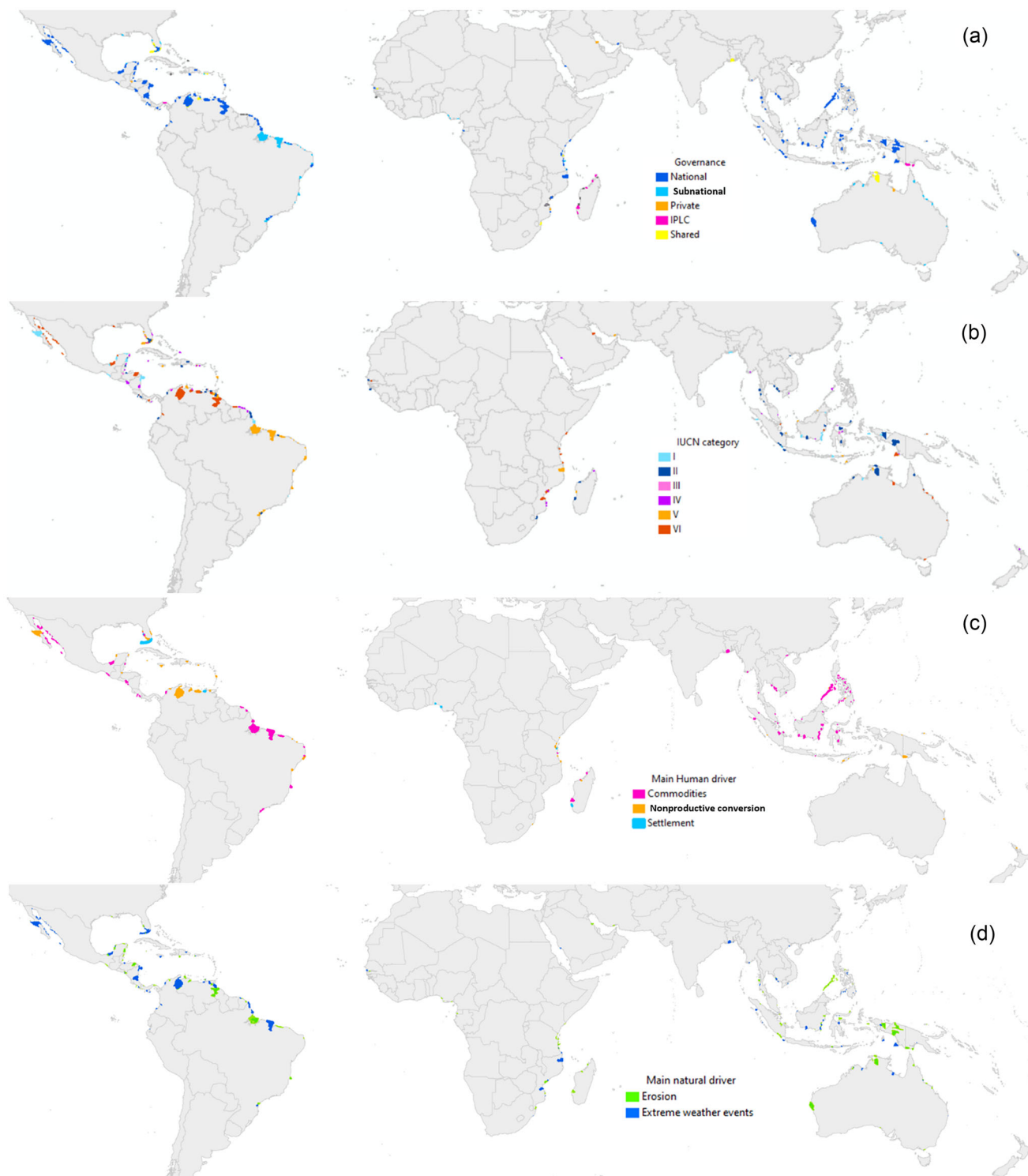


FIGURE 2 Distribution of (a) protected mangrove areas by governance type, (b) protected mangrove areas by International Union for Conservation of Nature (IUCN) protected area category, (c) the main human driver of mangrove loss for each protected area, and (d) the main natural driver of mangrove loss for each protected area.

& 4). Human-driven mangrove loss in shared governance PAs in South America occurred mainly because of nonproductive conversion (Figure 4).

There were regional differences in mangrove loss across IUCN categories (see Appendix S9). Overall, PAs across all categories were less effective in preventing human-driven loss

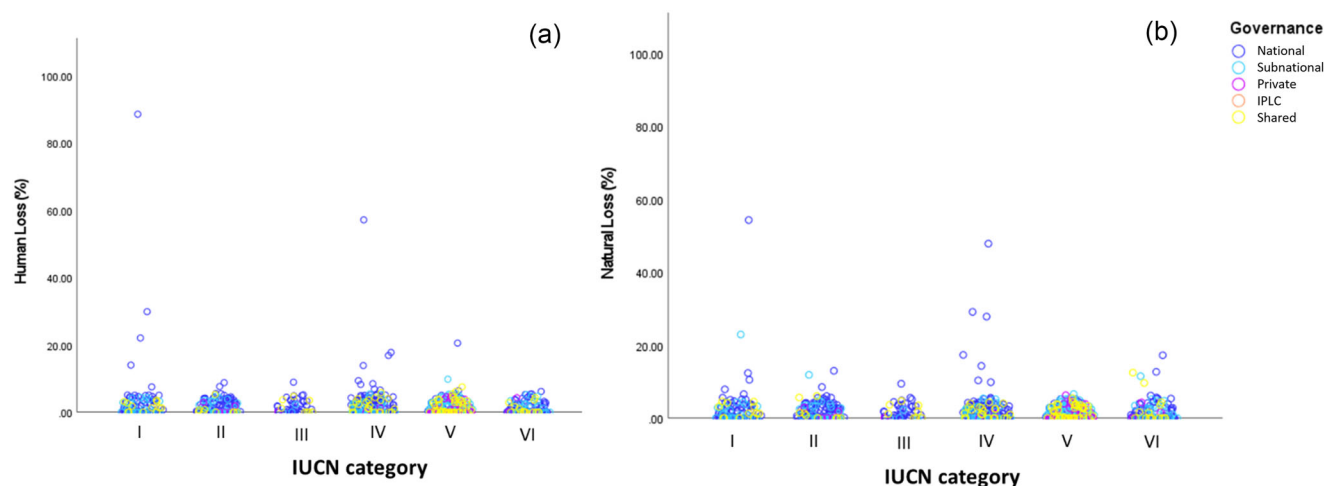


FIGURE 3 Percent (a) human-driven loss and (b) naturally driven loss of mangroves in individual protected areas in each International Union for Conservation of Nature (IUCN) protected area category by governance type (IPLC, indigenous peoples and local communities).

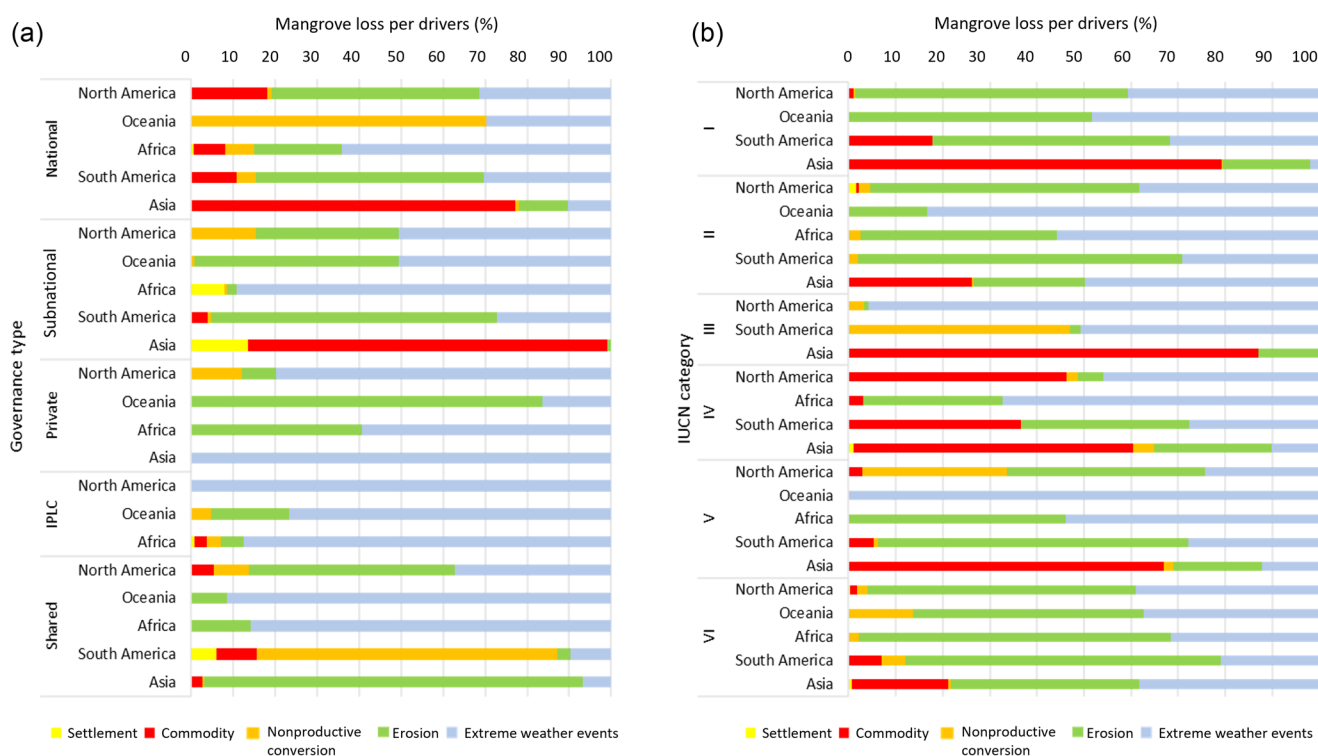


FIGURE 4 Mangrove loss as a percentage of total mangrove loss in each region for individual loss drivers by (a) each governance type and (b) each International Union for Conservation of Nature (IUCN) protected area category (IPLC, indigenous peoples and local communities).

in Asia and South America than in other regions (Appendix S13). For example, PAs with higher levels of protection (I & II) in Oceania in particular had significantly lower human-driven loss compared with categories I and II PAs in South America ($U = -6.161, p < 0.001$) and Asia ($U = -3.813, p < 0.001$) (see Appendix S9). The same pattern was observed for PAs in categories III and IV. PAs with lower levels of protection (categories

V & VI) were more effective in preventing human-driven loss in North America compared with South America ($U = -3.866, p = 0.007$) and Asia ($U = -3.785, p = 0.004$) and in Africa compared with Asia ($U = -3.152, p = 0.044$). In categories I and III PAs, human-driven mangrove loss due to conversion to commodities production mainly occurred in Asia (Figures 2d & 4), even though this use is not allowed in these IUCN categories.

DISCUSSION

We conducted the first global analysis of variations in mangrove loss and its human and natural drivers across governance types (i.e., government, private, IPLCs, and shared) and IUCN management categories. Combining global remote sensing mangrove cover loss data and data on MPA attributes, we found that mangrove loss rates vary based on PA governance type and IUCN category.

For human-driven loss, our results are in line with increasing calls for less top-down and more collaborative governance of PAs compared with top-down approaches (e.g., Begum et al., 2021; Di Franco et al., 2020; Petrić & Mandić, 2021; Ulate et al., 2018). Although PAs across all governance types showed similar mangrove loss rates due to natural drivers, human-driven loss mainly occurred in national government PAs. These areas contained the largest proportion of mangroves around the globe but were least effective in preventing human-driven mangrove loss compared with all other governance types. We also found a difference in mangrove loss between national and subnational governance types; government agencies at the regional level were more effective at reducing mangrove loss than at the national level, indicating that even in state-governed PAs, the level of government can influence conservation outcomes.

Our results suggest that regional contexts also shape conservation outcomes. Government PAs were least effective in preventing human-driven mangrove loss in Asia due to the conversion of mangroves for commodity production, such as agriculture and aquaculture, which are the main drivers of mangrove loss in this region in general, including outside PAs (Richards & Friess, 2016). In addition, top-down economic pressures from governments also have an impact on mangrove forest conversions in Asia, such as aquaculture production targets (Rimmer et al., 2013), which could make it more difficult to prevent the expansion of this use in government PAs that provide habitats for production of commodities, such as aquaculture. PAs governed by national and subnational management agencies might be more affected by the larger context, such as economic policy decisions, and needs of growing, dense populations (Geist & Lambin, 2001; Richards & Friess, 2016) than other governance types. Thus, a tailored approach that considers specific drivers of mangrove loss and regional contextual factors could be important to increase mangrove conservation success.

We also found that the regional contexts might shape the success of shared and bottom-up governance in preventing mangrove loss. PAs with private or shared governance in our study lost fewer mangroves in Asia compared with other governance types. Sharing power between government and nongovernmental entities thus seemed to be more effective in preventing mangrove loss in this region. Shared governance, however, might not necessarily lead to effective conservation globally as PAs in this governance type had high mangrove loss due to a mix of conversion to commodities production and nonproductive conversions in South America. A potential explanation could be that shared governance in this region might not allow for the real participation of local partners

(Shafer, 2020) and a lack of equal power distribution (Casson, 2015; Gardner et al., 2018; Mollick et al., 2021). Other potential explanations could be financial sustainability issues (Gardner et al., 2018).

Our findings that total mangrove loss was lower in PAs not governed by national governments suggest important implications for global and national conservation strategies and climate mitigation actions and investments. Mangrove forests are highly effective storehouses of carbon with rapidly increasing funding and interest in enhancing global mangrove cover for improved carbon storage (Richards et al., 2020). However, these blue carbon actions are typically driven by national governments through national or international agreements. The same applies to international commitments to increase the protection of mangroves (e.g., via the 30 × 30 initiative [Global Mangrove Alliance, 2023]). Yet, we found that national government PAs were not effective in conserving mangrove extent compared with other governance types. Although PAs at the more local level could enable access of local and Indigenous communities to national and international carbon markets, thereby pioneering novel financing options (Howard et al., 2017), these PAs only covered a small portion of mangroves. More effective governance by national government agencies or an increase in shared or more localized governance thus seems critical for ensuring the effectiveness of international agreements that focus on the conservation of mangroves and their associated ecosystem services.

Similarly, IUCN categories with the strictest level of protection actually performed worse in terms of preventing mangrove loss relative to categories with fewer restrictions on human use. The highest mangrove loss due to human drivers occurred in category I, mainly due to conversion to commodities production, even though IUCN I PAs typically had the highest level of restrictions of human use (Day et al., 2019; Dudley, 2008). PAs with lower protection levels that allowed for sustainable resource use (IUCN VI), in contrast, lost the least percentage of mangroves due to human drivers. This finding is contrary to the expectation that PAs in these categories are less effective in preventing human-driven loss as they allow for sustainable resource use (Locke & Dearden, 2005).

Globally, the greatest loss of mangrove cover in category I we found contrasts with the findings from a study of all forest cover by Leberger et al. (2020), who found a lower loss of global forest cover in categories I and II than other PAs. PAs with high levels of restrictions thus seem globally less effective in preventing mangrove cover loss compared with general forest loss (Leberger et al., 2020). Yet, at the regional scale, our results match findings on global forest loss; other studies also detected higher forest loss in Asia in categories I–III compared with categories IV–VI (Leberger et al., 2020).

In terms of human-driven mangrove loss, Leroux et al. (2010) also detected higher-than-expected human footprints in category Ia and lower than expected in category VI. Potential explanations of mangrove loss in category I could be a misinterpretation of IUCN categories in some places and subsequently a lack of regulations for human activities that are typically required in category I PAs. Inadequate regulations, for example,

could be a potential explanation for mangrove loss due to conversion to commodities production in Asia and nonproductive use in South America, which are typically not allowed in category I. Better guidance on how to apply the IUCN criteria, for example, through the expansion of social networks among conservation practitioners (Nelson et al., 2019) and the development of a PA verification program, might help reduce this issue (Dudley et al., 2004; Grorud-Colvert et al., 2021; UNEP-WCMC, 2007). Another explanation of human-driven mangrove loss in category I could be the existence of adequate regulations but a lack of management capacity to effectively prevent the illegal use of mangroves in PAs that have higher levels of restrictions. A lack of management capacity is indeed a common issue in conservation management and can be one of the main reasons for conservation failures (Gill et al., 2017).

Our findings indicated the importance of governance for ensuring conservation success regardless of IUCN-designated protection levels. PAs with the highest human-driven loss in our study across all IUCN categories were governed by national and subnational government agencies. Matching the level of protection with the actual capacity of the governance type could be therefore critical for more effective protection of mangroves.

Finally, our findings support the need, for all governance types and IUCN categories, to improve preparation to deal with natural-driven losses in mangrove PA from cyclones and coastal erosion. Natural losses, which are outside of regulatory controls (Duke et al., 2017), were ubiquitous across all types of governance and IUCN categories. Private PAs and IPLCs, for example, lost considerable amounts of mangroves due to erosion and extreme weather events across all regions. These impacts are expected to increase in the future as changes in cyclone frequency will pose important challenges to preventing the loss of mangroves and other coastal ecosystems (Duke, 2020; Taillie et al., 2020). Natural mangrove loss in PAs could be mitigated by increasing active intervention, such as restoration efforts that can be both effective in restoring biodiversity as well as providing social, economic, and cultural benefits to coastal communities (Narayan et al., 2020; Su et al., 2021). The failure to mitigate these natural-driven losses can have significant long-term implications for the ability of mangroves to provide key ecosystem services, such as coastal protection or carbon sequestration. Yet, even activities for managing natural-driven loss need to be supported by sufficient funding, management capacity, and good governance to be successful (Akbar et al., 2021), emphasizing the importance of effective management and governance in reducing mangrove loss not only for human drivers, but also for natural drivers.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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